

Heinz Tschaetsch

Metal Forming Practise

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Processes – Machines – Tools

Translated by Anne Koth

 Springer

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Wilthener Str. 6a
01324 Dresden, Germany

Originally German edition published by Vieweg Verlag, Wiesbaden 2005

Library of Congress Control Number: 2006926219

ISBN-10 3-540-33216-2 Springer Berlin Heidelberg New York

ISBN-13 978-3-540-33216-9 Springer Berlin Heidelberg New York

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Printed in Germany

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Cover design: Erich Kirchner, Heidelberg

Production: LE-TeX Jelonek, Schmidt & Vöckler GbR, Leipzig

Printed on acid-free paper 62/3100/YL - 5 4 3 2 1 0

Preface

The book “Metal Forming”, a translation of the eighth revised edition of “Umformtechnik” in German, describes the latest technology in the sector of metal forming.

Part I covers metal forming and shearing processes. It describes the main features of these processes, the tooling required and fields of application. Practical examples show how to calculate the forces involved in forming and the strain energy.

Part II describes forming machines and shows how to calculate their parameters.

This section also introduces flexible manufacturing systems in metal forming and the handling systems required for automation (automatic tool changing and workpiece conveyor systems).

Part III includes tables and flow diagrams with figures needed to calculate forming forces and strain energy.

These production units are automated as much as possible using modern CNC engineering to reduce non-productive time and changeover time, and thus also manufacturing costs. Alongside these economic advantages, however, another important reason for using metal working processes is their technical advantages, such as:

- material savings
- optimal grain direction
- work hardening with cold forming.

This book runs through all the main metal forming and shearing processes and the tooling and machines they involve. Incremental sheet forming was recently added in Chapter 15.4.

For engineers on the shop floor, this book is intended as an easily-navigable reference work. Students can use this book for reference, saving them time making notes in the lecture theatre so that they can pay better attention to the lecture.

I would particularly like to thank my colleague, Prof. Jochen Dietrich, Ph.D.eng. h.c., lecturer in production processes and CNC engineering at Dresden University of Applied Sciences, Germany (Hochschule für Technik und Wirtschaft), for his involvement as co-author from the 6th edition.

Thanks also to Dr. Mauerman of the Fraunhofer Institute for Machine Tools and Forming Technology, Chemnitz, Germany (Institut für Werkzeugmaschinen und Umformtechnik), for his collaboration on the 7th edition of the book.

Bad Reichenhall and Dresden, November 2005

Heinz Tschätsch

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Terms, symbols and units

Term	Symbol	Unit (selection)
Work, mechanical	W	Nm
Force (force of pressure)	F	N
Drawing force	F_{dr}	N
Blank holder force	F_{BH}	N
Velocity	v	m/s, m/min
Strain rate	$\dot{\phi}$	s ⁻¹
Pressure	p	Pa, bar
Shear stress	τ	N/mm ²
Tensile stress	R, σ	N/mm ²
Tensile strength	R_m	N/mm ²
Yield strength	R_e	N/mm ²
Elastic limit	$R_{P0.2}$	N/mm ²
Elongation	ε	m/m, %
Flow stress	k_{str}	N/mm ²
Flow stress before forming (cold forming)	k_{str0}	N/mm ²
Flow stress after forming (cold forming)	k_{str1}	N/mm ²
Resistance to flow	p_{fl}	N/mm ²
Deformation resistance	k_r	N/mm ²
Modulus of elasticity	E	N/mm ²
Density	ρ	t/m ³ , kg/dm ³ , g/cm ³
Blank length before forming	h_0, l_0	m, mm
Blank length after forming	h_1, l_1	m, mm
Area	A	m ² , mm ²
Area before forming	A_0	m ² , mm ²
Area after forming	A_1	m ² , mm ²
Volume	V	m ³ , mm ³
Forming temperature	T	K, °C
Coefficient of friction	μ	–
Efficiency	η	–

Term	Symbol	Unit (selection)
Deformation efficiency	η_F	–
Impact effect (with hammers)	η_i	–
Power	P	Nm/s, W
Acceleration	a, g	m/s ²
Press strokes per minute	n	min ⁻¹ , s ⁻¹
Stroke length	H, h	m, mm
Mass moment of inertia	I_d, θ	kgm ²
Mass	m	kg
Angular velocity	ω	s ⁻¹
Moment	M	Nm, J
Tangential force (with crank presses)	T_p	N
Crank angle (with crank presses)	α	°

Part I: Metal forming and shearing processes

1 Types of manufacturing process

The manufacturing processes are subdivided into six main groups.

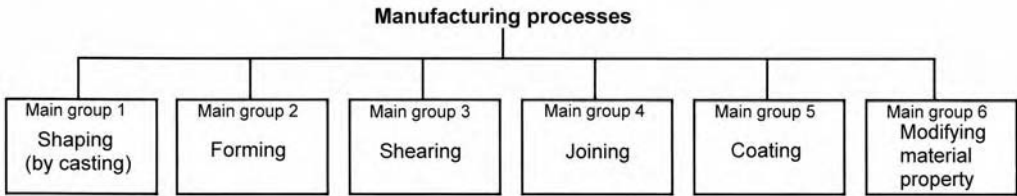
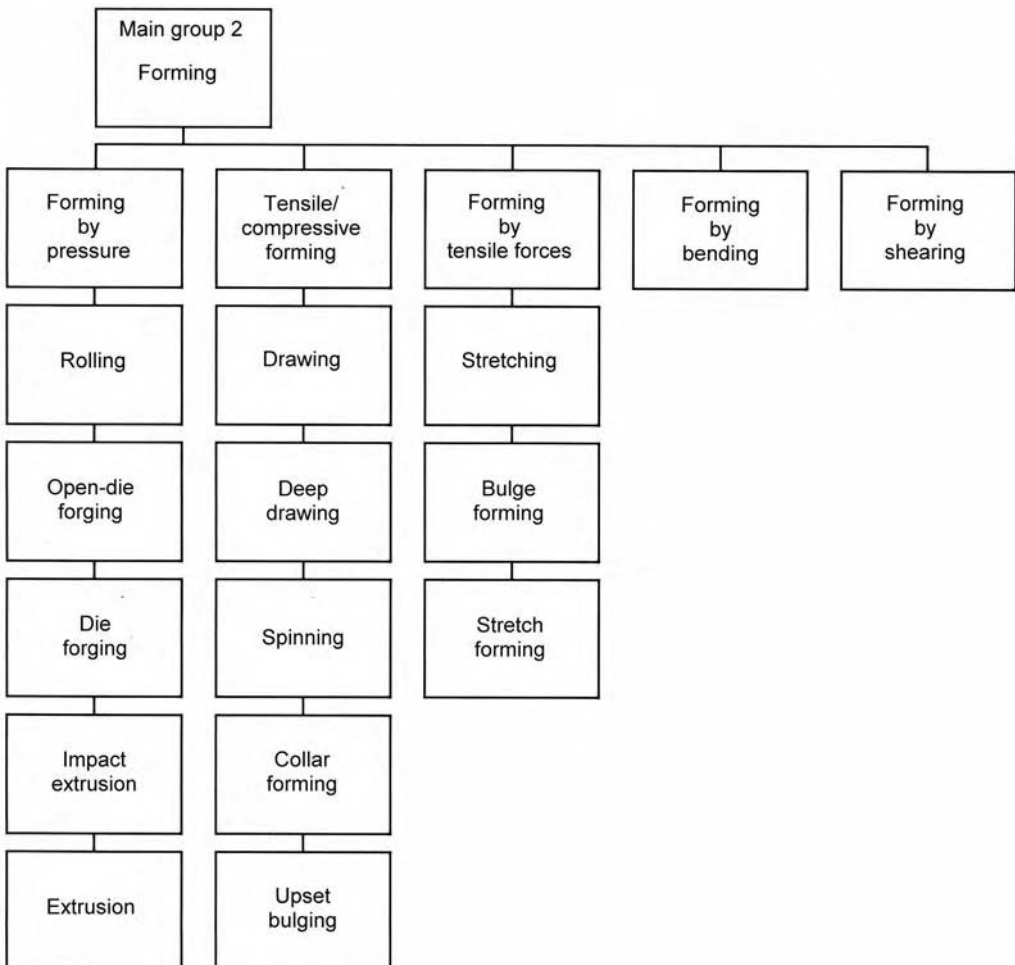


Fig 1.1 Types of production process

Of these six main groups, this book will study metal forming processes (Fig 1.2) and shearing processes (Fig. 1.3).

Metal forming is producing parts by plastic modification of the shape of a solid body.

During this process, both mass and material cohesion are maintained.



Shearing is separating adjacent parts of a workpiece, or shearing apart whole workpieces without creating chips.

With the separation processes, a difference is made between shearing and wedge-action cutting according to the form of the blade.

In industry, shearing is of greater importance (Fig. 1.4).

Main group 3
Shearing without the creation of chips
Shearing

Shearing off

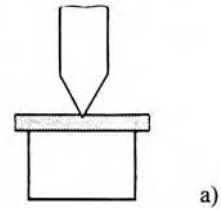
Blanking

Lancing

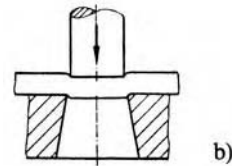
Notching

Notching and trimming

Piercing



a)



b)

Fig. 1.4 (top) Cutting.
a) Wedge-action cutting, b) Shearing

Fig. 1.3
(left) Types of shearing method

2 Terms and parameters of metal forming

2.1 Plastic (permanent) deformation

Unlike elastic deformation, during which, for example, a rod under a tensile load returns to its initial length as long as a defined value (elastic limit of the material, $R_{p0,2}$ limit) is not exceeded, a workpiece which is plastically deformed retains its shape permanently.

For the elastic range, the following applies:

$$\sigma_Z = \varepsilon \cdot E$$

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{l_0 - l_1}{l_0}$$

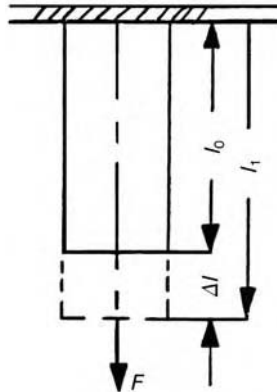


Fig. 2.1 Tension test bar – change in length under stress

σ_z	in N/mm^2	tensile stress
ε	in –	elongation
l_0	in mm	initial length
l_1	in mm	length under the influence of force
Δl	in mm	lengthening
R_m	in N/mm^2	tensile strength (was σ_B)
R_e	in N/mm^2	resistance at the yield point (was σ_S)
E	in N/mm^2	modulus of elasticity.

In the plastic range,

a permanent deformation is caused by sufficiently high shear stresses. This makes the atoms in row A_1 (Fig. 2.2) change their state of equilibrium in relation to row A_2 . The extent of the displacement is proportional to the extent of the shear stress τ .

If the effective shear stress is less than τ_f (τ_f yield shear stress) then $m < a/2$ and after the stress is removed the atoms return to their original position - elastic deformation.

If, however, the yield shear stress limit is exceeded, then $m > a/2$ or $m > n$, the atoms move into the field of attraction of the adjacent atoms and a new, permanent state of equilibrium is attained – plastic deformation.

The limit which must be exceeded is known as the plasticity criterion, and the associated resistance as the

flow stress k_{str}

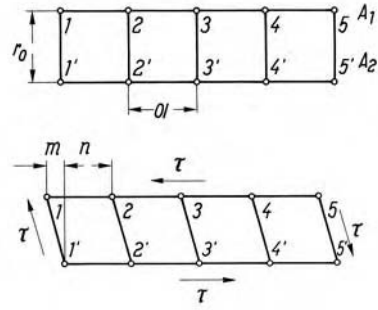


Fig. 2.2 Ideal process of position change of the atoms

2.2 Flow stress k_{str} in N/mm^2

2.2.1 Cold forming

In cold forming, k_{str} depends only on the extent of the deformation φ_p (principal strain) and on the material to be formed. The diagram showing the flow stress depending on the extent of the deformation (Fig. 2.3) is called a flow stress curve.

This denotes the strain hardening behaviour of a material. Flow stress curves can be approximately represented by the following equation.

$$k_{str} = k_{str100\%} \cdot \varphi^n = c \cdot \varphi^n$$

n – strain hardening coefficient

c – equivalent to k_{str1} when $\varphi = 1$ or when $\varphi = 100\%$

k_{str0} – flow stress before forming for $\varphi = 0$.

Mean flow stress k_{strm}

In some manufacturing processes the “mean flow stress” is needed to calculate force and work. It can be approximately determined from:

$$k_{strm} = \frac{k_{str0} + k_{str1}}{2}$$

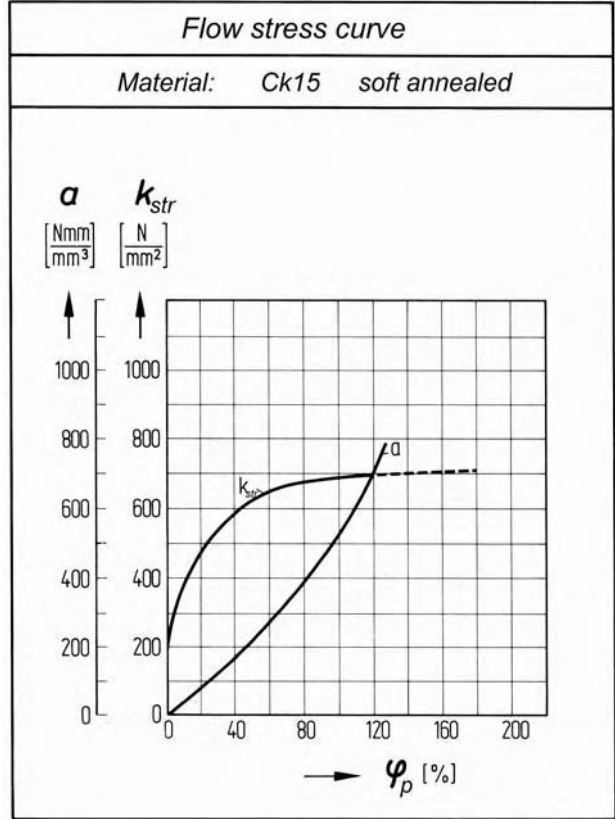
k_{strm} in N/mm^2 mean flow stress

k_{str0} in N/mm^2 flow stress for $\varphi = 0$

k_{str1} in N/mm^2 flow stress at the end of forming ($\varphi_p = \varphi_{max}$).

Fig. 2.3

Flow stress curve - cold forming
 $k_{str} = f(\varphi_p)$ $a = f(\varphi_p)$ a in Nmm/mm³
 specific strain energy



2.2.2 Hot forming

In hot forming above the recrystallisation temperature, k_{str} is independent of the degree of deformation φ . Here, k_{str} depends upon the strain rate $\dot{\varphi}$ (Fig. 2.4), the deformation temperature (Fig. 2.5) and the material to be deformed.

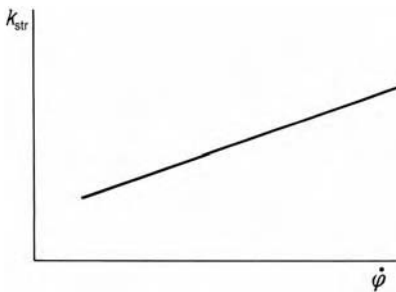


Fig. 2.4 $k_{str} = f(\dot{\varphi})$ in hot forming

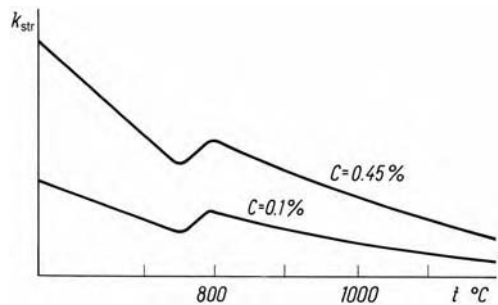


Fig. 2.5 $k_{str} = f(\text{temperature and of the material})$ in hot forming. With higher carbon steels, k_{str} decreases at a faster rate than with low carbon steels.

At high strain rates k_{str} rises during hot forming since the cohesion-reducing processes which arise due to recrystallisation no longer take place completely.

2.2.3 Calculation of the flow stress $k_{str_{sh}}$ for semi-hot forming

$$k_{str_{sh}} = c \cdot \varphi_p^n \cdot \dot{\varphi}^m \quad c = \frac{1400 - T}{3}$$

$k_{str_{sh}}$	in N/mm^2	flow stress in semi-hot forming
T	in $^{\circ}C$	temperature in semi-hot forming
c	in N/mm^2	empirical calculation coefficient
φ_p	–	principal strain
n	–	exponent of φ_p
$\dot{\varphi}$	in s^{-1}	strain rate
m	–	exponent of φ

Table 2.1 Exponents and semi-hot forming temperatures

Material	n	m	T $^{\circ}C$	C
C 15	0.1	0.08	500	300
C 22	0.09	0.09	500	300
C 35	0.08	0.10	550	283
C 45	0.07	0.11	550	283
C 60	0.06	0.12	600	267
X 10 Cr 13	0.05	0.13	600	267

Example:

where:	material C 60	
	operating temperature:	$T = 600 \text{ }^{\circ}C$
	principal strain:	$\varphi_p = 1.10 = 110 \%$
	strain rate	$\dot{\varphi} = 250 \text{ s}^{-1}$

solution:

$c = 267$, $n = 0.06$, $m = 0.12$ from Table 2.1

$$k_{str_{sh}} = c \cdot \varphi_p^n \cdot \dot{\varphi}^m = 267 \cdot 1.1^{0.06} \cdot 250^{0.12}$$

$$k_{str_{sh}} = 267 \cdot 1.0 \cdot 1.94 = \underline{\underline{515 \text{ N/mm}^2}}$$

2.3 Deformation resistance k_f

The resistance to be overcome during a deformation is composed of the flow stress and the friction resistances in the tool, which are brought together under the term “resistance to flow”.

$$k_r = k_{str} + p_{fl}$$

k_r in N/mm² deformation resistance
 k_{str} in N/mm² flow stress
 p_{fl} in N/mm² resistance to flow

The resistance to flow p_{fl} can be calculated mathematically for rotationally symmetric pieces.

$$p_{fl} = \frac{1}{3} \mu \cdot k_{str} \frac{d_1}{h_1}$$

From this it follows that for the deformation resistance k_w

$$k_r = k_{str} \left(1 + \frac{1}{3} \mu \cdot \frac{d_1}{h_1} \right)$$

k_{str} in N/mm² flow stress at the end of forming
 d_0 in mm diameter before forming
 h_0 in mm height before forming (Fig. 4.6)
 μ – coefficient of friction ($\mu = 0.15$)
 d_1 in mm diameter after forming
 h_1 in mm height after forming
 η_F – deformation efficiency.

For asymmetric pieces, which can only be studied mathematically to a limited extent, the deformation resistance is determined with the help of the deformation efficiency.

$$k_r = \frac{k_{str}}{\eta_F} .$$

2.4 Deformability

This means the ability of a material to be deformed. It depends upon:

2.4.1 Chemical composition

In steels, for example, the cold deformability depends on the C content, the components of the alloy (Ni, Cr, Va, Mo, Mn) and the phosphor content. The higher the C content, the P content and the alloy components, the lower the deformability is.

2.4.2 Crystalline structure

Here, the grain size and above all the pearlite structure are important.

– Grain size

Steels should be as fine-grained as possible, since in steels with small to medium grain size, the crystallites are easier to displace on the crystallite slip planes.

- Pearlite structure

Pearlite is the carbon carrier in the steel. It is difficult to deform. For this reason it is important that the pearlite is equally distributed in the ferritic matrix, which is easy to cold form.

2.4.3 Heat treatment

An equally-distributed structure is achieved by normalising (above A_{c3}) and fast cooling. The resulting hardness is cancelled out by subsequent soft annealing (around A_{c1}).

Note: only soft annealed material can be cold formed.

2.5 Degree of deformation and principal strain

2.5.1 Bulk forming process

The measure of the extent of a deformation is the degree of deformation. The calculation is generally made from the relation between an indefinitely small measurement difference, dx , and an existing measurement x . By integrating it into the limits x_0 to x_1 this produces

$$\varphi_x = \int_{x_0}^{x_1} \frac{dx}{x} = \ln \frac{x_1}{x_0}.$$

when it is presumed that the volume of the body to be deformed remains constant during forming.

$$V = l_0 \cdot w_0 \cdot h_0 = l_1 \cdot w_1 \cdot h_1.$$

According to which value changes the most during forming, a difference is made (Figure 2.6) between

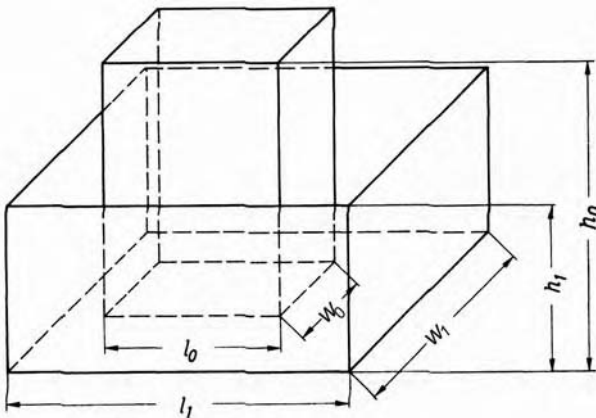


Figure 2.6

Cuboid before forming with the measurements h_0 , w_0 , l_0 and after forming with the measurements h_1 , w_1 , l_1

$$\text{Degree of upsetting} \quad \varphi_1 = \ln \frac{h_1}{h_0}$$

$$\text{Degree of lateral flow} \quad \varphi_2 = \ln \frac{w_1}{w_0}$$

$$\text{Degree of elongation.} \quad \varphi_3 = \ln \frac{l_1}{l_0}$$

If the change of cross section or the change of wall thickness are dominant values, φ can also be determined from these values:

$$\text{in the case of a change in wall thickness} \quad \varphi = \ln \frac{s_1}{s_0}$$

$$\text{in the case of a change of cross section} \quad \varphi = \ln \frac{A_1}{A_0} .$$

The sum of the three deformations in the three main directions (length, width, height) is equal to 0. What is lost in the height is gained in width and length – Figure 2.6.

$$\varphi_1 + \varphi_2 + \varphi_3 = 0$$

This means one of these three deformations is equal to the negative sum of the two others.

$$\text{For example, } \varphi_1 = -(\varphi_2 + \varphi_3).$$

This, the greatest deformation, is known as the **principal strain**, “ φ_p ”.

It characterises the manufacturing process and enters into the calculation of force and work.

It is how the extent of a deformation is measured.

The degree of deformation that a material can withstand, i.e. how great its deformability is, can be taken from tables of standard values showing permissible deformation $\varphi_{p \text{ perm}}$.

The workpiece can only be produced in a single pass if actual deformation during its production is equal to or less than $\varphi_{p \text{ perm}}$. Otherwise, several passes are required with intermediate annealing (soft annealing).

2.5.2 Sheet metal forming

During deep drawing, the number of draws required can be determined from the drawing ratio β .

$$\beta = \frac{D}{d} = \frac{\text{blank diameter}}{\text{punch diameter}} .$$

As the values D and d are known for a particular workpiece during deep drawing, they can be used to calculate β .

Here, tables of standard values (see the chapter on deep drawing) are once more used to find the permissible drawing ratio β_{perm} ; it is then compared with the calculated drawing ratio. The workpiece can only be produced in a single phase if β is equal to or less than β_{perm} . Otherwise, several passes are necessary.

2.6 Strain rate

If a deformation is carried out in the time t , this results in an average strain rate of:

$$w_m = \frac{\varphi}{t}$$

w_m	in %/s	mean strain rate
φ	in %	degree of deformation
t	in s	deformation time

It may, however, also be determined by the ram / slide velocity and the initial height of the workpiece.

$$\dot{\varphi} = \frac{v}{h_0}$$

$\dot{\varphi}$	in s^{-1}	strain rate
v	in m/s	velocity of the ram / slide
h_0	in s	height of the blank.

2.7 Exercise on Chapter 2

- Which conditions must be met in order to achieve plastic (permanent) deformation?
- What is meant by “flow stress” k_{str} ?
- How can the flow stress value be ascertained?
- How can the mean yield stress be (approximately) calculated?
- What influence does the forming temperature have on flow stress?
- What influence does the strain rate have on flow stress?
 - during cold forming
 - during hot forming?
- What is meant by “cold forming”?
- What is meant by “deformability”?
- What factors does the deformability of a material depend upon?
- Explain these terms:
 - degree of upsetting
 - degree of lateral flow
 - degree of elongation.
- What is meant by “principal strain”?

3 Surface treatment

If the blanks (sections of wire or rods) were simply inserted into the moulding die and then pressed, the die would be made useless after only a few units. Galling would occur in the die because of cold welding between the workpiece and the die. As a result, burrs would form on the die which would make the pressed parts unusable. For this reason, the blanks must be carefully prepared before pressing. This preparation, which is summed up as “surface treatment”, includes

pickling, phosphating, lubricating.

3.1 Cold bulk forming

3.1.1 Pickling

The pickling process is intended to remove oxidic coatings (rust, scale) so that the surface of the press blank is metallurgically clean, ready for the actual surface treatment.

Diluted acids are used as a pickling agent, e.g. for steel, 10% sulphuric acid (percent by volume).

3.1.2 Phosphating

If grease, oil or soap were directly applied to a metallurgically clean (pickled) blank as a lubricant, the lubricant would have no effect. The film of lubricant would come off during pressing and cold welding and galling would take place.

Therefore a lubricant carrier coating must be applied first, forming a firm bond with the blank material.

Phosphates are used as a carrier coating. Phosphating applies a non-metallic lubricant carrier, firmly bonded with the base material of the blank made of

steel (with the exception of Nirosta steels)
zinc and zinc alloys
aluminium and aluminium alloys.

This porous layer acts as a lubricant carrier. The lubricant diffuses into the pores and can thus no longer be rubbed off of the blank. Coating thicknesses of the applied phosphates range between 5 and 15 μm .

3.1.3 Lubrication

– *Function of the lubricant:*

The lubricant is intended to:

- prevent the die and the workpiece from coming into direct contact with one another, in order to make it impossible for material to be transferred from the die to the workpiece (cold welding);
- reduce friction between the surfaces gliding against one another;
- keep the heat which occurs during forming within limits.

– *Lubricants for cold forming*

For cold forming, the following materials can be employed as lubricants.

– *Lime (liming)*

Liming means that the blanks are immersed in a solution of water with 8 percent lime by weight heated to 90°C. Liming can only be used for steel for small deformations.

– *Soap*

Here, for example, solutions of hard soap are used with 4-8 percent soap by weight at 80°C and an immersion time of 2-3 minutes. Their use is appropriate when there is a medium lubricant requirement.

– *Mineral oils (possibly with a little supplementary grease)*

These lubricants, available on the market as “Press Oils”, are suited to high lubricant requirements, above all in automatic production. As well as lubrication, they also assume a cooling function.

– *Molybdenum disulphide (molycote suspensions)*

For lubricants on a molybdenum disulphide basis, which are suited to the highest lubrication requirements,

MoS₂ water suspensions

are mainly used. Immersion time ranges from 2 to 5 minutes at a temperature of 80 °C. The concentration (mean value) is around 1 : 3 (i.e. 1 part molycote, 3 parts water).

For particularly difficult deformations, higher-concentrated suspensions are also used.

3.2 Cold sheet forming

As a rule pure lubricating agents such as drawing oils or drawing greases suffice for deep drawing, preventing direct contact between the die and the workpiece.

3.3 Hot forming (drop forging)

During drop forging, sawdust and graphite suspensions are used as lubricants and anti-seize agents. Optimal results can be achieved with 4% colloidal graphite in water or light oil. With the liquid lubricants, however, attention must be paid to correct dosage. Too much suspension raises the gas pressure in the die and makes moulding difficult.

3.4 Exercise on Chapter 3

1. What is the function of the lubricant during forming?
2. Why can the blank not simply be lubricated with oil or grease during cold forming?
3. How must the blanks be pre-treated (surface treated) before a cold forming pressing process?
4. What lubricants are used in cold forming?
5. What lubricants are used in drop forging?

4 Upset forging

4.1 Definition

Upset forging is a bulk forming process where the effect of the pressure is on the longitudinal axis of the workpiece.

4.2 Application

Commonly used for the production of mass-produced parts such as screws, rivets, head bolts, valve lifters etc. (Figures 4.1, 4.2 and 4.3).

4.3 Starting stock

The starting stock is a length of rod cut from round or shaped stock. In many cases, above all in screw and bolt production, production is carried out from wire coils (Figure 4.2). As rolled stock is cheaper than drawn stock, it is used most commonly.

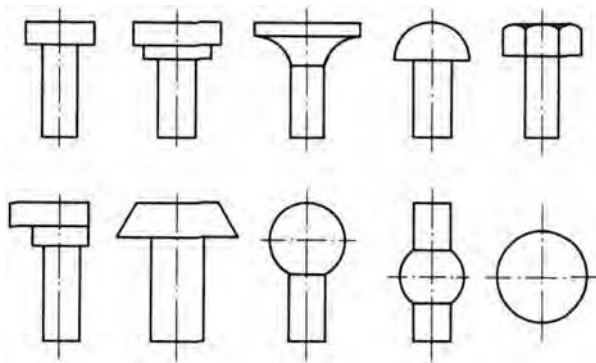


Figure 4.1 Typical upset parts

Figure 4.2

Steps in the production of a bolt on a transfer press with a thread rolling device. 0 shear off stock, 1 pre-form head, 2 finish head, 3 reduce shank to diameter for thread rolling, 4 stamp out hexagon, 5 chamfer shank (round off), 6 thread rolling

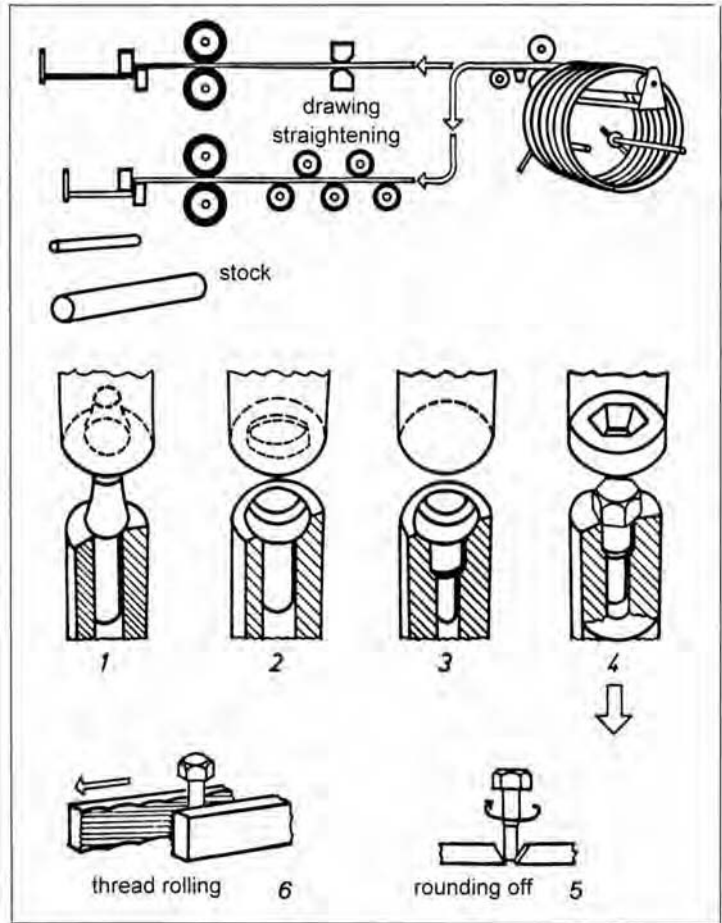
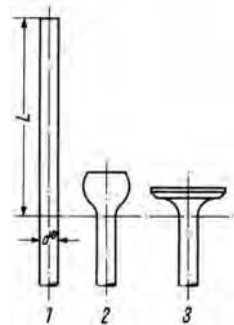


Figure 4.3

Production of a valve lifter.

- 1 initial blank
- 2 pre-form
- 3 final heading



4.4 Permissible deformations

Here, a difference must be made between two criteria:

4.4.1 Measurement for the extent of deformation

This sets the limits for the material to be formed (deformability).

Upsetting ε_p

$$\varepsilon_p = \frac{h_0 - h_1}{h_0}$$

Degree of upsetting φ_p

φ_p Degree of upsetting
 φ_p in % = $\varphi_h \cdot 100$

$$\varphi_p = \ln \frac{h_1}{h_0}$$

$$\varphi_p = \left(\ln \frac{h_1}{h_0} \right) \cdot 100[\%]$$

Initial length or length after upset forging, if the permissible deformation is provided

$$h_0 = h_1 \cdot e^{\varphi_p}$$

h_0 in mm length before upset forging
 h_1 in mm length after upset forging

Calculation of φ_p from ε_p

$$\varphi_p = \ln (1 - \varepsilon_p)$$

Table 4.1 Permissible deformation

Material	$\varphi_{p\text{perm}}$
Al 99,88	2.5
Al MgSil	1.5 – 2.0
Ms 63–85 CuZn 37–CuZn 15	1.2 – 1.4
Ck10–Ck 22 St 42–St 50	1.3 – 1.5
Ck 35–Ck 45 St 60–St 70	1.2 – 1.4
Cf 53	1.3
16 MnCr 5 34 CrMo 4	0.8 – 0.9
15 CrNi 6 42 CrMo 4	0.7 – 0.8

4.4.2 Upsetting ratio

The upsetting ratio s sets the limits of stock dimensions in relation to the danger of buckling during upset forging. What is known as the “upsetting ratio” is the ratio of free length of stock not inserted in the die to the initial diameter of the stock (Figure 4.4).

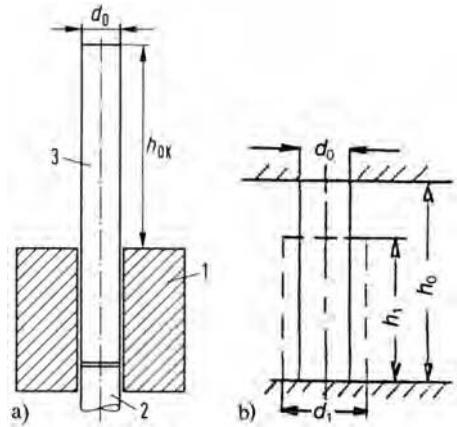
Upsetting ratio s

$$s = \frac{h_0}{d_0} = \frac{h_{0hd}}{d_0}$$

- h_0 in mm stock length
- h_1 in mm length after upset forging
- d_0 in mm initial diameter
- h_{0hd} in mm length of stock not inserted into the die

Figure 4.4

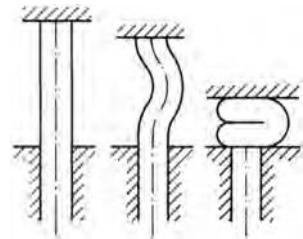
a) free length of bolt not inserted in the die. 1 bottom die, 2 ejector, 3 stock before upset forging; b) open-die upset forging, between parallel surfaces



If the permissible upsetting ratio is exceeded then the bolt buckles (Fig 4.5).

Figure 4.5

Buckling of the blank when the upsetting ratio is exceeded



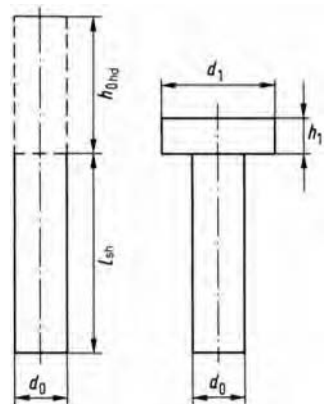
Permissible upsetting ratio:

- if the upset part is to be produced in one operation (Figure 4.6).

$$s \leq 2.6$$

Figure 4.6

Head bolt produced in one operation



- If the upset part is to be produced in two operations (Figure 4.7) then:

$$s \cong 4.5$$

Tapered forms (Figure 4.8) are used as pre-forms as they flow very well.

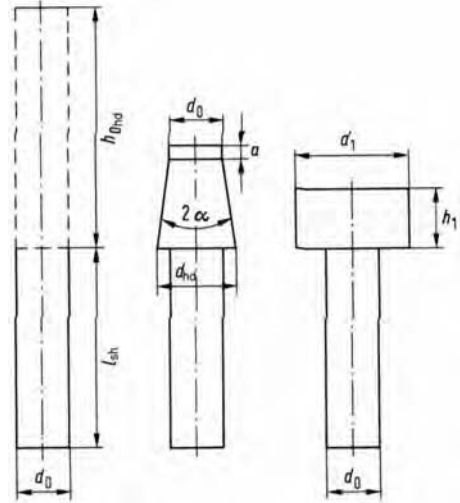


Figure 4.7 Head bolt produced using the two-stage method, with tapered pre-form

Table 4.2 Dimensions of solid pre-forming tools.

Upsetting ratio	Cone angle	Guide length	Length of the tapered part of the pre-former
$s = h_0/d_0$	2α [degree]	a [mm]	c [mm]
2.5	15	$0.6 d_0$	$1.37 d_0$
3.3	15	$1.0 d_0$	$1.56 d_0$
3.9	15	$1.4 d_0$	$1.66 d_0$
4.3	20	$1.7 d_0$	$1.66 d_0$
4.5	25	$1.9 d_0$	$1.45 d_0$

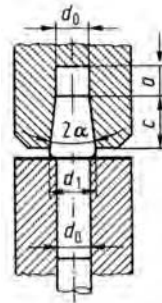


Figure 4.8 Dimensions of solid pre-formers

When the volume of the finished part is provided (e.g. head volume of the head bolt in Figure 4.6), the following equation can be used to calculate the minimum required size of the initial diameter d_0 at a certain upsetting ratio s .

$$d_0 = \sqrt[3]{\frac{4 \cdot V}{\pi \cdot s}}$$

- d_0 in mm required stock diameter
- V in mm^3 volume involved in the deformation
- s - upsetting ratio

4.5 Upsetting force

4.5.1 For rotationally symmetric parts

- F in N upsetting force
- A_1 in mm^2 surface after upset forging
- k_{str_1} in N/mm^2 flow stress at the end of upset forging
- μ – coefficient of friction
($\mu = 0.1 - 0.15$)
- d_1 in mm diameter after upset forging
- h_1 in mm height after upset forging

$$F = A_1 \cdot k_{\text{str}_1} \left(1 + \frac{1}{3} \cdot \mu \frac{d_1}{h_1} \right)$$

4.5.2 For bodies of any shape

- η_F – deformation efficiency

$$F = \frac{A_1 \cdot k_{\text{str}_1}}{\eta_F}$$

4.6 Upset forging work

- W in Nmm upset forging work
- V in mm^3 volume involved in the deformation
- k_{str_m} in N/mm^2 mean flow stress
- φ_p – principal strain
- η_F – deformation efficiency ($\eta_F = 0.6 - 0.9$)
- h_0 in mm stock height
- x – process factor
- F_m in N mean force
- F_{max} in N maximum force

$$W = \frac{V \cdot k_{\text{str}_m} \cdot \varphi_p}{\eta_F}$$

or from the force and deformation path

$$W = F \cdot s \cdot x$$

$$W = F(h_0 - h_1) \cdot x$$

$$x = \frac{F_m}{F_{\text{max}}} \quad x \cong 0.6$$

The process factor x is attained from an imagined ideal mean force (Figure 4.9), imagined to be constant across the whole deformation displacement, and the maximum force. The mean resultant force is placed in the force-displacement diagram in such a way that an oblong which is equal in area is produced.

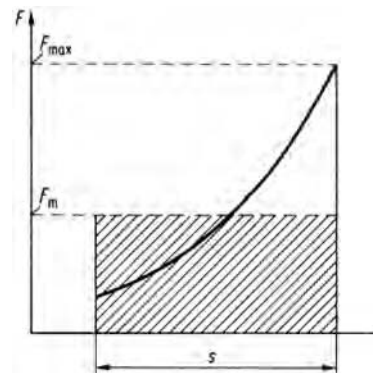


Figure 4.9 Force-displacement diagram during upset forging

4.7 Upsetting tooling

The main stresses on upset-forging tooling are pressure and friction. For this reason it must be designed to withstand breakage and wear. The basic construction of an upsetting assembly is shown in Figure 4.10.

Table 4.3 shows the materials used in the most important tooling elements (Figure 4.11).

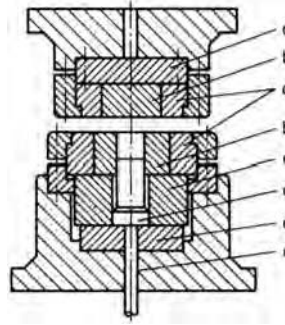


Fig. 4.10 Basic components of an upsetting assembly. a) Pressure plate, b) punch (snap die), c) retaining ring (shrink fit), d) counterpunch, e) ejector

Table 4.3 Tooling materials

Description of the tool	Steel grade used for the tool		Hardness of the tool HRC
	Short designation	Material no.	
a) Shearing blade	X 155 CrVMo 12 1 X 165 CrMoV 12 S 6-5-2 60 WCrV 7	1.2379 1.2601 1.3343 1.2550	57 to 60 57 to 60 57 to 60 48 to 55
b) Shearing bottom die	X 155 CrVMo 12 1 X 165 CrMoV 12 S 6-5-2 60 WCrV 7	1.2379 1.2601 1.3343 1.2550	57 to 60 57 to 60 57 to 60 54 to 58
c) Solid pre-former	C 105 W 1 100 V 1 145 V 33	1.1545 1.2833 1.2838	57 to 60 57 to 60 57 to 60
c) Shrunk pre-former	X 165 CrMoV 12 S 6-5-2	1.2601 1.3343	60 to 63 60 to 63
d) Solid finishing punch	C 105 W1 100 V 1 145 V 33	1.1545 1.2833 1.2838	58 to 61 58 to 61 58 to 61
d) Shrunk finishing punch	X 165 CrMoV 12 S 6-5-2	1.2601 1.3343	60 to 63 60 to 63
e) Solid bottom die	C 105 W 1 100 V 1 145V33x	1.1545 1.2833 1.2838	58 to 61 58 to 61 58 to 61
e) Shrunk bottom die	S 6-5-2 X 155 CrVMo 12 1 X 165 CrMoV 12	1.3343 1.2379 1.2601	60 to 63 58 to 61 58 to 61

f) Retaining ring	56 NiCrMoV 7 X 40 CrMoV 5 1 X 3 NiCoMoTi 1895	1.2714 1.2344 1.2709	41 to 47 41 to 47 50 to 53
g) Ejector	X 40 CrMoV 5 1 60 WCrV 7	1.2344 1.2550	53 to 56 55 to 58
Shearing tool: (Figure 4.11 b)			
1 Bottom die	S 6-5-2	1.3343	58 to 61
2 Punch	60 WCrV 7 X 155 CrMo 12 1 X 165 CrMoV 12	1.2550 1.2379 1.2601	58 to 61 58 to 61 58 to 61
3 Ejector	X 40 CrMoV 51 60 WCrV 7	1.2344 1.2550	53 to 56 55 to 58

Fig. 4.11 a)
The most important elements of an upset-forging assembly
a shearing blade
b shearing bottom die
c pre-former
d heading punch
e bottom die / reducing die
f reinforcement
g ejector

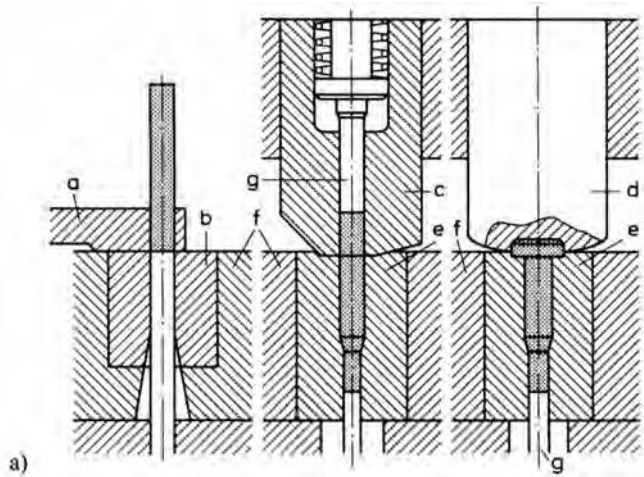
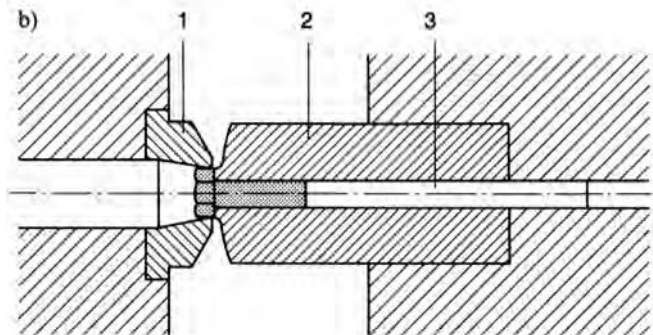


Fig. 4.11 b)
Shearing tool to punch out the hexagon
1 bottom die
2 punch
3 ejector



Instead of steel bottom dies, with reinforced tools (Figure 4.12) cemented carbides are also employed as they are particularly wear resistant. Table 4.4 shows tried and tested carbide types compared to tool steels for bulk forming.

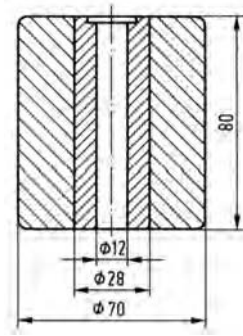


Figure 4.12

Press bottom die with cemented carbide core for M12 bolt

Table 4.1 Cemented carbides for bulk forming processes

Tool	Type of cemented carbide	HV 30 N/mm ² · 10 ³	Comparable steels	
			Material no.	Designation
Punch	GT 20	13	1.3343	S 6-5-2
Punch	GT 30	12	1.3207	S 10-4-3-10
Bottom die + punch	GT 40	10.5	1.2601	X 165 CrMoV 12
Bottom die + punch	GT 55	8.5	1.2080	X 210 Cr 12
Bottom die + punch	BT 30	11.5	1.2550	60 WCrV 7
Bottom die + punch	BT 40	11.0	1.2542	45 WCrV 7

4.8 Achievable precision

4.8.1 Cold upset forging

The precision which can be achieved with mass-produced parts produced without chips depends upon the working method, the condition of the machine and the condition of the tooling. The tolerances always relate to an optimal tool workload (tool life). Far smaller tolerances are technically achievable.

Table 4.5 Dimensional accuracy during cold upset forging

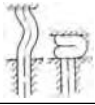



Nominal size in mm	5	10	20	30	40	50	100
Head height tolerance in mm	0.18	0.22	0.28	0.33	0.38	0.42	0.5
Head Ø tolerance in mm	0.12	0.15	0.18	0.20	0.22	0.25	0.3

4.8.2 Hot upset forging

During hot upset forging, the diameter and height tolerances are roughly five times as high as those during cold upset forging.

4.9 Defects in upset forging

Table 4.6 Upset forging defects and their causes

Defect	Cause	Steps to be taken
Buckling of the shank 	Upsetting ratio s exceeded.	Reduce s by pre-forming
Longitudinal crack in the head 	Die scars or surface damage in the starting material.	Check the stock for surface damage.
Shear cracks in the head 	Deformability exceeded $\phi_p > \phi_{perm}$	Reduce degree of deformation Divide forming into two operations.
Internal cracks in the head 		

4.10 Example calculations

Example 1

The aim is to produce head bolts from a sketch (Fig. 4.13) out of Ck 35.

Where: $\eta_F = 0.8$; $\mu = 0.15$

- Find:
- Dimensions of starting stock
 - Number of upsetting operations
 - Upset forging force
 - Upset forging work

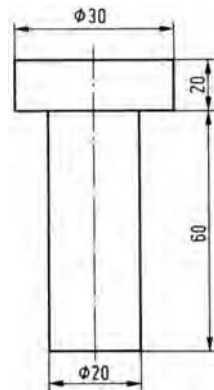


Figure 4.13 Head bolt

Solution:

1. Volume of the head of the part to be produced

$$V_{\text{hd}} = \frac{d^2 \cdot \pi \cdot h}{4} = \frac{(30 \text{ mm})^2 \cdot \pi \cdot 20 \text{ mm}}{4}$$

$$= 14137 \text{ mm}^3.$$

An extra 1-2% are usually added to this volume to make up for melt and pickling losses. This extra percentage is left out here for simplification.

2. Determination of the initial diameter

As the shank diameter is 20 mm, here the initial diameter is chosen as

$$d_0 = 20 \text{ mm}.$$

For the initial area, this means

$$A_0 = \frac{d_0^2 \pi}{4} = 314.2 \text{ mm}^2.$$

3. Initial height of the head (Figure 4.6)

$$h_{0\text{hd}} = \frac{V_{\text{hd}}}{A_0} = \frac{14137 \text{ mm}^3}{314.2 \text{ mm}^2} = 45 \text{ mm}.$$

4. Blank length

$$L = h_{0\text{hd}} + h_{\text{sh}} = 45 \text{ mm} + 60 \text{ mm} = 105 \text{ mm}.$$

This results in the dimension of the blank:

$$\text{Ø}20 \times 105 \text{ long}.$$

5. Upsetting ratio

$$s = \frac{h_{0\text{hd}}}{d_0} = \frac{45 \text{ mm}}{20 \text{ mm}} = 2.25$$

Because s is smaller than the highest permissible value, 2.6, the workpiece can be produced in one operation from the point of view of bulging.

6. Size of principal strain

$$\varphi_p = \ln \frac{h_1}{h_{0\text{hd}}} = \ln \frac{20 \text{ mm}}{45 \text{ mm}} = 0.81 \rightarrow 81\%.$$

The permissible deformation from Table 1 is

$$\varphi_{p \text{ perm}} = 140 \%$$

Because the actual deformation based on the dimensions, φ_p , is smaller than the permissible deformation $\varphi_{p \text{ perm}}$, it is also possible to produce the workpiece in one operation from the point of view of deformability.

7. Flow stress

The values for k_{str} are taken from the flow stress curve for the material Ck 35, or from Table 1, Part III

$$k_{\text{str}0} = 340 \text{ N/mm}^2 \text{ for } \varphi_p = 0 \%,$$

$$k_{\text{str}1} = 920 \text{ N/mm}^2 \text{ for } \varphi_p = 81 \%,$$

$$k_{\text{str}m} = \frac{k_{\text{str}0} + k_{\text{str}1}}{2} = \frac{340 + 920}{2} = 630 \text{ N/mm}^2.$$

8. Upset forging force

$$\begin{aligned} F &= A_1 \cdot k_{\text{str}1} \cdot \left(1 + \frac{1}{3} \mu \cdot \frac{d_1}{h_1} \right) \\ &= \frac{(30 \text{ mm})^2 \cdot \pi}{4} \cdot 920 \frac{\text{N}}{\text{mm}^2} \left(1 + \frac{1}{3} \cdot 0.15 \cdot \frac{30 \text{ mm}}{20 \text{ mm}} \right). \\ F &= 699082.8 \text{ N} = 699 \text{ KN}, \end{aligned}$$

9. Upset forging work

Example 2

The aim is to produce spheres 30 mm in diameter out of 42 CrMo 4. The initial diameter is to be set in such a way that the upsetting ratio is $s = 2.6$.

Where: $\eta_F = 0.8$; $\mu = 0.15$.

Find:

1. volume of the sphere
2. blank diameter d_0 for $s = 2.6$
3. blank dimensions
4. actual upsetting ratio
5. upset forging force
6. upset forging work

Solution:

1. Volume of the sphere

$$V = \frac{4}{3} \pi \cdot r^3 = \frac{4}{3} \cdot \pi \cdot (15 \text{ mm})^3 = 14137.16 \text{ mm}^3.$$

2. Initial diameter from upsetting ratio

$$d_0 = \sqrt[3]{\frac{4 \cdot V}{\pi \cdot s}} = \sqrt[3]{\frac{4 \cdot 14137.16 \text{ mm}^3}{\pi \cdot 2.6}} = 19.05 \text{ mm} \quad |$$

As material (rolled steel) in this size (19.05 \varnothing) is not commercially available, instead

$$d_0 = 20 \text{ mm } \varnothing \text{ is chosen.}$$

At the same time, this choice means that the upsetting ratio is on the safe side, as it means it goes down to less than 2.6.

3. Blank length

$$h_0 = \frac{V}{A_0} = \frac{14137.16 \text{ mm}^3}{(20 \text{ mm})^2 \cdot \pi / 4} = 44.99 \text{ mm}$$

$$h_0 = 45 \text{ mm chosen.}$$

4. Actual upsetting ratio from the blank dimensions

$$s = \frac{h_0}{d_0} = \frac{45 \text{ mm}}{20 \text{ mm}} = 2.25.$$

Because

$$s_{\text{actual}} < s_{\text{perm}} \\ 2.25 < 2.6,$$

the sphere can safely be produced from these blank dimensions without any danger of buckling.

5. Upsetting force

$$5.1 \quad \varphi_p = \ln \frac{h_1}{h_0} = \ln \frac{30 \text{ mm}}{45 \text{ mm}} = 0.4 \rightarrow 40\%$$

$\varphi_{p \text{ perm}} = 80\%$ (from Table 1), therefore possible in one operation from the point of view of deformability

- 5.2 Take k_{str} values from flow stress curve:

$$k_{\text{str}0} = 420 \text{ N/mm}^2, \quad k_{\text{str}1} = 960 \text{ N/mm}^2$$

$$k_{\text{strm}} = \frac{k_{\text{str0}} + k_{\text{str1}}}{2} = \frac{420 + 960}{2} = 690 \text{ N/mm}^2$$

$$\begin{aligned} 5.3 \quad F &= A_1 \cdot k_{\text{str1}} \cdot \left(1 + \frac{1}{3} \cdot \mu \cdot \frac{d_1}{h_1}\right) \\ &= (30 \text{ mm})^2 \cdot \frac{\pi}{4} \cdot 960 \text{ N/mm}^2 \cdot \left(1 + \frac{1}{3} \cdot 0.15 \cdot \frac{30 \text{ mm}}{30 \text{ mm}}\right) \\ F &= 712513.2 \text{ N} = 712 \text{ kN}. \end{aligned}$$

6. Upset forging work

$$\begin{aligned} W &= \frac{V \cdot k_{\text{strm}} \cdot \varphi_h}{\eta_F \cdot 10^3 \text{ mm/m}} = \frac{14137.16 \text{ mm}^3 \cdot 690 \text{ N/mm}^2 \cdot 0.4}{0.8 \cdot 10^3 \text{ mm/m}} \\ W &= 4877.3 \text{ N m} = 4.8 \text{ kN m} \end{aligned}$$

Calculation sheet: upset forging

1. Material: _____
2. $d_0 =$ _____ mm, $A_0 =$ _____ mm²
3. Volume
 $V =$ _____ mm³
4. $h_0 = \frac{V}{A_0} =$ _____ = _____ mm
5. $s = \frac{h_0}{d_0} =$ _____ = _____
6. $\varphi_p = \ln \frac{h_0}{h_1} = \ln$ _____ = \ln _____ = _____ %
7. $k_{\text{str0}} =$ _____ ; $k_{\text{str1}} =$ _____ ; $k_{\text{strm}} =$ _____ N/mm²
8. $F = A_1 \cdot k_{\text{str1}} \cdot \left(1 + \frac{1}{3} \cdot \mu \cdot \frac{d_1}{h_1}\right)$
 $F =$ $\left(1 + \frac{1}{3} \cdot 0.15 \cdot \frac{\quad}{\quad}\right)$
 $F =$ $N =$ _____ kN
- 8.1 $F = \frac{A_1 \cdot k_{\text{str1}}}{\eta_F} = \frac{\quad}{0.7 \cdot 10^3} =$ _____ kN

$$9. \quad W = \frac{V \cdot k_{\text{str}_m} \cdot \varphi_p}{\eta_F \cdot 10^6} = \frac{\quad}{0.7 \cdot 10^6}$$

$$W = \underline{\underline{\quad}} \quad \text{kN m}$$

10^6 = Conversion factor of N mm into kN m.

4.11 Exercise on Chapter 4

1. What is upset forging used for most commonly?
2. What is the measure of the extent of a deformation?
3. How can you find information on the permissible deformation values ?
4. How can you use deformability to check the number of operations required to produce an upset part?
5. What else must be taken into account apart from deformability?
6. What happens if the permissible upsetting ratio is exceeded?
7. Name the most important elements of upset forging tooling.
8. What has gone wrong if shear cracks appear on the head of the upset part?
9. What steps are required to produce a hexagonal bolt?
10. Why is it cheaper to produce a bolt using the forging method shown on Page 19 than with an automatic lathe?
11. Which special forging presses are used today to produce screws and bolts? (Chap. 27.2)

5 Extrusion

5.1 Definition

Extrusion is a bulk forming process in which the material is made to flow using high pressure. The deformation takes place mainly at room temperature – cold extrusion – as by this means plate-finished workpieces with close dimensional accuracy are obtained.

The billets are only heated to forging temperature – hot extrusion – if extreme conditions would be necessary for cold forging (high punch force, high degree of deformation, etc).

Workpieces produced in this way are of low dimensional accuracy and have rough surfaces due to scaling, requiring reworking in most cases.

5.2 Application of the process

With this process, both solid and hollow parts of various shapes (Figs 5.1, 5.2 and 5.3) are produced.

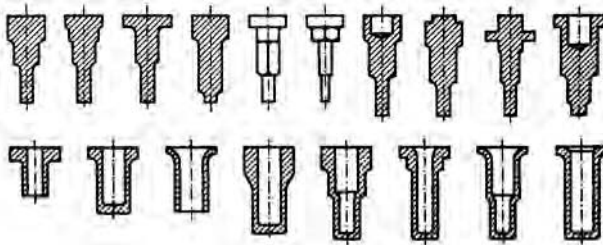


Figure 5.1 Forward extrusions

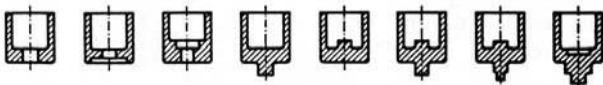


Figure 5.2 Backward extrusions



Figure 5.2 a) Typical backward extrusions

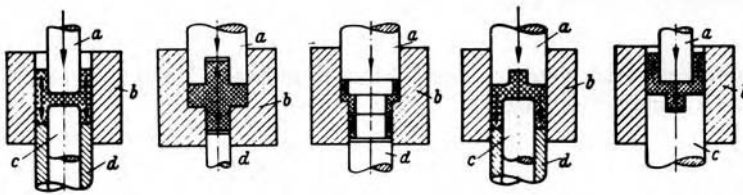


Figure 5.3 Typical parts for combined extrusion, a) punch, b) die, c) counter-punch, d) ejector

5.3 Types of extrusion process

Direct extrusion (forward extrusion)

The movement of the punch and the flow of the material are in the same direction. During the extrusion process the pressure of the punch forces the material to flow in the direction of the movement of the punch, in the process of which the workpiece being formed takes on the shape of the inside of the die.

Indirect extrusion (backward extrusion)

The flow of the material is in the opposite direction to the movement of the punch. The material is made to flow by the pressure of the punch above the yield point. As a lateral escape is not possible the material flows upwards

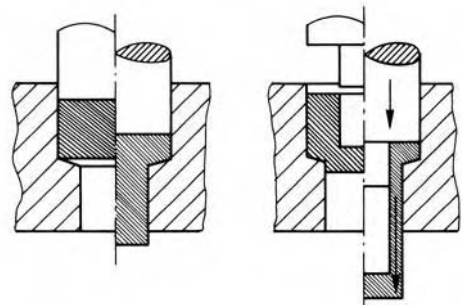


Figure 5.4 The principle of forward extrusion

through the annular gap formed between the die and the punch, in the opposite direction to the movement of the punch. This method is also used to produce tubes.

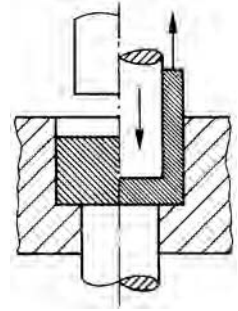


Figure 5.5 The principle of backward extrusion

Combined extrusion process

Here, on the punch down-stroke the material flows both in the same and in the opposite direction to the movement of the punch.

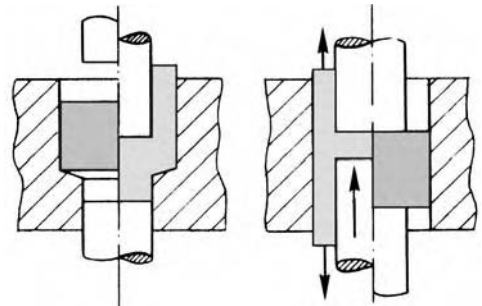


Figure 5.6 The principle of combined extrusion

5.4 Starting stock

5.4.1 Direct extrusion

Section of rod, pre-formed cup, tube section.

5.4.2 Indirect extrusion

Blank (disc), section of rod.

5.5 Principal strain φ_p

5.5.1 Direct extrusion

A_0 in mm^2 area before forming
 A_1 in mm^2 area after forming
 D_0 in mm diameter of the blank
 d in mm diameter of the punch
 φ_p - principal strain

$$\varphi_p = \ln \frac{A_0}{A_1}$$

5.5.2 Indirect extrusion in general

$$\varphi_p = \ln \frac{A_0}{A_1}$$

Commonly used for thin-walled parts:

$$\varphi_p = \ln \frac{D_0}{D_0 - d} - 0.16$$

Permissible deformations are shown in the following table.

Table 5.1 Permissible deformations during extrusion 1

Material	Forward extrusion φ_{pperm}	Backward extrusion φ_{pperm}
Al 99.5 – 99.8	3.9	4.5
AlMgSi 0.5; AlMgSi 1; AlMg 2; AlCuMg 1	3.0	3.5
CuZn 15-CuZn 37 (Ms 63); CuZn 38 Pb 1	1.2	1.1
Mbk 6; Ma 8; and steels with a low C content.	1.4	1.2
Ck10; Ck15; Cq10; Cq15	1.2	1.1
Cq 22; Cq 35; 15 Cr3	0.9	1.1
Ck45; Cq45; 34 Cr 4; 16 MnCr 5	0.8	0.9
42 CrMO 4; 15 CrNi 6	0.7	0.8

5.6 Calculation of force and mechanical work

Direct extrusion

Force:

$$F = \frac{A_0 \cdot k_{str m} \cdot \varphi_p}{\eta_F}$$

$\eta_F = 0.6 - 0.8$ (see Table 5.7)

F in N	extrusion force
A_0 in mm^2	area before forming
k_{strm}	in N/mm^2 mean flow stress
φ_p -	principal strain
η_F -	deformation efficiency
W in Nm	strain energy
s_w in mm	displacement
h_0 in mm	blank height
h_{hd} in mm	head height (Figure 5.7)
h_1 in mm	bottom thickness (Figure 5.8)
x -	process factor ($x = 1$)
A_p in mm^2	cross-sectional area of the punch

Mechanical work:

$$W = F \cdot s_w \cdot x$$

$$s_w = h_0 - h_{\text{hd}}$$

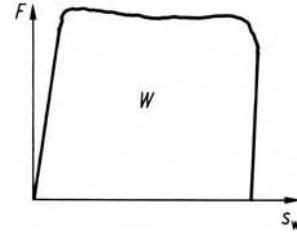


Figure 5.9 Force-displacement diagram during extrusion

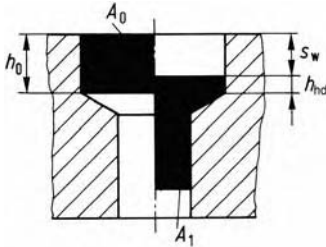


Figure 5.7 Aspect ratio during direct extrusion

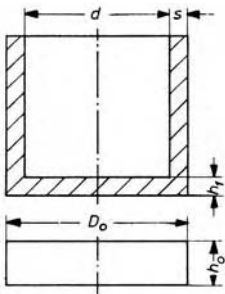


Figure 5.8 Parameters in backward extrusion

Indirect extrusion

Force:

a) for thick-walled parts ($D_0/s \leq 10$)

$$F = \frac{A_0 \cdot k_{\text{strm}} \cdot \varphi_p}{\eta_F}$$

with $\eta_F \approx 0.5$ to 0.7
(see Table 5.7)

b) for thin-walled parts ($D_0/s \geq 10$)

$$F = A_p \cdot \frac{k_{\text{strm}}}{\eta_F} \left(2 + 0.25 \frac{h_0}{s} \right)$$

Mechanical work:

$$W = F \cdot s_w \cdot x$$

with $x = 1$

$$s_w = h_0 - h_1$$

5.7 Extrusion tooling

Extrusion tooling is subject to high stresses. Successful extrusion depends upon their design, choice of materials, hardness on installation and pre-stressing of the die.

For steel extrusion the die must always be reinforced.

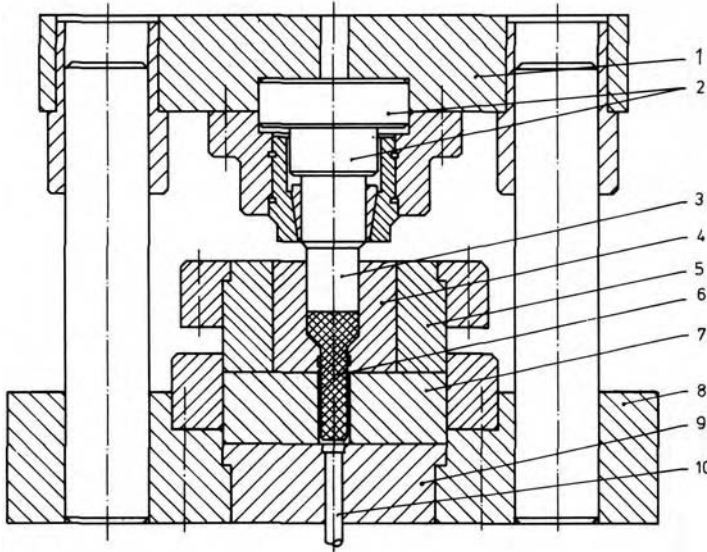


Figure 5.10
Equipment for forward extrusion

- 1 top plate
- 2 pressure plate
- 3 punch
- 4 die
- 5 retaining ring (shrink fit)
- 6 workpiece
- 7 distance plate
- 8 base plate
- 9 pressure plate
- 10 ejector

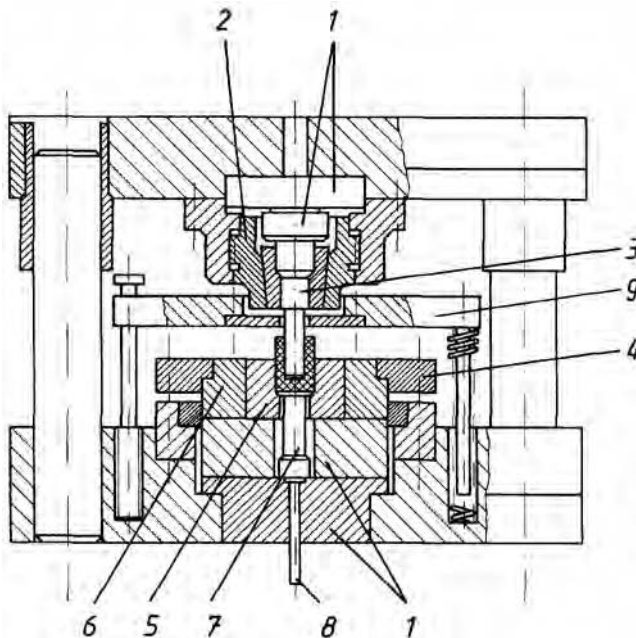


Figure 5.11
Equipment for backward extrusion

- 1 die plate
- 2 clamp nut for punch
- 3 punch
- 4 tension ring for the die
- 5 die
- 6 retaining ring (reinforcement)
- 7 counter-punch
- 8 ejector
- 9 stripper

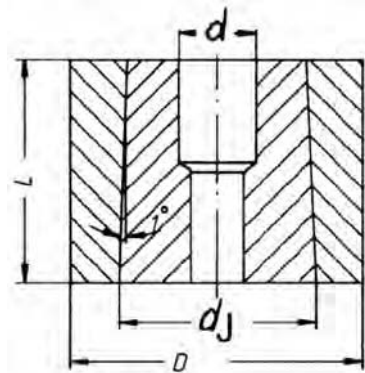
Table 5.2 Tool materials and hardness at installation for extrusion tooling

	Material		Assembly hardness HRC	Used for				R_e N/mm ²
	Name	No.		Punch	Die	Reinforcement	Ejector	
Tool steels	S 6-5-2 (M 2)	1.3343	62 to 64	× ×	× ×		× ×	2100
	S 18-0-1 (B 18)	1.3355	59 to 62	× ×	×			2100
	S 6-5-3 (M 4)	1.3344	62 to 64	× ×				2200
	X 165 CrMoV 12	1.2762	60 to 62	×	×		×	2000
	X 40 CrMoV 51	1.2344	50 to 56		×	× ×	×	1200 – 1400
	42 CrMo 4	1.7225	30 to 34			× ×	×	700 – 900
Hard metals	G 40		1100 HV	×	×			
	G50		1000 HV		×			
	G60		950 HV	×	× ×			

× – suitable; × × – used most commonly; elastic modulus of steel = 210,000 N/mm²

5.8 Reinforcement calculation for single-reinforced dies

- D in mm external diameter of the retaining ring (generally depends on the insertion bore of the machine)
- d_j in mm junction diameter
- d in mm inside diameter of the die
- R_{e1} inN/mm² elastic limit of the hardened die
- R_{e2} inN/mm² elastic limit of the reinforcement ring
- p_i inN/mm² internal pressure in the tool
- F_p in N punch force during extrusion



A_p	in mm^2	cross-sectional area of the punch
z_1	in mm	absolute interference of the die on the junction diameter d_F
ϑ	in $^\circ\text{C}$	temperature in $^\circ\text{C}$
T	in $^\circ\text{K}$	temperature to join the retaining ring [$T(^{\circ}\text{K}) = \vartheta(^{\circ}\text{C}) + 273$]
α	in mm/mmK	thermal coefficient of expansion for steel $\alpha = 12.5 \cdot 10^{-6}$ mm/mmK
c	in mm	desired clearance,
E	in N/mm^2	modulus of elasticity ($E_{\text{steel}} = 210 \text{ kN}/\text{mm}^2$)

Table 5.3 Permissible internal pressure depending on reinforcement

$p_{i\text{perm}}$ (N/mm^2)	Reinforcement
1000	None
1000 – 1600	Single
1700 – 2000	Double
$p_i = \frac{F_p}{A_p} - k_{\text{str}0}$	1
$p_c = \frac{p_i}{R_{e1}}$	2
$K_1 = \frac{R_{e1}}{R_{e2}}$	3
$Q_1 = \sqrt{\frac{1}{2} \left(1 + \frac{1}{K_1} \right)} - p_c$	4
$Q_2 = Q_1 \cdot K_1$	5
$Q = Q_1 \cdot Q_2$	6
$d_J \approx 0.9 \cdot \sqrt{D \cdot d}$	7
$d_J = \frac{d}{Q_1}$	8
$D = \frac{d}{Q}$	9
$z_1 = \frac{d_F \cdot R_{e1}}{E} \cdot \left(\frac{1}{K_1} - Q_1^2 \right)$	10
$T = \frac{z_1 + c}{d_F \cdot \alpha}$	11

(p_i according to [14-2/2 P. 1008])

As d and D are generally known, the junction diameter is most often calculated with equation 7.

Example:

Calculate the junction diameter and the required die clearance for the following data.

Where:

$$p_i = 1000 \text{ N/mm}^2 \text{ (assumed value)}$$

$$D = 120 \text{ mm } \varnothing \text{ (die holder bore fitted in the machine)}$$

$$d = 40 \text{ mm } \varnothing$$

$$R_{e1} = 2100 \text{ N/mm}^2 \text{ (for the die material S 6-5-2)}$$

$$R_{e2} = 1400 \text{ N/mm}^2 \text{ (for the reinforcement material X 40 CrMoV 51).}$$

Solution:

$$d_j \cong 0.9 \cdot \sqrt{D \cdot d} = 0.9 \cdot \sqrt{120 \text{ mm} \cdot 40 \text{ mm}} = 62.3 \text{ mm}$$

$$d_j = 65 \text{ mm is selected}$$

$$p_c = \frac{p_i}{R_{e1}} = \frac{100 \text{ N/mm}^2}{2100 \text{ N/mm}^2} = 0.476$$

$$K_1 = \frac{R_{e1}}{R_{e2}} = \frac{2100 \text{ N/mm}^2}{1400 \text{ N/mm}^2} = 1.5$$

$$Q_1 = \sqrt{\frac{1}{2} \cdot \left(1 + \frac{1}{K_1}\right)} - p_c = \sqrt{\frac{1}{2} \cdot \left(1 + \frac{1}{1.5}\right)} - 0.476 = 0.59$$

$$z_1 = \frac{d_j \cdot R_{e1}}{E} \cdot \left(\frac{1}{K_1} - Q_1^2\right) = \frac{65 \text{ mm} \cdot 2100 \text{ N/mm}^2}{210000 \text{ N/mm}^2} \cdot \left(\frac{1}{1.5} - 0.592\right)$$

$$z_1 = \underline{\underline{0.20 \text{ mm}}}$$

If there is total freedom as to the external diameter of the die, then d_j can be determined from equation 8 and D from equation 9; with these values, z_1 can then be calculated.

In this way, however, considerably larger dimensions for the die usually result.

5.9 Achievable precision

The accuracies which can be achieved with cold extrusion are shown in Tables 5.4.1 and 5.4.2.

Table 5.4.1 Diameter tolerances for cold extrusions made of steel

Applies to	Range in mm						Mass in kg
	up to 10	over 10 to 16	over 16 to 25	over 25 to 40	over 40 to 63	over 63 to 100	
Inside diameter	0.05	0.06	0.06	0.07	0.08		up to 0.1
	0.08	0.09	0.10	0.11	0.12	0.14	− 0.5
	0.10	0.11	0.12	0.14	0.16	0.18	− 4.0
	0.12	0.14	0.16	0.18	0.20	0.22	− 25
Outside diameter	0.09	0.11	0.14	0.18	0.22	0.28	up to 0.1
	0.14	0.18	0.22	0.28	0.35	0.45	− 0.5
	0.18	0.22	0.28	0.35	0.45	0.56	− 4.0
	0.22	0.28	0.35	0.45	0.56	0.71	− 25

Table 5.4.2 Wall thickness tolerances in backward cup extrusion for $l/d < 2.5$

l in mm bore length

d in mm bore diameter

Wall thickness in mm	Tolerance in mm
0.3 to 0.6	± 0.05
0.6 to 1.0	± 0.075
1.0 to 2.5	± 0.1
>2.5	± 0.2

Surface quality

Cold extrusions have high surface quality and therefore good wear characteristics.

Presuming that

- the surface quality of the tools is good,
- the lubricant and the method of applying it have been correctly chosen,
- the deformation remains within permissible limits,

it is possible to achieve roughness in the region of




$$R_t = 5 \text{ to } 10 \mu\text{m}$$

on the surfaces where material flow takes place.

5.10 Defects during extrusion

The main defects which can occur during extrusion are summed up in Table 5.5.

Table 5.5 Defects and their causes during extrusion

Defect	Cause	Steps to be taken
Internal surface cracks 	Deformability exceeded	Split deformation into two operations and anneal between them
Shear cracks below 45 ° 	Deformability exceeded during setting process (upsetting) – Work operation before extrusion to produce a precise billet	Choose a larger initial diameter
External surface cracks 	Wrong lubrication. Too much liquid lubricant which can not escape from the die during extrusion results in the lubricant exploding. This produces cracks.	Use less lubricant

5.11 Sequence of operations diagram

In most cases several operations are required to produce an extrusion. The results of each step in the process and the dimensions of the intermediate forms are put together in a diagram known as a

“sequence of operations diagram”.

As well as the dimensions for each step, the sequence of operations diagram also includes data on

- heat and surface treatment,
- the extent of the deformation,
- the force and mechanical work required for forming.

The sequence of operations diagram is the most important manufacturing document in establishing the metal forming machines required, the construction of the tools and the time needed for production.

Figure 5.12 shows a sequence of operations diagram for an M12 x 60 bolt.

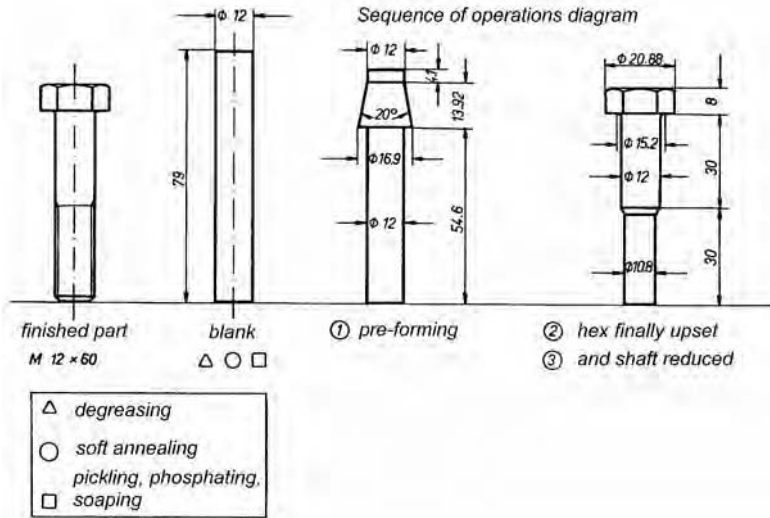


Figure 5.12 Steps in the production of a bolt with a pressed hexagonal head

5.12 Example calculations

Example 1

The aim is to produce bolts as in Figure 5.13 out of 42 CrMo 4. The following must be established:

operating method, stock, force and mechanical work,

where: $\eta = 0.7$.

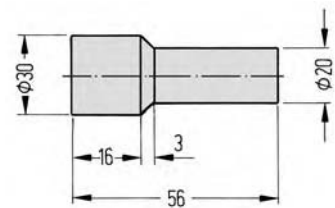


Figure 5.13 Collar bolt

Solution:

1. Operating method: forward extrusion

2. Stock

2.1. Volume of the finished item

$$V_F = \frac{D^2 \pi}{4} \cdot h_1 + \frac{\pi}{12} \cdot h_2 (D^2 + D \cdot d + d^2) + \frac{d^2 \pi}{4} h_3$$

$$= \frac{\pi}{4} \left[D^2 h_1 + \frac{h_2}{3} (D^2 + D \cdot d + d^2) + d^2 h_3 \right]$$

$$= 0.785 \left[(30 \text{ mm})^2 \cdot 16 \text{ mm} + \frac{3 \text{ mm}}{3} (900 \text{ mm}^2 + 30 \text{ mm} \cdot 20 \text{ mm} + 400 \text{ mm}^2) + (20 \text{ mm})^2 \cdot 37 \text{ mm} \right]$$

$$V_F = 24413 \text{ mm}^3.$$

Extra for melt and pickling losses: 2 %

$$V_{Me} = \frac{2}{100} \cdot 24\,413 \text{ mm}^3 = 488 \text{ mm}^3.$$

Volume of the stock $V_B = V_F + V_{Me} = 24\,413 \text{ mm}^3 + 488 \text{ mm}^3 = 24\,901 \text{ mm}^3$.

2.2. Stock dimensions

$$D_0 = 30.0 \text{ mm selected}, \quad A_0 = \frac{(30 \text{ mm})^2 \pi}{4} = 706.5 \text{ mm}^2$$

$$h_0 = \frac{V_B}{A_0} = \frac{706.5 \text{ mm}^2}{314 \text{ mm}^2} = 35.24 \text{ mm}, \quad h_0 = 35.0 \text{ mm selected.}$$

3. Force F

$$3.1. \quad \varphi_p = \ln \frac{A_0}{A_1} = \ln \frac{706.5 \text{ mm}^2}{314 \text{ mm}^2} = \ln 2.25 = 0.81, \quad \varphi_p = 81 \text{ \%}.$$

$$3.2. \quad k_{str0} = 420 \text{ N/mm}^2, \quad k_{str1} = 1080 \text{ N/mm}^2, \quad k_{strm} = \frac{k_{str0} + k_{str1}}{2} = 750 \text{ N/mm}^2.$$

$$3.3. \quad F = \frac{A_0 \cdot k_{strm} \cdot \varphi_p}{\eta_F} = \frac{706.5 \text{ mm}^2 \cdot 750 \text{ N/mm}^2 \cdot 0.81}{0.7} = 613141 \text{ N} = 613 \text{ kN}.$$

4. Work W

$$s_w = h_0 - h_k = 35 \text{ mm} - 16 \text{ mm} = 19 \text{ mm} = 0.019 \text{ m}$$

$$W = F \cdot s_w \cdot x = 613 \text{ kN} \cdot 0.019 \text{ m} \cdot 1 = 11.6 \text{ kNm}.$$

Example 2

The aim is to produce casings as in Figure 5.14 out of Al 99.5.

where: $\eta_F = 0.7$

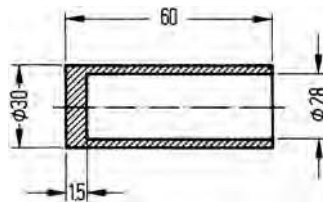


Figure 5.14 Casing

The following must be established:
operating method, stock, force and mechanical work.

Solution 1:

1. Operating method: backward extrusion

2. Stock

2.1. Volume of the finished item

$$\begin{aligned} V_F &= d_1^2 \frac{\pi}{4} \cdot s_b + (D^2 - d_1^2) \frac{\pi}{4} h_1 \\ &= (28 \text{ mm})^2 \cdot \frac{\pi}{4} \cdot 1.5 \text{ mm} + (30^2 - 28^2) \text{ mm}^2 \cdot \frac{\pi}{4} \cdot 60 \text{ mm} = 6386.7 \text{ mm}^3 \end{aligned}$$

Extra to make up for melt and pickling losses: 1 %

$$V_{Me} = \frac{1}{100} \cdot 6336 \text{ mm}^3 \cong 64 \text{ mm}^3.$$

Volume of the stock $V_B = V_F + K_{Me} = 6386.7 \text{ mm}^3 + 64 \text{ mm}^3 = 6451 \text{ mm}^3$.

2.2. Stock dimensions

$$\begin{aligned} D_0 &= 30_{-0.1} \text{ mm}, \quad A_0 = 706.5 \text{ mm}^2 \\ h_0 &= \frac{V_F}{A_0} = \frac{6451 \text{ mm}^3}{706.5 \text{ mm}^2} = 9.13 \text{ mm}, \quad h_0 = 9.0 \text{ mm selected.} \end{aligned}$$

3. Force F

$$\begin{aligned} 3.1. \quad \varphi_p &= \ln \frac{D_0}{D_0 - d} - 0.16 = \ln \frac{30 \text{ mm}}{30 \text{ mm} - 28 \text{ mm}} - 0.16 = \ln 15 - 0.16 \\ &= 2.70 - 0.16 = 2.54 \\ \varphi_p &= 254 \%. \end{aligned}$$

3.2. Flow stress from the flow stress curve or Table 1 (Part III)

$$\begin{aligned} k_{str_0} &= 60 \text{ N/mm}^2, \quad k_{str_1} = 184 \text{ N/mm}^2, \\ k_{str_m} &= \frac{k_{str_0} + k_{str_1}}{2} = \frac{60 \text{ N/mm}^2 + 184 \text{ N/mm}^2}{2} = 122 \text{ N/mm}^2 \end{aligned}$$

$$\begin{aligned} 3.3. \quad F &= A_p \cdot \frac{k_{str_m}}{\eta_F} \cdot \left(2 + 0.25 \frac{h_0}{c} \right) = \frac{(28 \text{ mm})^2 \pi}{4} \cdot \frac{122 \text{ N/mm}^2}{0.7} \cdot \left(2 + 0.25 \frac{9}{1} \right) \\ &= 455836 \text{ N} = 456 \text{ kN.} \end{aligned}$$

4.1. Deformation displacement

$$s_w = h_0 - h_1 = 9 \text{ mm} - 1.5 \text{ mm} = 7.5 \text{ mm} = 0.0075 \text{ m}$$

$$4.2. \quad W = F \cdot s_w \cdot x = 456 \text{ kN} \cdot 0.0075 \text{ m} \cdot 1 = 3.4 \text{ kNm.}$$

Example 3

The aim is to produce workpieces as in Figure 5.15. The stock diameter must be selected so that initial calculations result in an upsetting ratio of $s = 2$. The calculated diameter, d_0 , must be rounded up to the nearest mm. The calculated stock length, h_0 , must also be rounded up to the nearest mm.

where: Material Ck 15, $\eta = 0.7$, $\mu = 0.15$.

Create the sequence of operations diagram.

Solution:

1. Volume

1.1. Head volume

$$V_{\text{HD}} = \frac{4}{3} \pi \cdot r^3 - \pi \cdot h^2 \cdot \left(r - \frac{h}{3} \right)$$

$$V_{\text{HD}} = \pi \cdot \left[\frac{4}{3} \cdot 25^3 - 5^2 \cdot \left(25 - \frac{5}{3} \right) \right]$$

$$V_{\text{HD}} = \underline{\underline{63617 \text{ mm}^3}}$$

1.2. Volume of both shanks

$$V_1 + V_2 = \frac{\pi}{4} (30^2 \cdot 35 + 20^2 \cdot 25)$$

$$= 24740 + 7854.$$

1.3. Total volume

$$V_{\text{tot}} = V_{\text{HD}} + V_1 + V_2 = \underline{\underline{96211 \text{ mm}^3}}$$

2. Establish the required d_0 from the upsetting ratio

$$d_0 = \sqrt[3]{\frac{4 \cdot V_{\text{HD}}}{\pi \cdot s}}$$

$$d_0 = \sqrt[3]{\frac{4 \cdot 63617 \text{ mm}^3}{\pi \cdot 2}} = 34.34 \text{ mm}$$

$$d_0 = \underline{\underline{35 \text{ mm } \varnothing \text{ selected.}}}$$

3. Stock length h_0

$$h_0 = \frac{V_{\text{tot}}}{A_0} = \frac{96211 \text{ mm}^3}{35^2 \pi/4 \text{ mm}^2} = 99.99 \text{ mm}, \quad h_0 = \underline{\underline{100 \text{ mm selected.}}}$$

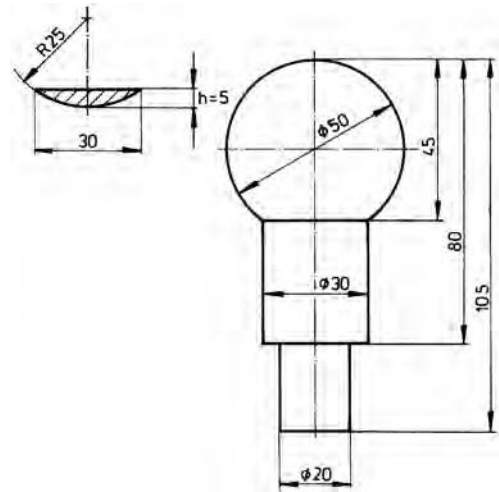


Figure 5.15 Round-headed bolt

3.1. Required stock length for the round head h_{0HD}

$$h_{0HD} = \frac{V_{HD}}{A_0} = \frac{63617 \text{ mm}^3}{962.11 \text{ mm}^2} = \underline{\underline{66.1 \text{ mm}}}$$

4. Forward extrusion

$$4.1. \quad \varphi_p = \ln \frac{A_0}{A_1} = \ln \frac{d_0^2}{d_1^2} = \ln \frac{35^2}{20^2} = 1.12 \rightarrow \underline{\underline{112\%}}, \quad \varphi_{p\text{perm}} = 120\%$$

$$4.2. \quad k_{str_0} = 280, \quad k_{str_1} = 784, \quad k_{str_m} = 532 \text{ N/mm}^2$$

$$4.3. \quad F = \frac{A_0 \cdot k_{str_m} \cdot \varphi_p}{\eta_F} = \frac{962.11 \text{ mm}^2 \cdot 532 \text{ N/mm}^2 \cdot 1.12}{0.7} = 818948 \text{ N} = \underline{\underline{819 \text{ kN}}}$$

$$4.4. \quad s_W = h_0 - h_{0HD} = 100 - 66.1 = 33.9 \text{ mm} = 0.0339 \text{ m}$$

$$4.5. \quad W = F \cdot s_W \cdot x = 819 \text{ kN} \cdot 0.0339 \text{ m} \cdot 1 = 27.8 \text{ kNm.}$$

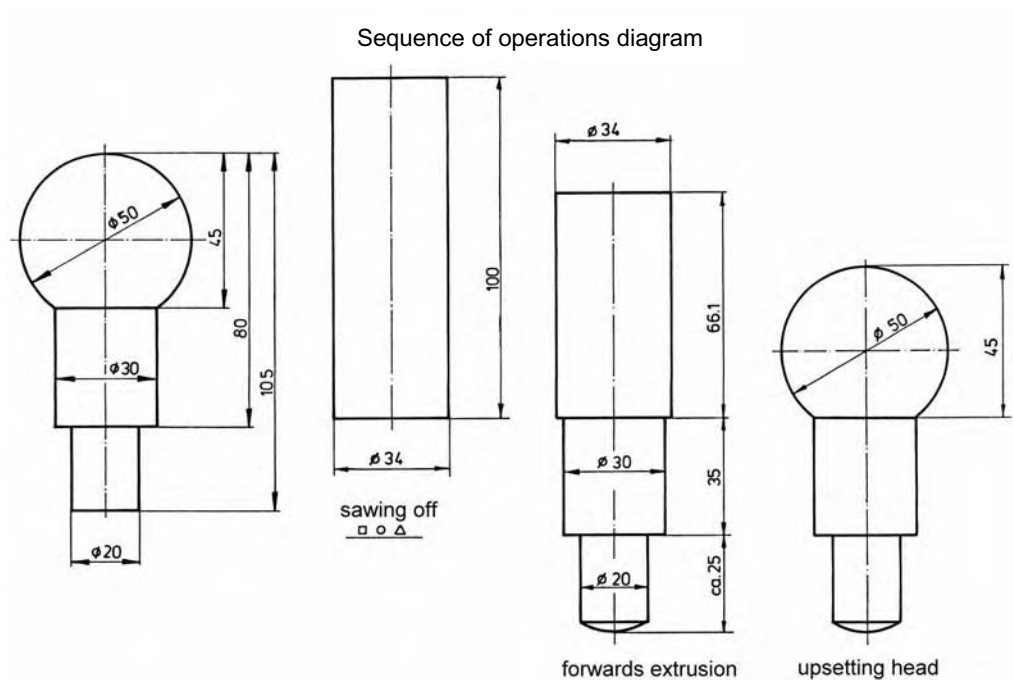


Figure 5.16 Sequence of operations for the production of a round-headed bolt

5. Upsetting (heading)

$$5.1 \quad \varphi_p = \ln \frac{h_{0HD}}{h_{HD}} = \ln \frac{66.1}{45} = 0.384 \rightarrow \underline{\underline{38.4\%}}$$

$$\varphi_p = 150 \%$$

$$5.2 \quad k_{str0} = 280, \quad k_{str1} = 670, \quad k_{strm} = 475 \text{ N/mm}^2$$

$$5.3 \quad F = A_1 \cdot k_{str1} \cdot \left(1 + \frac{1}{3} \mu \frac{d_1}{h_1} \right)$$

$$= \frac{50^2 \pi}{4} \text{ mm}^2 \cdot 670 \text{ N/mm}^2 \cdot \left(1 + \frac{1}{3} \cdot 0.15 \cdot \frac{50 \text{ mm}}{45 \text{ mm}} \right)$$

$$F = 1\,387\,896.7 \text{ N} = \underline{\underline{1388 \text{ kN}}}$$

$$5.4 \quad W = \frac{V_{HD} \cdot k_{strm} \cdot \varphi_p}{\eta_F} = \frac{63617 \text{ mm}^3 \cdot 475 \text{ N/mm}^2 \cdot 0.384}{0.7}$$

$$W = 16\,576\,771 \text{ Nmm} = \underline{\underline{16.6 \text{ kN m}}}$$

5.13 Shape classification

For operations scheduling, during which the sequence of operations plans for the extrusions are produced, it is important to collect and record empirical values.

This is why a shape classification table is used in which the various extrusion shapes are ordered according to operating method, sequence of operations, degree of difficulty etc. Table 5.6 shows a shape classification table. The advantages of this kind of classification are:

- Production of sequence of operations plans for new parts.
If sequence of operations plans already exist in the shape classification table for similar parts, this makes the production of a new sequence of operations plan easier as it can be based on similar shapes.
This means the induction of new inexperienced workers is made far simpler and the need for specialists is reduced.
- Furthermore, groups of the same shape have the same or a similar amount of difficulty during pressing.
Depending on the group of shapes, the extent of the deformation efficiency to be expected can also be deduced (see Table 5.7).
- There are also advantages for tool manufacture. Similar shapes also produce similar elements as concerns tools; these elements can be standardised within a company, simplified and thus produced at less expense.

Table 5.6 Shape classification according to length

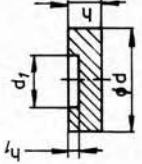
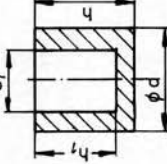
Class 1 flat shape $d > h$ $d_f > h_f$ 	upper base lateral surface area		without secondary element		with cavity (hollow part)		with protrusion		with cavity and protrusion			
	on one side	on two sides	on one side	on two sides	on one side	on two sides	on one side	on two sides	on one side	on two sides		
Main body cylindrical 1.1		—										
	Main body bored through 1.2		—									
		Main body with convex, contoured or conical shaped parts 1.3										
			Main body cylindrical 2.1		—							
Main body with head or flange 2.2		—										
	Main body bored through 2.3			—								
Main body with convex, contoured or conical shaped parts 2.4												
	Class 2 low shape $d = h$ $d_f = h_f$ 		—									
		—										

Table 5.6 Shape classification according to length

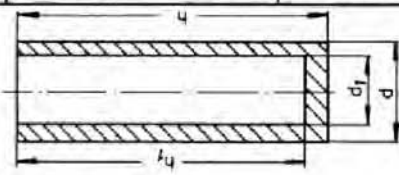
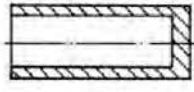
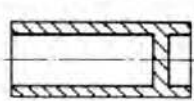
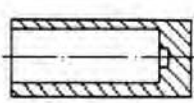
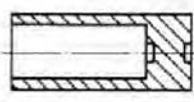
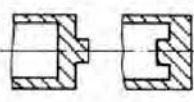
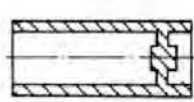
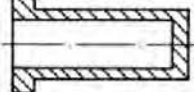
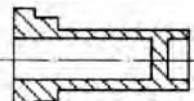
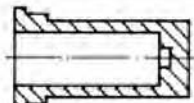
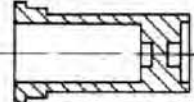
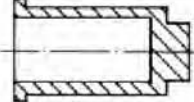
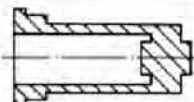
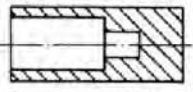
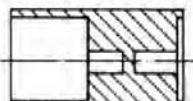
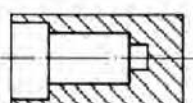
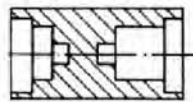
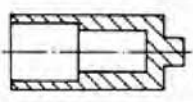
Class 4 long shape hollow	upper base lateral surface area		without secondary element		with cavity (hollow part)		with protrusion		with cavity and protrusion							
	on one side	on two sides	on one side	on two sides	on one side	on two sides	on one side	on two sides	on one side	on two sides						
<p>$d < h$ $d < h$</p> 	<p>Main body smooth inside and out</p> <p>4.1</p>															
			<p>Main body reduced outside smooth inside</p> <p>4.2</p>													
					<p>Main body smooth outside reduced inside</p> <p>4.3</p>											

Table 5.6 Shape classification according to length

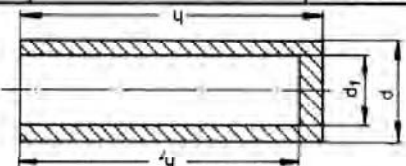
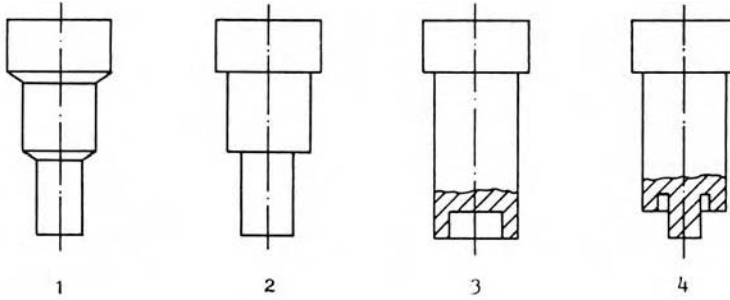
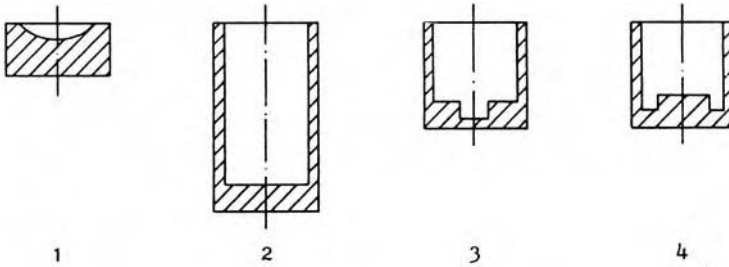
Class 4 long shape hollow $d < h$ $d < h$	upper base lateral surface area		without secondary element on one side		with cavity (hollow part) on one side		with protrusion on one side		with cavity and protrusion on one side		with cavity and protrusion on two sides	
		Main body reduced inside and out 4, 4		Main body bored through 4, 5		Main body with convex, contoured or conical shaped parts 4, 6						
												

Table 5.7 Deformation efficiency $\eta_F = f(\text{workpiece shape and degree of deformation } \varphi_p)$ *Forward extrusion*

φ_p	Deformation efficiency η_F			
	Shape 1	Shape 2	Shape 3	Shape 4
$< 0.4 - 0.6$	0.6	0.55	0.45	0.4
$> 0.6 - 1.0$	0.65	0.6	0.5	0.45
$> 1.0 - 1.6$	0.7	0.65	0.55	0.5
> 1.6	0.75	0.7	0.6	0.55

Backward extrusion

φ_p	Deformation efficiency η_F			
	Shape 1	Shape 2	Shape 3	Shape 4
0.4	0.55	0.52	0.5	0.48
$> 0.4 - 1.2$	0.57	0.55	0.52	0.5
$> 1.2 - 1.8$	0.58	0.56	0.54	0.52
> 1.8	0.6	0.58	0.56	0.55

5.14 Exercise on Chapter 5

1. What extrusion methods do you know?
2. Which values are principal strain calculated from during extrusion?
3. How is the deformation displacement established?
4. Name the most important elements of extrusion tooling.
5. Why must the die be reinforced?
6. What values does the deformation efficiency depend upon?
7. What has gone wrong if internal surface cracks appear during backward extrusion?
8. What is a sequence of operations diagram and what is it used for?
9. What kind of workpieces are produced using backward extrusion and what with forward extrusion?
10. What method must be used to produce a round-headed bolt?
11. What manufacturing process is used to produce a toothpaste tube? Sketch the sequence of operations diagram.
12. Why is a pillar guide needed in extrusion tooling?

6 Thread rolling

Thread rolling is a bulk cold forming process for the production of threads of all kinds, knurling and helical gearing.

6.1 Types of method

The method is divided according to die type into:

6.1.1 Dies with finite working surfaces

a) Flat die method (Figure 6.1)

The thread is produced by two flat dies which have the profile of the thread to be produced. The profile grooves are inclined by the pitch angle of the thread to be produced. One flat die is fixed and the other is moved backwards and forwards by a crank mechanism. The blank to be rolled is carried along by friction.

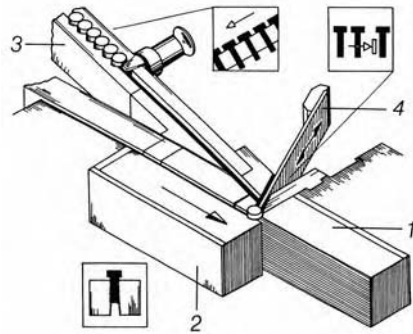


Figure 6.1 Layout for flat-die thread rolling 1 fixed die, 2 moving die, 3 conductor bar, 4 pusher

b) Segment (planetary type) method (Figure 6.2)

Here, instead of a straight rolling die, curved segments are used; their length is the circumference of the blank to be rolled. The counterpart to the segments (there may be several in a row around it) is a rotating rotary die. On one revolution of this die, the number of segments arranged around it equals the number of workpieces rolled.

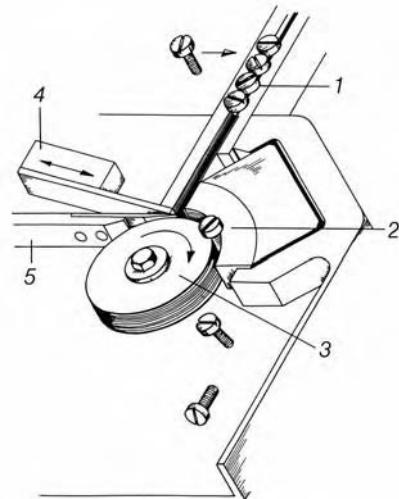


Figure 6.2 Layout for thread rolling with segments. 1 conductor bar, 2 segment, 3 rotating roll, 4 locking slide, 5 pusher

6.1.2 Dies with infinite work surfaces

a) *Infeed process* (Figure 6.3)

In the infeed process, the profile grooves of the rolls have the pitch of the thread to be produced. The rolls, driven at the same speed, move in the same direction. During rolling, the workpiece moves due to friction with no axial shifting. As the thread produced by this means is an exact copy of the rolling dies, threads of this kind have a very high pitch accuracy. The maximum length of the thread is limited by the width of the rollers (30-200 mm).

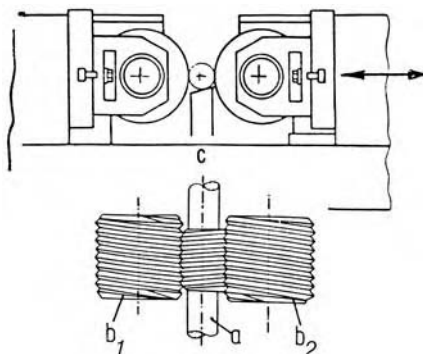


Figure 6.3

Arrangement of the workpiece and the tools during infeed process. a) workpiece, b) dies, b_1 fixed, b_2 adjustable die, c) work rest

b) *Through-feed method* (Figure 6.4)

Here, the rolling dies have grooves with no pitch; the groove cross section is that of the standard flank profile. The thread pitch is produced by skewing the die axes by the pitch angle of the thread. By this means the workpiece is given an axial thrust and moves one pitch length in axial direction for every full revolution. As the axial thrust kicks in immediately when the workpiece enters the assembly, larger threads are not formed to full depth in one pass.

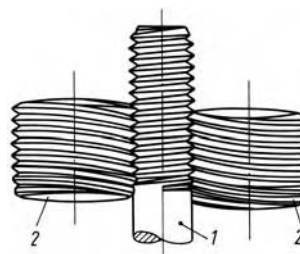


Figure 6.4

Arrangement of the workpiece and the dies during the through-feed method
1 workpiece, 2 dies

c) *Combined infeed-through-feed method*

The combined infeed-through-feed method is a combination of both basic methods.

- Slow axial penetration with axial movement of the workpiece,
- change of direction of rotation when final axial position is reached
- process repeated until the required thread depth is achieved.

6.2 Application of the process

6.2.1 Flat die and segment methods

Used predominantly in mass production for the manufacture of screws and threaded bolts for which the required accuracy is not very high.



Figure 6.5 Typical parts for rolling with flat dies and segments

6.2.2 Infeed process

For threads with very high pitch precision, e.g. measuring spindles for micrometer screws.

This method is being used increasingly in mass production thanks to the technical improvements which have been made to thread rolling machines, resulting in shrinking production times.

6.2.3 Combined infeed-through-feed method

For long, deep threads which require a large deformation. As well as trapezoidal thread spindles, shaped parts such as ball knobs, gear wheels with helical gearing and worms can be produced using this method.

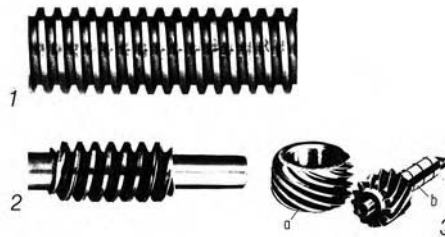


Figure 6.6 Workpieces produced with a combined infeed-through-feed method

1 Spindle with trapezoidal thread Tr 70 x 10 made of C45, rolling time: 2×60 s/m; 2 helical gear, modulus 4, rolling time: 80 s; 3 helical gear wheel and drive pinion, modulus 1.25, rolling time: 10s

The following tables show some technical data for rolling with thread rolls.

Table 6.1 Technical data for rolling with rolls

Rolling forces in kN	10 – 600
Workpiece diameter in mm	5 – 130
Workpiece length in mm – infeed method – through-feed method	max. 200 max. 5000
Thread pitch in mm	max. 14
Modulus for worms and helical gears in mm	max. 5
Helix angle between tooth profile and gear axis in degrees	30 – 70
Roller diameter in mm – infeed method – through-feed method	} 130 – 300
Rolling times – infeed method in s/piece – through-feed method in s/m	2 – 12 60

Table 6.2 Number of pieces per minute which can be produced by flat-die thread rolling

Thread	M 6	M 10	M 20	Starting material
Number of pieces per min.	500	220	100	$R_m \sim 500 \text{ N/mm}^2$
Number of pieces per min.	200	100	40	$R_m \sim 1000 \text{ N/mm}^2$

6.3 Advantages of thread rolling

– *Optimal grain direction*

The grain direction follows the external contour of the thread, thus considerably reducing the notch effect in comparison to threads produced by machining. By this means, the fatigue limit can be raised by up to 50%.

– *Plate-finished surfaces*

Rolled threads have mirror-finished, smooth surfaces.

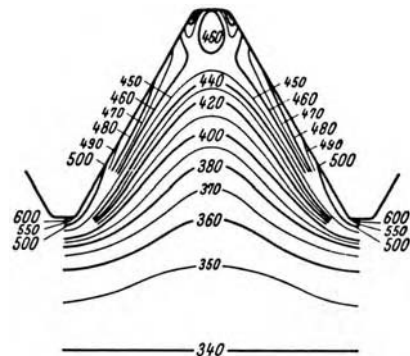


Figure 6.7
Grain direction and hardness pattern in rolled threads made of alloy steel.

– *Work hardening*

Thanks to work hardening, there is a considerable increase in strength (Figure 6.7) which, in combination with the plate-finished surface, means mechanical wear is lessened.

– *Material savings*

The material savings with rolled threads, compared to machined threads, is about 20%.

– *Short production times*

Rolling times are very short compared to the production of threads by machining (see Tables 6.1 and 6.2).

– *Nearly all the main materials used in practice can be rolled*

Nearly all steels can be rolled, except for free-cutting steels, up to a failure strain of over 8% and a maximum strength of 1200 N/mm². Soft Ms 58-63 can also be rolled.

6.4 Establishing the initial diameter

The initial diameter of the bolt can be established mathematically with the following equations depending on the kind of thread.

For metric threads

$$d_0 = d - 0.67 \cdot h$$

For Whitworth threads

$$d_0 = d - 0.64 \cdot h$$

For coated threads

e.g. galvanized, chromium-plated

$$d_{ct} = d_0 - \frac{2z}{\sin \frac{\alpha}{2}}$$

h in mm thread pitch

d_0 in mm initial diameter of bolt

d in mm external diameter of thread

d_p in mm pitch diameter

α in degrees thread angle

z in mm thickness of the metal coating

d_{ct} in mm initial bolt diameter for parts which are metal coated.

6.5 Rolling speeds with cylindrical dies

Rolling speeds are between 30 and 100 m/min depending upon the material to be rolled.

6.6 Rolling dies

6.6.1 Flat dies

The profile of the flat dies is that of the thread to be produced. The slope of the grooves corresponds to the pitch angle of the thread.

$$\tan \alpha = \frac{h}{\pi \cdot d_p}$$

h in mm thread pitch
 d_p in mm pitch diameter



Figure 6.8 The shape of the grooves on a flat die

There are various designs as regards the shape of the thread rolling dies. Here, a common shape is shown.

$$z = 3 \cdot d_0$$

$$\beta = 3 \text{ to } 7^\circ$$

d_0 in mm initial diameter
 β in degrees angle of intake zone
 z in mm intake zone length

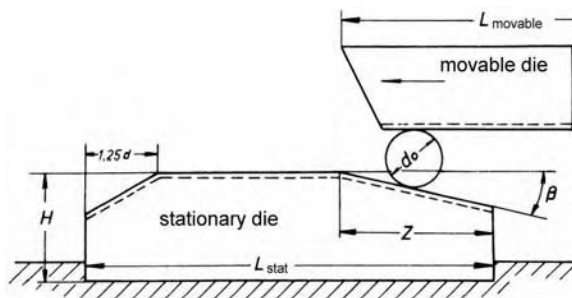


Figure 6.9 Dimensions and arrangement of the flat dies

The thread profile is also fully deep in the intake area.

The length of the die should be at least $15 d_0$.

The movable die should be 15 to 20 mm longer than the stationary die.

The die width DW

$$DW = L_1 + 3h$$

DW	in mm	die width
h	in mm	thread pitch
L_1	in mm	length of the thread on the workpiece
H	in mm	die thickness
L	in mm	die length

Table 6.3 Die dimensions for metric threads

Nominal thread diameter	Die length in mm		Die width DW in mm	Die thickness H in mm	Intake length z in mm
	movable L_m	fixed L_f			
M 6	125	110	40	25	20
M 10	170	150	45	30	28
M 16	250	230	65	45	46

Table 6.4 Tool materials for flat dies and rollers

Material no.	1.2379	1.2601	1.3343
HRC assembly hardness	59 to 61	59 to 61	60 to 61

6.6.2 Dimensions of the rolling dies

- Infeed method (screw threads)

$$D_p = d_p \cdot \frac{FL}{fl}; \quad D_p / d_p = FL / fl = k$$

$$D_p = k \cdot d_p$$

$$D_{ex} = k \cdot d_p + t$$

D_p in mm	pitch diameter of the rollers
d_r in mm	pitch diameter of the thread to be rolled
D_{ex} in mm	external diameter of the roll
t in mm	thread depth
FL by number	number of flights on the die
fl by number	number of flights on the thread
k	factor which depends upon the ratio of FL/fl

– *Through-feed method with rolling grooves without a pitch*

In the through-feed production method, the diameter of the roller does not depend upon the diameter of the thread to be produced. For this reason it is generally selected according to the dimensions of the machine.

– *Combined infeed-through-feed method*

$$D_p = k \cdot d_p \frac{\sin \alpha_w}{\sin(\alpha_w - \varepsilon)}$$

α_w = pitch angle of the workpiece thread

ε = swivel angle of the die axes

Table 6.5 shows common rotary die materials and the corresponding assembly hardnesses. Rotary die life depends upon the strength of the material to be rolled.

Table 6.5 Tool lives of rotary dies

Material strength R_m in N/mm ²	Number of units per tool
1 000	100 000
800	200 000
600	300 000

6.7 Example

The aim is to produce threads of M10 x 50 long.
Calculate the initial diameter required.

Solution:

$$d_0 = d - 0.67 \cdot h = 10 \text{ mm} - 0.67 \cdot 1.5 \text{ mm} = 9.0 \text{ mm}$$

$h = 1.5 \text{ mm}$ from the table.

6.8 Thread rolling machines

Here, a difference is made between:

Flat die thread rolling machines
 Thread rolling machines with cylindrical dies
 Thread rolling machines with cylindrical and segment dies.

6.8.1 Flat die thread rolling machines

The basic concept behind the construction of these machines is practically the same for all manufacturers. The standard is built as a box-shaped cast construction or, as in the machine shown in Figure 6.10, a combination of welded and cast construction. A slide takes up the movable die. The slide guide is mostly designed as an adjustable prism or V-block. The rolling slide (Figure 6.11) is driven by the crank wheel (3) located on the crankshaft (4), via the connecting rod (2). The smooth running of the machine is achieved by means of the pulley, which is designed as a flywheel.

The workpieces are sorted using a trommel (Figure 6.10) or an oscillating conveyor and guided into the working area by hardened conductor tracks. A pusher (Figure 6.1) controlled by cams brings the blank between the rollers.

The number of pieces per time unit which can be produced using these machines is shown in Table 6.2.

Flat die thread rolling machines are used mainly in the screw and standard part industry.



Figure 6.10
 Automatic high-performance thread rolling machine, type R 2 L (Photograph from Hilgeland works, Wuppertal, Germany)

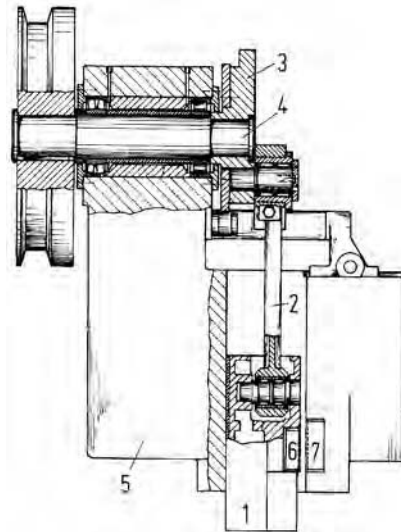


Figure 6.11
 The drive of a flat die thread rolling machine of the Hilgeland company. 1 slide, 2 connecting rod, 3 crank wheel, 4 crankshaft, 5 standard, 6 moving flat die, 7 fixed flat die

6.8.2 Cylindrical-die thread rolling

When rolling with cylindrical dies, feed is provided by rotation and the motion of the tools. Both dies are powered. The rolling slide moves longitudinally, carrying one roller and providing the rolling force; it is hydraulically driven. Both the speed of movement and the force of the hydraulic lifting piston can be controlled with great precision using the CNC control.

Whereas conventional machines work on a power-controlled basis, in CNC machines the process takes place in a closed loop, based on feed, i.e. penetration depth and material displacement are co-ordinated for every workpiece revolution. This means that material displacement is no longer influenced by the force which builds up, but can be deliberately controlled. This allows the calculation of

- rolling time
- distribution of force and
- distribution of moment

from the influencing factors involved in the deformation process, e.g:

- rolling method, profile shape, material, stock dimensions, degree of rolling, tool geometry and lubrication

with fairly high certainty.

The CNC-controlled thread rolling machine shown in Figure 6.12 is built in six different sizes from 100-1000 kN of rolling force.

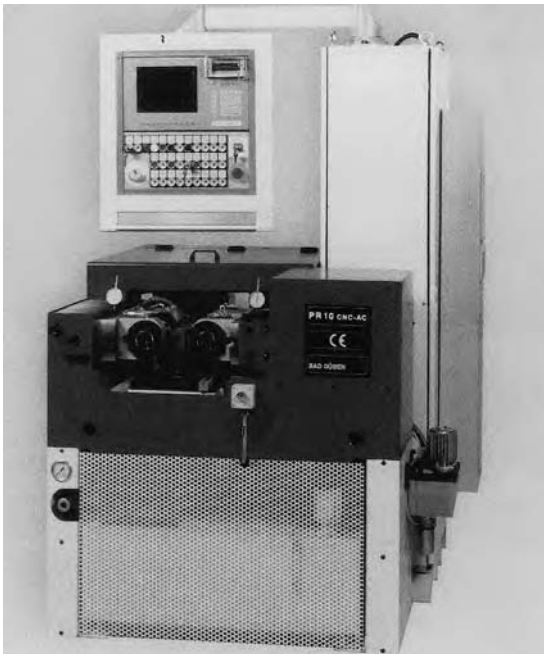


Figure 6.12
PW10 CNC/AC thread rolling machine
(Photograph from the Profiroll Technologies GmbH works, Bad Dübén, Germany)

The machine body is built as a C-frame and its open top guarantees good access to the working area. The rolling process can be precisely controlled by the latest proportional valve and drive technology combined with the three-axis CNC control. The graphic user interface allows fast, uncomplicated operation of the machine. The graphical representation of the process includes the most important parameters of the method, such as force and torque, in the curves for planned slide and spindle movement, which means that the rolling process can be optimised.

The data management system provides all the comforts of comprehensive data organisation. It also means that repeat orders can be processed with very little preparation.

In the thread rolling machine pictured in Figure 6.13, the standard is also produced as a box construction which is bend- and torsion-resistant.

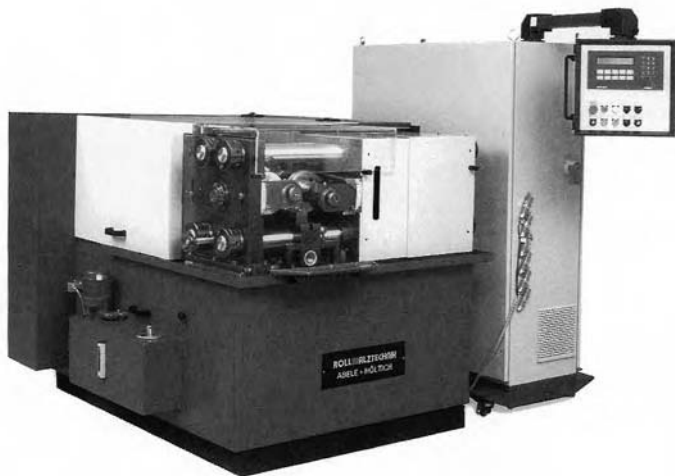


Figure 6.13
RTW 30x CNC/AC thread
rolling machine
(Photograph from Roll-
walztechnik Abele + Höllich
GmbH works, Engen, Germany)

The rolling spindle (Figure 6.14) is driven by two three-phase servomotors via propeller shafts. The rotation speed is controlled with frequency converters. The angles of both die axes can be adjusted from 7-10.

The longitudinally-moving roller slide which provides the rolling force is operated hydraulically. The hydraulic piston can be delicately controlled by the CNC control in terms of both rolling force and speed of movement. The position and control signals are transferred and supervised in connection with an incremental measuring system. The crucial innovation in this control concept is that the track of both rollers towards one another is adjusted by pressing keys. The value ascertained is saved and constantly monitored during the rolling process. The saved values can also be retrieved for new workpieces with similar technical data, thus saving preparation time.

Figure 6.15 shows the rolling process with the workpiece inserted.

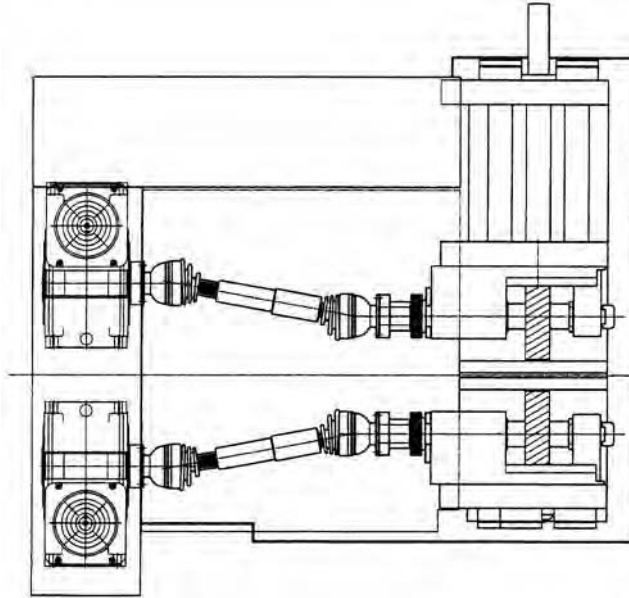


Figure 6.14 Drive layout of the rolling dies and rolling slide (Photograph from Rollwalztechnik Abele + Hältlich GmbH works, Engen, Germany)

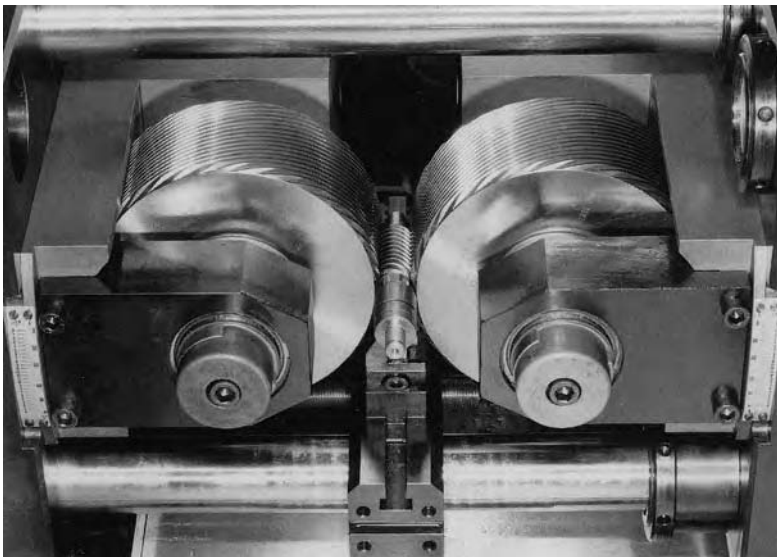


Figure 6.15 Rolling dies and workpiece during the rolling process (Photograph from Rollwalztechnik Abele + Hältlich GmbH works, Engen, Germany)

The following table shows some technical data for the kind of thread rolling machines on the market today.

Table 6.6 Technical data for the thread rolling machines

Rolling force	in kN	80 - 1000
Rolling spindle diameter	in mm	28 - 100
Uptake length of the rolling spindle	in mm	80 - 300
Diameter of cylindrical die	in mm	70 - 235
Workpiece diameter	in mm	2 - 120
Rolling times	in s	1 - 120
Drive capacity (rolling spindle motor)	in kW	2.5 - 30

Range of application of thread rolling machines with cylindrical dies

These machines can be used for

- the infeed method,
- the through-feed method and
- the combined infeed-through-feed method.

Because of this they are used to produce:

- special high-precision screws
- very strong waisted-shank bolts
- single and multi-thread worms
- trapezoidal threads and ballscrew spindles
- knurling work.

6.9 Exercise on Chapter 6

1. What methods of thread rolling are there?
2. Which method is used to produce long, deep threads?
3. What are the advantages of thread rolling?
4. What kinds of thread rolling machines are there?

6.10 Methods and machines for rolling gears

6.10.1 Introduction

Gear rolling is gaining in importance due to its technical advantages as a method, such as:

- high achievable surface finish,
- increase in strength due to work hardening,
- high load capacity due to adapted grain structure,
- short processing times and high reproducibility,
- economic use of material due to chipless production,
- low deformation forces due to only partial deformation.

6.10.2 Gear rolling

A principal difference is made between the following different methods when transverse rolling gears:

1. Infeed rolling: The rolling dies penetrate into the rotationally symmetric blank by a reduction in their radial axis distance, forming the profile by the rolling kinematic of the tool and the workpiece.

2. Through-feed rolling: In this process the rolling dies move across the entire length of the gear to be rolled in an axial direction, their centres at a constant distance. The centre distance is defined by the gear tooth parameters of the workpiece profile (root circle and addendum circle diameters). In this process, as opposed to pure transverse rolling, part of the deformation forces must also be applied in the longitudinal direction, so the rolling dies must have sloped intakes. Their slope angle establishes the relationship between the axial and radial material flow.

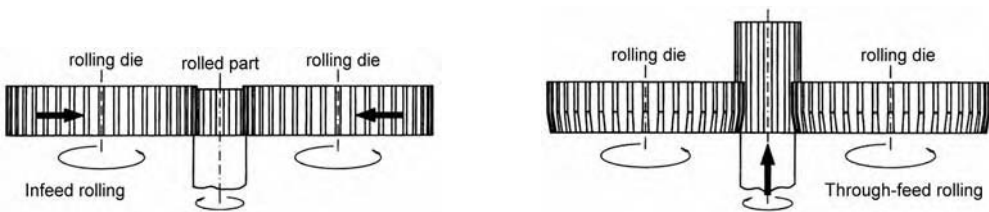


Figure 6.16 Comparison of the infeed rolling and through-feed methods with cylindrical dies

A combination of both methods is used in thread rolling. In this combined version, the infeed-through-feed method, the rolling dies are set up with a smaller pitch angle than the gear teeth to be cut. Feeding in the dies provides the axial thrust and equals out the pitch difference between the die and the workpiece.

6.10.2 a) Interrelations during rolling

In transverse rolling, the shape of the workpiece is created by a rolling motion between the die profile and the involute flank of the gear tooth.

In this process the mechanised feed motion makes the rolling dies penetrate the workpiece, with direction and speed adjusted depending upon the diameter, causing the material to flow into the profile space on the die. This process continues until the required gear tooth parameters are obtained (root circle and addendum circle diameter).

When the constructional setup of the rolling tooling is planned mathematically, the constantly changing kinematic rolling interrelations from the penetration of the die teeth into the workpiece must be taken into account.

The process means that the material flow is asymmetric, causing the flanks of the teeth to deviate in shape from that intended; this can be counteracted by controlled reversing (change of rolling die direction during the cylindrical rolling process) which swaps the flank coast and drive sides.

The depression which forms along the top land of the tooth when gear teeth are rolled has no effect on the gear tooth function, as the quality of an involute tooth shape is defined by its load-bearing flank. A comparison of target and actual values of the geometry of the rolled gear after trial rolling should be drawn upon when correcting the rolling tools.

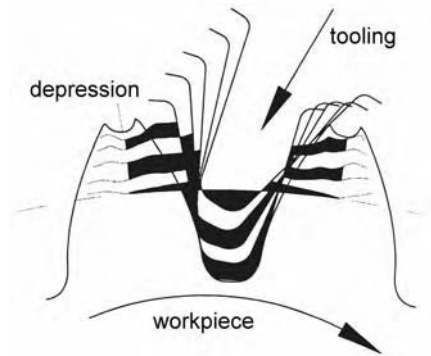


Figure 6.17 Interrelations during rolling

6.10.2 b) Influencing factors when rolling gear teeth

In Figure 6.18 the main influencing factors on the adequate quality of rolled parts are shown. They have been divided into technological/machine-related factors and those related to construction/mathematics. The design and construction of the rolling tools for the deformation process must be mathematically precise for the method to achieve the necessary quality. The quality depends upon the complicated kinematic relationship between the rolling die and the workpiece, as well as a mastering of the typical problems associated with the rolling method.

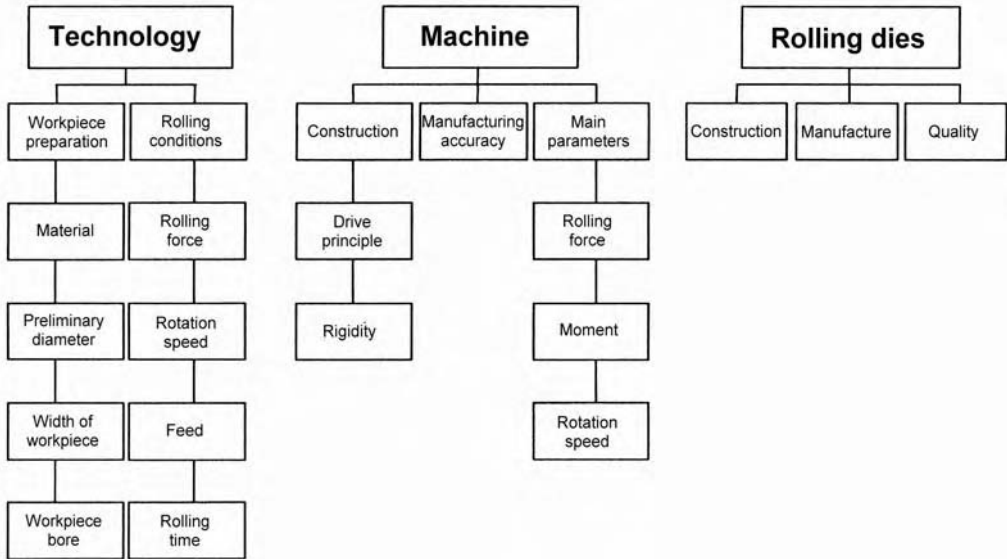


Figure 6.18 Factors which influence the quality of rolled parts

6.10.2 c) Establishing the theoretical pre-turning diameter d_{pre}

One crucial advantage of manufacturing gear tooth profiles by forming is the fact that there is essentially no material loss.

The technician forming the part is confronted with the task of defining initial forms with a volume the same as that of the final form. The quality of the rolled part which can be achieved depends strongly upon the selection of the theoretical pre-turning diameter d_{pre} of the rotationally symmetric starting form.

When this parameter is established by mathematical / geometrical means, two main criteria must be weighed up. On one hand, the pre-turning diameter is worked out according to the material displacement which takes place during the forming process.

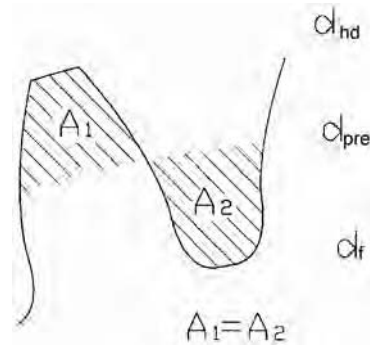


Figure 6.19 d_{pre} if volume is constant

On the other hand, the calculation must also take into account the fact that the spacing rolled on the external diameter of the blank is determined by the spacing of the addendum circle of the rolling dies. If there are substantial differences between the theoretical pre-turning diameter according to the volume and the value after the exact spacing is set down, repeated corrections must be made.

When determining the theoretical pre-turning diameter, the following formula can be used as a basis:

$$d_{\text{pre}} = \frac{d_{\text{hd}} + d_{\text{p}}}{2} + (0.35) \cdot m_{\text{n}}$$

Example:

The aim is to roll a helical gear with an involute flank profile out of C45 with the following gear tooth parameters. Determine the theoretical pre-turning diameter of the rotationally symmetric starting stock.

$$m = 1.5875$$

$$\alpha = 25.75^\circ$$

$$z = 10$$

$$d_{\text{hd}} = 21.7 \text{ mm}$$

$$d_{\text{p}} = 14.9 \text{ mm}$$

Solution: $d_{\text{pre}} = \frac{21.7 \text{ mm} + 14.9 \text{ mm}}{2} + (0.35) \cdot \frac{1.5875}{\cos 25.75^\circ} = \underline{\underline{18.92 \text{ mm}}}$

6.10.3 Method and machines for rolling gear teeth

Figure 6.20 lays out the main rolling methods for the manufacture of gear teeth profiles by forming.

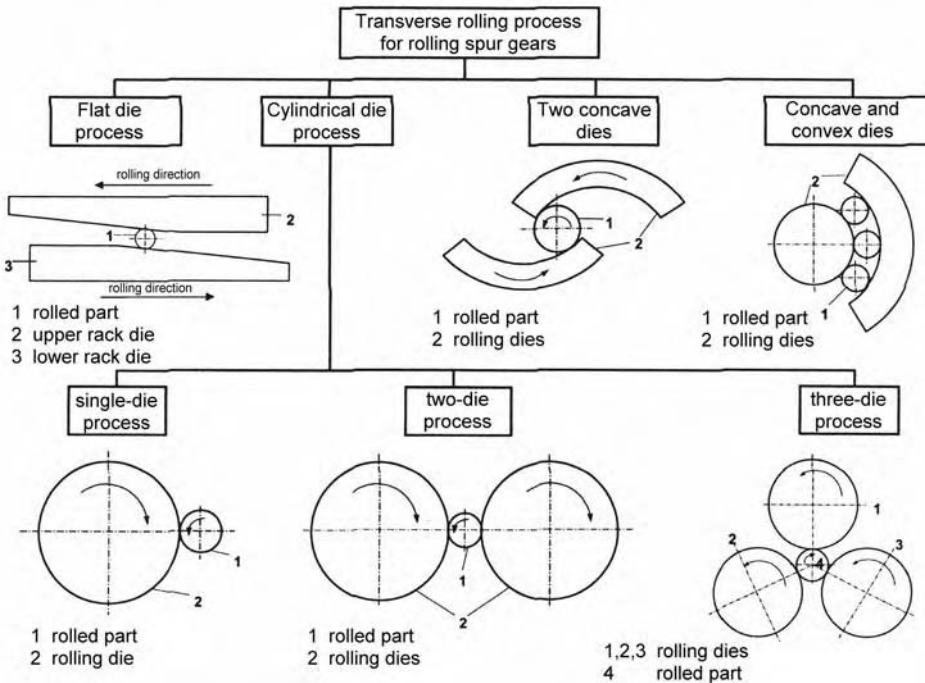


Figure 6.20 Transverse rolling method for the production of gear teeth profiles

6.10.3 a) Rolling with the flat die method

The principle of rolling with flat dies (Figure 6.21) is a movement of the upper and lower dies in opposite directions, in order to roll a defined profile onto a rotationally symmetric initial form. In the rolling process which takes place, the geometry of the die is moulded onto the workpiece (teeth) and involute flank profiles are formed.

At the start of the rolling process, the blank is held between drive centres. The upper and lower dies move against one another in a translatory movement, simultaneously come into contact with the workpiece and set the blank revolving by friction. The sloped intake zones of the dies mean that the die teeth penetrate the workpiece to increasing depth with a continuous feed. At the same time the material is displaced at the points of contact and flows into the spaces of the die profile.

After the full-depth profile has been rolled at the end of the intake zone, the teeth are calibrated in two further rolling revolutions to improve surface finish, the shape of the flanks and radial runout. In the subsequent sloped die runout zone, the deformation forces ease off and the rolled gear tooth system is removed.

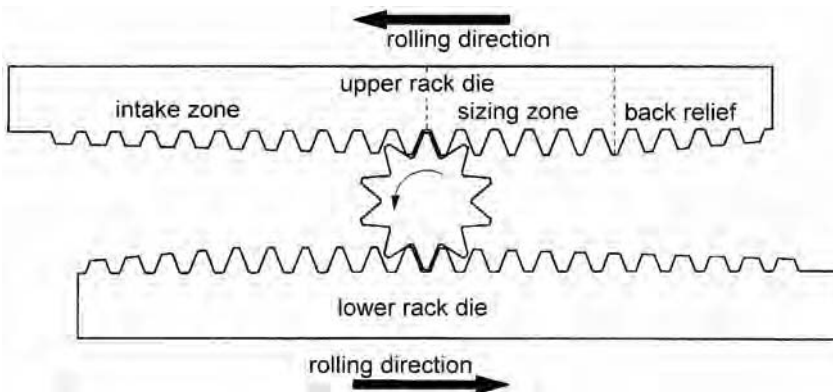


Figure 6.21 The principle of the flat-die method with upper and lower rack dies

6.10.3 b) Rolling with the cylindrical die method

When transverse rolling with the cylindrical die method, the rotationally symmetric blank is held in an axial direction between tooth tips. Two or three cylindrical dies (depending upon the method used) shape the gear teeth on the blank, moving in the same direction and at a constant rotation speed. The die teeth penetrate the workpiece by means of a radial shortening of the distance between the axes of the cylindrical dies. This infeed motion is controlled hydraulically or with a movable rolling die. The second cylindrical die is fixed. It must be possible to move the workpiece holding device in the direction of the infeed movement so that the blank to be centred during the deformation process. Another viable solution is rolling with a support guide.

In this variant, the axis of the workpiece is slightly below that of the rolling die in order to prevent the blank from being pushed out during the deformation process.

As it is possible to re-roll several times, the rotary rolling method can be seen as a forming process with an infinite die length.

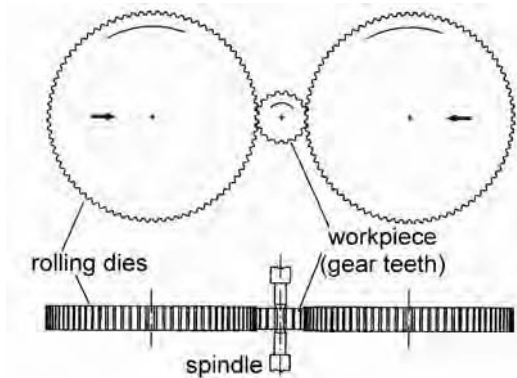


Figure 6.22
Principle of the cylindrical rolling method with two rolling dies

The current state of technological standards mean that it is possible to roll good-quality gear teeth with cylindrical dies up to a modulus of $m = 1.5$. When the modulus increases, the kinematic conditions involved in rolling mean that spacing, flank shape and symmetry defects occur to a degree which has a substantial effect on the performance of the workpieces when in use. Profile rolling machines using the cylindrical rolling method are basically designed with either two or three dies. The design used most often in rolling gear teeth profiles is a machine design following the proven two-roll principle (Figure 6.23) with two moving roller slides.

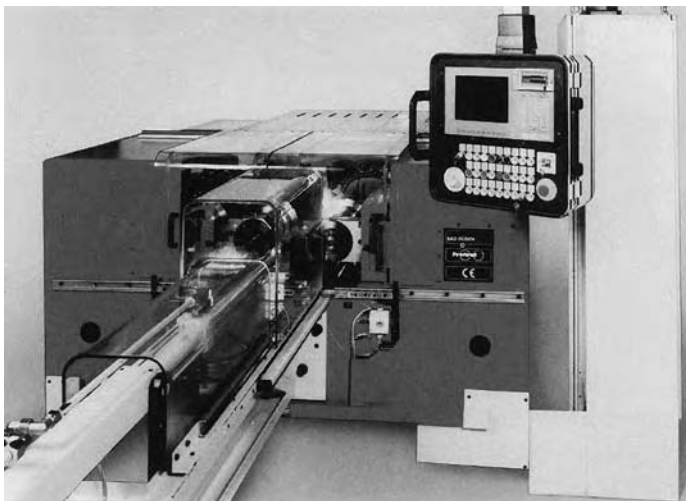
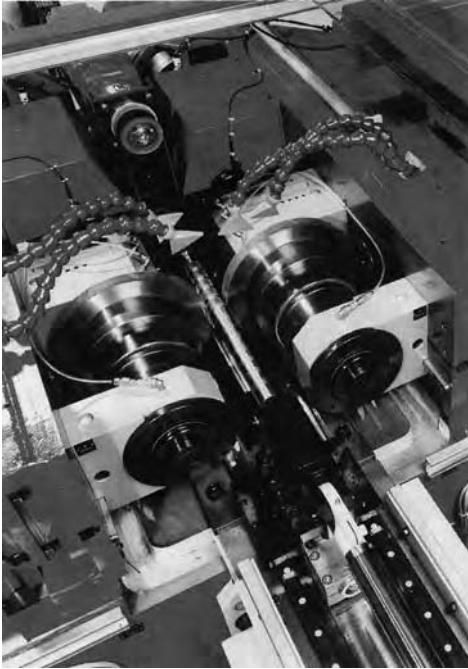


Figure 6.23 “Rollex” two-roll machine (Photograph from Profiroll Technologies works, Bad Döben, Germany)

Two main spindles, driven synchronously in the same direction, are used to take up the rolling dies. One of the two rolling spindles is fixed, the other is moved mechanically or hydraulically so that the rolling dies penetrate the rotationally symmetric blank.



Using CNC control it is possible to control and visualise the processing of the values involved in the rolling and their functions, in a reproducible manner.

When rolling large profile depths with cylindrical dies, forces of up to 800 kN can be used in the deformation (PRZ80, Profiroll, Bad Döben, Germany). Gear tooth profiles with a standard modulus are formed using forces in the region of 200 kN depending on the workpiece.

Figure 6.24

The working area of a two-die machine (Profiroll Technologies, Bad Döben, Germany)

6.10.4 Rolling defects in processing

During the rolling process, the complicated kinematics mean that the following rolling defects typical to the rolling of gear teeth profiles occur:

- undercut in the tooth root area of the gear,
- deviations in the shape of the flank,
- deviations in the flank alignment,
- spacing defects,
- deviations in radial runout.

Radial runout, spacing, flank shape and alignment affect the quality of the rolled part and the optimising of the gear tooth profile.

6.10.4. a) Undercut in the gear tooth root area

Undercut occurs in the gear tooth root area if the tooth number limit, t_L , is not reached in the profile to be rolled.

- at an engagement angle of $\alpha_0 = 20^\circ$: $t_L = \frac{2}{\sin^2 \cdot \alpha_0}$

The engagement and rolling interrelations mean that the addendum radius of the die profile penetrates the target contour of the gear tooth root area, undercutting the usable involute flank. The ensuing rolling defect is considered to be damaging if the load-bearing flank of the tooth is undercut so much that it impairs the load-bearing capacity of the gear teeth during gear engagement. This effect during rolling can be counteracted with a positive addendum modification. The peak value of this addendum modification is limited by the formation of a peak on the top land of the gear tooth.

7 Cold hubbing

7.1 Definition

Cold hubbing is a cold bulk forming process where a hardened punch (male hub) penetrates a workpiece at a low speed (slower than extrusion).

7.2 Application of the process

For the production of cavities in dies for moulding, stamping, injection moulding, plastic moulding and drop forging.

For example:

Screw and bolt production (Figure 7.1)

The hubbing of screw and bolt head shapes in punches and dies.

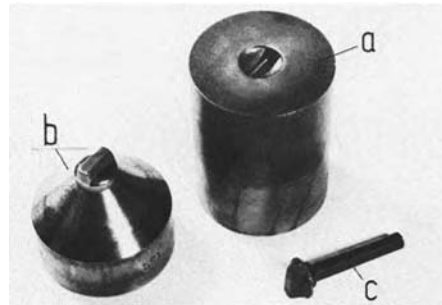


Figure 7.1 a) cold hubbed bolt die, b) hub, c) carriage bolt produced by upsetting

Production of cutlery (Figure 7.2)

The hubbing of cutlery cavities in stamping dies.



Figure 7.2 Forging die for cutlery handle, a) hub, b) hubbed stamping die

The production of forging dies (Figure 7.3)
Hubbing cavities in drop forging dies.

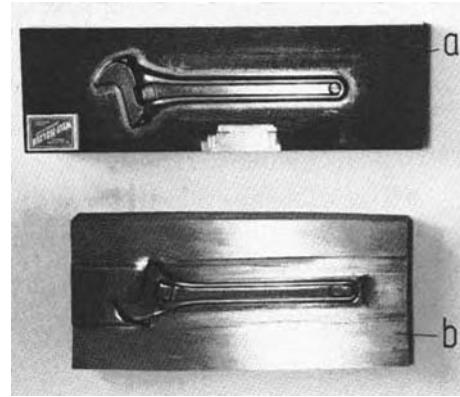


Figure 7.3 Cold hubbed cavity in a drop forging die,
a) hub,
b) hubbed cavity

7.3 Permissible deformations

The limits for cold hubbing are derived from the deformability of the tool steels and the permissible maximum surface pressure of the hub. As yet there is, however, no precise method of calculation for this.

7.4 Calculation of force and mechanical work

7.4.1 Hubbing force

$$F = p_{\max} \cdot A$$

equivalent diameter d

$$D = 1.13 \cdot \sqrt{A}$$

F	in N	hubbing force
A	in mm ²	hub area
d	in mm	diameter of the hub
t	in mm	hubbing depth
p_{\max}	in N/mm ²	specific hubbing force

(from Table 7.1)

For hubs which are not round, an equivalent diameter d can be calculated from the hub area A .

Table 7.1 Specific hubbing force p_{\max} in N/mm² = f (material and $\frac{t}{d}$)

$\frac{t}{d}$		0.1	0.2	0.4	0.6	0.8	1.0
Material group	I	1700	2000	2300	2600	2800	2900
	II	2400	2750	3200	–	–	–
	III	3100	[4000]	–	–	–	–

7.4.2 Hubbing work

$$W = F \cdot t$$

W in Nmm hubbing work

7.5 Materials which can be hubbed

Table 7.2 Steels which can be hubbed

Material group	Quality Short designation	Material number	Special notes on use
Screw and bolt tooling			
I or II	C 100 W 1 95 V 4	1.1540 1.2835	} Heading punches and bottom dies for cold work
II III	X 32 CrMoV 3 3 X 38 CrMoV 5 1 45 CrMoW 5 8 X 30 WCrV 5 1 X 30 WCrV 9 3	1.2365 1.2343 1.2603 1.2567 1.2581	
Drop forging tooling			
II	C 70 W 1	1.1520	
II	45 CrMoV 6 7 X 32 CrMoV 3 3	1.2323 1.2365	Forging dies for light metals Forging dies for non-ferrous heavy metals and for steels being pressed
III	55 NiCrMoV 6 56 NiCrMoV 7	1.2713 1.2714	} Forging dies for steels being hammered
Die-casting tooling			
I	X 8 CrMoV 5	1.2342	Zinc pressure die-casting moulds
II	45 CrMoV 6 7 X 32 CrMoV 3 3 X 38 CrMoV 5 1 X 32 CrMoV 3 3	1.2323 1.2365 1.2343 1.2365	Zinc and light metal die-casting moulds Light metal die-casting moulds Light-metal die-casting moulds Brass die-casting moulds
Stamping dies			
I or II II	C 100 W 1 90 Cr 3	1.1540 1.2056	} Coining punches (minting)
II III	45 CrMoV 6 7 55 NiCr 10 X 45 NiCrMo 4 X 165 CrMoV 12	1.2323 1.2718 1.2767 1.2601	} Moulds for jewellery, electronic parts and furniture mountings (minting)

7.6 Hubbing speed

Hubbing speeds are between

$$v = 0.01 \text{ mm/s and } 4 \text{ mm/s}$$

with higher-strength steels and difficult shapes needing to be hubbed at the lower hubbing speed.

7.7 Lubrication during hubbing

To prevent cold welding between the hub and the workpiece, the following measures are necessary:

- The surfaces of the hub which come into contact with the workpiece must be polished.
- Brush the hub surface with copper sulphate solution (acts as a lubricant binder).
- Lubricate with molybdenum disulphide (MoS_2).

7.8 Characteristics of the workpieces to be hubbed

- For the workpieces which are to be hubbed, their external diameter and their height must be in relation to the hubbing diameter and the hubbing depth.

$D = 2.5 \cdot d$
$D_A = 1.5 \cdot d$
$h \geq 2.5 \cdot t$
$\alpha = 1.5 \text{ to } 2.5^\circ$

- The workpiece to be hubbed needs to have recesses in its sides and base. This makes the material flow easier and the hubbing capacity higher.

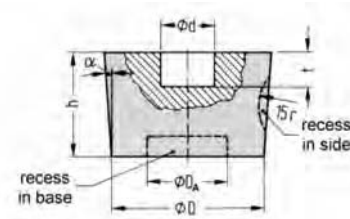


Figure 7.4 Measurements of the workpiece to be hubbed

d hubbing diameter, t hubbing depth, D external diameter, D_A recess in the base, r radius for the recesses in the sides, α slope angle $\cong 1^\circ$

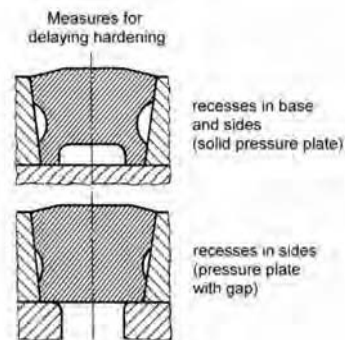


Figure 7.5 Recesses in the workpiece

7.9 Hubbing tooling

Hubbing tooling consists of the hub, a reinforcing ring, a retaining ring, a hardened base and fixing devices. The fixing devices are for keeping the hub and the retaining ring firmly in place.

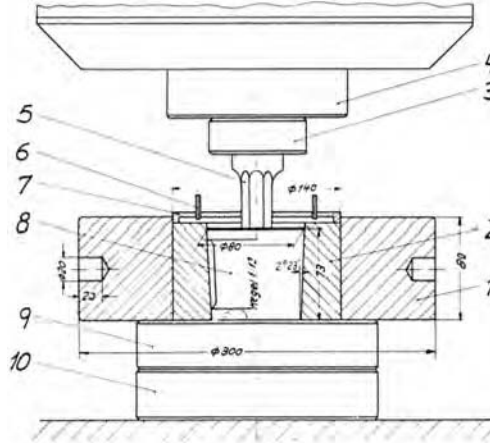


Figure 7.6 Hubbing tooling. 1 retaining ring, 2 armouring, 3 hub support, 4 pressure plate, 5 hub, 7 eccentric ring, 8 die to be hubbed, 9 and 10 pressure plates

Retaining ring (reinforcement, Figure 7.7)

During hubbing, as extreme radial forces occur in the dies to be hubbed, causing high tangential stresses, the dies must be reinforced in a retaining ring (shrink fit). The pre-stressing of the retaining ring counteracts the tangential stresses in the tool. The height h of the retaining rings is equivalent to that of the workpiece. The inner retaining ring a is hardened, with a hardness of 58 ± 2 HRC. The outer retaining ring is also hardened. Its strength should be around 1200 N/mm^2 . Its external diameter D_1 should be $2.5 D$.

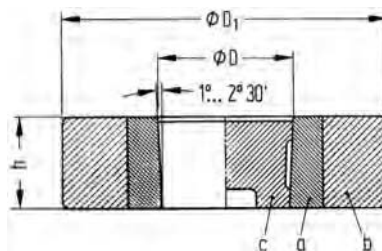


Figure 7.7 Layout of reinforcing ring, retaining ring and the workpiece to be hubbed:
a) reinforcement, b) retaining ring, c) die to be hubbed

The tool which actually does the hubbing is the male hub (Figure 7.8):

- It should not have any sharp edged ridges.
- The head of the hub should be about 20 mm larger than the shank.
- The shank must be finely ground and polished up to and including the radius of the junction with the head.

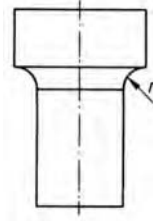


Figure 7.8 Hub

Table 7.3 Hub materials and permissible surface pressure

Material no.	p_{perm} in N/mm ²	HRC hardness
1.3343	3200	63
1.2601	3000	62
1.2762	2600	61

7.10 Advantages of cold hubbing

- healthy, unbroken grain structure (Figure 7.9)
- plate-finished smooth surfaces on the hubbed profile
- high dimensional accuracy of the hubbed profile
tolerances: 0.01 – 0.02 mm
- higher tool life due to optimal grain direction and high surface finish
- considerably shorter production times than with production involving chipping.

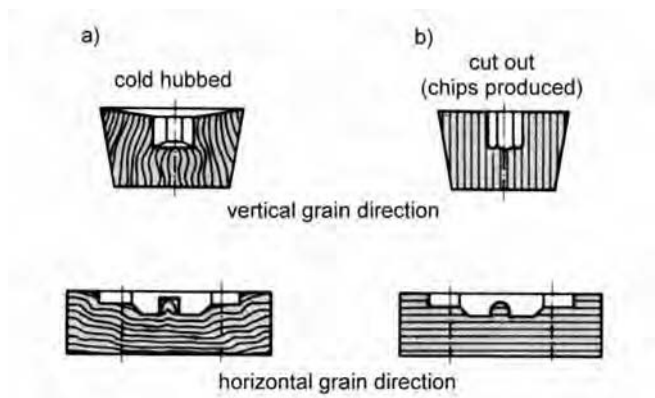



Figure 7.9 Grain direction: a) with workpiece produced by hubbing – b) by a chip-producing method

7.11 Defects during cold hubbing

Table 7.4 Hubbing defects and their causes

Defect	Cause	Steps to be taken
Workpiece cracks radially 	Hubbing has taken place without a reinforcing ring	Reinforce workpiece before hubbing and if necessary hub pre-form which flows more easily.
Work hardening too high during hubbing	Workpiece has no recesses on the base and at the sides (Figure 7.4). Material can not flow outwards.	Make recesses in workpiece.
Hub breaks off.	Permissible surface pressure exceeded. Hub designed unfavourably.	Carry out intermediate annealing of workpiece after partial hubbing. Design the hub head form to flow better.

7.12 Machines for cold hubbing

Special hydraulic presses are used for hubbing. These machines are characterised by an especially stable construction and the precision with which the hubbing speed can be controlled.

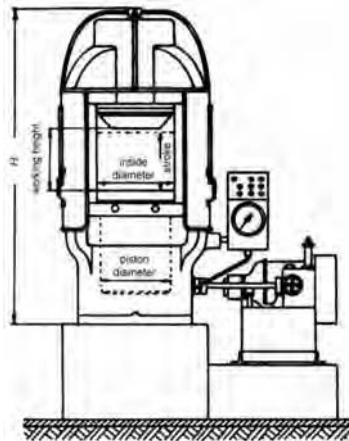


Figure 7.10 Hubbing press

Table 7.5 Construction measurements of hubbing presses (Sack und Kiesselbach manufacturers)

F in kN	H in mm	Piston diameter in mm	Inside diameter in mm	Stroke height in mm
1 600	1 700	210	220	160
3 150	2 000	285	320	250
6 300	2 245	400	415	275
12 500	2 300	570	585	355
25 000	2 700	800	830	380
200 000	5 600	—	1 640	400

7.13 Example calculations

Example 1

The aim is to hub a square 15 mm deep into a press die (Figure 7.11). The square must have a side width of 12 mm.

Material:

X 8 CrMoV 5 Material group I

Find:

hubbing force.

Solution:

Equivalent diameter d

$$d = 1.13\sqrt{A} = 1.13 \cdot \sqrt{(15 \text{ mm})^2} = 16.95 \text{ mm}$$

$$t/d = 12 \text{ mm}/16.95 \text{ mm} = 0.707$$

p_{\max} from Table 7.1 for $t/d = 0.71$ and material group I

$$p_{\max} = 2710 \text{ N/mm}^2$$

$$F_{\max} = p_{\max} \cdot A = 2710 \text{ N/mm}^2 \cdot (15 \text{ mm})^2 = 609750 \text{ N} = 609.7 \text{ kN}$$

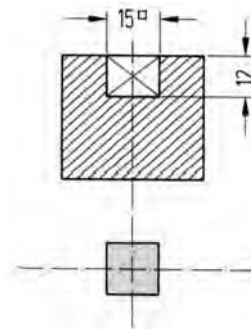


Figure 7.11 Press die

Example 2

The aim is to hub a hexagon 4.2 mm deep into a bolt die made of 45 CrMoW5 8. The hexagon must have a diameter across flats $s = 20 \text{ mm}$.

Find: force and mechanical work.

Solution:

$$A = \frac{a \cdot h}{2} \cdot 6$$

where $h = \frac{s}{2} = 10 \text{ mm}$

$$a^2 - \frac{a^2}{4} = h^2$$

$$a = \sqrt{\frac{4}{3}} \cdot h = \sqrt{\frac{4}{3}} \cdot 10 = 11.54 \text{ mm}$$

$$A = \frac{a \cdot h}{2} \cdot 6 = \frac{11.54 \cdot 10}{2} \cdot 6 = \underline{\underline{346.2 \text{ mm}^2}}$$

$$d_{\text{eq.}} = 1.13 \cdot \sqrt{A} = 1.13 \cdot \sqrt{346.2} = \underline{\underline{21.0 \text{ mm}}}$$

$$F = p_{\text{max}} \cdot A = \frac{4000 \text{ N/mm}^2 \cdot 346.2 \text{ mm}^2}{10^3} = \underline{\underline{1384.8 \text{ kN}}}$$

$$\frac{t}{d} = \frac{4.2}{21} = \underline{\underline{0.2}}$$

$$W = F \cdot t = 1384.8 \text{ kN} \cdot 0.0042 \text{ m} = \underline{\underline{5.8 \text{ kNm}}}$$

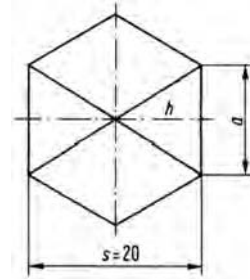


Figure 7.12 Hexagon with measurements

7.14 Exercise on Chapter 7

1. What is meant by “cold hubbing”?
2. What is this method used for?
3. Describe the hubbing tooling.
4. What has gone wrong if the workpiece cracks during hubbing?
5. What are the advantages of cold hubbing?
6. What are the advantages of the cold hubbing process compared to a chip-producing manufacturing process when producing a bolt die with a hexagon cavity?

8 Coining (stamping)

8.1 Definition

Coining is a cold forming process where certain surface forms are produced with low material displacement.

8.2 Types and applications of coining processes

8.2.1 Coining

In coining the thickness of the material in the starting stock is altered.

Application:

Coin production (Figure 8.1), indenting impressions into badges, coining components for mechanical engineering and the electrical engineering industry (Figure 8.2).

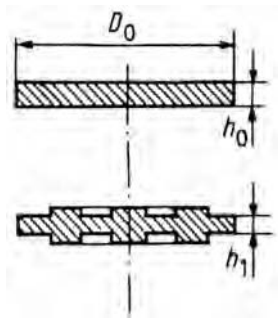


Figure 8.1 Coin production

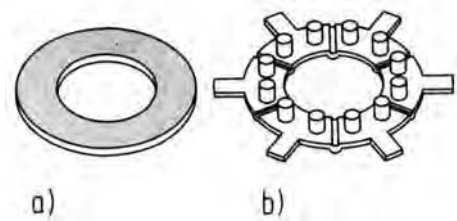


Figure 8.2 Coiled control lever (contact piece)
a) blank, b) finished part

8.2.2 Sizing

This is used to give higher dimensional accuracy to a blank which has already been pre-formed. For example, drop forged connecting rods (Figure 8.3) can be given higher dimensional precision by sizing the thickness of the hub and the spacing of the hub centres.

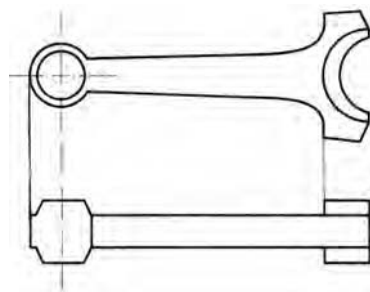
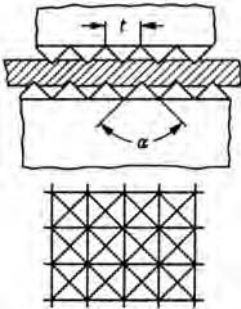


Figure 8.3 Sizing a connecting rod

8.2.3 Planishing (straightening)

This is used to straighten twisted or warped stamped parts.



By stamping a grid pattern (Figure 8.4) (rough straightening) stresses can be relieved and the parts straightened out.

Figure 8.4 Grid pattern on a straightening die, α angle of the points, t spacing

8.3 Calculation of force and mechanical work

8.3.1 Force

In force calculation a difference is made between embossing and impressing lettering, and deep coining. In deep coining, the depth of the relief, and thus also the deformation stress, k_r , (Table 8.1) is greater than when embossing.

Table 8.1 k_r values for coining in N/mm²

Material	R_m in N/mm ²	k_r in N/mm ²	
		Embossing	Deep coining
Aluminium, 99 %	80 to 100	50 to 80	80 to 120
Aluminium alloy	180 to 320	150	350
Brass, Ms 63	290 to 410	200 to 300	1500 to 1800
Copper, soft	210 to 240	200 to 300	800 to 1000
Steel	280 to 420	300 to 400	1200 to 1500
Stainless steel	600 to 750	600 to 800	2500 to 3200

punch area A

$$A = \frac{D_0^2 \cdot \pi}{4}$$

A in mm² punch area
 D_0 in mm blank diameter

max. coining force F

$$F = k_r \cdot A$$

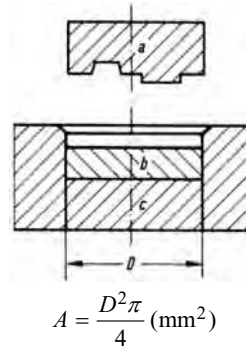


Figure 8.5 Basic dimensions in coining. a) punch, b) blank, c) die

8.3.2 Coining work

$$W = F \cdot h \cdot x$$

$$h = \frac{V_1}{A_{proj}}$$

$$h_0 = h_1 + h$$

W	in Nm	coining work
x		process factor
V_1	in mm ³	volume of impression
A_{proj}	in mm ²	projected area of the coined part
h	in mm	punch displacement
h_0	in mm	blank thickness
h_1	in mm	remaining thickness after deformation

The process factor x can be determined from the force-displacement diagram (Figure 8.6).

$$x = \frac{F_m}{F_{max}}$$

$$x \cong 0.5$$

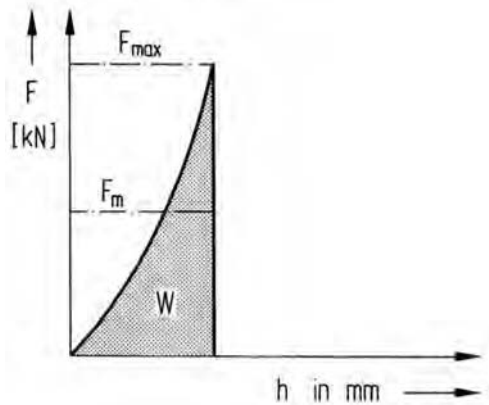


Fig. 8.6 Force-displacement diagram during coining

8.4 Tooling

Coining assemblies are usually guided by a pillar guide frame (Figure 8.7). The raised sections on the punch are the negative of the indentations to be produced on the workpiece. As with forging dies, a difference is also made here between closed dies and open dies. Closed dies are used with lower material displacement, such as when producing coins. Open dies, which give rise to burrs on the workpiece, are used when coining forgings with large deformation strains.

Table 8.2 shows common die materials.

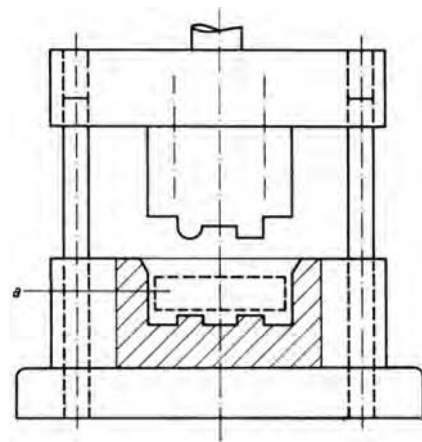


Figure 8.7 Closed coining die with pillar guide, a) blank

Table 8.2 Materials for coining punches and dies

Material	Material no.	HRC assembly hardness
C 110 W1	1.1550	60
90 Cr 3	1.2056	62
90 Mn V 8	1.2842	62
50 Ni Cr 13	1.2721	58

8.5 Defects during coining (Table 8.3)

Defect	Cause	Steps to be taken
Impression is incompletely formed	Too low a coining force	Raise force
Cracking on workpiece	Material deformability exceeded	Carry out intermediate annealing

8.6 Example

The aim is to coin an impression as in Figure 8.8.

Material: Ms 63. (Cu Zn 37)

Find: Coining force and coining work

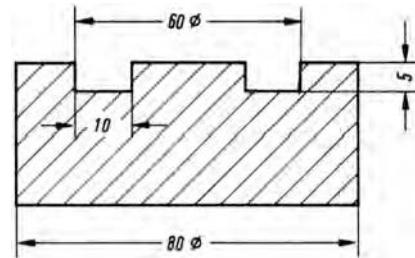


Figure 8.8 Coined workpiece

$$F = k_r \cdot A = 1500 \frac{\text{N}}{\text{mm}^2} \cdot \frac{(80 \text{ mm})^2}{4} = 1500 \cdot 5024 \text{ N} = 7536000 \text{ N} = 7536 \text{ kN}$$

$$k_r \text{ selected from Table 8.1} = 1500 \text{ N/mm}^2$$

$$h = \frac{V_I}{A_{\text{proj}}} = \frac{50 \text{ mm} \cdot \pi \cdot 10 \text{ mm} \cdot 5 \text{ mm}}{5024 \text{ mm}^2} = 1.56 \text{ mm}$$

$$W = F_{\text{max}} \cdot h \cdot x = 7536 \text{ kN} \cdot 0.00156 \text{ m} \cdot 0.5 = 5.89 \text{ kN m}$$

$$h_0 = h + h_1 = 1.56 + 8 = 9.56 \text{ mm.}$$

8.7 Exercise on Chapter 8

1. What is meant by “coining”?
2. What methods of coining are there?
3. What are the main elements of coining dies?
4. What is coining used for millions of times in practice?

9 Ironing (wall ironing)

9.1 Definition

Ironing is a bulk forming process where the deformation force (tensile force) must be absorbed by the cup wall which is deformed. If the stress in the formed cup wall exceeds the tensile strength of the cup material, the base is torn off.

9.2 Application of the process

For the production of flanged hollow parts whose base is thicker or thinner than the wall. With this method, hollow parts with inner tapering can also be produced.

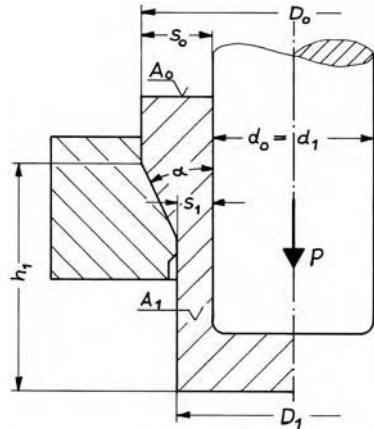


Figure 9.1 Cup with flange.
Ironing with a ring

9.3 Starting stock

The starting stock is a pre-formed (mainly produced by extrusion), thick-walled cup.

9.4 Principal strain (Figure 9.1)

$$\varphi_p = \ln \frac{A_0}{A_1} = \ln \frac{D_0^2 - d_0^2}{D_1^2 - d_1^2} = \ln \frac{D_0^2 - d_0^2}{D_1^2 - d_1^2}$$

- A_0 in mm^2 ring area before forming
- A_1 in mm^2 ring area after forming
- D_0 in mm external diameter before forming
- d_0 in mm inside diameter before forming
- D_1 in mm external diameter after forming
- d_1 in mm inside diameter after forming (usually $d_0 = d_1$)
- φ_p – principal strain

If φ_p is provided and the limiting diameter D_1 is sought where $d_0 = d_1 = \text{const.}$, then:

$$D_1 = \sqrt{\frac{D_0^2 - d_0^2}{e^{\varphi_p}} + d_0^2}.$$

During ironing with a die ring (Figure 9.1), the values provided in Table 9.1 are permissible. When ironing with several die rings arranged one after the other (Figure 9.2), approx. 20% more deformation can be allowed (e.g. not 35% but 40%).

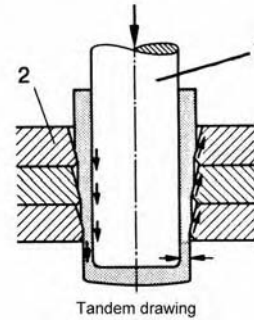


Figure 9.2 Multiple ironing. 1 punch, 2 die ring

Table 9.1 Permissible deformations with a die ring

Material	$\varphi_{p\text{perm}}$
Al 99.8; Al 99.5; Al Mg 1; Al MgSi 1; Al Cu Mg 1	0.35
Cu Zn 37(Ms 63)	0.45
Ck 10 – Ck 15, Cq 22 – Cq 35	0.45
Cq 45; 16 Mn Cr 5; 42 Cr Mo 4	0.35

The number of ironing operations required can be determined from the quotients of actual and permissible deformation.

Number of ironing operations required:

$$n = \frac{\varphi_p}{\varphi_{p\text{perm}}} = \frac{\left(\ln \frac{A_0}{A_n} \right) \cdot 100}{\varphi_{p\text{perm}}}$$

- n number of ironing operations required
 A_0 in mm^2 cross-sectional area before the first operation
 A_n in mm^2 cross-sectional area after the last (n th) operation
 $\varphi_{p\text{perm}}$ in percent permissible deformation
 φ_p in percent principal strain.

The actual limiting values, however, result from the ironing force. This must remain lower than the product of the ring area A_1 after forming and the strength of the material.

$$F < A_1 \cdot R_e < A_1 \cdot R_m$$

(R_e previously σ_s – R_m previously σ_B).

- If $F > A_1 \cdot R_c$: then a further, undesired deformation occurs.
 If $F > A_1 \cdot R_m$: then the cup tears off near the base.

9.5 Calculation of force and mechanical work

9.5.1 Force

$$F = \frac{A_1 \cdot k_{str_m} \cdot \varphi_p}{\eta_F \cdot 10^3}$$

F	in kN	ironing force
A_1	in mm ²	cross-sectional area after forming
k_{str_m}	in N/mm ²	mean flow stress
φ_p	–	principal strain
η_F	–	deformation efficiency
10^3	in N/kN	conversion factor

9.5.2 Mechanical work

$$W = F \cdot h_1 \cdot x$$

W	in kN m	mechanical work
h_1	in m	punch displacement
x	–	process factor ($x = 0.9$).

9.6 Example

The aim is to form a thick-walled pre-formed cup into a cup with reduced wall thickness (Figure 9.3).

Where: material Cq 45; $\eta_F = 0.7$.

Find:

- principal strain
- number of ironing operations
- smallest possible diameter for the first operation ($\varphi_{pperm} = 35\%$)
- force for the first operation

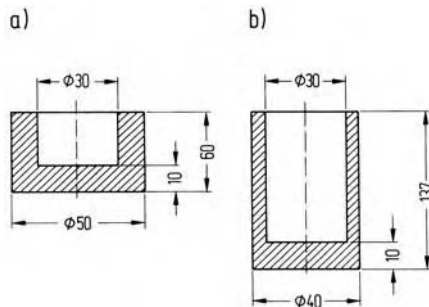


Figure 9.3 Ironed workpiece.

- a) blank – pre-formed cup,
 b) finished part after three operations

Solution:

Principal strain:

$$\varphi_p = \ln \frac{D_0^2 - d_0^2}{D_1^2 - d_0^2} = \ln \frac{50^2 \text{ mm}^2 - 30^2 \text{ mm}^2}{40^2 \text{ mm}^2 - 30^2 \text{ mm}^2} = 0.82.$$

Number of ironing operations required:

$$n = \frac{\varphi_p}{\varphi_{p\text{perm}}} = \frac{82\%}{35\%} = 2.34$$

$n = 3$ operations required.

(Repeated soft annealing required after each operation.)

Smallest possible diameter for the first operation:

$$D_1 = \sqrt{\frac{D_0^2 - d_0^2}{e^{\varphi_h}} + d_0^2} = \sqrt{\frac{50^2 \text{ mm}^2 - 30^2 \text{ mm}^2}{e^{0.35}} + 30^2 \text{ mm}^2}$$

$$D_{1\text{min}} = \sqrt{\frac{1600}{1.419} + 900} = \underline{\underline{45 \text{ mm}}}.$$

Force for the first operation:

For $\varphi_p = 35\%$: $k_{\text{str}0} = 390 \text{ N/mm}^2$; $k_{\text{str}1} = 860 \text{ N/mm}^2$; $k_{\text{str}m} = 625 \text{ N/mm}^2$.

During the first operation, $D_1 = 45 \text{ mm}$, $d_0 = d_1 = 30 \text{ mm}$

$$F = \frac{A_1 \cdot k_{\text{str}m} \cdot \varphi_p}{\eta_F \cdot 10^3} = \frac{(D_1^2 - d_0^2) \cdot \pi \cdot k_{\text{str}m} \cdot \varphi_p}{4 \cdot \eta_F \cdot 10^3}$$

$$F = \frac{(45^2 \text{ mm}^2 - 30^2 \text{ mm}^2) \cdot \pi \cdot 625 \text{ N/mm}^2 \cdot 0.35}{4 \cdot 0.7 \cdot 10^3} = \underline{\underline{276 \text{ kN}}}.$$

9.7 Exercise on Chapter 9

1. How does ironing differ from forward extrusion?
2. What limits the extent of the deformation?
3. What workpiece shapes is it used for?

10 Wire drawing

10.1 Definition

Wire drawing is a form of drawing using a sliding action (Figure 10.1) where a wire of a larger size (d_0) is pulled through a drawing ring of a smaller size (d_1). In this process the wire is given the shape and the cross-sectional dimensions of the drawing ring. Wire drawing belongs to the production processes which involve forming by tensile and compressive forces, as a state of stress develops in the deformation zone due to deformation by both tension and pressure. In wire drawing, a difference is made according to the dimensions of the wire between:

- coarse drawing: $d = 16$ to 4.2 mm
- medium drawing: $d = 4.2$ to 1.6 mm
- fine drawing: $d = 1.6$ to 0.7 mm
- ultra-fine drawing: $d < 0.7$ mm

and according to the machine used, between:

- single-draft drawing
- tandem drawing.

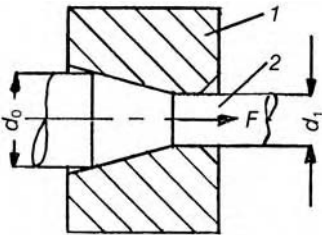


Figure 10.1 The principle of wire drawing.
1 die, 2 wire

10.2 Application

Wire and rod drawing are used to produce wires and rods with smooth surfaces and low tolerances for various fields of application (Table 10.1).

Table 10.1 Fields of application of drawn wires and rods

Material	Application
Low-carbon steels, C 10 – C22	Wires, wire meshes, barbed wire, pins, nails, screws and bolts, rivets
High-carbon steels (up to 1.6% C)	Rod material for automatic processing, wire cables
Alloy steels	Industrial springs, welding wires
Copper and copper alloys	Wires, wire meshes, screws, bolts and shaped parts, parts for the electrical industry
Aluminium and Al alloys	Screws and bolts, shaped parts, electrical lines, etc.

10.3 Starting stock

The starting stock for wire drawing is hot-rolled wires. For rod drawing, rods produced by hot rolling or extrusion moulding are used as starting stock.

10.4 Principal strain

The principal strain results from the aspect ratio before and after drawing.

$$\varphi_p = \ln \frac{A_0}{A_1}$$

$$d_1 = \frac{d_0}{e^{\varphi_p/2}}$$

- A_0 in mm^2 cross-section before drawing
 A_1 in mm^2 cross-section after drawing
 d_0 in mm diameter before drawing
 d_1 in mm diameter after drawing
 $e = 2.718$ basic number of the natural logarithm
 φ_p principal strain

10.5 Permissible deformations

The following table contains standard values for the drawing reductions and the permissible total deformation in tandem drawing.

Table 10.2 Permissible deformations with tandem drawing

Material	Intake strength	Intake diameter	Drawing reduction between two draws	Total deformation (tandem drawing)	Number of drawing stations
	R_m in N/mm^2	d_0 in mm	$\varphi_{p\text{perm}}$ (%)	$\varphi_{p\text{perm}}$ (%)	
Steel wire	400	4 – 12	18 – 22	380 – 400	8 to 21
	1200	4 – 12	18 – 22	380 – 400	
	1200	0.5 – 2.5	12 – 15	120 – 150	
Cu materials	Cu (soft)	8 – 10 wet draws	40 – 50	350 – 400	5 to 13
	250	1 – 3.5	18 – 20	200 – 300	
Al materials	Al (soft) and Al alloy	12 – 16 wet draws	20 – 25	250 – 300	5 to 13
	80	1 – 3.5	15 – 20	150 – 200	

In single drawing, the permissible deformations are around:

- Steel wires = 150 – 200 %
- Cu materials = 200 %
(Cu soft)
- Al materials = 200 %
(Al soft).

10.6 Drawing force

According to Siebel, the drawing force can be calculated with the following equation

$$F_{\text{dr}} = A_1 \cdot k_{\text{strm}} \cdot \varphi_p \left(\frac{\mu}{\alpha} + \frac{2 \cdot \hat{\alpha}}{3 \cdot \varphi_p} + 1 \right).$$

The mean coefficient of friction is around $\mu = 0.035$ ($\mu = 0.02$ to 0.05). The optimum drawing angle, requiring the least force, is around $2 \alpha = 16^\circ$. From this it follows for the angle in radians:

$$\hat{\alpha} = \frac{\pi}{180^\circ} \cdot \alpha^\circ = \frac{\pi}{180^\circ} \cdot 8^\circ = 0.13.$$

If these values are brought into the above equation, then the drawing force during wire drawing can be determined approximately with the simplified equation and the deformation efficiency $\eta = 0.6$.

$$F_{\text{dr}} = \frac{A_1 \cdot k_{\text{strm}} \cdot \varphi_p}{\eta_F}$$

- | | |
|--|--|
| F_{dr} in N | drawing force |
| k_{strm} in N/mm ² | mean flow stress |
| A_1 in mm ² | cross-section of the wire after drawing |
| φ_p – | principal strain |
| η_F – | deformation efficiency ($\eta_F = 0.6$). |

10.7 Drawing speeds

10.7.1 Single-draft drawing

The drawing speeds for single-draft drawing can be taken from the following table.

Table 10.3 drawing speeds v for single-draft draws

Material	Intake strength R_m in N/mm ²	v_{\max} in m/s
Steel wire	(iron wire) 400	20
	800	15
	1300	10
Cu (soft)	250	20
Brass, bronze	400	
Al and Al alloys	80 – 100	25

10.7.2 Tandem drawing

In tandem drawing, the drawing speed differs at every drawing. As the volume is constant, the speed is higher when the wire cross-section is reduced.

$$v_1 \cdot A_1 = v_2 \cdot A_2$$

$$v_1 \cdot A_1 = v_n \cdot A_n$$

$$v_1 = \frac{v_n \cdot A_n}{A_1}$$

v_1 in m/s drawing speed at the first draw

v_2 in m/s drawing speed at the 2nd draw

v_n in m/s drawing speed at the n th draw

A_1 in mm² wire cross-section after the 1st draw

A_2 in mm² wire cross-section after the 2nd draw

A_n in mm² wire cross-section after the n th draw

In tables of standard values, the highest speeds, applying to the last drawing, are always listed for tandem drawing machines.

Table 10.4 Drawing speed v_n for tandem drawing

Material	Intake strength R_m in N/mm ²	v_n in m/s
Steel wire	(iron wire) 400	20
	800	15
	1300	10
Cu (soft)	250	25
Brass, bronze	400	
Al (soft), Al alloys	80 – 100	

The block rotation speed n may then also be calculated from the drawing speed which corresponds to the block peripheral speed involved.

$$n = \frac{v \cdot 60 \text{ s/min}}{d \cdot \pi}$$

v in m/s drawing speed
 d in m block diameter
 n in min^{-1} block rotation speed

10.8 Drive power

The drive power of the wire drawing machine is determined from the drawing force and the drawing speed.

10.8.1 Single-draft drawing machine (Figure 10.2)

$$P = \frac{F_{\text{dr}} \cdot v}{\eta_M}$$

P in kW drive power
 F_{dr} in kN drawing force
 v in m/s drawing speed
 η_M efficiency of the machine
 ($\eta_M = 0.8$).

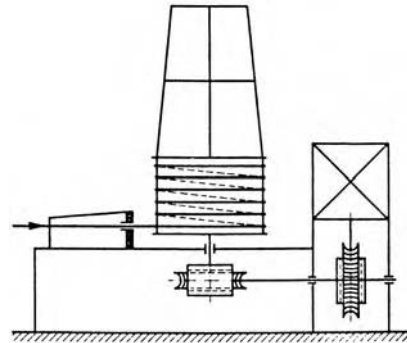


Figure 10.2 The principle of the single-draft drawing machine

10.8.2 Tandem drawing machine (Figure 10.3)

With tandem drawing machines, the total drive power results from adding together the power required for each draw.

$$P_M = \sum P$$

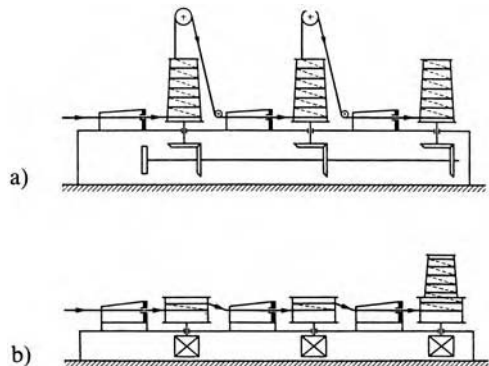


Figure 10.3 The principle of the tandem drawing machine. Wire feed:
 a) from above with two loops,
 b) longitudinally without redirection

10.9 Drawing tooling

The drawing die (Figure 10.4) consists of three zones. These are the cone-shaped intake with the entry angle 2β and approach angle 2α , the bearing land l_3 and the cone-shaped back relief l_4 with the back relief angle 2γ .

The length of the cylindrical guide bush l_3 is around:

$$l_3 = 0.15 \cdot d_1$$

The approach angle 2α influences the drawing force and the surface finish of the wire.

Table 10.5 shows optimum values.

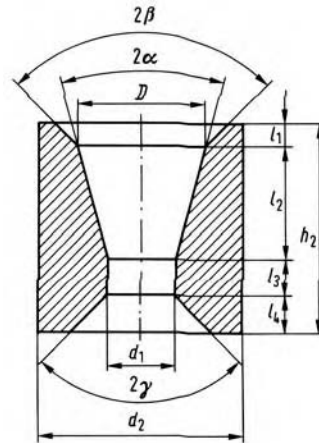


Figure 10.4 Designations of the angles and measurements on the drawing die.

Table 10.5 Optimum approach angle 2α depending upon the material, the extent of deformation and the type of drawing.

Approach angle 2α				
Material		Material		φ_p in %
Steel (C < 0.4 %), brass, bronze		Steel (C > 0.4 %)		
Wet draw	Dry draw	Wet draw	Dry draw	
11°	9°	10°	8°	10
16°	14°	15°	12°	22
19°	17°	18°	15°	35

10.9.1 Drawing die materials

Drawing dies are produced from steel, carbide and diamonds.

Steel drawing dies

Table 10.6 Steels and assembly hardnesses for steel drawing dies

Material	HRC working hardness	Fields of application
1.2203 1.2453 1.2080 1.2436	63 – 67	Rod and tube drawing

Carbide drawing dies (Figure 10.5)

Lower-diameter wires are nearly always drawn with dies made of sintered carbides.

For this purpose, the carbide application groups G10 to G60 are used (the lower the number, the higher the hardness).

Table 10.7 shows the dimensions of carbide drawing dies (Figure 10.5) and the corresponding steel reinforcement.

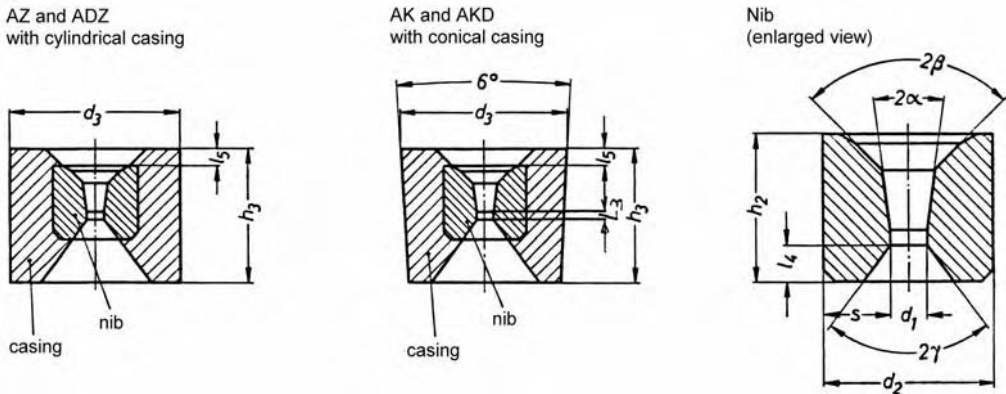


Figure 10.5 Carbide drawing dies for steel wires

Table 10.7 Dimensions of carbide drawing dies for steel wires (ISO-A) and wires made of nonferrous metals (ISO-B)

Steel wire d_1 in mm	Nonferrous metals d_1 in mm	d_2 in mm	h_2 in mm	d_3 in mm	h_3 in mm	l_3 in mm	2β in degrees	2γ in degrees
1.0	1.5	8	4	28	12	0.5	90	90
2.0	2.5	10	8	28	16	0.5		
3.0	3.5	12	10	28	20	0.6		
5	6	16	13	43	25	0.9	60	75
6.5	8	20	17	43	32	1.2	60	60
9	10.5	25	20	75	35	1.5		
12	13	30	24	75	40	1.8		

Designation of a carbide drawing die for steel wires (A)¹ with cylindrical casing (Z)¹, nib diameter $d_2 = 14$ mm, casing diameter $d_3 = 28$ mm, drawing hole diameter d_1 e.g. 1.8 mm, approach angle 2α e.g. 16° (16), nib made of carbide from the application group G10, steel (St) casing:

Drawing die AZ 14 – 28 – 1.8 – G 10 – St

Diamond drawing dies

Diamond drawing dies are used for drawing fine and ultra-fine wires (0.01 mm to 1.5 mm) made of copper, steel, tungsten and molybdenum.

The diamonds are sintered into a steel casing. This surrounds the diamond with a controlled level of pre-stressing.

Figure 10.6 shows the principle of a diamond drawing die and a magnified view of the shape of the drawing hole.

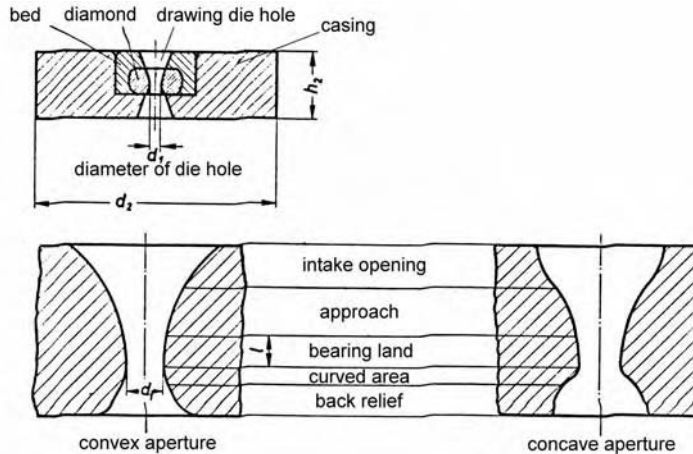


Figure 10.6 Elements of a diamond drawing die. a) Drawing hole details

The ratio of the length of the drawing ring to the drawing hole diameter l/d_1 is:

Steel wires of 0.01 – 1.0 mm diameter:	1 to 2.5
Brass and bronze of 0.2 – 1.0 mm diameter:	0.8 to 1.5
Aluminium of 0.2 – 1.0 mm diameter:	0.5 to 1.0

Designation of a diamond drawing die with a casing of 25×6 (25) made of brass Ms 58 for the wet drawing of copper (B), drawing hole diameter $d_1 = 0.18$ mm (0.18), ratio of the bearing land to the drawing hole diameter $l/d_1 = 0.6$ (0.6):

25 B 0.18 \times 0.6.

Designation of a diamond drawing die with no casing for the hot drawing of tungsten wire (H), drawing hole diameter $d_1 = 0.02$ mm (0.02), ratio of the bearing surface to the drawing hole diameter $l/d_1 = 1.5$ (1.5):

H 0.02 \times 1.5.

10.10 Example

The aim is to draw wire rod made of 42 Cr Mo 4, $R_m = 1200$ N/mm², from a diameter of $d_0 = 12.5$ mm to $d_1 = 5.3$ mm in a tandem drawing process. A machine with eight drawing stations is available. Where:

$$\begin{aligned}v_{\max} &= v_n = 10 \text{ m/s} \\ \eta_f &= 0.6 \text{ deformation efficiency} \\ \eta_M &= 0.7 \text{ efficiency of the drawing machine.}\end{aligned}$$

Find:

1. Total deformation
2. Deformation per draw
3. Intermediate diameter at 2nd to 7th draws where deformation between draws is the same
4. Drawing force for the 1st draw
5. Driving power for the 1st draw.

Solution:

$$1. \quad \varphi_{\text{ptot.}} = \ln \frac{A_0}{A_1} = \ln \frac{12.5^2 \pi / 4}{5.3^2 \pi / 4} = 1.72 = 172 \%$$

$$2. \quad \varphi_{\text{pdraw}} = \frac{\varphi_{\text{ptot.}}}{Dr} = \frac{172 \%}{8} = 21.5 \% \text{ per draw}$$

$$3. \quad d_1 = \frac{d_0}{e^{\varphi/2}} = \frac{12.5}{e^{0.215/2}} = \frac{12.5}{e^{0.1075}} = \frac{12.5}{1.11349} = 11.2 \text{ mm } \varnothing$$

$$d_2 = \frac{d_1}{e^{\varphi/2}} = 10.05 \text{ mm } \varnothing \text{ etc.}$$

$$d_3 = 9.02, \quad d_4 = 8.10, \quad d_5 = 7.27, \quad d_6 = 6.52, \quad d_7 = 5.85, \quad d_8 = 5.3$$

4. Drawing force (1st draw)

$$F_{\text{dr}} = \frac{A_1 \cdot k_{\text{km}} \cdot \varphi_p}{\eta_F}$$

$$\varphi_{p1} = 21.5 \% = 0.215$$

$$k_{\text{str}_0} = 420 \text{ N/mm}^2, \quad k_{\text{str}_1} = 880 \text{ N/mm}^2, \quad k_{\text{str}_m} = \frac{420 + 880}{2} = 650 \text{ N/mm}^2$$

$$A_1 = \frac{d_1^2 \pi}{4} = \frac{(11.2 \text{ mm})^2}{4} = \underline{\underline{98.52 \text{ mm}^2}}$$

$$F_{\text{dr}} = \frac{98.52 \text{ mm}^2 \cdot 650 \text{ N} \cdot 0.215}{0.6 \cdot \text{mm}^2} = 22\,946 \text{ N} = \underline{\underline{22.9 \text{ kN}}}$$

5. Driving power (1st draw)

- 5.1 Drawing speed (1st draw)

$$v_1 = \frac{v_n \cdot A_n}{A_1} = \frac{10 \text{ m} \cdot (5.3 \text{ mm})^2 \pi / 4}{(11.2 \text{ mm})^2 \pi / 4}$$

$$v_1 = \underline{\underline{2.24 \text{ m/s}}}.$$

- 5.2 Driving power (1st draw)

$$P_1 = \frac{F_{\text{dr}} \cdot v_1}{\eta_M} = \frac{22.9 \text{ kN} \cdot 2.24 \text{ m}}{0.7 \cdot \text{s}} = \underline{\underline{73.3 \text{ kW}}}.$$

10.11 Exercise on Chapter 10

1. What methods of wire drawing are there?
2. What kinds of machines for wire drawing are there?
3. How is the principal strain determined in wire drawing?
4. Why are the drawing speeds different at every drawing ring in tandem drawing?
5. What materials are drawing dies made of?
6. Which wires are carbide drawing dies used for?

11 Tube drawing

11.1 Definition

Tube drawing is the drawing of hollow parts, where the outside is formed by a drawing die hole and the inside by a plug or a rod.

11.2 Tube drawing processes

Several manufacturing processes have been developed for drawing tubes. What the processes all have in common is that the tube to be drawn is pointed at one end (pressed between two semi-circular jaws). This pointed end is pushed through the drawing ring and then held tight by the gripper attached to the carriage of the drawing machine. The drawing carriage then pulls the tube through the stationary drawing ring. Table 11.1 shows tube drawing processes and the features which characterise them.

Table 11.1 Tube drawing processes

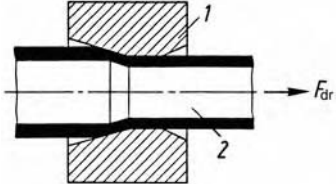
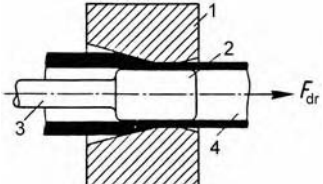
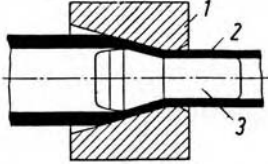
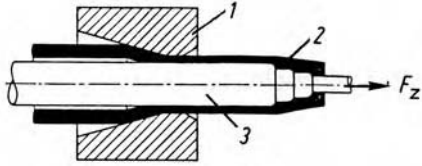
<p><i>Drawing without a mandrel (tube sinking)</i></p> <p>The tube is pulled through the drawing die hole with no support from inside. In this process, only the external diameter measurements are precise; the wall thickness and internal diameter deviate more. This process, known as tube sinking, is only applied to tubes with smaller internal diameters.</p>	 <p>The diagram shows a cross-section of a tube being pulled through a drawing die. The die is labeled '1' and consists of two semi-circular jaws. The workpiece is labeled '2'. An arrow labeled F_{dr} indicates the direction of the drawing force. The tube is shown being pulled through the die hole.</p> <p>Figure 11.1 The principle of tube drawing without a mandrel. 1 Drawing die, 2 workpiece</p>
<p><i>Drawing over a stationary mandrel (plug)</i></p> <p>Here, the tube is pushed over a plug attached to the mandrel. During the drawing process, the tube is drawn through the annular gap formed between the drawing ring and the plug.</p> <p>As the annular gap is smaller than the wall thickness of the tube to be drawn, the wall thickness is reduced and the tube takes on the dimensions of the drawing die hole for its external diameter, and of the plug for its internal diameter.</p>	 <p>The diagram shows a cross-section of a tube being drawn over a stationary mandrel. The drawing ring is labeled '1', the workpiece is labeled '2', the mandrel is labeled '3', and the plug is labeled '4'. An arrow labeled F_{dr} indicates the direction of the drawing force. The tube is shown being pulled through the drawing ring over the mandrel and plug.</p> <p>Figure 11.2 The principle of drawing over a stationary mandrel. 1 Drawing ring, 2 workpiece, 3 mandrel, 4 plug</p>

Table 11.1 Tube drawing process (continued)

<p><i>Drawing over a floating plug</i></p> <p>The set-up is the same as with plug drawing. Here, however, the plug is not attached to a mandrel, but is pushed in before drawing takes place. Because of its conical shape, during the drawing process it is automatically drawn in the direction of drawing, through the die.</p>	 <p>Figure 11.3 The principle of drawing over a floating plug. 1 Drawing ring, 2 workpiece, 3 floating plug</p>
<p><i>Drawing over a moving mandrel</i></p> <p>Instead of a plug, here, a long rod (mandrel), reduced at the foremost end and with a cylindrical shoulder, is pushed into the tube. The cylindrical tip is pushed through the pointed end of the tube. The drawing grip takes hold of this cylindrical peg.</p> <p>During the drawing operation, the rod and the tube are then simultaneously moved in the drawing direction.</p>	 <p>Figure 11.4 The principle of drawing over a moving mandrel. 1 Drawing ring, 2 workpiece, 3 moving mandrel</p>

11.3 Principal strain and drawing force

The limits for the permissible principal strains come from the required drawing force.

As the drawing force must be carried by the tube cross-section A_x (Figure 11.5) after deformation, it must remain lower than the tensile force.

$$F_{dr} < F_{perm}$$

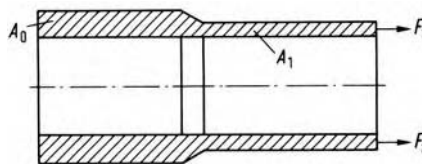


Figure 11.5 Tube cross-sections A_0 before and A_1 after the draw

This provides the permissible deformations. If the required cross-sectional reduction can not be achieved at one drawing, as $F_{dr} > F_{perm}$, then intermediate annealing must be carried out after the first draw.

Table 11.2 shows how the drawing force F_{dr} and the tensile force F_{perm} can be calculated mathematically.

Table 11.2 Calculating principal strain and drawing force

Type of drawing	Permissible deformation φ_{pperm} in % (from drawing force)	Principal strain φ_p (-)	Drawing force in N
Tube sinking	20 – 50	$\varphi_p = \ln \frac{d_0}{d_1}$ $\varphi_{p\%} = \varphi_p \cdot 100$ (%)	$F_{dr} = \frac{A_1 \cdot k_{strm} \cdot \varphi_p}{\eta_F}$
Plug drawing	30 – 50	$\varphi_p = \ln \frac{A_0}{A_1}$ $\varphi_p = \ln \frac{D_0^2 - d_0^2}{D_1^2 - d_1^2}$	for $2 \alpha = 16^\circ$ (optimum opening angle): $\eta_F = 0.4 - 0.6$ for $\varphi_p = 15\%$ $\eta_F = 0.7 - 0.8$ for $\varphi_p = 50\%$ $F_{perm} = A_1 \cdot R_m$
Rod drawing	40 – 60	$\varphi_{p(\%)} = \varphi_p \cdot 100$ (%)	F_{dr} must be lower than F_{perm} , however, or the tube breaks off.
φ_p – principal strain D_0 in mm external diameter before drawing d_0 in mm internal diameter before drawing A_0 in mm ² tube cross-section before drawing D_1 in mm external diameter after drawing d_1 in mm internal diameter after drawing A_1 in mm ² tube diameter after drawing		k_{strm} in N/mm ² R_m in N/mm ² F_{dr} in N F_{perm} in N η_F –	mean flow stress tensile strength of the tube material drawing force maximum force which can be carried into the tube cross-section deformation resistance

11.4 Drawing tooling

Drawing tooling made of carbide is mainly used for tube drawing.

The drawing die is similar in construction to those shown in Figure 10.5 for wire drawing.

The drawing mandrel consists of the steel body (Figure 11.6) and the actual mandrel made of carbide.

Once more, G10 to G60 are common carbide types used.

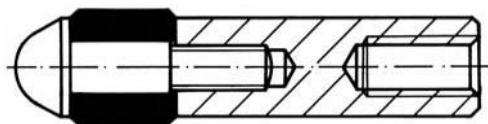


Figure 11.6 Drawing mandrel with screwed-on carbide ring

11.5 Example

The aim is to draw a tube made of Ck 45 ($R_m = 800 \text{ N/mm}^2$) with initial dimensions of $D_0 = 45$, $d_0 = 30$, bringing it to $D_1 = 40$ und $d_1 = 28$.

Find:

1. Drawing force
2. Permissible limiting force
3. Can the cross-sectional reduction be achieved in one drawing?

Solution:

$$\varphi_p = \ln \frac{D_0^2 - d_0^2}{D_1^2 - d_1^2} = \ln \frac{45^2 - 30^2}{40^2 - 28^2} = 0.32 \rightarrow 32\%$$

$$k_{str_0} = 390, \quad k_{str_1} = 840, \quad k_{str_m} = 615 \text{ N/mm}^2$$

$$F_{dr} = \frac{A_1 \cdot k_{str_m} \cdot \varphi_p}{\eta_F} = \frac{(40^2 - 28^2) \cdot \pi \text{ mm}^2 \cdot 615 \text{ N} \cdot 0.32}{4 \cdot 0.7 \text{ mm}^2}$$

$$F_{dr} = 180\,178 \text{ N} \cong \underline{180 \text{ kN}}$$

$$F_{perm} = \frac{A_1 \cdot R_m}{10^3 \text{ N/kN}} = \frac{640.9 \text{ mm}^2 \cdot 800 \text{ N}}{10^3 \text{ N/kN} \cdot \text{mm}^2} = \underline{512.7 \text{ kN}}$$

As F_{dr} is considerably smaller than F_{perm} , this deformation can take place in one drawing.

11.6 Exercise on Chapter 11

1. What kinds of tube drawing processes are there?
2. How do they differ from one another?

12 Extrusion

12.1 Definition

Extrusion (Figure 12.1) is a bulk forming process where a heated billet, confined in a container, is pressed through a shaping die by a punch. In this process, the emerging product takes on the shape of the die.

Extrusion is a forming process involving pressure. The actual deformation from a billet into an extrusion takes place in the funnel-shaped deformation zone in front of the die.

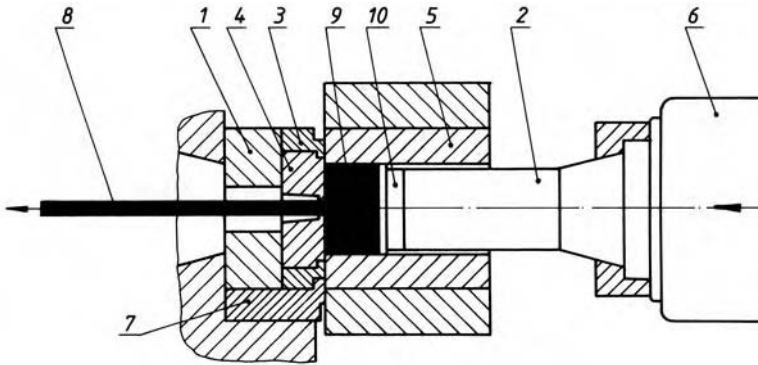


Figure 12.1 The principle of direct extrusion of a solid shape. 1 pressure plate, 2 punch, 3 die (tool) holder, 4 die, 5 container, 6 plunger, 7 slider, 8 extrusion, 9 billet, 10 dummy block

12.2 Application

The process is used to produce solid and hollow profiles of all kinds (Figure 12.2) from aluminium and copper alloys and from steel.

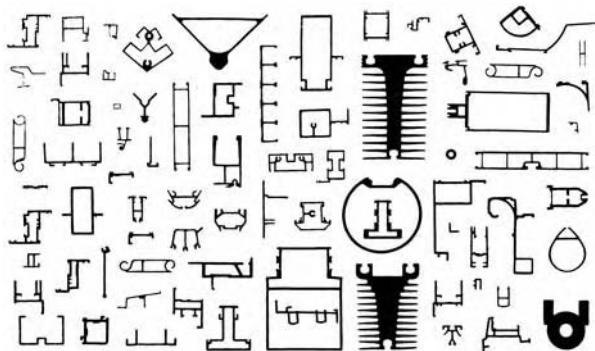


Figure 12.2 Typical extrusion profiles

12.3 Starting stock

Solid or hollow billets heated to hot forming temperature.

To manufacture hollow profiles, hollow billets are required.

In tube production, the hollow billet can also be produced in the extrusion press by a piercing operation which precedes the actual extrusion.

12.4 The extrusion process

Extrusion processes are divided up:

- a) depending on the way the billet is pushed into the container, into:
 - direct and indirect extrusion.*
- b) depending on the product produced during extrusion, into:
 - solid and hollow extrusion.*

12.4.1 Direct extrusion (forward extrusion)

Here, the material flow of the extruded product and the punch movement (Figure 12.1) are in the same direction.

The billet (Figure 12.3), heated to forming temperature, is put into the machine. The punch, separated from the material by the dummy block, presses the billet through the die.

The residual material is laid clear by moving the container back, then sheared or sawn off.

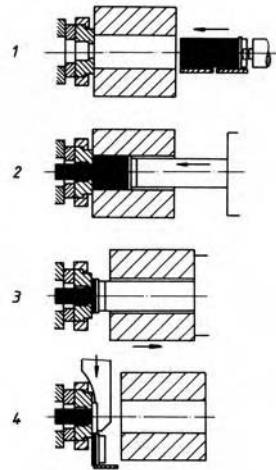


Figure 12.3

Sequence of operations during direct extrusion. 1 put billet and dummy block in the press, 2 extrude billet, 3 move the container back, 4 cut off residual material

12.4.2 Indirect extrusion (backward extrusion)

In backward extrusion (Figure 12.4) the die is located on top of the extrusion punch, which is hollowed out.

The flow of the material is in the opposite direction to the relative motion of the punch. Here, the plunger and the container carry out the extrusion movement simultaneously.

This means that in backward extrusion there is no relative motion between the billet and the container. This relative motion (in forward extrusion) is a disadvantage as it produces further heat by friction, which can only be kept within limits by reducing the speed of the press.

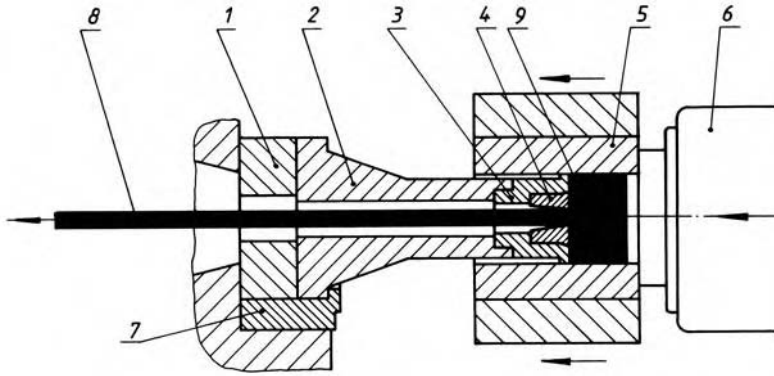


Figure 12.4 The principle of indirect extrusion. 1 pressure plate, 2 punch, 3 die holder (tool container), 4 die, 5 container, 6 plunger, 7 slide, 8 profile, 9 billet, 10 dummy block

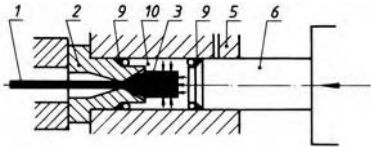
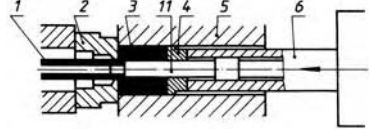
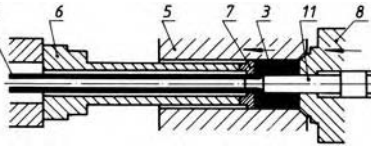
12.4.3 Solid and hollow extrusion

Producing solid profiles is known as solid extrusion, and producing hollow profiles is known as hollow extrusion. Table 12.1 shows an overview of the processes.

Table 12.1 Extrusion processes

Basic schematic diagram	Process	Application
	<p>Direct extrusion: the die and container are fixed against one another. The punch moves and presses the billet through the die.</p>	<p>Solid profiles, rods and strips made from solid billets</p>
	<p>Indirect extrusion: the die, with a dummy block, is on a stationary, hollow punch. Movement is made by the container with blank, closed at one end. The container is moved against the stationary die.</p>	<p>Wires and profiles made from solid billets</p>

Table 12.1 The extrusion process (continued)

Basic schematic diagram	Process	Application
	<p>Direct hydrostatic extrusion: the billet is formed by means of a high-pressured liquid (12,000 bar) The pressure is created by the forwards movement of the punch.</p>	<p>Small, simple profiles made of materials which are hard to extrude, which can not be extruded by other processes.</p>
	<p>Direct tube extrusion over a stationary mandrel: the blank is a hollow billet. The stationary mandrel and the die form the annular gap. The hollow punch makes the extrusion movement.</p>	<p>Tubes and hollow profiles made from hollow billets.</p>
	<p>Indirect tube extrusion with stationary mandrel: the closed container makes the extrusion movement. The die is located on the front of the stationary punch.</p>	<p>Tubes and solid profiles made from hollow billets or solid billets which are pierced in the press.</p>

1 Product, 2 die, 3 billet, 4 dummy block, 5 container, 6 punch, 7 dummy block with die, 8 plug, 9 sealant, 10 extrusion liquid, 11 mandrel

Table 12.2 Advantages and disadvantages of extrusion processes

Process	Advantages	Disadvantages
Forward extrusion	Ease of operation, good product surface, easy cooling of extrusion	High frictional heat between dummy block and container, change in material properties due to raised temperature, lower extrusion speeds
Backward extrusion	Higher extrusion speeds, lower deformation resistance, lower residual materials as flow patterns are optimal all the way into final zone, lower wear in container	Extrusion diameter limited as passed through the hollow punch. Cooling down harder, requires good dummy block surface (generally machined surface)
Hydrostatic extrusion	Forming purely by pressure, ideal flow pattern, brittle materials can also be formed, highest degrees of deformation up to $\phi = 900\%$ e.g. with Al materials	Problems with sealing due to high working pressure necessary (up to 20,000 bar)

12.5 Principal strain

- φ_p – principal strain
- A_0 in mm^2 cross section before deformation
- A_1 in mm^2 cross section after deformation
- λ – degree of extrusion

$\varphi_p = \ln \frac{A_0}{A_1}$
$\lambda = \frac{A_0}{A_1}$

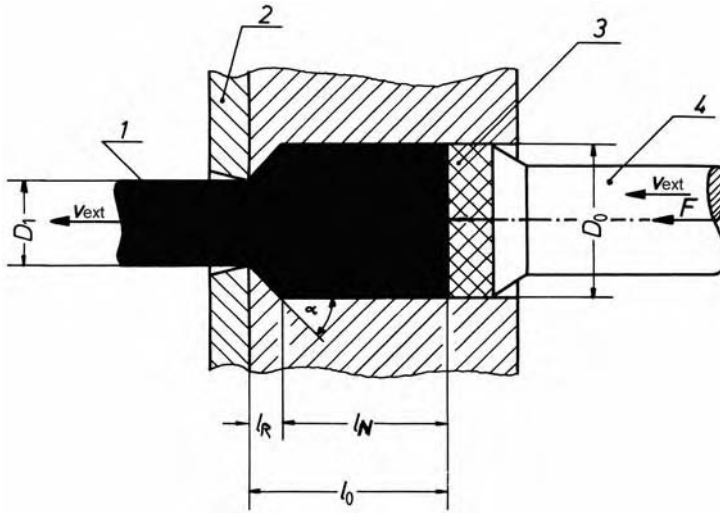


Figure 12.5 Parameters for calculation of force and mechanical work in solid extrusion

12.6 Strain rates during extrusion $\dot{\varphi}$

Because of the complicated flow of material in the deformation zone (Figure 12.6) the strain rate during extrusion is determined approximately with the following formulae:

- $\dot{\varphi}$ in s^{-1} strain rate
- v_p in mm/s punch speed
- D in mm container diameter, principal strain
- v_{ext} in m/min exit speed of the extrusion
- A_0 in mm^2 cross-section before deformation
- A_1 in mm^2 cross-section after deformation
- D_0 in mm billet diameter
- D_1 in mm extrusion diameter
- 10^3 mm/m conversion factor for m into mm
- 60 s/min conversion factor for min into s

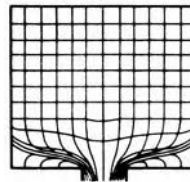


Figure 12.6 Flow pattern during forward solid extrusion with $\alpha = 90^\circ$

$\dot{\varphi} \cong \frac{6 \cdot v_p \cdot \varphi_p}{D}$
$\dot{\varphi} \cong \frac{2 \cdot v_p}{D_1}$
$v_p = \frac{10^3 \cdot v_{\text{ext}} \cdot A_1}{60 \cdot A_0}$

Table 12.3 Permissible deformation, extrusion temperatures, speeds and extrudability for steel, copper and Al materials

Material		Extrusion temperature in °C (mean value)	Max. flash λ_{\max}	$\varphi_{p\text{perm}}$	Speed		Extrudability (formability)		
					Extrusion	Punch	good	medium	bad
					v_{ext} in m/min	v_p in m/s for λ_{\max}			
Al	Al 99.5	430	1000	6.9	50 – 100	1.6	×		
	AlMg 1	440	150	5.0	30 – 75	8.3	×		
	AlMgSi 1	460	250	5.5	5 – 30	2.0		×	
	AlCuMg 1	430	45	3.8	1.5 – 3	1.1			×
Cu	E-Cu	850	400	6.0	300	12.5		×	
	CuZn 10 (Ms 90)	850	50	3.9	50 – 100	33			×
	CuZn 28 (Ms 72)	800	100	4.6	50 – 100	16.6		×	
	CuZn 37 (Ms 63)	775	250	5.5	150 – 200	13.3		×	
	CuSn 8	800	80	4.4	30	6.2			×
St	C15 C35 C45 C60	1200	90	4.5	360	66	×		
	100 Cr 6	1200	50	3.9	360	120	×		
	50 CrMo 4	1250	50	3.9	360	120	×		
Ti	TiA 15 Sn 2.5	950	100	4.6	360	60			×

12.7 Extrusion force

12.7.1 Forward solid extrusion

$$F = F_{\text{def}} + F_{\text{fr}}$$

$$F = \frac{A_0 \cdot k_{\text{str}} \cdot \varphi_p}{\eta_F} + D_0 \cdot \pi \cdot l \cdot \mu_w \cdot k_{\text{str}}$$

$$\eta_F = 0.4 - 0.6 \quad \mu_w = 0.15 - 0.2 \text{ with good lubrication}$$

12.7.2 Backward solid extrusion

Here, the frictional force in the container does not apply as the billet does not move in the container.

$$F = \frac{A_0 \cdot k_{\text{str}} \cdot \varphi_{\text{p}}}{\eta_{\text{F}}}$$

F	in N	total extrusion force
F_{def}	in N	deformation force
F_{fr}	in N	frictional force in the container
A_0	in mm ²	billet cross-sectional area
D_0	in mm	billet diameter
φ_{p}	–	principal strain
η_{F}	–	deformation efficiency
μ_{W}	–	coefficient of friction for the wall friction in the container
k_{str}	in N/mm ²	yield strength

In hot forming, the yield strength, k_{str} , depends upon:

- the deformation temperature
- the strain rate.

The k_{str} values for the optimum deformation temperatures can be taken from Table 12.4 for a strain rate of $\dot{\varphi} = 1 \text{ s}^{-1}$.

The k_{str} value when the actual strain rate is taken into consideration can be calculated using the following equation:

$$k_{\text{str}} = k_{\text{str}_1} \left(\frac{\dot{\varphi}}{\dot{\varphi}_1} \right)^m$$

As $\dot{\varphi}_1 = 1$ is given the value s^{-1} (basic value in Table 12.4) the equation can be simplified:

$$k_{\text{str}} = k_{\text{str}_1} \cdot \dot{\varphi}^m$$

k_{str} in N/mm² yield strength with optimum deformation temperature and the actual strain rate

$\dot{\varphi}$ in s^{-1} actual strain rate $\left(\dot{\varphi} = \frac{6 \cdot v_{\text{st}} \cdot \varphi_{\text{p}}}{D} \right)$

$\dot{\varphi}_1$ in s^{-1} basic speed $\dot{\varphi}_1 = 1 \text{ s}^{-1}$

k_{str_1} in N/mm² yield strength with optimum deformation temperature and basic speed $\dot{\varphi}_1 = 1 \text{ s}^{-1}$

m – material exponent

k_{str_1} and m can be taken from Table 12.4.

12.8 Mechanical work

In extrusion, as in other processes, the deformation work can be determined using Siebel's fundamental equation.

$$W = \frac{V \cdot \varphi_p \cdot k_{\text{str}}}{10^6 \cdot \eta_F}$$

W	in kNm	deformation work
V	in mm ³	volume involved in the deformation
k_{str}	in N/mm ²	yield strength
10^6		conversion factor from Nmm to kNm

The force-displacement diagram (Figure 12.7) shows the flow of force during direct extrusion. The total work (area below the curve) is divided into

- W_1 upsetting by the dummy block
- W_2 setting flow into action
- W_3 actual deformation (shear, frictional and sliding resistance in the deformation zone)
- W_4 friction between the surface of the dummy block and the container bore.

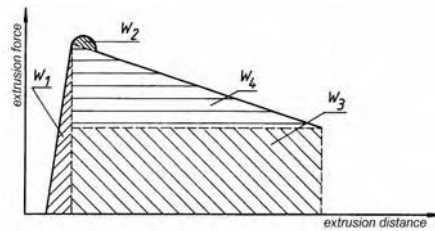


Figure 12.7 Force-displacement diagram

Table 12.4 Basic k_{str1} values for $\dot{\phi}_1 = 1 \text{ s}^{-1}$ with the deformation temperatures provided and material exponent m to calculate $k_{\text{str}} = f(\dot{\phi})$

Material		m	k_{str1} where $\dot{\phi}_1 = 1 \text{ s}^{-1}$ (N/mm ²)	T (°C)
St	C 15	0.154	99/ 84	1100/1200
	C 35	0.144	89/ 72	
	C 45	0.163	90/ 70	
	C 60	0.167	85/ 68	
	X 10 Cr 13	0.091	105/ 88	1100/1250
	X 5 CrNi 18 9	0.094	137/116	
	X 10 CrNiTi 18 9	0.176	100/ 74	
Cu	E-Cu	0.127	56	800
	CuZn 28	0.212	51	800
	CuZn 37	0.201	44	750
	CuZn 40 Pb 2	0.218	35	650
	CuZn 20 Al	0.180	70	800
	CuZn 28 Sn	0.162	68	800
	CuAl 5	0.163	102	800
Al	Al 99.5	0.159	24	450
	AlMn	0.135	36	480
	AlCuMg 1	0.122	72	450
	AlCuMg 2	0.131	77	450
	AlMgSi 1	0.108	48	450
	AlMgMn	0.194	70	480
	AlMg 3	0.091	80	450
	AlMg 5	0.110	102	450
	AlZnMgCu 1.5	0.134	81	450

$$k_{\text{str}} = k_{\text{str1}} \left(\frac{\dot{\phi}}{\dot{\phi}_1} \right)^m \quad \text{For } \dot{\phi}_1 = 1 \text{ s}^{-1} \text{ then } \boxed{k_{\text{str}} = k_{\text{str1}} \cdot \dot{\phi}^m}$$

12.9 Tooling

Extrusion assemblies are under high mechanical and thermal stress. Figure 12.8 shows an assembly for direct extrusion split into its separate parts; Figure 12.9 shows an assembly for the indirect extrusion of tubes over a moving mandrel.

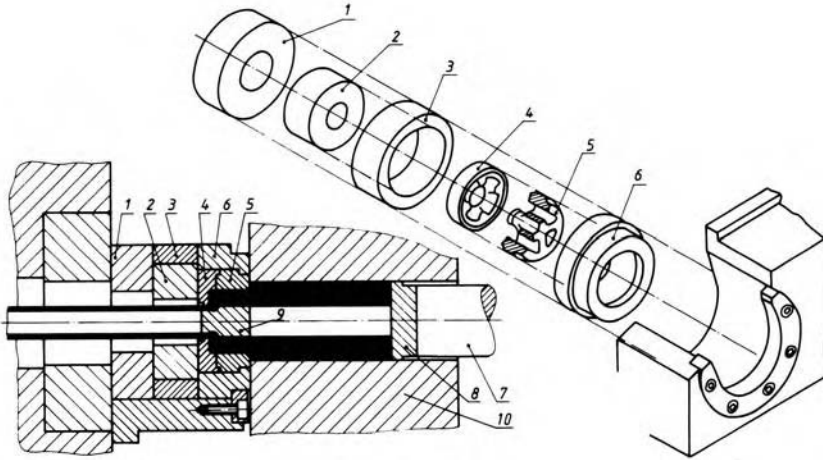


Figure 12.8 Direct extrusion of tubes. 1 pressure plate, 2 bolster, 3 holder for bolster, 4 die, 5 mandrel, 6 die holder, 7 extrusion punch, 8 dummy block, 9 mandrel, 10 container

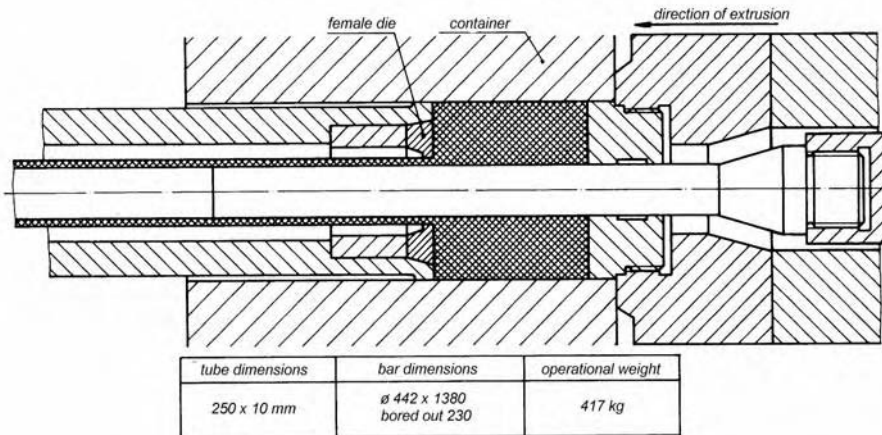
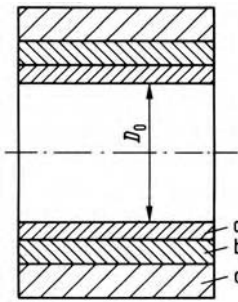


Figure 12.9 Assembly for the indirect extrusion of tubes over a moving mandrel

**Figure 12.10**

The component parts of the container (Part 10 in Figure 12.8)

- a) outer ring,
- b) middle ring,
- c) inner ring

The container (part 10 in Figure 12.8) is reinforced and generally consists of three parts, as shown in Figure 12.10.

In extrusion, care has to be taken that lubrication is optimal, as well as that the assembly elements have the correct dimensions. Glass, graphite, oil and MoS_2 are most often used as lubricants.

Table 12.5 below shows tooling materials for extrusion tooling.

Table 12.5 Tooling materials for extrusion tooling (Figures 12.8 and 12.10)

Tooling components	Al alloys		Cu alloys		Steel and steel alloys	
	Material	HRC as-assembly hardness	Material	HRC as-assembly hardness	Material	HRC as-assembly hardness
Container (Figure 12.10) inner ring c	1.2343	40 – 45	1.2367	40 – 45	1.2344	40 – 45
middle ring b	1.2323	32 – 40	1.2323	32 – 40	1.2323	32 – 40
outer ring a	1.2312	30 – 32	1.2323	30 – 32	1.2343	30 – 32
Punch head 7	1.2344	45 – 52	1.2365	45 – 52	1.2365	45 – 52
Dummy block 8	1.2343	42 – 48	1.2344	42 – 48	1.2365	42 – 48
Bottom die 4	1.2343	42 – 48	1.2367	42 – 48	1.2344	42 – 48
Bottom die holder 3	1.2714	40 – 45	1.2714	40 – 45	1.2714	40 – 45

12.10 Extrusion presses

With extrusion presses, a difference is made between the extrusion of solid and tubular shapes.

A standard extrusion press (Figure 12.11) is mainly used to produce solid profiles, e.g. rods, strips and wires.

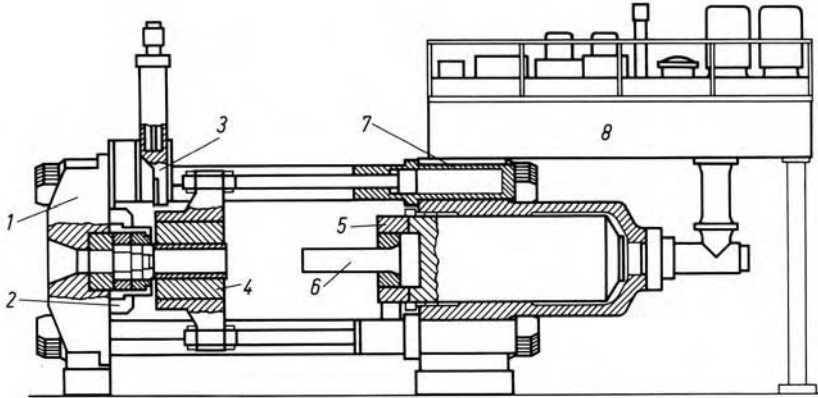


Figure 12.11 Diagrammatic view of a forward extrusion press for solid profiles, rods, strips and wires. 1 platen, 2 die slide or die turner, 3 shear blade, 4 billet container, 5 platen ring, 6 punch, 7 cylinder platen 8 oil receptacle with drive and controls. (Illustration from the SMS Hasenclever Maschinenfabrik works, Düsseldorf, Germany)

Tube extrusion presses (Figure 12.12) are commonly used for the production of tubes and hollow profiles.

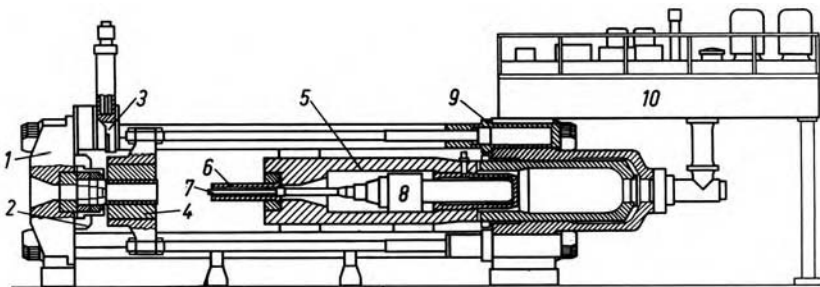


Figure 12.12 Diagrammatic view of a forward rod and tube extrusion press. 1 platen, 2 die slide or die turner, 3 shear blade, 4 billet container, 5 platen ring, 6 punch, 7 mandrel, 8 piercer, 8 cylinder platen, 10 oil receptacle with drive and controls. (Illustration from the SMS Hasenclever Maschinenfabrik works, Düsseldorf, Germany)

The tube extrusion press, unlike the standard extrusion press, has a mandrel which can move independently to the punch. This means both hollow and solid billets can be formed into tubes or hollow profiles on this machine. For hollow billets a mandrel pusher (low force) suffices; for solid billets a stronger piercer (part 8 in Figure 12.12) is needed to pierce the billet.

Extrusion presses are driven by oil or water hydraulics.

Small to medium-sized presses are mainly run on oil hydraulics. For larger plants with high extrusion speeds, a water accumulator drive is commonly used. Here, water mixed with oil is used as a hydraulic fluid.

The following table shows the dimensions of forward extrusion presses.

Table 12.6 Dimensions of forward extrusion presses

Extrusion force in kN	Billet dimensions	
	Diameter D_0 in mm	Length L_{\max} in mm
5 000	80 – 140	375
8 000	100 – 180	475
16 000	140 – 250	670
25 000	180 – 315	850
40 000	224 – 400	1060
63 000	280 – 500	1330
100 000	355 – 630	1680
125 000	400 – 710	1870

(10 kN = 1 t)

12.11 Example

The aim is to manufacture round rods with a diameter $d = 15\text{mm}$, out of AlMgSi

where:

Extrusion punch speed: $2\text{ mm/s} = v_p$

Density of AlMgSi: $\rho = 2.7\text{ kg/dm}^3$

Billet dimensions: $D_0 = 180\text{ mm } \varnothing$, $L = 475\text{ mm}$ long

Forming temperature: $450\text{ }^\circ\text{C}$ (Table 12.4).

Find: Extrusion force.

Solution:

1. Principal strain

$$\varphi_p = \ln \frac{A_0}{A_1} = \ln \frac{180^2 \pi / 4 \text{ mm}^2}{15^2 \pi / 4 \text{ mm}^2} = \underline{\underline{4.96}}$$

$$\varphi_{p_{\text{perm}}} = 5.5 \quad \text{Table 12.3}$$

as $\varphi_p < \varphi_{pperm}$ the extrusion dimensions can be produced in one extrusion operation.

2. Exit speed of the extrusion

$$v_{ext} = \frac{v_p \cdot 60 \cdot A_0}{10^3 \cdot A_1} = \frac{2 \text{ mm} \cdot 60 \text{ s} \cdot 1 \text{ m} \cdot 180^2 \cdot \pi / 4 \text{ mm}^2}{\text{s} \cdot \text{min} \cdot 10^3 \text{ mm} \cdot 15^2 \pi / 4 \text{ mm}^2}$$

$$v_{ext} = \underline{\underline{17.28 \text{ m/min}}}$$

3. Strain rate $\dot{\varphi}$

$$\dot{\varphi} = \frac{6 \cdot v_p \cdot \varphi_p}{D} \quad D \sim D_0.$$

$$\dot{\varphi} = \frac{6 \cdot 2 \text{ mm} \cdot 4.96}{\text{s} \cdot 180 \text{ mm}} = \underline{\underline{0.33 \text{ s}^{-1}}}.$$

4. Yield strength k_{str}

$$k_{str1} = 48 \text{ N/mm}^2 \quad \text{for } T = 450^\circ \text{ C and } \dot{\varphi} = 1 \text{ s}^{-1}, \text{ Table 12.4}$$

$$k_{str} = k_{str1} \cdot \dot{\varphi}^m, \quad m = 0.108 \text{ from Table 12.4}$$

$$k_{str} = 48 \cdot 0.33^{0.108} = 48 \cdot 0.887 = 42.57 \text{ N/mm}^2.$$

5. Extrusion force for solid forward extrusion

$$F = \frac{A_0 \cdot k_{str} \cdot \varphi_p}{\eta_F} + D_0 \cdot \pi \cdot l \cdot \mu_W \cdot k_{str}$$

$$\eta_F = 0.5; \quad \mu_W = 0.15 \text{ selected.}$$

$$F = \frac{180^2 \pi / 4 \text{ mm}^2 \cdot 42.6 \text{ N} \cdot 4.96}{0.5 \cdot \text{mm}^2} + 180 \text{ mm} \cdot \pi \cdot 475 \text{ mm} \cdot 0.15 \cdot 42.6 \text{ N/mm}^2$$

$$= 10753655 \text{ N} + 1716393 \text{ N} = \underline{\underline{12470 \text{ kN}}}.$$

12.12 Exercise on Chapter 12

1. What criteria are used to differentiate between the extrusion processes?
2. Name the most important extrusion processes and the typical fields of application.
3. What are the advantages and disadvantages of the extrusion process?
4. What values does k_{str} mainly depend upon?
5. How are extrusion presses categorised?

13 Impression-die forging (closed-die forging)

13.1 Definition

Impression-die forging is a hot bulk forming process. It is a pressure forming process where shaped dies are moved towards one another so that the material is forced in a certain direction, taking on the shape of the cavity in the die (see Table 13.2, page 124).

13.2 Starting stock

13.2.1 Type of material

Table 13.1 Feedstock associated with the forging processes

Process	Type of material
Rod forging	Rod stock up to approx. 40 Ø
Billet forging	Sections of billets with round or square cross-sections
Forging sheared sheet blanks	Rolled sheets

13.2.2 Mass of material required m_A

$$m_{\text{req}} = m_f + m_{\text{fla}} + m_{\text{sc}}$$

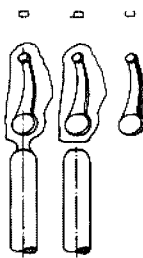
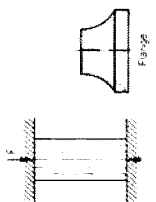
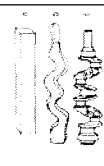
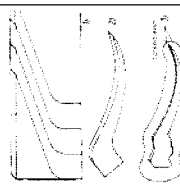
- m_{req} in kg mass of material required
- m_f in kg mass of the finished forging
- m_{fla} in kg mass of flash
- m_{sc} in kg mass of scale.

The mass of material required depends upon the shape of the workpiece and its mass.

However, standard values have been put together so that it is not necessary to determine the mass of scale and flash for every new workpiece. In these standard values, the mass ratio factor W indicates how many times greater the mass of the required material m_{req} has to be than the mass of the finished product. As the shape of the flash can be very different depending on the shape of the forging, however, the W factor takes into account the shape of the forging as well as the final mass. Certain characteristic shapes which give rise to the same problems during manufacture are sorted into groups. Table 13.3 below shows a small extract from this shape classification table.

13.3 Types and application of the process

Table 13.2

Basic diagram	Process	Description	Advantages	Disadvantages	Fields of application
 <p>Rod forging, a) forging, b) cutting off, c) trimming</p>	Rod forging	Rolled rod, approx. 2m long, is heated at one end and forged in the die. After forging the workpiece is separated from the rod by a last blow of the hammer.	Ease of operation, no energy-wasting gripping with forging tongs. Time saved by ease of insertion into die.	More material required as the volume can not be precisely determined.	For elongated lower-mass workpieces (2 to 3 kg)
 <p>Production of a crankshaft, a) blank, b) intermediate shape, c) finished crankshaft</p>	Billet forging	Here the starting stock is a sawn or sheared-off section of rod.	Ideal grain flow follows the external contour.	Slightly higher amount of material required.	Compact, disc-shaped parts.
	<p>Forging along the grain:</p> <p>Forging in a transverse direction:</p> 	<p>When the deformation is in the direction of the grain.</p> <p>When the deformation is perpendicular to the grain.</p>	<p>Ideal grain flow follows the external contour.</p> <p>Ideal grain flow follows the external contour.</p>	<p>Slightly higher amount of material required.</p> <p>Slightly higher amount of material required.</p>	<p>Parts with pronounced longitudinal axis e.g. crankshafts.</p>
<p>Production of a forked lever.</p> <p>1 Cutting the cropped blank, 2 upsetting, 3 final forging</p> 	Forging cropped blanks	The feedstock is cut from a strip of sheet metal with hardly any loss by scrap-free blanking. Then a pre-form is produced by upsetting or bending. The workpiece is given its finished shape in the die.	Low material consumption (precise blank volume, therefore low flash), short forging times as redistribution of material mass is low.	Grain flow can not be optimally adapted to the shape of the forging.	For mass-produced parts which do not need to be very strong, e.g. knives, scissors, pliers, spanners.

Numerical tables for the W factor have been put together from the shape classification table and the final mass of the impression-die forgings. The mass of material required, m_{req} , can be easily determined using these tables (13.4).

$$m_{\text{req}} = W \cdot m_f$$

Table 13.3 Shape classification table (excerpt from Billigmann & Feldmann, *Stauchen und Pressen*)

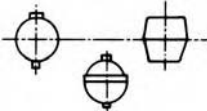

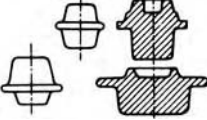

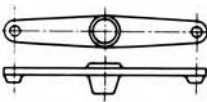

Examples of application	Shape group	Explanation
	1.1	Roughly spherical and cube-shaped parts, solid hubs with small flanges, cylinders and parts with no secondary elements.
	1.2	Roughly spherical and cube-shaped parts, cylinders with secondary elements on one side.
	2.1	Hubs with small flanges; formed partly by the vertical flow of material in the upper die, partly by vertical flow in the lower die.
	2.2	Rotationally symmetric forgings with hole in the hub and an outside rim. Hub with hole and outside rim are connected by thin webs.
	3.1	Two-armed lever with solid cross-section, thicker at the centre and at both ends; parts must be pre-shaped, e.g. foot pedals and clutch levers.
	3.2	Very long forgings with several large changes in cross-section where the material has to flow a great deal vertically; crankshafts with forged counterweights and more than six throws. Very high amount of flash due to repeated intermediate trimming

Table 13.4 Mass ratio factor W as $f(m_f$ and shape group)

m_f in kg		1.0	2.5	4.0	6.3	20	100
W with shape group	1	1.1	1.08	1.07	1.06	1.05	1.03
	2	1.25	1.19	1.17	1.15	1.08	1.06
	3	1.5	1.46	1.41	1.35	1.20	—

13.4 Processes in the forging die

The processes in the forging die can be split into three phases (Figure 3.1):

1. Upsetting
2. Lateral flow
3. Vertical flow (*rise*)

Upsetting

During upsetting, the height of the workpiece is reduced with no appreciable flow paths along the walls of the die.

Lateral flow

Lateral flow is when the material flow is mainly transverse to the movement of the die. The flow paths where the material touches the walls of the die are relatively long. Because of this, a lot of friction occurs and high deformation forces are required.

Vertical flow

The vertical flow of the material is the last forging phase in the die. Here, the flow of the material is in the opposite direction to the forging motion. The initial height of the workpiece is raised in places.

However, in order for vertical flow to occur in the die to begin with, the resistance to flow in the flash gap must be higher than that required for vertical flow in the die. The material must not flow into the flash gap until the die cavity is completely filled. This resistance to flow in the flash gap depends upon the ratio of flash land width to flash land height (w/s).

13.4.1 Calculation of the resistance to flow in the flash gap

According to Siebel, the resistance to flow p_{fl} for upsetting between parallel plates is:

$$p_{fl} = 2\mu \cdot k_f \cdot \frac{b}{s}$$

p_{fl} in N/mm^2	resistance to flow
w in mm	flash land width
s in mm	flash land height
μ -	coefficient of friction
k_{str} in N/mm^2	yield strength.

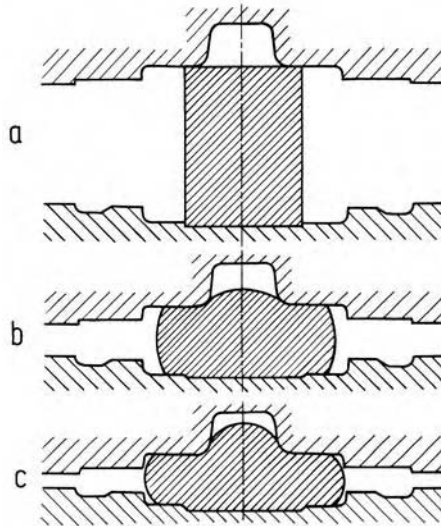


Figure 13.1
Processes in the forging die, a) upsetting, b) lateral flow, c) vertical flow

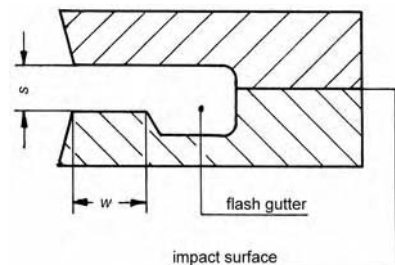


Figure 13.2 Shape of the flash land

By changing the flash land ratio w/s the internal pressure in the die can be varied to meet the requirements of the workpiece. Where the material in the die has to flow a long way vertically, workpieces need high internal pressure and thus a high flash land ratio (e.g. $w/s = 5$ to 10).

13.4.2 Calculation of the flash gap

The flash gap height can be calculated approximately:

$$s = 0.015 \cdot \sqrt{A_s}$$

s in mm flash land height
 A_s in mm² projected area of the workpiece *without* flash.

Table 13.5 flash land ratio $w/s = f(A_s)$ and the type of deformation)

A_s in mm ²	w/s mainly for		
	Upsetting	Lateral flow	Vertical flow
up to 2000	8	10	13
2 001 – 5 000	7	8	10
5 001 – 10 000	5.5	6	7
10 001 – 25 000	4	4.5	5.5
26 000 – 70 000	3	3.5	4.5
71 000 – 150 000	2	2.5	3.5

13.5 Calculation of force and mechanical work

It is not possible to calculate force and mechanical work more precisely for impression-die forging, as here, the deformation process is affected by too many influencing factors, such as the forging temperature, intergranular processes in the material, strain rate, the shape of the workpiece, the kind of material and the kind of machine used for forging.

The force and work can be calculated approximately as follows:

Calculation process:

1. Strain rate

$$\dot{\phi} = \frac{v}{h_0}$$

$\dot{\phi}$ in s⁻¹ strain rate
 v in m/s ram or punch impact velocity
 h_0 in m initial height of the blank

Table 13.6 shows v values for the presses generally used in this case.

Table 13.6 Strain rate $\dot{\varphi} = f$ and initial height h_0 of the blank

Machine	Ram impact velocity $\dot{\varphi}$ in m/s		$\dot{\varphi} = \frac{v}{h_0}$ (s^{-1})												
	$h_0 \rightarrow$		for $h_0 =$ (mm)												
Hammer	5.6		5	10	20	30	40	50	100	150	200	250	300	400	500
			1120	560	280	187	140	112	56	37.3	22.4	18.6	14	11.2	
			1200	600	300	200	150	120	60	40	24	20	15	12	
Screw press	1.0		2400	1200	600	400	300	240	120	80	60	48	40	30	24
			200	100	50	33.3	25	20	10	6.7	5.0	4.0	3.3	2.5	2.0
Hydraulic presses	0.25		50	25	12.5	8.3	6.2	5	2.5	1.7	1.25	1.0	0.83	0.6	0.5
Crank pr. where $\alpha = 30^\circ$	0.6		120	60	30	20	15	12	6.0	4.0	3.0	2.4	2.0	1.5	1.2

2. Yield strength

$$k_{\text{str}} = k_{\text{str}1} \cdot \dot{\varphi}^m$$

m – material exponent

k_{str} in N/mm^2 yield strength for the strain rate $\dot{\varphi}$ and the forging temperature T

$k_{\text{str}1}$ in N/mm^2 yield strength for $\dot{\varphi} = 1$ (s^{-1}) at forging temperature T ($k_{\text{str}1}$ from Table 12.4, page 117)

$\dot{\varphi}$ in s^{-1} strain rate (for $\dot{\varphi}$ from 1 to 300 s^{-1} , k_{str} can also be taken from Table 13.7)

3. Yield strength at the end of forging

$$k_{\text{re}} = y \cdot k_{\text{str}}$$

k_{re} in N/mm^2 yield strength at the end of forging Take shape factor y (takes the shape of the workpiece into account) from Table 13.8.

4. Maximum forging force

$$F = A_d \cdot k_{\text{re}}$$

F in N max. forging force

A_d in mm^2 projected area of the forging *including* flash land.

5. Mean principal strain

As the height h_1 of the forging can not be precisely defined, here the mean final height h_{1m} is worked with, determined from the volume and the projected area of the forging (Figure 13.3).

$$\varphi_p = \ln \frac{h_1}{h_0}, \quad h_{1m} = \frac{V}{A_d}$$

$$\varphi_{pm} = \ln \frac{V}{A_d \cdot h_0}$$

h_1 in mm height after forging

h_0 in mm blank height

V in mm^3 volume of the forging

φ_{pm} – mean principal strain

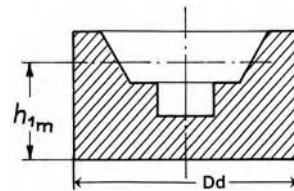


Figure 13.3 Definition of the mean final height

Table 13.7 yield strength depending on the forging speed for the forging temperature $T = \text{constant}$

Material	T (°C)	$k_{\text{str}} = f(\dot{\phi})$ for $T = \text{const.}$ k_{str} in N/mm ²								
		$\dot{\phi} = 1$ (s ⁻¹)	$\dot{\phi} = 2$ (s ⁻¹)	$\dot{\phi} = 4$ (s ⁻¹)	$\dot{\phi} = 6$ (s ⁻¹)	$\dot{\phi} = 10$ (s ⁻¹)	$\dot{\phi} = 20$ (s ⁻¹)	$\dot{\phi} = 30$ (s ⁻¹)	$\dot{\phi} = 40$ (s ⁻¹)	$\dot{\phi} = 50$ (s ⁻¹)
C 15	1200	84	93	104	110	120	133	141	145	153
C 35	1200	72	80	88	93	100	111	118	122	126
C 45	1200	70	78	88	94	102	114	122	128	132
C 60	1200	68	76	86	92	100	112	120	126	131
X 10 Cr 13	1250	88	94	100	104	109	116	120	123	126
X5CrNi 18 9	1250	116	124	132	137	144	154	160	164	168
X 10 CrNiTi 18 9	1250	74	84	94	101	111	125	135	142	147
E-Cu	800	56	61	67	70	75	82	86	89	92
CuZn 28	800	51	59	68	75	83	96	105	111	117
CuZn 37	750	44	51	58	63	70	80	87	92	97
CuZn 40 Pb 2	650	35	41	47	51	58	67	73	78	82
CuZn 20 Al	800	70	79	90	97	106	120	129	136	142
CuZn 28 Sn	800	68	76	85	91	99	110	118	124	128
CuAl 5	800	102	114	128	137	148	166	178	186	193
Al 99.5	450	24	27	30	32	35	39	41	43	45
AlMn	480	36	40	44	46	49	54	57	59	61
AlCuMg 1	450	72	78	85	90	95	104	109	113	116
AlCuMg 2	450	77	84	92	97	104	114	120	125	129
AlMgSi 1	450	48	52	56	58	62	66	69	71	73
AlMgMn	480	70	80	92	99	109	125	135	143	150
AlMg 3	450	80	85	91	94	99	105	109	112	114
AlMg 5	450	102	110	119	124	131	142	148	153	157
AlZnMgCu 1.5	450	81	89	98	103	110	121	128	133	137

$\dot{\phi} = 70$ (s ⁻¹)	$\dot{\phi} = 100$ (s ⁻¹)	$\dot{\phi} = 150$ (s ⁻¹)	$\dot{\phi} = 200$ (s ⁻¹)	$\dot{\phi} = 250$ (s ⁻¹)	$\dot{\phi} = 300$ (s ⁻¹)
161	170	181	189	196	201
133	140	148	154	159	164
140	148	158	166	172	177
138	147	157	164	171	176
130	134	139	143	145	148
173	179	186	191	195	198
156	166	179	188	196	202
96	101	106	110	113	116
126	135	148	157	164	171
103	111	120	128	133	138
88	96	104	111	117	121
150	160	172	182	189	195
135	143	153	160	166	171
204	216	231	242	251	258
47	50	53	56	58	59
64	67	71	74	76	78
121	126	133	137	141	144
134	141	148	154	159	163
76	79	82	85	87	89
160	171	185	196	204	212
118	122	126	130	132	134
163	169	177	183	187	191
143	150	159	165	170	174

6. Deformation work

$$W = \frac{V \cdot \varphi_{pm} \cdot k_{str}}{\eta_F}$$

W in Nmm deformation work



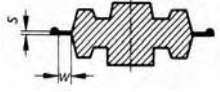
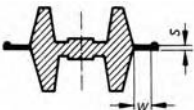
k_{str} in N/mm² mean flow stress

η_F – deformation efficiency

V in mm³ volume of the forging

φ_{pm} – degree of deformation from mean final height h_m .

Table 13.8 Shape factor y , deformation efficiency η_F , and flash land ratio w/s depending upon the shape of the forging.

Shape	Workpiece	y	η_F	w/s
1	Upsetting in the die without formation of flash 	4	0.5	3
2	Upsetting in the die with slight formation of flash 	5.5	0.45	4
3	Impression-die forging of simple parts with formation of flash 	7.5	0.4	6–8
4	Impression-die forging of complicated parts with flash 	9	0.35	9–12

$$k_{re} = y \cdot k_{str}$$

13.6 Tooling

Tooling for impression die forging is subject to high mechanical and thermal stresses.

Mechanical: due to forging force (impact stress) up to $p = 2000$ N/mm².

Result: shear cracks on the surface of the cavity.

Thermal: by contact with the blanks heated to forging temperature. Because of this, temperature fluctuations of up to 200 °C occur in the forging tooling which lead to extreme heat change stresses. This can lead to net-shaped surface cracks (checks) across the dies.

As the duration of contact between the die and the workpiece depends on the machine used for impression-die forging, a difference is made between:

Hammer forging dies: especially high mechanical stresses.

Press forging dies: especially high thermal stresses, as contact duration is longer.

Figure 13.4 shows the elements of a die, and Table 13.9 shows some typical materials with the corresponding assembly hardnesses.

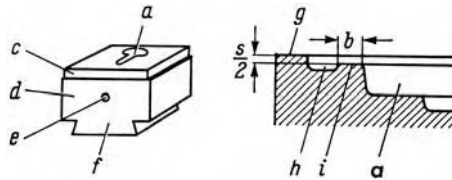
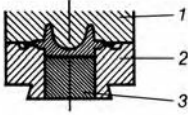

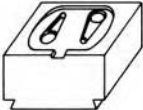
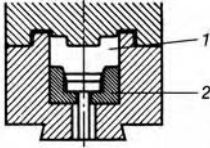
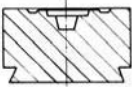
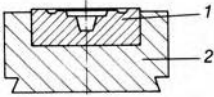
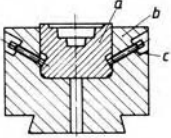
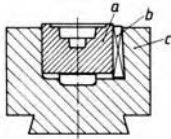


Figure 13.4 Die elements, a) cavity, c) datum planes, d) body, e) handling hole, f) fastening element, g) impact face, h) flash gutter, i) flash land

Table 13.9 Die materials for hammer, pressing and upsetting machine dies

Tool	Hammer		Press		Horizontal forging machines		
	Material	Assembly hardness N/mm ²	Material	Assembly hardness N/mm ²	Tool	Material	Assembly hardness N/mm ²
Solid die	1.2713	1200–1360	1.2713	1200–1350	Bottom die	1.2344	1300–1800
	1.2714	1200–1800	1.2714	1200–1800		1.2365	1300–1800
			1.2343	1300–1700		1.2367	1300–1800
			1.2344	1300–1700		1.2889	1500–1900
			1.2365	1300–1700	Mandrel	1.2365	1500–1800
			1.2367	1300–1700		1.2367	1500–1800
Die holder	1.2713	1020–1360	1.2713	1000–1200		1.2889	1500–1900
Die insert	1.2714	1300–1800	1.2343	1300–1800			
	1.2344	1300–1800	1.2344	1300–1800			
			1.2367	1300–1800			
			1.2606	1300–1800			
Cavity insert	1.2365	1500–1800	1.2365	1500–1800			
	1.2889	1500–1800	1.2889	1500–1800			

Table 13.10 Die construction forms

Distinctive feature: Flash gap	
 <p>1 upper die, 2 lower die, 3 ejector</p>	<p><i>Die with flash gap (open die)</i></p> <p>With this die, the excess volume can flow into the flash gap.</p>
	<p>There can be any number of cavities. If it has only one cavity for one workpiece, then it is a <i>single die</i></p>
	<p>If there are several cavities for two or more workpieces, e.g. one cavity for pre-forming and one for final forming, then it is a <i>multiple die</i></p>
 <p>1 punch, 2 workpiece</p>	<p><i>Die without a flash gap (closed die)</i></p> <p>Here the volume of the blank must be exactly the same as that of the finished part, as excess material can not escape.</p> <p>Application: for precision forgings</p>
Distinctive feature: Die material	
	<p><i>Solid die</i></p> <p>Lower and upper parts of the die are each made from one piece, made of high-quality die steel.</p>
 <p>1 Master die, 2 die insert</p>	<p><i>Die with die inserts</i></p> <p>a) Master die (die holder) and die insert are made of different materials. Only the die insert is made of expensive die steel. Here, a difference is made according to the way the die insert is affixed, between:</p>
	<p>b 1) The insert is pressed in (interference pressure $p \sim 50 - 70 \text{ N/mm}^2$). Interference approx. 1% of diameter</p>
	<p>b 2) b 1) – fitted with screw b 2) – fitted with wedge</p>

13.6.1 Die alignment

So that the forging does not have any mismatch, the upper and lower dies must be moved precisely towards one another.

Flat, round and bolt guides are the most common.

Bolt guides (Figure 13.5) are cheaper to produce and if wear sets in, the guide elements (bolt and sleeve) are easy to replace, so they are preferred.

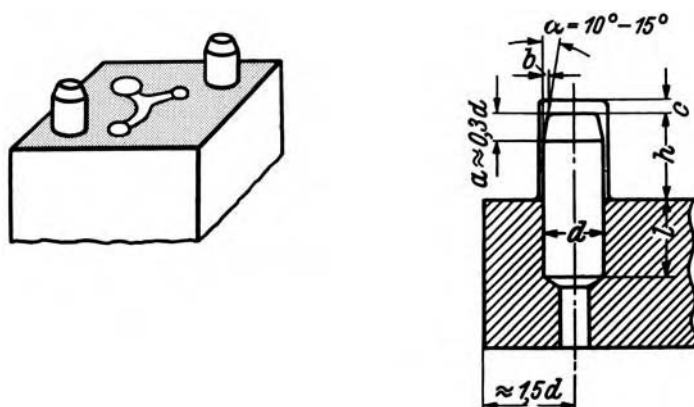


Figure 13.5 Bolt guide

13.6.2 Die block dimensions

The dimensions selected for the die block depend on the depth of the cavity.

Table 13.11 Minimum block dimensions

Depth of cavity h in mm	Minimum thickness a in mm	Minimum die block height H in mm
10	20	100
25	40	160
40	56	200
63	80	250
100	110	315

13.7 Design of impression-die forgings

The general rules for designing impression-die forgings may be summed up as follows:

- Construct as simple shapes as possible and consider the question of materials in their design.
- Avoid sharp corners and abrupt transitions in the cross-section.
- When designing the shape, consider how it can be gripped for mechanical processing.
- Consider whether complicated forms can be produced more easily using other manufacturing processes.

As well as these rules, when designing forgings, the following points in particular should be taken into account:

13.7.1 Drafts (Figure 13.6)

On the inner surfaces created by a mandrel penetrating the workpiece, there is a danger of them shrinking onto the mandrel. For this reason the inner surfaces should have a draft angle (Figure 13.6) of $\alpha = 6^\circ$. As an ejector is usually available to release the outer contour, here an angle of $\alpha = 1 - 3^\circ$ is enough.

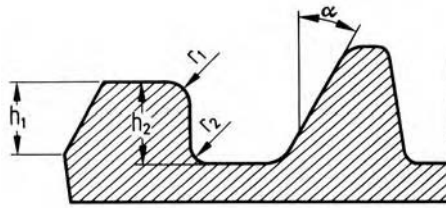


Figure 13.6 Corner and fillet radii and draft angles

13.7.2 Curvature of external corners and fillets

Sharp corners raise the danger of notching on the tooling and shorten its lifetime, so it is important to make sure that they have a minimum radius of curvature. The size of the radii of curvature r_1 and r_2 can be approximately determined depending upon the web thicknesses h_1 and h_2 .

$$r = \frac{1}{10} \cdot h \quad \text{for } h_1 \text{ and } h_2 \text{ up to } 100 \text{ mm}$$

$$r = \frac{1}{20} \cdot h \quad \text{for } h_1 \text{ and } h_2 \text{ from } 120 - 250 \text{ mm}$$

13.8 Achievable precision

The precision which can normally be achieved in impression-die forging is between IT 12 and IT 16. In special cases (what is known as precision forging) tolerances of up to IT 8 can also be achieved for certain measurements on a forging.

13.9 Example

The aim is to manufacture pulleys as in Figure 13.7 from the material C45. The forging machine available in the work area is a crank press with a mean punch velocity of $v = 600$ mm/s.

The following must be established:

1. Required material mass
2. Flash thickness and width of flash land
3. Deformation force
4. Deformation work

Solution:

1. Required material mass m_{req}

- 1.1. Mass of the finished forging

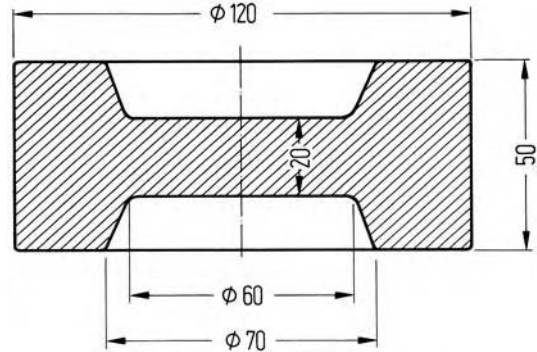


Figure 13.7 Pulley

$$m_f = (D^2 \cdot h_1 - d_m^2 \cdot h_2) \frac{\pi}{4} \cdot \rho =$$

$$= \left[(1.2 \text{ dm})^2 \cdot 0.5 \text{ dm} - (0.65 \text{ dm})^2 \cdot 0.3 \text{ dm} \right] \frac{\pi}{4} \cdot 7.85 \text{ kg/dm}^3 = 3.63 \text{ kg}$$

- 1.2. Select weight coefficient $W = f(\text{shape groups 2 and } m_f)$ from Table 13.4, page 125

$$W = 1.18 \text{ selected}$$

- 1.3. Required mass m_{req}

$$m_{\text{req}} = W \cdot m_f = 1.18 \cdot 3.63 \text{ kg} = 4.28 \text{ kg}$$

- 1.4. Blank volume

$$V = \frac{m}{\rho} = \frac{4.28 \text{ kg}}{7.85 \text{ kg/dm}^3} = 0.545223 \text{ dm}^3 = 545\,223 \text{ mm}^3$$

1.5. Blank dimensions

initial diameter $D_0 = 110$ mm selected

$$h_0 = \frac{V}{A_0} = \frac{545223 \text{ mm}^3}{\frac{(110 \text{ mm})^2 \pi}{4}} = 57.40 \text{ mm}$$

$h_0 = 60$ mm selected

2. Flash height s

$$A_s = 120^2 \cdot \pi / 4 = 11\,309 \text{ mm}^2$$

$$s = 0.015 \cdot \sqrt{A_s} = 0.015 \cdot \sqrt{11\,309} = 1.59 \text{ mm}$$

$s = 1.6$ mm selected.

The workpiece corresponds to shape 2 (Table 13.8, upset part with slight formation of flash), so a flash land ratio of $w/s = 4$ is assumed (Table 13.5). From this it follows that:

$$w = 4 \cdot s = 4 \cdot 1.6 \text{ mm} = 6.4 \text{ mm}$$

$w = 6.0$ mm selected.

From the flash land width and the diameter of the finished part, the projected diameter D_d and the projected area of the forging including flash land A_d can now be determined.

Projected diameter:

$$D_d = D + 2 \cdot w = 120 \text{ mm} + 2 \cdot 6 \text{ mm} = 132 \text{ mm}$$

Projected area A_d :

$$A_d = D_d^2 \frac{\pi}{4} = \frac{(132 \text{ mm})^2 \pi}{4} = 13\,678 \text{ mm}^2$$

3. Deformation force and deformation work

3.1. Strain rate $\dot{\varphi}$

$$\dot{\varphi} = \frac{v}{h_0} = \frac{600 \text{ mm/s}}{60 \text{ mm}} = 10 \text{ s}^{-1}$$

3.2. Yield strength

$$k_{\text{str}} = k_{\text{str}_1} \cdot \varphi_m = 70 \text{ N/mm}^2 \cdot 10^{0.163} = 102 \text{ N/mm}^2$$

from Table 12.4:

$$m = 0.163 \quad k_{\text{str}_1} = 70 \text{ N/mm}^2 \text{ for } T = 1200 \text{ }^\circ\text{C}$$

or from Table 13.7 the k_{str} value for $\dot{\varphi} = 10 \text{ s}^{-1}$.

3.3. Deformation resistance at the end of deformation

$$k_{re} = y \cdot k_{str} = 5.5 \cdot 102 \text{ N/mm}^2 = 561 \text{ N/mm}^2 \quad y = 5.5 \text{ from Table 13.8 – Shape 2}$$

3.4. Deformation force

$$F = A_d \cdot k_{re} = 13678 \text{ mm}^2 \cdot 561 \text{ N/mm}^2 = 7673 \text{ 358 N} = 7673 \text{ kN}$$

3.5. Mean principal strain

$$\varphi_{pm} = \ln \frac{V_f}{A_d \cdot h_0} = \ln \frac{110^2 \cdot \pi \cdot \text{mm}^2 \cdot 60 \text{ mm}}{4 \cdot 13 \text{ 678 mm}^2 \cdot 60 \text{ mm}} = 0.364$$

V_f in mm^3 volume employed with $h_0 = 60 \text{ mm}$

3.6. Deformation work

$$W = \frac{V_f \cdot \varphi_{pm} \cdot k_{str}}{\eta_F} = \frac{570 \text{ 199 mm}^3 \cdot 0.364 \cdot 102 \text{ N/mm}^2}{0.45 \cdot 10^6} = 52.9 \text{ kNm}$$

$\eta_F = 0.45$ from Table 13.8

10^6 – conversion factor in kNm

13.10 Exercise on Chapter 13

1. What are the different impression-die forging processes?
2. What auxiliary factor can be used to determine the required masses to be used?
3. What is the significance of the flash land on the forging die and what can it be used to control?
4. What values does the yield strength depend upon during impression-die forging?
5. As a result, what must be considered for the application of the machines?
6. Which criteria are used to differentiate between the construction forms of the forging dies?
7. Name the three phases which take place in the die during impression-die forging.
8. What factors concerning the die can be used to influence the resistance to flow in the flash gap?
9. Which machines are most commonly used for impression-die forging?

Table 13.12 $k_{\text{str1}} = f(T)$ for $\dot{\phi} = 1 \text{ s}^{-1}$ (12.4)

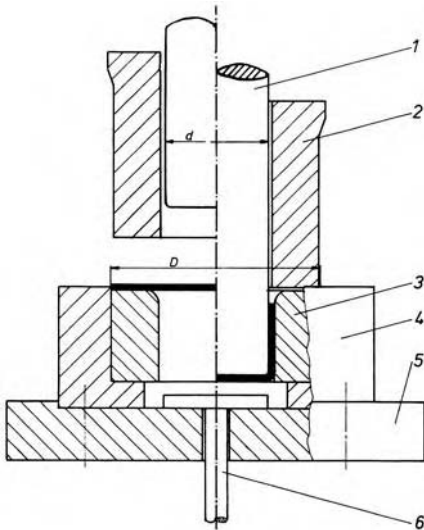
Material		m	k_{str1} where $\dot{\phi} = 1 \text{ s}^{-1}$ (N/mm ²)	T (°C)
St	C 15	0,154	99/ 84	1100/1200
	C 35	0,144	89/ 72	
	C 45	0,163	90/ 70	
	C 60	0,167	85/ 68	
	X 10 Cr 13	0,091	105/ 88	1100/1250
	X 5 CrNi 18 9	0,094	137/116	
	X 10 CrNiTi 18 9	0,176	100/ 74	
Cu	E-Cu	0,127	56	800
	CuZn 28	0,212	51	800
	CuZn 37	0,201	44	750
	CuZn 40 Pb 2	0,218	35	650
	CuZn 20 Al	0,180	70	800
	CuZn 28 Sn	0,162	68	800
	CuAl 5	0,163	102	800
Al	Al 99.5	0,159	24	450
	AlMn	0,135	36	480
	AlCuMg 1	0,122	72	450
	AlCuMg 2	0,131	77	450
	AlMgSi 1	0,108	48	450
	AlMgMn	0,194	70	480
	AlMg 3	0,091	80	450
	AlMg 5	0,110	102	450
	AlZnMgCu 1.5	0,134	81	450

$$k_{\text{str}} = k_{\text{str1}} \left(\frac{\dot{\phi}}{\dot{\phi}_1} \right)^m \quad \text{For } \dot{\phi} = 1 \text{ s}^{-1} \text{ then } \boxed{k_{\text{str}} = k_{\text{str1}} \cdot \dot{\phi}^m}$$

14 Deep drawing

14.1 Definition

Deep drawing is the forming of smooth (sheet) blanks into hollow parts. It is a process which involves forming by tensile and compressive forces. The deformation takes place using:



a deep drawing ring, drawing punch and blank holder (Figure 14.1)

In the process, the punch draws the material through the gap formed by the punch and the drawing ring, forming it into a cup.

Figure 14.1 Tooling and workpiece layout during the deep drawing process. 1 drawing punch, 2 blank holder, 3 drawing ring, 4 container, 5 base plate, 6 ejector

14.2 Application of the process (Figures 14.2 and 14.3)

The process is used to produce hollow parts of all shapes where the wall thickness is the same as that of the bottom.



Figure 14.2 Deep drawn parts for the household

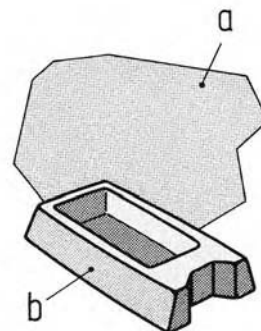


Figure 14.3 Deep drawn oil pan.
a) blank, b) finished part

14.3 Forming process and stress distribution

14.3.1 The individual phases of the drawing process

- Place the round blank on the drawing ring, in the centre (Figure 14.1).
- Blank holder presses blank firmly onto drawing ring.
- Drawing punch draws blank over radius of die, through opening of drawing ring, This reduces the external diameter of the blank until it has been completely formed into a cup.
- If a flange of sheet metal remains on the drawn part, the deep drawing must be limited.

14.3.2 Formation of characteristic triangles

If a hollow part is formed back into a circular sheet, then it can be seen that

- the bottom of the cup with its radius r_C remains unchanged;
- the walls of the hollow part are formed from a series of rectangles with a width of w and a length of $(r_a - r_C)$;
- triangular areas – “characteristic triangles” remain between the rectangles (Figure 14.4).

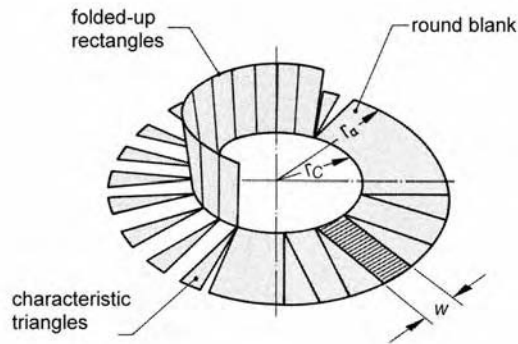


Figure 14.4 Folded-up rectangles form the walls of the drawn part. Characteristic triangles between the rectangles.

14.3.3 Consequences of the characteristic triangles

- Excess material does not go to waste, but without a blank holder it would lead to wrinkling.
- The blank holder therefore prevents wrinkling.
- As the material can not escape, the sheet is compressed between the blank holder and the drawing ring, then stretched again between the drawing ring and the punch, which lengthens the drawn part.
- The blank holder force must also be applied, as well as the actual drawing force; for this reason the drawing force is raised.
- At first, the drawing force is carried by the material cross-section of the drawn part, near the bottom, then – as the drawing process progresses – by the cylindrical part near the bottom.

f) This results in a weakening of the material cross-section near the bottom.

14.3.4 Stress distribution (Figure 14.5)

Tangential compression σ_t occurs as the material is forced into smaller and smaller diameters.

Radial tensile stress σ_r occurs due to the tensile force when the blank is drawn into the space between the punch and the die.

Compressive stress σ_p occurs due to the blank holder force – the material is subjected to pressure.

Bending stress σ_b occurs when the blank is bent over the radius of the die.

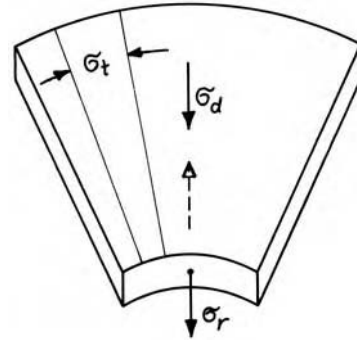


Figure 14.5 State of stress of the blank during deep drawing

14.4 Starting stock

The starting stock is a disk of sheet metal. The size and shape of the blank are important for material consumption (correct sizing reduces waste during trimming), for the design of the deep drawing tooling and the cost-effectiveness of the process.

When determining the size of the blank, it is assumed that the material thickness remains constant throughout drawing.

14.4.1 Determining the blank size for cylindrical parts with small radii ($r < 10$ mm)

Cup without flange (Figure 14.6)

$$\frac{D^2 \cdot \pi}{4} = \frac{d^2 \cdot \pi}{4} + d \pi h$$

$$D = \sqrt{d^2 + 4 dh}$$

D in mm diameter of the blank
 d in mm } see Figure 14.6
 h in mm }

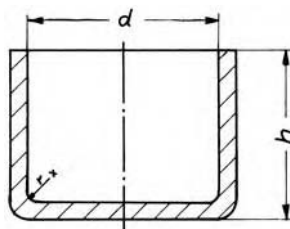


Figure 14.6 Cup with small bottom radius ($r < 10$ mm)

Cup with flange (Figure 14.7)

$$\frac{D^2 \pi}{4} = \frac{d_1^2 \pi}{4} + d_1 \pi h + (d_2^2 - d_1^2) \frac{\pi}{4}$$

$$\frac{D^2 \pi}{4} = \frac{\pi}{4} (d_1^2 + 4 d_1 h + d_2^2 - d_1^2)$$

$$D = \sqrt{d_2^2 + 4 d_1 h}$$

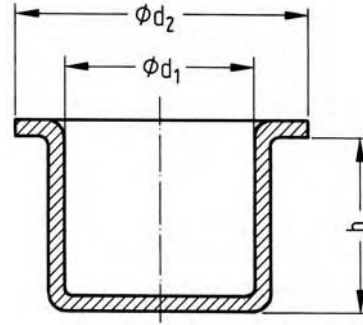


Figure 14.7 Cup with flange

14.4.2 Determining the blank size for axisymmetric (rotationally symmetric) parts with large radii ($r > 10$ mm)

Bottom radii of > 10 mm must be given particular consideration when determining the blank size. This takes place using Guldin's (Pappus's) theorem: "The surface of a body of revolution generated by rotating a curve around its axis is equal to the product of the generating curve and the distance travelled by its geometric centroid at distance r_s from the axis of rotation."

$$S = 2 r_c \cdot \pi \cdot l$$

- S in mm^2 surface of revolution
 r_c in mm radius of the centroid
 l in mm length of the rotating curve
 D in mm diameter of the blank

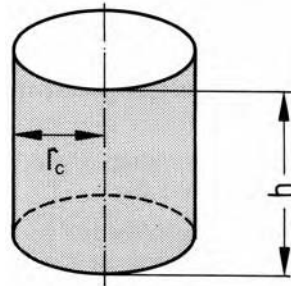


Figure 14.8 Surface of revolution

This surface must correspond to the area of the blank (Figure 14.9)

$$\frac{D^2 \pi}{4} = 2 \pi r_c \cdot l$$

$$\frac{D^2 \pi}{4} = 4 \cdot 2 \cdot \frac{\pi}{4} \cdot r_c \cdot l$$

$$D = \sqrt{8 \cdot r_c \cdot l}$$

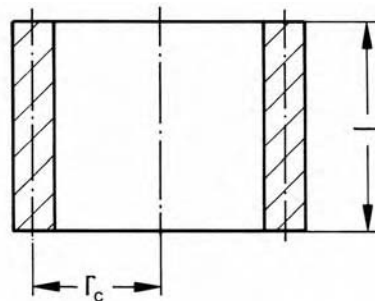


Figure 14.9 Size of the centroid radius in a body of revolution

For bodies of any type, which have more than one limiting line and therefore more than one centroid radius, the following applies (Figure 14.10)

$$D = \sqrt{8 \cdot \sum (r_c \cdot l)}$$

Example:

$$1. \quad l_1 = \frac{d - 2r}{2} \quad r_{c1} = \frac{d - 2r}{4}$$

$$2. \quad l_2 = \frac{2r\pi}{4} = \frac{r\pi}{2} \quad r_{c2} = 0.64r + \frac{d - 2r}{2}$$

$$3. \quad l_3 \cong h - r \quad r_{c3} = \frac{d}{2}$$

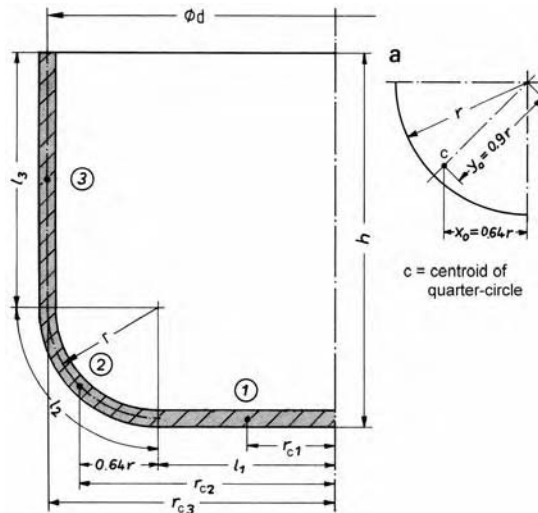


Figure 14.10 Determining the centroid radii and lengths of the segmented parts of a body of revolution with large radii ($r > 10$ mm), a) centroid of a quarter-circle

$$D = \sqrt{8 (l_1 \cdot r_{c1} + l_2 \cdot r_{c2} + l_3 \cdot r_{c3})}$$

$$= \sqrt{8 \left[\left(\frac{d - 2r}{2} \right) \left(\frac{d - 2r}{4} \right) + \frac{r\pi}{2} \left(0.64r + \frac{d - 2r}{2} \right) + (h - r) \frac{d}{2} \right]}$$

$$D = \sqrt{(d - 2r)^2 + 4 [1.57 r (d - 2r) + 2 r^2 + d (h - r)]}$$

Table 14.1 Formulae for calculating the blank diameter of various receptacle shapes

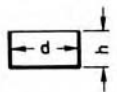
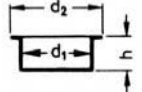
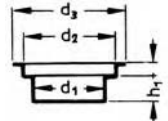
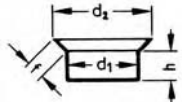
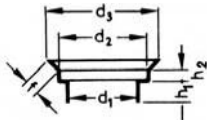

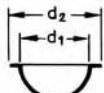
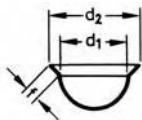
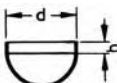
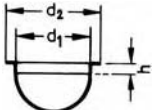
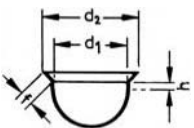
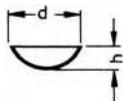
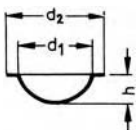
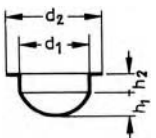
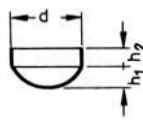
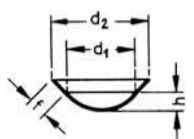
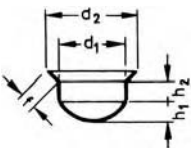
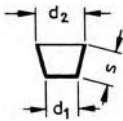
	$\sqrt{d^2 + 4 d h}$
	$\sqrt{d_2^2 + 4 d_1 h}$
	$\sqrt{d_3^2 + 4 (d_1 h_1 + d_2 + h_2)}$
	$\sqrt{d_1^2 + 4 d_1 h + 2 f \cdot (d_1 + d_2)}$
	$\sqrt{d_2^2 + 4 (d_1 h_1 + d_2 h_2) + 2 f \cdot (d_2 + d_3)}$
	$\sqrt{2 d^2} = 1.4 d$
	$\sqrt{d_1^2 + d_2^2}$
	$1.4 \sqrt{d_1^2 + f(d_1 + d_2)}$
	$1.4 \sqrt{d^2 + 2 d h}$

Table 14.1 (continued)

	$\sqrt{d_1^2 + d_2^2 + 4 d_1 h}$
	$1.4 \sqrt{d_1^2 + 2 d_1 h + f \cdot (d_1 + d_2)}$
	$\sqrt{d^2 + 4 h^2}$
	$\sqrt{d_2^2 + 4 h^2}$
	$\sqrt{d_2^2 + 4(h_1^2 + d_1 h_2)}$
	$\sqrt{d^2 + 4(h_1^2 + d h_2)}$
	$\sqrt{d_1^2 + 4h^2 + 2 f \cdot (d_1 + d_2)}$
	$\sqrt{d_1^2 + 4[h_1^2 + d_1 h_2 + \frac{1}{2} \cdot (d_1 + d_2)]}$
	$\sqrt{d_1^2 + 2 s (d_1 + d_2)}$

14.4.3 Determining the blank size for rectangular drawn parts

The blank size for rectangular drawn parts is determined by breaking down the hollow part into elements of equal area:

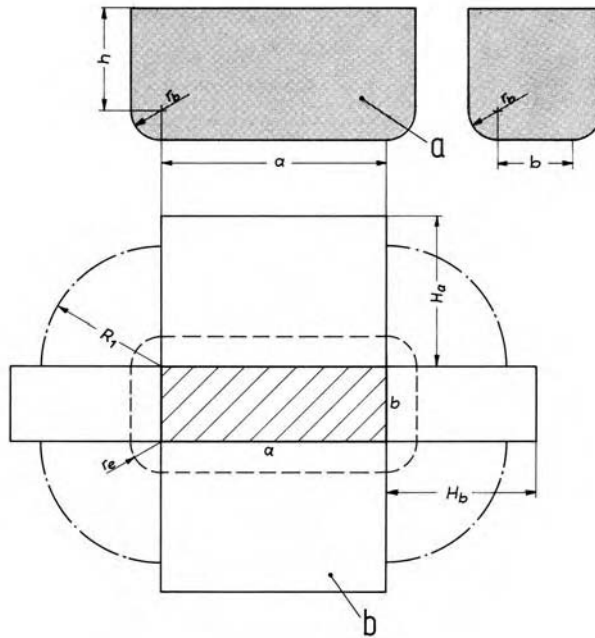


Figure 14.11 Breakdown of a rectangular hollow part a), into elements of equal area b)

1. Sketch the bottom of the cup without the radius. A rectangle with sides a and b is produced (Figure 14.11).
2. Move the side walls including the radius r_b around (lay out the radius) and add them on the corresponding sides of the rectangle $a - b$.
3. The cross this produces has lengthened the basic $a - b$ rectangle by H_a on side a and by H_b on side b .
4. In the re-entrant angles of the cross, a quarter circle is drawn with the radius R_1 .
5. The sharp, angular spaces in between are balanced out by drawing arcs or other curves so that the area of the basic body remains the same.
The compensation radii R_a and R_b are set at about $a/4$ or $b/4$ (Figure 14.12). If $a = b$ then the blank is a circle.
6. With simple shapes, the evening-out can also be done using a straight line (this produces an octagon). However, this method is less precise.

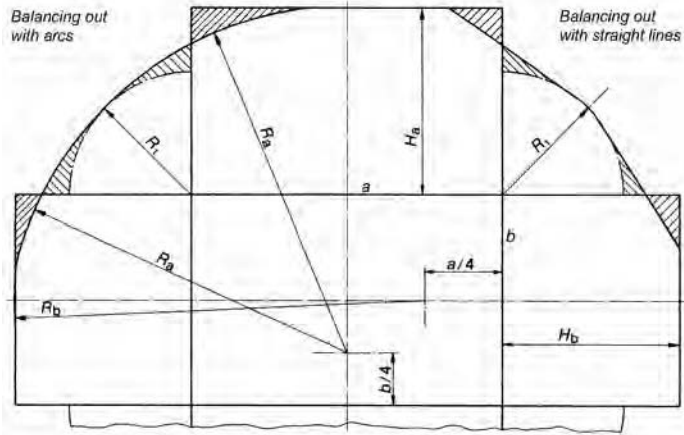


Figure 14.12 Evening out the design of the blank using arcs or straight lines

14.4.3.1 Calculating the design values R_1 , H_a , H_b when h , a , b , r are provided

Case 1: corner radius = bottom radius

$$r_e = r_b = r$$

Design radius R :

$$R = 1.42\sqrt{r \cdot h + r^2}$$

Correction value x :

$$x = 0.074\left(\frac{R}{2r}\right)^2 + 0.982$$

Corrected design radius R_1 :

$$R_1 = x \cdot R$$

Developed length H_a :

$$H_a = 1.57r + h - 0.785(x^2 - 1)\frac{R^2}{a}$$

Developed length H_b :

$$H_b = 1.57r + h - 0.785(x^2 - 1)\frac{R^2}{b}$$

$$a = L - 2r_e$$

$$b = B - 2r_e$$

$$h = H - r_b$$

$$r_e = r_b$$

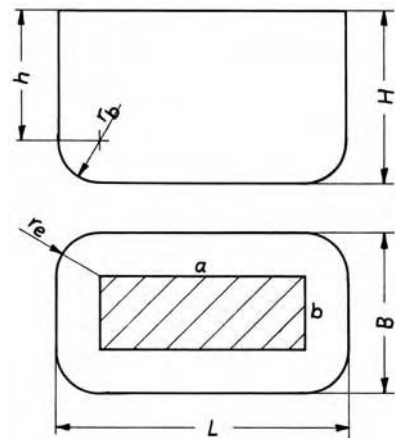


Figure 14.13 Rectangular hollow part with different bottom and corner radii

Case 2: corner radius different to bottom radius

$$r_e \neq r_b$$

Design radius R :

$$R = \sqrt{1.012 r_e^2 + 2 r_e (h + 0.506 r_b)}$$

Correction value x :

$$x = 0.074 \left(\frac{R}{2 r_e} \right)^2 + 0.982$$

Corrected design radius R_1 :

$$R_1 = x \cdot R$$

Developed length H_a :

$$H_a = 0.57 r_b + h + r_e - 0.785 (x^2 - 1) \frac{R^2}{a}$$

Developed length H_b :

$$H_b = 0.57 r_b + h + r_e - 0.785 (x^2 - 1) \frac{R^2}{b}$$

14.4.4 Determining blank design for oval and various curved, cylindrical drawn parts

Here, the blank is generally taken to be cylindrical, as long as the relationship of the semi-axes of the ellipse is

$$\frac{a}{b} \leq 1.3 .$$

14.5 Permissible deformation

In deep drawing, the limits for the permissible deformation are set by the draw ratio. The draw ratio is used to

- a) determine how many drawing operations are necessary to produce a drawn part;
- b) judge the drawability of deep drawing steels;
- c) determine the correction value $n = f$ (draw ratio) to calculate the drawing force.

A difference is made between:

14.5.1 Lowest draw ratio m

$$m = \frac{d}{D} = \frac{\text{punch diameter}}{\text{blank diameter}}$$

The smallest permissible draw ratio m is the limit for the ratio of the punch diameter to the blank diameter. The actual draw ratio m_{actual} may be equal to or larger than, but not lower than m_{perm} .

$$m_{\text{actual}} \geq m_{\text{perm}}$$

14.5.2 Highest draw ratio β

β is the reciprocal value of m .

$$\beta = \frac{D}{d} = \frac{\text{blank diameter}}{\text{punch diameter}}$$

14.5.2.1 Largest permissible draw ratio at the first draw

$$\beta_{0 \text{ perm}} = \frac{D}{d}$$

Table 14.2 Mean values for $\beta_{0 \text{ perm}}$, e.g. for WUSt 1403, USt 1303, Ms 63, Al 99.5

d/s	30	50	100	150	200	250	300	350	400	450	500	600
$\beta_{0 \text{ perm}}$	2.1	2.05	2.0	1.95	1.9	1.85	1.8	1.75	1.7	1.65	1.60	1.5

The actual draw ratio β_{actual} may be the same as or lower than, but not higher than the permissible draw ratio $\beta_{0 \text{ perm}}$.

The permissible draw ratio β for the first draw can also be calculated mathematically: for materials with good drawability, e.g. St 1403, Ms 63

$$\beta_{0 \text{ perm}} = 2.15 - \frac{d}{1000 \cdot s}$$

For materials which draw less well, e.g. St 1203

$$\beta_{0 \text{ perm}} = 2.0 - \frac{1.1 \cdot d}{1000 \cdot s}$$

d in mm punch diameter
 s in mm sheet thickness

14.5.2.2 Permissible draw ratio on further draws (second, third draw)

For deep drawing steels such as St 1203 and St 1303 the average permissible draw ratio is around

$$\beta_1 = 1.2 \text{ to } 1.3$$

At the second draw, the higher value must be assumed, and at the third draw the lower.

e.g. on the 2nd draw, $\beta_1 = 1.3$
 on the 3rd draw, $\beta_1 = 1.2$ } without intermediate annealing

If intermediate annealing takes place after the first draw, then the values are higher by about 20%. Then,

$$\beta_1 = 1.6$$

can be assumed for the second draw.

14.6 Deep drawing steps

14.6.1 Deep drawing steps for cylindrical parts

$$1^{\text{st}} \text{ draw} \quad d_1 = \frac{D}{\beta_0}$$

$$2^{\text{nd}} \text{ draw} \quad d_2 = \frac{d_1}{\beta_1}$$

$$3^{\text{rd}} \text{ draw} \quad d_3 = \frac{d_2}{\beta_1}$$

$$n^{\text{th}} \text{ draw} \quad \boxed{d_n = \frac{d_{n-1}}{\beta_1}}$$

The required number of draws for cylindrical cups can be roughly calculated with Hubert's approximation formula (Figure 14.14).

$$\boxed{n \cong \frac{h_n}{d_n} = \frac{D^2 - d_n^2}{4 \cdot d_n^2}}$$

- n — required number of draws
- h_n in mm cup height after the n^{th} draw
- D_n in mm cup diameter after the n^{th} draw
- D in mm diameter of the blank

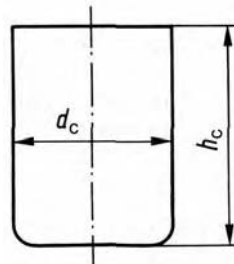


Figure 14.14 Cylindrical cup

14.6.2 Deep drawing steps for oval parts and parts with an elliptical base

For $\frac{a}{b} \leq 1.3$ the deep drawing steps are the same as with round parts, starting out from a circular blank.

$$\beta = \frac{D}{d_0} = \frac{\text{blank diameter}}{\text{small diam. of ellipse}}$$

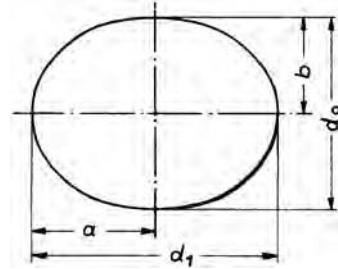


Figure 14.15 Drawn part with elliptical base

The smaller diameter of the ellipse is the decisive factor for the draw ratio.

For $\frac{a}{b} > 1.3$ the deep drawing steps are the same as with rectangular drawn parts.

14.6.3 Deep drawing steps for rectangular parts

This depends upon the design radius R_1 (see section 14.4.3.1) and the material constant q .

For St 12 to St 14 deep drawing steel:

$$q \approx 0.3$$

- 1st draw $r_1 = 1.2 \cdot q \cdot R_1$
- 2nd draw $r_2 = 0.6 \cdot r_1$
- 3rd draw (fin. part) $r_3 = 0.6 \cdot r_2$

If further draws are necessary, then the following generally applies:

$$n^{\text{th}} \text{ draw } r_n = 0.6 \cdot r_{n-1}$$

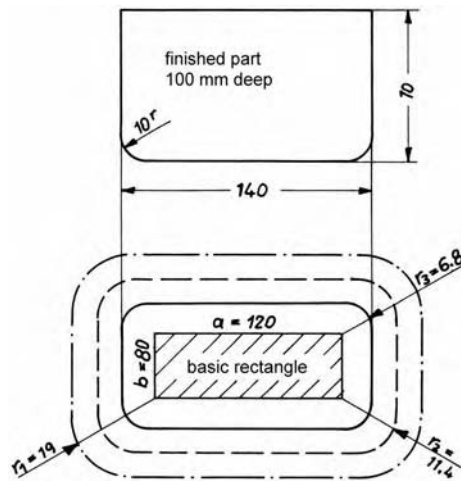


Figure 14.16 Deep drawing steps with a rectangular drawn part

In other words, just as when determining the blank size, the cup base is assumed to be a basic rectangle and the permissible corner radii are determined.

The number of draws required is that which will produce the final corner radius.

Example:

Determine the steps for a rectangular drawn part.

Sheet thickness $s = 1\text{ mm}$

$r_e = r_b = 10\text{ mm}$

$q = 0.34$

$R_1 = 46.8\text{ mm}$

1st draw: $r_1 = 1.2 \cdot q \cdot R_1 = 1.2 \cdot 0.34 \cdot 46.8\text{ mm} = 19\text{ mm}$

2nd draw: $r_2 = 0.6 \cdot r_1 = 0.6 \cdot 19\text{ mm} = 11.4\text{ mm}$

3rd draw: $r_3 = 0.6 \cdot r_2 = 0.6 \cdot 11.4\text{ mm} = 6.84\text{ mm}$

n^{th} draw: $r_3 = 6.84\text{ mm} < 10\text{ mm}$ (< than the radius of the finished part),
so the finished part can be produced with three draws.

14.7 Calculating the drawing force

14.7.1 Drawing force for cylindrical parts at the first draw

$$F_{\text{dr}} = C \cdot s \cdot R_m \cdot n = d \cdot \pi \cdot s \cdot R_m \cdot n$$

F_Z in N	drawing force
C in mm	circumference of the drawing punch
d in mm	punch diameter
s in mm	sheet thickness
R_m in N/mm ²	tensile strength
n	correction value

The correction value n takes into account the ratio of drawing tension to tensile strength. It depends mainly upon the actual draw ratio, which comes from the dimensions of the drawn part.

Table 14.3 Correction value $n = f(\beta_{\text{actual}})$

n	0.2	0.3	0.5	0.7	0.9	1.1	1.3
$\beta_{\text{actual}} = \frac{D}{d}$	1.1	1.2	1.4	1.6	1.8	2.0	2.2

Table 14.4 Maximum tensile strengths R_m of some deep drawing steels

Material	St 1303	St 1404	CuZn28 (Ms 72)	Al 99.5 (F10)
$R_{m\text{max}}$ in N/mm ²	400	380	300 D. drawing quality	100 medium hard

14.7.2 Drawing force for cylindrical parts at the second draw

$$F_{\text{sec}} = \frac{F_{\text{dr}}}{2} + d_1 \cdot \pi \cdot s \cdot R_m \cdot n$$

d_1 punch diameter at the second draw.

14.7.3 Drawing force for rectangular parts

$$F_{\text{dr}} = \left(2 \cdot r_e \cdot \pi + \frac{4 + (a + b)}{2} \right) \cdot R_m \cdot s \cdot n$$

r_e in mm corner radius (see Figure 14.11)

a in mm length of the cup without bottom radius r_b (Figure 14.11)

b in mm width of the cup without bottom radius r_b .

14.8 Blank holder force

14.8.1 Blank holder pressure

$$p = \left[(\beta_{\text{actual}} - 1)^2 + \frac{d}{200 \cdot s} \right] \cdot \frac{R_m}{400}$$

p in N/mm² blank holder pressure

d in mm punch diameter

D in mm diameter of the blank

s in mm sheet thickness

R_m in N/mm² tensile strength

β_{actual} – actual draw ratio (first draw).

14.8.2 Blank holder area

$$A_{\text{BH}} = (D^2 - d_e^2) \cdot \frac{\pi}{4}$$

$$d_e = d + 2 \cdot w + 2 \cdot r_M \quad (\text{see Figure 14.17})$$

A_{BH} in mm² blank holder area

d_e in mm effective diameter of the blank holder

w in mm drawing clearance

r_M in mm die edge curvature radius.

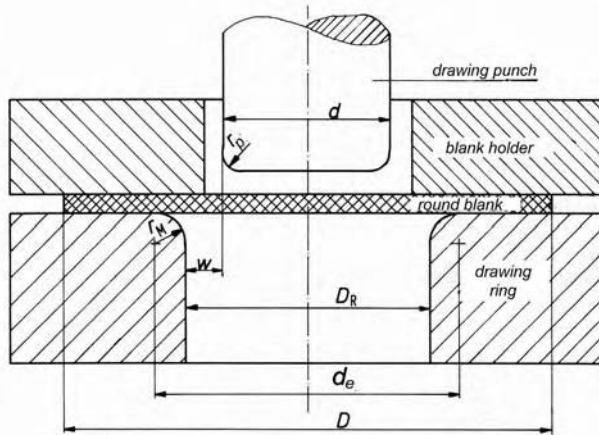


Figure 14.17 Layout of drawing punch, blank holder and drawing ring

14.8.3 Blank holder force

$$F_{\text{BH}} = p \cdot A_{\text{BH}}$$

F_{BH} in N blank holder force.

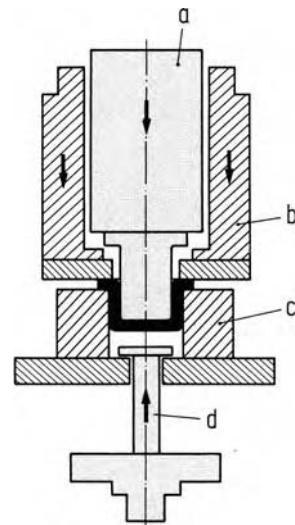
14.9 Drawing work

14.9.1 With double-action presses:

$$W = F_{\text{dr}} \cdot x \cdot h$$

A double-action press basically has two rams (Figure 14.18). The outer ram is used for the blank holder and the inner ram for the actual drawing operation. Both rams can be controlled separately. Normal deep drawing requires this kind of double-action press; in other words: a drawing press is always double-action.

Figure 14.18 The principle of the deep drawing process with a double-action press;
 a) drawing ram,
 b) blank holder,
 c) drawing ring,
 d) ejector.



14.9.2 With single-action presses:

$$W = (F_{dr} \cdot x + F_{BH}) \cdot h$$

- W in Nmm drawing work
- F_{dr} in N drawing force
- F_{BH} in N blank holder force
- h in mm cup height = drawing depth
- x – process factor
($x = 0.63$).

A single-action press has only one ram and an ejector. This ejector can be used to operate the blank holder, if the drawing die is rotated by 180°. Then, the drawing ring is fixed onto the ram and the drawing punch (the pommel) is fixed to the lower platen. The blank holder is operated by the ejector using thrust pins. As the blank holder force needs to be variable, this kind of machine can only be used for deep drawing if the ejector force is adjustable. A device of this kind, when installed specially for deep drawing, is known as a die cushion.

In this kind of assembly, as the ram has to overcome not only the drawing force F_{dr} , but also the blank holder force F_{BH} , the two forces add up when calculating mechanical work.

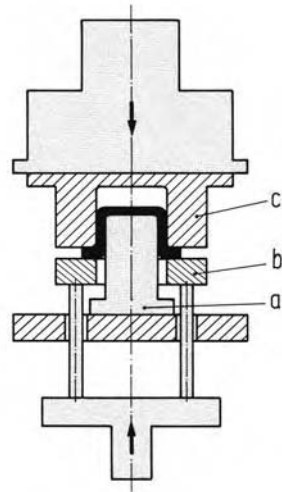


Figure 14.19 The principle of the deep drawing process with a single-action press, a) drawing punch (pommel), b) blank holder, c) drawing ring,

Diagram of work (force-displacement diagram):

The work diagram shows the force-displacement path during deep drawing. The force-displacement curve is nearly an inverted parabola. The area under the parabola is the drawing work. To determine the drawing work mathematically from the force and the drawing depth, the mean resultant force F_m is used, imagined as constant across the entire path. The area of the rectangle formed by F_m and s must be the same as the area under the parabola. The F_m/F_{max} ratio is considered the process factor as it characterises the force path of the particular manufacturing process.

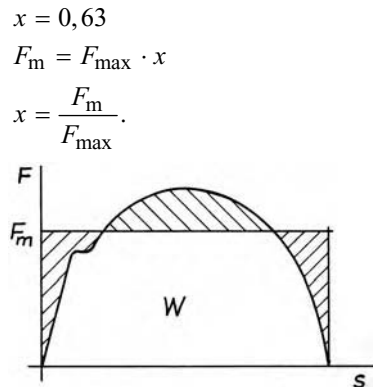


Figure 14.20 Force-displacement path during deep drawing

14.10 Drawing tooling (Figure 14.17)

14.10.1 Drawing clearance w

The drawing clearance, w , is half the difference between the diameter of the drawing ring and the diameter of the punch.

$$w = s \sqrt{\frac{D}{d}}$$

- w in mm drawing clearance
 D in mm diameter of the blank
 d in mm punch diameter
 s in mm sheet thickness

For more precise calculations, the following applies (according to Oehler):

$$w = s + k \cdot \sqrt{s}$$

Table 14.5 Material factor k to determine the drawing clearance w

Material	Steel	High-temperature alloys	Aluminium	Other nonferrous metals
k in $\sqrt{\text{mm}}$	0.07	0.2	0.02	0.04

14.10.2 Punch radius r_p for cylindrical parts

$$r_p = (4 \dots 5) \cdot s$$

This depends upon the part being drawn.

14.10.3 Die edge curvature r_M

For cylindrical parts:

Too small radii subject the sheet to additional strain. Too large radii lead to the formation of wrinkles at the end of the draw, as then the blank holder is no longer effective.

$$r_M = \frac{0.035}{\sqrt{\text{mm}}} [50 \text{ mm} + (D - d)] \cdot \sqrt{s}$$

r_M	in mm	die edge curvature radius
D	in mm	diameter of the blank
d	in mm	diameter of the finished part = punch diameter
s	in mm	sheet thickness

So r_M depends upon:

the sheet thickness s

the blank diameter D

the diameter of the finished part d (= punch diameter).

With low drawing depths, a smaller r_M must be selected as otherwise, the area where the blank holder presses is too small.

The parts of the drawing rings which come into contact with the sheet must be kept smoothly ground and polished to reduce frictional forces.

For rectangular parts:

a) for rectangle side a : (see Figure 14.11)

$$r_a = \frac{0.035}{\sqrt{\text{mm}}} [50 \text{ mm} + 2(H_a - r_e)] \cdot \sqrt{s}$$

b) for rectangle side b :

$$r_b = \frac{0.035}{\sqrt{\text{mm}}} [50 \text{ mm} + 2(H_b - r_e)] \cdot \sqrt{s}$$

c) radii in the corners of the rectangular die:

$$r_e \approx 1.5 r_a.$$

14.10.4 Structural design of drawing tooling

The structural design of drawing tooling is determined by two factors:

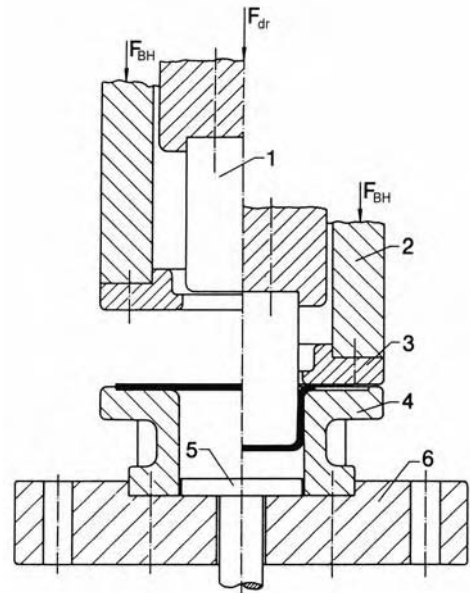
1. The type of deep drawing

Here, a difference is made between tooling for the first draw and for further draws (second, third, fourth).

The main elements of deep drawing tooling are shown in Figure 14.21 for the first draw and Figure 14.22 for further draws (second, third, etc.).

Figure 14.21 Deep drawing tooling for the first draw:

- 1 drawing punch,
- 2 blank holder ram,
- 3 blank holder,
- 4 drawing ring,
- 5 ejector,
- 6 base plate

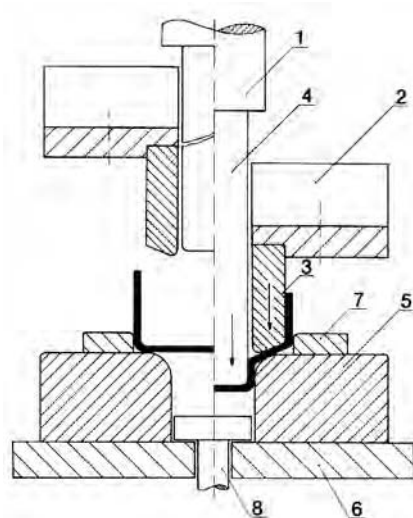


2. The press which is available (single or double-action presses).

If a deep drawing operation is carried out on a single-action press, then the drawing ring must be fixed onto the ram and the blank holder must be operated from the die cushion.

Figure 14.22 Deep drawing tooling for the second draw:

- 1 drawing ram,
- 2 blank holder ram,
- 3 blank holder,
- 4 drawing punch,
- 5 drawing ring,
- 6 base plate,
- 7 centring ring,
- 8 ejector.



The principle of the tooling layout for the first draw is shown in Figure 14.19; Figure 14.23 shows an assembly for the second draw.

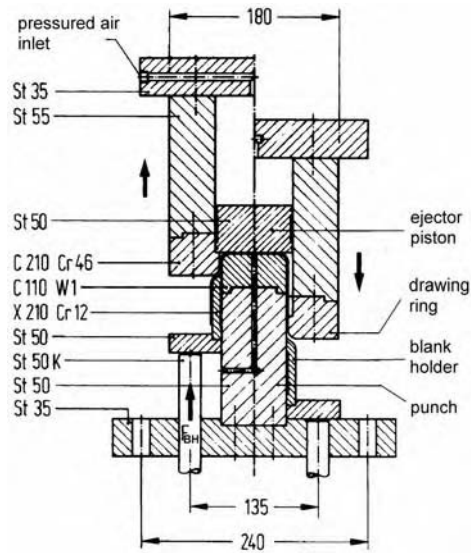


Figure 14.23 Drawing tooling for the second draw for a single-action press

Instead of a conventional second draw, reverse (inside-out) redrawing can also be used. In reverse redrawing, the pre-formed cup (Figure 14.2) is brought down to the next diameter reduction by being turned inside-out. After reverse redrawing the inner walls of the drawn cup become outer walls. Figure 14.25 shows the principle of a reverse redrawing assembly.

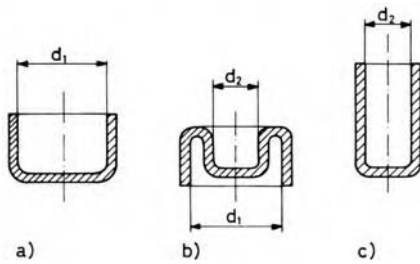


Fig. 14.24 (above) Reverse-redrawn workpiece, a) before, b) during, c) after reverse redrawing.

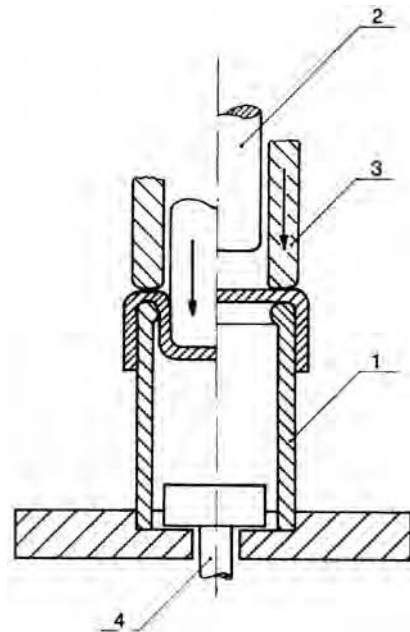


Figure 14.25 (right). The principle of the reverse redrawing assembly, 1 drawing ring, 2 drawing punch, 3 blank holder, 4 ejector

3. Drawing tooling for irregular flat forms e.g. for automobile manufacturing

Drawing tooling for irregular, flat forms, such as those which occur often in automobile parts, is characterised by difficult forming conditions. Instead of a conventional drawing ring, a shaping drawing die is used which has the negative form of the workpiece. This tooling is produced by casting, often full mould (lost foam) casting followed by a chip-producing (cutting) finishing process.

To form the shape, the tensile-compressive stresses must be accompanied by uniaxial or biaxial tensile and bending stresses created by a suitable tooling design. The (draw) bead shown in Figure 14.26 is generally put on the die and the draw beads (lock beads) are arranged on the blank holder, with gaps in the die to fit them.

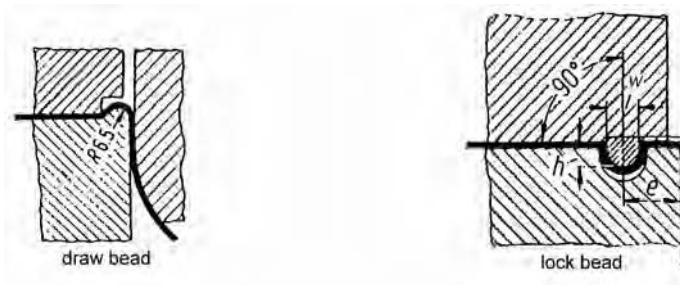


Figure 14.26 Draw beads and lock beads
(range of $w \times h$: $10 \times 8 \dots 20 \times 25$ mm)

The lock beads are of more importance than the draw beads and are positioned in places where problems occur with varying stress ratios and an associated material flow. For example, Figure 14.27 shows the arrangement of lock beads on a drawn part.

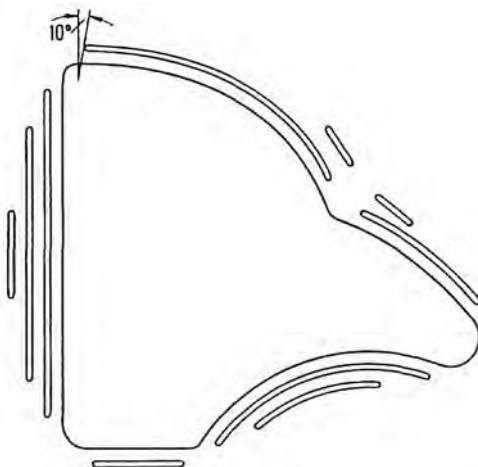
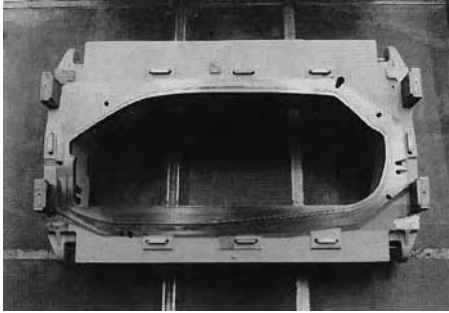
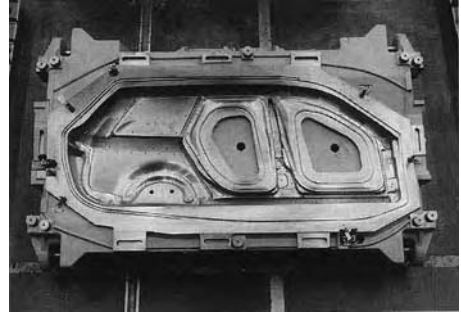


Figure 14.27 The arrangement of lock beads on a drawn automobile part

The draw beads and lock beads mean that the material flow can be controlled, fine-tuned by FEM simulation and ultimately the toolmaker's experience, so that the defects of cracking, over-reduction of sheet thickness and wrinkling can be avoided. Figure 14.28 shows the deep drawing punch, the blank holder, the drawing die and a component, the side door of an Audi Avant automobile.



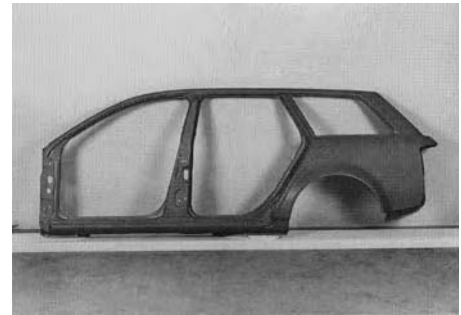
Blank holder



Drawing die



Drawing punch



Side wall component of Audi Avant

Figure 14.28 Toolset for manufacturing the Audi Avant side wall (Photograph from KUKA Werkzeugbau Schwarzenberg GmbH works, Germany)

The problems presented by this complicated drawing tooling mean that in practice, when pre-developing new automobile components, prototype tooling is still required to produce a limited number of components for test purposes, as well as FEM simulations of the viability of the process and the construction of tooling.

In Figure 14.29, for example, there are three toolsets for manufacturing prototype components which allow rapid production of the tooling, and therefore also the workpieces, from 3D CAD construction data. In version 1, the tooling is produced by casting using an alloy with a very low melting point, MCP 137 (HEK GmbH works). This tooling can be used for up to approx. 30 parts, then it must be re-cast with the nearly 100% reusable MCP alloy. For larger numbers of prototype parts, a Zn alloy (ZAMAK) is used internationally which requires full mould casting followed by a chip-producing finishing process.

In version 2, the tooling is made up of layers of laser-cut sheet bonded together with pins, bolts, sometimes adhesives or, with large-scale tooling, by welding. The disadvantage of this version are the marks on the sheet parts caused by the ridged structure of the laminated tooling, meaning that this version is only used for automobile components which are out of sight. However, Japanese experience shows that a great deal of time and money can be saved with large-scale tooling.

Version 3 shows how high-speed cutting (HSC) can be used in tool manufacturing. The surface quality of the tools reaches that achieved by grinding; for the relatively small component studied here (approx. 130 mm × 100 mm × 35 mm, sheet thickness 1.5 mm; St 14) with a free-formed surface Version 3 worked out as the best solution regarding both time and expenses.

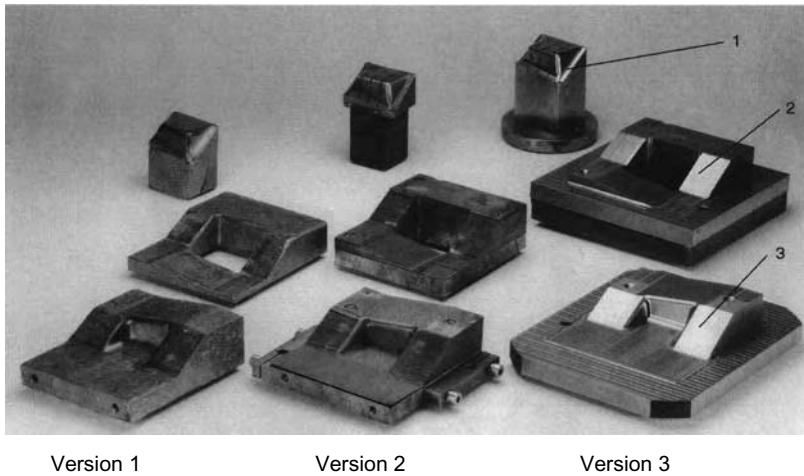


Figure 14.29 Drawing tooling for prototypes (Photograph by Sebb, Dresden University of Applied Sciences)
(1 – punch; 2 – blank holder; 3 – drawing die)

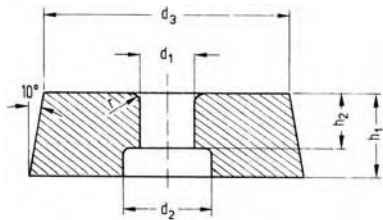
When using the newly-developed HSC hexapod Mikromat 6X milling machine, which works on the principle of parallel kinematics, first studies have shown that up to 40% more time can be saved. All three versions are considerably faster and better value than normal production, as can be seen from Table 14.6 a.

Table 14.6 a Comparison of production time and costs for prototype tooling (including CAD construction)

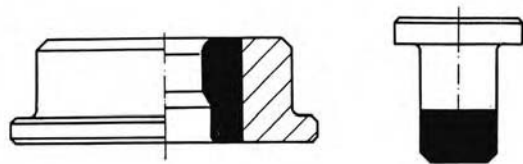
	Version 1 – casting	Version 2 – laminated object modelling	Version 3 – HSC milling	Conventional production (milling, electrical discharge machining)
Time / h /	51	53.5	33.2	104.5
Order by cost	2	3	1	4

Table 14.6 Drawing ring dimensions in mm

Blank D	d_1	d_2	d_3	h_1	h_2
18.5	10	13	50	20	10
22	12.5	16	50	20	10
29	16	20	50	25	13
36	20	24	63	25	13
45.5	25	29	63	25	13
58	31.5	38	80	32	16
73	40	46	80	32	16
90	50	56	100	32	16
116	63	70	125	32	20
145	80	88	160	40	20
180	100	108	200	40	20
225	125	132	250	40	25
290	160	168	315	40	25
360	200	208	400	50	25
455	250	258	500	50	32
580	315	328	630	63	32
725	400	408	800	63	32



Stahl



Hartmetall

Table 14.7 Tooling materials

Material no.	Designation	HRC assembly hardness	Drawing punch	Drawing die
1.1540	C 100 W1	63	×	×
1.2056	90 Cr 3	63	×	×
1.2842	90 Mn V 8	62	×	×
1.2363	105 Cr Mo V 5 – 1	63	×	×
1.2436	210 Cr W 12	62	×	×
Carbide	ISO designation	HV30 assembly hardness	Drawing punch	Drawing die
	G 20	1400	×	×
	G 30	1200	×	×

14.11 Achievable precision

Table 14.8 Height tolerances (\pm) in mm for cylindrical drawn parts without a flange

Material thickness in mm	Height of the drawn part in mm					
	20	21 to 30	31 to 50	51 to 100	101 to 150	151 to 200
1	0.5	0.6	0.8	1.1	1.4	1.6
1 to 2	0.6	0.8	1.0	1.3	1.7	1.8
2 to 4	0.8	1.0	1.2	1.6	1.9	2.2

Table 14.9 Height tolerances (\pm) in mm for cylindrical drawn parts with a flange



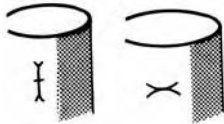
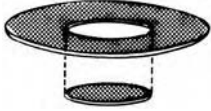
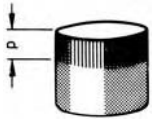
Material thickness in mm	Height of the drawn part in mm					
	20	21 to 30	31 to 50	51 to 100	101 to 150	151 to 200
1	0.3	0.4	0.5	0.7	0.9	1.0
1 to 2	0.4	0.5	0.6	0.8	1.1	1.2
2 to 4	0.5	0.6	0.7	0.9	1.3	1.4



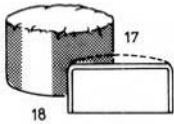
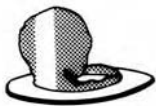

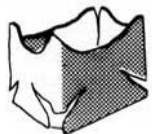
Table 14.10 Diameter tolerances in mm for cylindrical hollow parts without a flange, for sheet thicknesses of $s = 0.5$ to 2.0 mm

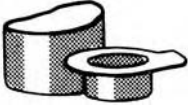

Draw ratio β	Diameter of the drawn part in mm				
	30	31 to 60	61 to 100	101 to 150	151 to 200
1.25	0.10	0.15	0.25	0.40	0.60
1.50	0.12	0.20	0.40	0.50	0.75
2.0	0.15	0.25	0.45	0.60	0.90

14.12 Defects during deep drawing

Table 14.11 Defects during deep drawing (according to G.W. Oehler)

Appearance	Type of defect	Cause of defect	Corrective action
<i>Material flaw</i>			
	Irregular cracking from the edge of the wall down. Cracks of this type often only develop days or weeks after drawing.	Too high stresses	Anneal the stock directly after drawing
	Deep crack on one side of the wall, crack is a curved shape. Clean edge to crack. Transverse crack on one side	Flaw in the sheet caused by thicker nodules or foreign bodies pressed in, e.g. metal chips.	
	Short transverse cracks in the wall. Black spots with flattened areas directly above and below them	Fine holes in the material, porous sheet	
<i>Defects in the tooling</i>			
	Bottom is torn off on all sides with no wall forming.	The drawing tooling is acting as a cutter, as <ol style="list-style-type: none"> 1. die edge curvature too low and sharp-edged or 2. drawing clearance too narrow or 3. too high blank holder pressure or 4. too high drawing speed. 	Raise the die edge radius, generally by grinding the punch or drawing ring. Reduce the blank holder pressure. Reduce the number of press strokes per minute.
	Bright compression mark at height p on the upper part of the wall, externally.	Drawing clearance too narrow.	Grind drawing ring or punch.

	Drawing successful except for frayed wall edge and flattened wrinkles.	<ol style="list-style-type: none"> 1. Mostly drawing clearance too wide or 2. die edge curvature too large. 	Replace tooling to reduce clearance.
	Draw almost successful except very wrinkled extra flange with horizontal cracks beneath it.	Too high die edge curvature, too low blank holder pressure.	Grind down the surface of the drawing ring and reduce edge radius. Set blank holder pressure higher.
	Blistering at the bottom edges. Bottom bulges as shown by the dashed line	<ol style="list-style-type: none"> 1. Bad punch ventilation, 2. occasionally also heavily-worn die radius 	Install or widen vents. Polish the die radius.
<i>Wrong blank size or wrong step difference</i>			
Appearance	Type of defect	Cause of defect	Corrective action
	Only a short wall stub is formed, at about the height of the die edge curvature, then the bottom tears off.	<p>Too great a difference between steps considering the drawing quality of the sheet.</p> <p>Punch off-centre to the drawing ring.</p>	<p>Determine β value (= highest permissible D/d ratio) using the cup test procedure.</p> <p>Perhaps make steps smaller or select sheet of higher drawing quality. Adjust tooling correctly.</p>
	Tearing in the corners of rectangles, starting out at the edge and moving down towards the bottom corner.	<ol style="list-style-type: none"> 1. Lack of material in the corners due to incorrect blank sizing. 2. Drawing clearance too narrow in the corners. 	Change blank. Rectangular draws requires a greater drawing clearance in the corners than at the sides.
	Cracks starting in the bottom corners of rectangular draws, then moving out diagonally.	<ol style="list-style-type: none"> 1. Excess material in the corners. 2. Differences between steps too great in the corners. 	Change the blank. Make steps smaller or use higher-quality deep drawing sheet.

	Earring on one side of the wall edge or on the sheet flange.	<ol style="list-style-type: none"> 1. Blank inserted off-centre. 2. Irregular blank holder pressure. 3. Off-centre positioning of the punch in the drawing ring (rarely). 4. Irregular sheet thickness 	<p>Use guide pins.</p> <p>Align tooling.</p>
<i>Operating errors</i>			
	Sheet flange too wide on one side near the web.	Blank inserted off-centre.	Fit stop pins.

14.13 Example

The aim is to manufacture sheet shells as in Figure 14.30 on a double-action drawing press.

Where: material St 1303

Find: blank diameter D , force, mechanical work (for the first draw)

Solution:

1. Determining blank size

$$D = \sqrt{d^2 + 4 d h}$$

$$= \sqrt{(80 \text{ mm})^2 + 4 \cdot 80 \text{ mm} \cdot 90 \text{ mm}}$$

$$D = 187.6 \text{ mm}$$

$$D = 188 \text{ mm selected}$$

2. Determining the number of draws required

2.1. The actual draw ratio

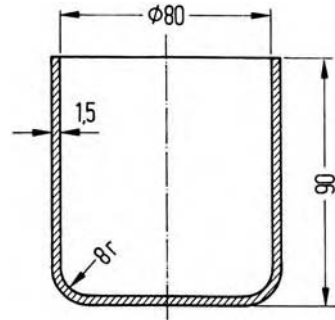
$$\beta_{\text{actual}} = \frac{D}{d} = \frac{188 \text{ mm}}{80 \text{ mm}} = 2.35$$

2.2. Diameter-wall thickness ratio d/s

$$\frac{d}{s} = \frac{80 \text{ mm}}{1.5 \text{ mm}} = 53.3$$

2.3. Permissible draw ratio for the first draw

$$\beta_{\text{perm}} \approx 2.05 \text{ from Table 14.2, page 151}$$



2.4. Decision

as $\beta_{0 \text{ perm}} < \beta_{\text{actual}}$

$$2.05 < 2.35$$

the part can not be produced in one draw as in Figure 14.26.

2.5. Deep drawing steps

$$1. \text{ draw } d_1 = \frac{D}{\beta_0} = \frac{188 \text{ mm}}{2.05} = 91.7 \text{ mm}$$

$$d_2 = \frac{d_1}{\beta_1} = \frac{91.7 \text{ mm}}{1.3} = 70.5 \text{ mm}$$

i.e. the drawn part can be produced with two draws.

So that it is not necessary to go up to the deformability limit at the first draw,

$$d_1 = 94.0 \text{ mm} \text{ is selected.}$$

Thus

$$\beta_{\text{actual}} = \frac{188 \text{ mm}}{94 \text{ mm}} = 2.0$$

At the second draw, this then produces an β_{actual} of

$$\beta_{\text{actual}} = \frac{d_1}{d_2} = \frac{94 \text{ mm}}{80 \text{ mm}} = 1.17$$

i.e. d_2 will also be safely achieved.

2.6. Height of the cup after the first draw

From $D = \sqrt{d^2 + 4 d h}$ we get:

$$h_1 = \frac{D^2 - d^2}{4 d} = \frac{(188 \text{ mm})^2 - (94 \text{ mm})^2}{4 \cdot 94 \text{ mm}} = \frac{35\,344 \text{ mm}^2 - 8836 \text{ mm}^2}{376 \text{ mm}}$$

$$h_1 = 70.5 \text{ mm.}$$

As slight earing is to be expected,

$$h = 70.5 \text{ mm} + 1.5 \text{ mm} = 72 \text{ mm} \text{ is assumed.}$$

3. Drawing force F_{dr}

$$F_{\text{dr}} = d \cdot \pi \cdot s \cdot R_{\text{m}} \cdot n = 94 \text{ mm} \cdot \pi \cdot 1.5 \text{ mm} \cdot 400 \text{ N/mm}^2 \cdot 1.1$$

$$F_{\text{dr}} = 194\,904 \text{ N} = \underline{\underline{195 \text{ kN}}}$$

For ($\beta_{\text{actual}} = 2.0$ then $n = 1.1$ from Table 14.3, $R_{\text{m}} = 400 \text{ N/mm}^2$ from Table 14.4.

4. Drawing clearance w

$$w = s \cdot \sqrt{\frac{D}{d}} = 1.5 \text{ mm} \cdot \sqrt{\frac{188 \text{ mm}}{94 \text{ mm}}} = 2.12 \text{ mm}$$

$$w = 2.1 \text{ selected.}$$

5. Die edge curvature r_{M}

$$r_{\text{M}} = \frac{0.035}{\sqrt{\text{mm}}} \cdot [50 \text{ mm} + (D - d)] \cdot \sqrt{s}$$

$$r_{\text{M}} = \frac{0.035}{\sqrt{\text{mm}}} \cdot [50 \text{ mm} + (188 \text{ mm} - 94 \text{ mm})] \cdot \sqrt{1.5 \text{ mm}}$$

$$r_{\text{M}} = 6.17 \text{ mm}$$

$$r_{\text{M}} = 6.0 \text{ mm selected.}$$

6. Blank holder force F_{BH}

6.1. Blank holder pressure

$$p = \left[(\beta_{\text{actual}} - 1)^2 + \frac{d}{200 \cdot s} \right] \cdot \frac{R_{\text{m}}}{400}$$

$$= \left[(2 - 1)^2 + \frac{94}{200 \cdot 1.5 \text{ mm}} \right] \cdot \frac{400 \text{ N/mm}^2}{400} = 1.31 \text{ N/mm}^2.$$

6.2. Blank holder area (see Figure 14.17)

$$d_{\text{e}} = d + 2 \cdot w + 2 \cdot r_{\text{M}} = 94 \text{ mm} + 2 \cdot 2.1 \text{ mm} + 2 \cdot 6 \text{ mm} = 110.2 \text{ mm}$$

$$A_{\text{BH}} = (D^2 - d_{\text{e}}^2) \cdot \frac{\pi}{4} = (188^2 - 110.2^2) \cdot \frac{\pi}{4} = 18\,221.2 \text{ mm}^2$$

6.3. Blank holder force

$$F_{\text{BH}} = A_{\text{BH}} \cdot p = 18\,221.2 \text{ mm}^2 \cdot 1.31 \text{ N/mm}^2 = 23\,869 \text{ N} = 23.9 \text{ kN.}$$

7. Work W

$$W = F_{\text{dr}} \cdot x \cdot h_1 = 195 \text{ kN} \cdot 0.63 \cdot 0.072 \text{ m} = 8.84 \text{ kNm.}$$

14.14 Hydromechanical deep drawing (HDD)

14.14.1 Definitions

In hydromechanical deep drawing (Figure 14.31) the circular blank to be formed (first draw) is pressed directly onto the downward-moving drawing die by a pressurised water pad giving it the exact shape of the drawing punch.

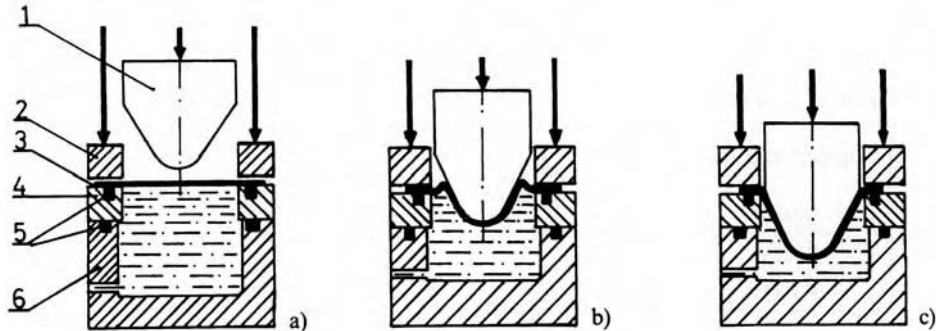


Figure 14.31 The principle of hydromechanical deep drawing, a) before, b) during, c) at the end of the first draw. 1 drawing punch, 2 blank holder, 3 blank, 4 drawing ring, 5 seal, 6 water chamber

For the second draw (Figure 14.32) the process is similar. Here, the outer diameter of the blankholder is the inner diameter of the cup after the first draw. This means that before the second draw, the cup is centred in the blank holder.

The punch has the new, reduced diameter to be produced in the second draw.

The punch has the new, reduced diameter to be produced in the second draw.

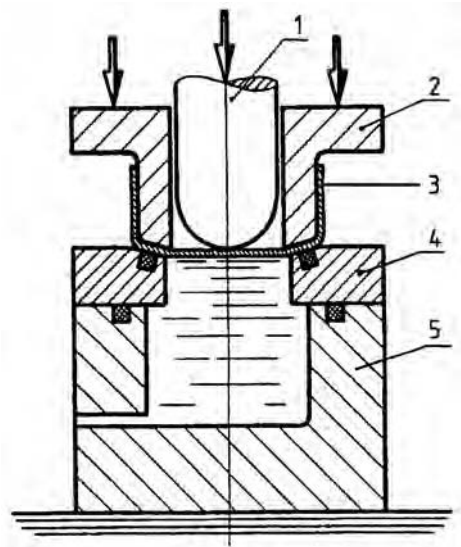


Figure 14.32 Tooling for the second draw:
1 drawing punch, 2 blank holder,
3 workpiece before the 2nd draw, 4 drawing ring,
5 water chamber

14.14.2 Advantages of hydromechanical deep drawing

When a processing medium is used in place of the rigid drawing ring, as the punch is moved down, this processing medium produces pressure on all sides, pressing the workpiece being formed onto the punch.

Frictional forces occur between the punch and the workpiece which transmit part of the drawing force onto the cup wall. This means that the force passed across the bottom of the drawn part is lower and the area of the workpiece under the most stress changes from the bottom of the workpiece towards the drawing radius. This provides the following advantages:

- The possible draw ratio is far better than with the conventional drawing process. Draw ratios of up to $\beta = 2.4$ are possible, e.g. for St 13 and $d/s = 100$.
- Conical and parabolic drawn parts are produced in one draw. In the conventional drawing process, 4-5 drawing operations with 1-2 intermediate anneals are often necessary for this kind of part.
- The reduction in sheet thickness at the bottom radii is very low, enabling thinner sheets to be deployed in many cases. Very small bottom radii can still be drawn efficiently for this reason.
- Blanks of varying thickness and different kinds of material can be processed with the same tooling.
- Production costs are lower than with conventional deep drawing.
- Low tooling costs
- Fewer steps in drawing
- Lower annealing costs.
- Any down-acting double-action press can be fitted with a hydromechanical unit, even as a later addition.
Expensive special-purpose machines are not necessary.

14.14.3 Application of the process

The hydromechanical process is mostly used for difficult drawn parts, especially difficult tapered and parabolic hollow parts which require several draws when using the conventional process.

14.14.4 Drawing force

$$F_{\text{dr}} = 1.5 \cdot R_m \cdot d \cdot \pi \cdot s + \frac{A_p \cdot p}{10}$$

R_m	in N/mm ²	tensile strength
d	in mm	punch diameter
s	in mm	sheet thickness
A_p	in cm ²	punch cross-section
p	in bar (daN/cm ²)	pressure in the chamber

Table 14.12 Operating pressures with hydromechanical deep drawing

Material	Al and Al alloys	deep drawing steel St 13, St 14	high-alloy steels e.g. stainless steels
Operating pressure p in bar	60 – 300	200 – 700	300 – 1000

14.14.5 Blank holder force (Siebel's method)

1. Blank holder pressure p

$$p = 2 \cdot 10^3 \left[(\beta_{\text{actual}} - 1)^2 + \frac{D}{200 \cdot s} \right] \cdot R_m$$

2. Blank holder force

$$F_{\text{BH}} = A_{\text{BH}} \cdot p$$

F_{BH}	in N	blank holder force
p	in N/mm ²	blank holder pressure
R_m	in N/mm ²	tensile strength
D	in mm	diameter of the blank
s	in mm	sheet thickness
A_{BH}	in mm ²	effective blank holder area
β_{actual}	–	actual draw ratio

14.15 Sheet hydroforming (external, high-pressure hydroforming)

14.15.1 Definition

In sheet hydroforming, a smooth large-area section of sheet is pressed onto a water chamber by a specially-designed blank holder and clamped down. Then pressure is applied with the processing medium, which makes the sheet bulge out in the opposite direction to that of the actual forming. The whole area of the component is shaped evenly, with accompanying work hardening. In this way, dent resistance can be considerably improved, especially for flat automobile industry components with a large surface area, such as doors and bonnets. This basic principle is also used in the active HDD process.

14.15.2 Principle of the operation in diagrams

Figure 14.33 shows the four steps. After the blank has been inserted, the tooling is closed and the blank holder force is applied. Next, the pressure from the processing medium can be applied to produce pre-bulging, with bulging against the punch movement and stretching of the stock. After this, the drawing punch carries out the deformation against the pressure of the processing medium, and the sheet stock comes up against the surface of the punch. Finally, with maximum blank holder pressure, the component is calibrated to deliberately raise the fluid pressure to a particular upper limiting value.

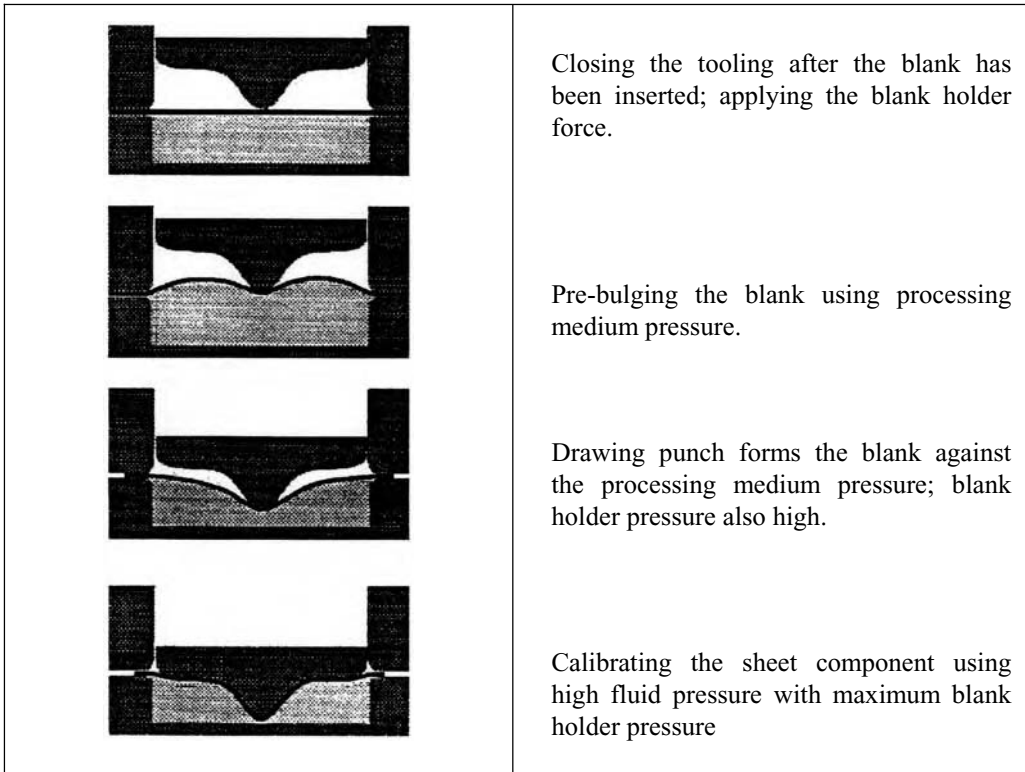
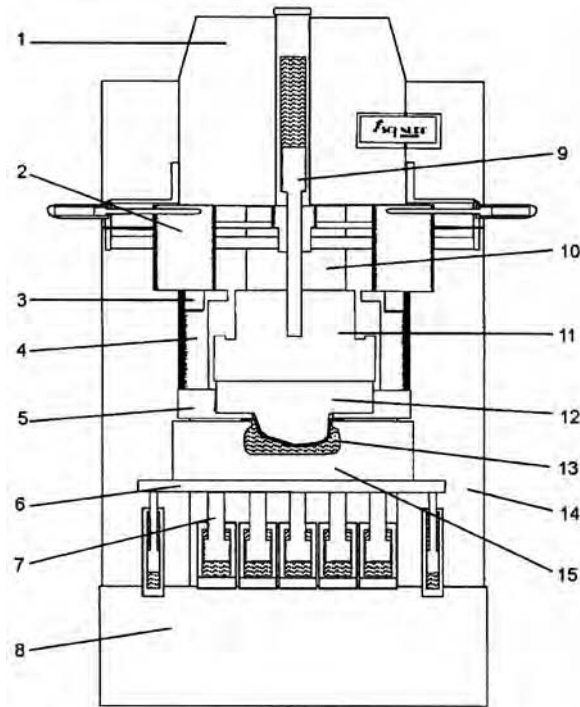


Figure 14.33 The principle of sheet hydroforming (Audi AG, Institute of Forming and Casting at Munich Technical University, Schnupp Hydraulik)

The press developed for sheet hydroforming stands out for its compact construction. It is made up of upper and lower beams, which are connected by four columns and pre-stressed by a tie rod. Both the blank holder and the ram are fixed mechanically with locking bars and the forming pressure is generated by a stack of 10×10 press-closing cylinders under the table. These cylinders are divided into two closed loops and can be run in six groups, meaning that a controlled press closing force can be applied even with asymmetrical components.

In Figure 14.34 there is a schematic diagram, a photograph of the press is shown in Figure 14.35.

**Figure 14.34**

The principle of a sheet hydroforming press (Schnupp Hydraulik)

- 1 upper beam
- 2 blank holder bar
- 3 blank holder cylinder
- 4 blank holder
- 5 blank holder ring
- 6 table
- 7 table-closing cylinder
- 8 lower beam
- 9 ram cylinder
- 10 ram bar
- 11 ram
- 12 punch
- 13 blank
- 14 column
- 15 water chamber

The technical specifications for the Schnupp press system used for the sheet hydroforming process, tube hydroforming and conventional deep drawing are as follows:

Forces:	press closing force	32,000 kN
	ram force	1,500 kN
	blank holder force	6,500 kN
Stroke height:	ram cylinder	1,150 mm
	blank holder cylinder	150 mm
	closing cylinder	
Pressure booster:	water pressure	max. 3000 bar
Installation space for tooling:		1,600 × 2,500 × 1,300/mm/
Press dimensions:		3,500 × 3,000 × 6,800 /mm/

Compared with conventional press technology, the sheet hydroforming press in particular stands out for its:

- precise positioning of the punch against the water chamber,
- high reproducibility,
- localised regulation of blank holder forces,
- no transverse forces on the press guides,
- good cost-performance ratio.



Figure 14.35 Schnupp sheet hydroforming press at the AUDI AG company
(Photograph from Schnupp GmbH & Co Hydraulik works, 94327 Bogen, Germany)

14.15.3 Application of the process

Sheet hydroforming is used to some advantage with large-area, relatively flat components of automotive body shells. The stretching (shaping) which can be carried out in the pre-bulging process produces considerable advantages compared with conventional drawing. Figure 14.36 shows the tool set, consisting of a punch, blank holder and water chamber, for the “creative door”, a joint project run by the AUDI AG company, the Institute of Forming and Casting at Munich Technical University, and the Schnupp Hydraulik company.

After hard work on theory and and experiments, they managed to determine the range of parameters necessary to produce sound parts, from a variety of possible combinations of parameters, such as the wiring of the table-closing cylinders, the blank holder forces, the path of the fluid pressure curves, the deformation pressure, the pre-bulging height, the pre-bulging pressure and the calibrating pressure. As a result, workpieces from different materials and sheet thicknesses can be produced with this toolset. Similar results have been announced by the Japanese firm Toyota as well as by Ford.

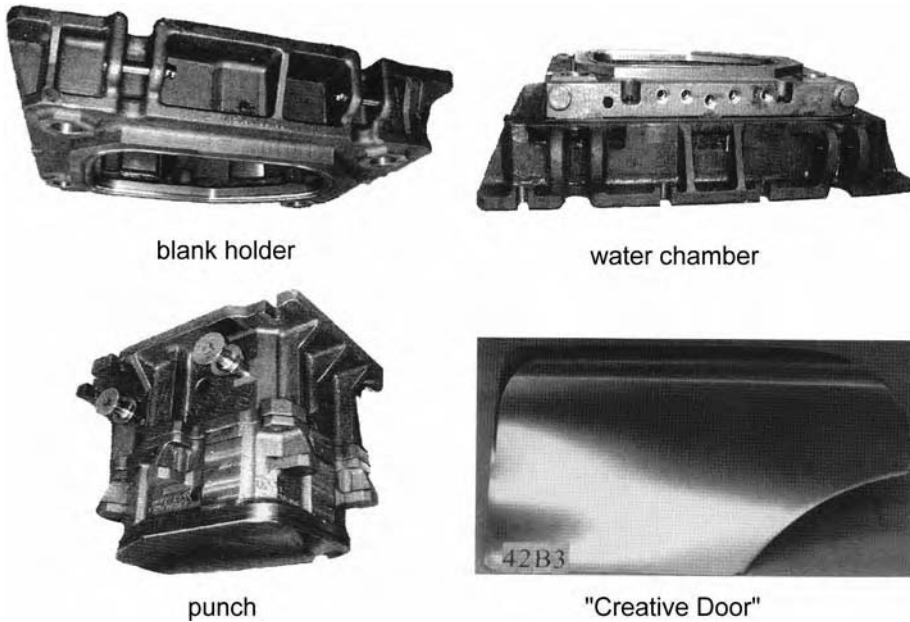


Figure 14.36 Toolset and workpiece for sheet hydroforming
(Photographs from AUDI AG works, Institute of Forming and Casting at Munich Technical University)

14.15.4 Evaluation of sheet hydroforming from the point of view of technology and cost-effectiveness

Apart from the advantages mentioned in point 14.14.2, sheet hydroforming also involves:

- higher dent resistance and stability of components;
- better surface quality of external shell, as no contact with metal tool elements, unlike in conventional drawing;
- considerably higher stretching results (shaping quality) compared with the conventional process.

What must also be taken into consideration in the economic evaluation are the longer cycle length, the slightly higher material consumption and the preparation and finishing steps which must be carried out with sheet hydroforming technology (generally laser cutting). Studies from the Massachusetts Institute of Technology (MIT) show that for up to 60,000 workpieces per year, sheet hydroforming is more cost-effective than conventional drawing technology. Compared with conventional technology, savings of up to 40% can be made in the main cost factor, tooling. For this reason, typical applications it can be used for are shell components for automotive niche products in small to very small lots, all the way up to customising mass-produced automobiles (e.g. long versions), as well as special components which are hard to draw, such as the fuel tank.

14.16 Tube hydroforming (internal high-pressure forming, IHF)

14.16.1 Definition

In tube hydroforming, tubular starting stock, which may already be pre-bent, is generally used to produce complicated hollow parts in a cold forming process, using high internal pressure applied with a processing medium and simultaneous axial or radial compression. Initial studies have also been published on forming flat, round blanks (with or without welding) into complicated hollow parts by internal pressure.

14.16.2 Principle of the process in diagrams

Figure 14.37 shows the principle of the process from the example of producing a pipe fitting. Although the principle of the process has been known for some time and has been the subject of scientific studies, the breakthrough into industrial use took place only after developments in high-pressure hydraulics, control and regulation technology, press and tooling technology and the use of the IHF process for automobile industry components.

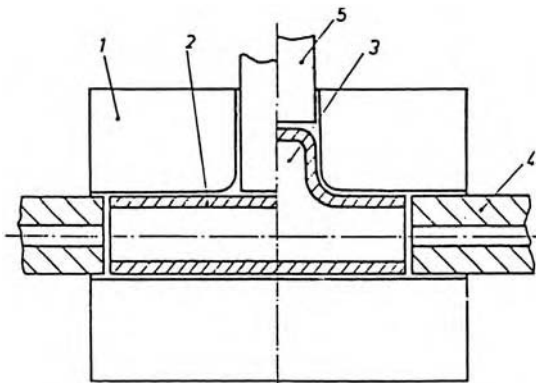


Figure 14.37 The principle of IHF
(Source: dissertation by R. Zschechel, Dresden Technical University, 1977)

The tubular starting stock 2 is inserted into the die 1, the die is closed and held shut with high pressure. The axial punches 4 seal off the tube ends, the processing medium 3 is introduced into the component through a bore-hole in the punches and the high internal pressure expands the tube, with the punches simultaneously feeding in the tube slightly. A pressure pad 5 limits the flow of material at the forming aperture for the T shape.

After internal high-pressure forming, the die is opened and the finished workpiece can be removed.

To control the process, the internal pressure of the processing medium and the end feed force for the axial punches must be precisely co-ordinated.

Two typical defects occur, if

- 1) internal pressure is too high, i.e. material stretched too much due to tensile stresses, forming cracking (“bursting”);
- 2) axial force is too high, leading to irreversible wrinkling.

The process must be controlled precisely to ensure that the reduction in wall thickness caused by the internal pressure does not become critical during forming, by using the axial punch to end feed material; on the other hand, the axial force must be limited to avoid undesired wrinkling or kinks. For this reason, fuzzy control systems for tube hydroforming have become popular in practice as well as the use of FEM simulations in preparing for internal high-pressure processes.

As well as providing forming force, the axial punches also serve to seal off the contact areas between the front of the punch and the front of the hydroformed component, enabling the processing medium to generate the correct internal pressure. Both force-closed and force-form-closed versions are in use, i.e. as well as conical seals, knife-edged seals and O-ring seals are also used.

One important process factor is the required press closing force, to ensure that the upper and lower die remain tightly closed when the internal sizing pressure, which can reach 7000 bar, is applied in the last phase of the process. The required closing force can be roughly calculated from the following aspects:

$$F_{\text{closing}} = A_{\text{proj}} \times p_i$$

A_{proj} – the surface of the hydroformed component projected onto the parting line

p_i – internal pressure required for sizing /N/mm²/

$$p_i \sim 1.5 \times p_{\text{burst}}$$

p_{burst} – bursting pressure /N/mm²/

$$p_{\text{burst}} = 2 \times R_m \times s_0 / d_0 - s_0$$

R_m – tensile strength /N/mm²/

s_0 – initial sheet thickness /mm/

d_0 – diameter of tube at start /mm/

14.16.3 Application of the process

The method enables the manufacturing of high-strength components with complex geometries, which help to improve cost-efficient production in widely-varying fields of application, as substantial reductions can be made on individual components and impressive reductions on mass-produced parts are possible.

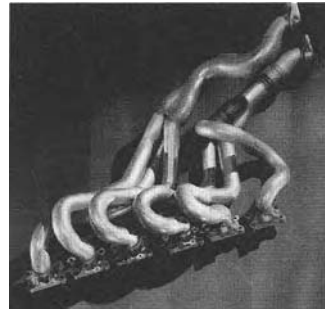
Some typical examples of application are

- parts for the plumbing and electrical industries (tube bends, T shapes, bushings, casings, etc);
- parts for the automotive industry and automotive supply industry (bends, stretchers, longitudinal beams, joints, frames etc.);
- parts for the tube and pipe industry (tube bends, crosspieces etc.).

Some examples are provided in the following pictures.



A



B

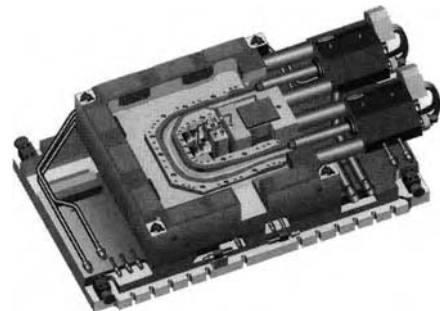


C

Figure 14.38 Examples of tube hydroforming (A – tube fittings; B – exhaust system for six-cylinder BMW M3; C – roll bar for Porsche Boxster (Photographs from Schuler Hydroforming GmbH & Co. KG works)



A



B

Figure 14.39 Example of a hydroformed structured part and schematic diagram of a tube hydroforming die (A – integral automobile engine mount (NAFTA region) (manufactured on 50,000-kN tube hydroforming unit); B – schematic diagram of a tube hydroforming die (lower die) for automobile engine mounts incl. axial forming cylinder) (Source: Siempelkamp Pressen Systeme, Krefeld, Germany)

Presses for tube hydroforming are often designed as four-pillar presses, to ensure easy access from all sides. The tooling dimensions, the position of the horizontal cylinder, the number of controlled hydraulic axles, the processing medium system and last but not least the closing force required for the particular press design are all designed specially for tube hydroforming, i.e. tailored to fit the range of workpieces planned for.

Figure 14.40, for example, shows a tube hydroforming press with 50,000 kN closing force for forming large-area hydroformed parts.



Figure 14.40 50,000-kN tube hydroforming press at the Fraunhofer Institute for Machine Tools and Forming Technology in Chemnitz (Photograph: Schuler Hydroforming GmbH & Co. KG works)

To produce hydroformed parts of the very precise shape and size required, achieved by the high internal pressure at the end of the process (sizing pressure), the tube hydroforming tooling must meet very high standards.

Figure 14.41 shows a tube hydroforming die used to produce elements for exhaust manifolds.

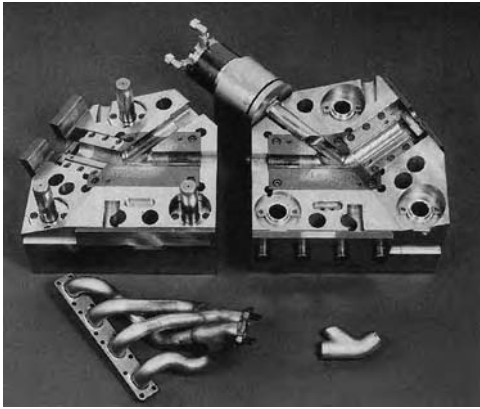


Figure 14.41
 Tube hydroforming die for exhaust manifolds
 (photograph from Schuler Hydroforming GmbH & Co. KG works)

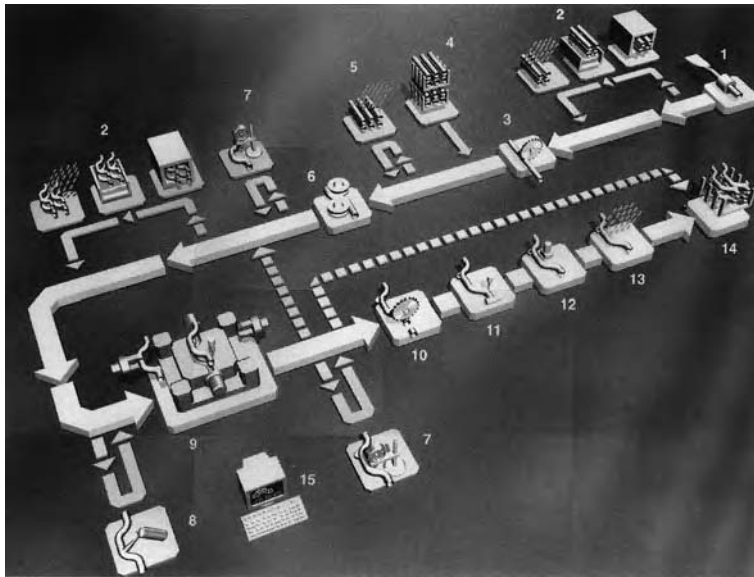


Figure 14.42 Schematic diagram of a full tube hydroforming unit (source: Siempelkamp Pressen Systeme, Krefeld, Germany)

- | | | |
|------------------------------|---------------------------------|------------------------|
| 1 Production of semis | 8 applying lubricant | 10 sawing |
| 2 heat and surface treatment | 9 feed-in | 11 punching; finishing |
| 3 trimming | pre-forming | 12 marking |
| 4 storage | forming | 13 cleaning |
| 5 washing | punching | 14 packing |
| 6 bending, pre-forming | removal | 15 process control |
| 7 checking, handling | preparing the processing medium | |

The disadvantage of the sometimes relatively long cycle compared with competing processes, which affects the number of parts which can be produced economically, is often balanced out by the superior qualities of the tube hydroformed components. The cost-effective production of IHF parts is only possible when the process is seen as a whole, from the pre-treatment of the starting stock, to heat and surface treatment, up to finishing.

Figure 14.42 shows an example of a complete tube hydroforming unit.

14.16.3 Advantages of tube hydroforming

The crucial advantages of tube hydroforming are:

- the production of complicated components which could previously only be produced from several separate parts,
- very precise sizing and shaping of components,
- increase in strength due to work hardening,
- low weight with optimum strength,
- high rigidity,
- high fatigue strength,
- fewer welding joints for complex components,
- low flow resistance (exhaust systems).

14.17 Exercise on Chapter 14

1. What kind of forming process is deep drawing?
2. Name typical workpieces which are produced using this process.
3. What are “characteristic triangles” and how are they formed?
4. Why can it be assumed that the surface of the workpiece and blank is equal when determining the blank dimensions?
5. Name the most important elements of deep drawing tooling.
6. How is the drawing tooling for the first draw different to that for the second draw?
7. What happens when the blank holder pressure is too low and what happens when it is too high?
8. Name the most important advantages of sheet hydroforming.
9. What main areas of application for sheet hydroforming do you know? Name their economic limits.
10. Explain the principle of the tube hydroforming (IHF) process.
11. Name typical workpieces which are produced using these processes.
12. How can the process factor of closing force be roughly calculated?
13. Name the most important advantages of tube hydroforming (IHF).
14. What typical defects occur with tube hydroforming?

15 Deep drawing without a blank holder; metal spinning

15.1 Deep drawing without a blank holder

When deep drawing without a blank holder, the die assembly is simpler as the blank holder is not used. What is more, deep drawing without a blank holder can be carried out on any single-action press.

15.1.1 Deep drawing limits without a blank holder

The permissible limits for the deep drawing steels St 12 – St 14 are around:

Table 15.1 Permissible drawing ratios

Draw→	1st draw	2nd draw
$\beta_{\text{perm}} = \frac{D}{d}$	< 1.8	< 1.2
D/s	< 58	< 60

15.1.2 Deep drawing die shape when deep drawing without a blank holder

The optimum drawing ratios which can be achieved are with a drawing die whose curve is an involute (Figure 15.1b).

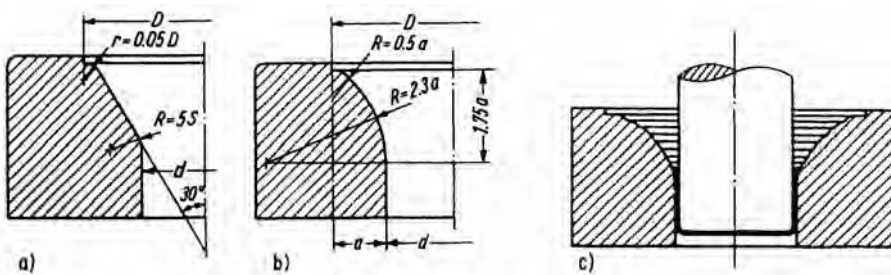


Figure 15.1 Shapes of the drawing die when deep drawing without a blank holder

Drawing dies of *c* shape have also proved themselves, as the lubricant adheres well. However, they are more expensive to manufacture.

The *a* shape conical drawing die, with a 60° cone angle (Figures 15.1a and 15.2) is the most useful drawing die. It is easy to produce and can achieve maximum drawing ratios.

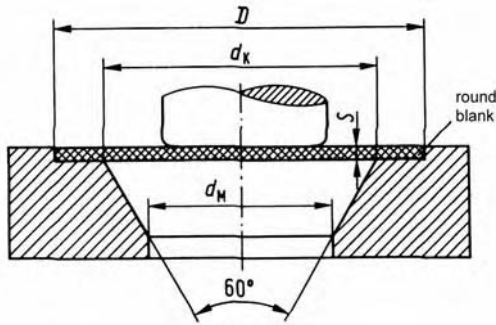


Figure 15.2
Conical deep drawing die

Table 15.2 Permissible drawing ratios depending on d_M/d_K for $D/s = 40$

d_M/d_K	0.6	0.7	0.8
β_{perm}	1.9	1.6	1.5

The lower the quotient of d_M by d_K (mean values are around 0.6 – 0.8), the higher the permissible drawing ratio is.

15.1.3 Calculation of force and mechanical work

The calculation of force and mechanical work is carried out as shown in Chapter 14.7.1 and 14.9.

15.1.4 Exercises on Chapter 15:

1. What are the advantages of this process?
2. What are the limits of its application?

15.2 Metal spinning

15.2.1 Definition

Metal spinning is when tensile and compressive forces are used to form pre-cut, round sections of sheet or hollow blanks into axisymmetric (rotationally symmetric) hollow parts with various kinds of outlines. This is done with roller tools which indent points, or occasionally lines, on workpieces which are generally rotating. There is no intention to change the thickness of the sheet.

The shear and tube spinning processes, often used in conjunction with spinning, are processes for producing rotationally symmetric hollow parts, with a change in the wall thickness intended.

15.2.2 Application of the process

The spinning process can boast a long historical development. In spinning, the rotating sheet metal blank is gradually fed against the spinning mandrel, the opposing tool which provides the shape, by controlled pressure from a spinning tool. Today, easily formable materials for handcrafts and art purposes are still spun manually. There has been a huge upswing in the industrial use of the process since the introduction of modern CNC machines. The low tooling costs compared to deep drawing and the high flexibility when CN controls are used are only some of the factors responsible for this.

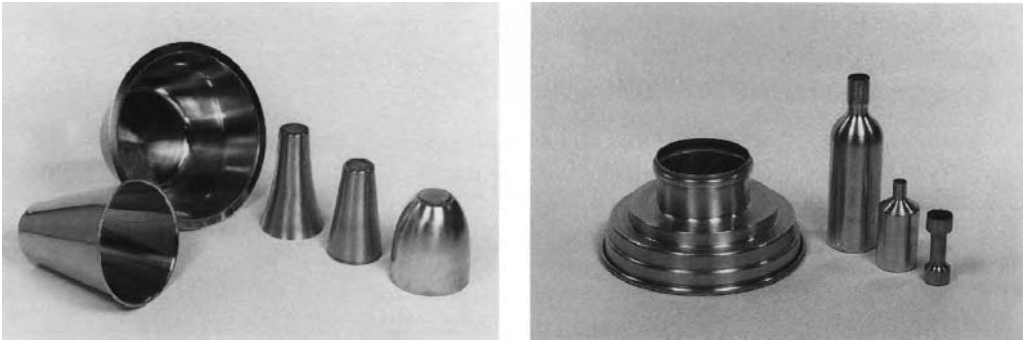


Figure 15.3 Spun shells (Photographs from the hdm-Metalldrückmaschinen GmbH works, Ahlen, Germany)

15.2.3 Description of the process

As in deep drawing, tangential compressive stresses and radial tensile stresses occur in the deformation zone, which is highly localised.

The movement of the tools along the surface of the workpiece created is carried out manually or is mechanised, using a template device or CNC.

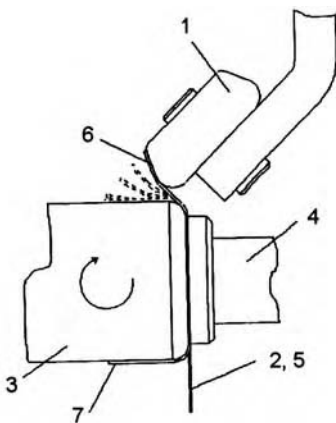


Figure 15.4 The principle of spinning

- 1 spinning roller
- 2 round blank
- 3 spinning mandrel
- 4 tailstock
- 5 initial state
- 6 intermediate state
- 7 final state

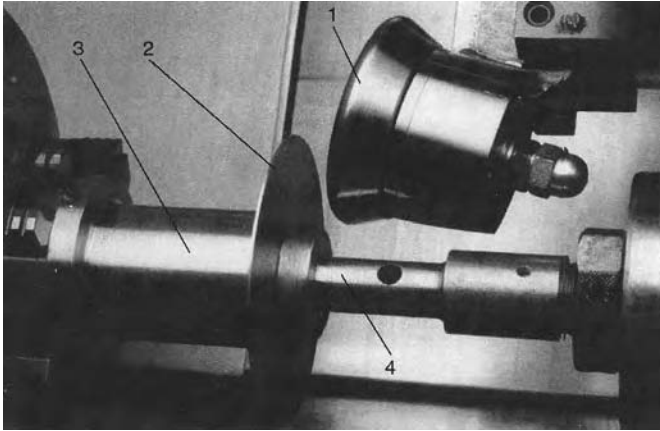


Figure 15.5 Experimental set-up for CNC spinning on a turning lathe (Dresden University of Applied Sciences, Germany; photographer: Sebb) (1 – spinning roller, 2 – blank, 3 – spinning mandrel 4 – tailstock)

For simple parts, the movements of the spinning roller can be easily adapted to suit each workpiece shape using the CNC program. In the following example, carried out on the experimental equipment in Figure 15.5, the photographs depict the steps required to gradually feed the sheet material onto the spinning mandrel.

In industrial practice, the spinning machines generally used have a “playback” system, i.e. the feed movements of the spinning rollers are carried out on the machine without a workpiece by an experienced operator using a joystick; these movements are saved in the CNC system. The saved feed movements can then also be edited on a graphic interface.

Figure 15.7 shows a high-performance spinning machine with an MC 2000 playback control system based on a Siemens SINUMERIK CNC system of type 840D.

The machine stands out for the high repeatability of the saved values starting at 0.001 mm, features fully automatic contour measurement by means of a specially-developed sensor head scanning process, and can take up to eight tools. Figure 15.8 shows the working area.

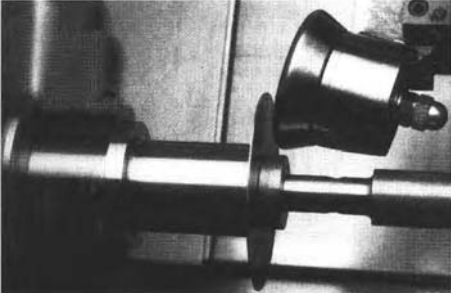
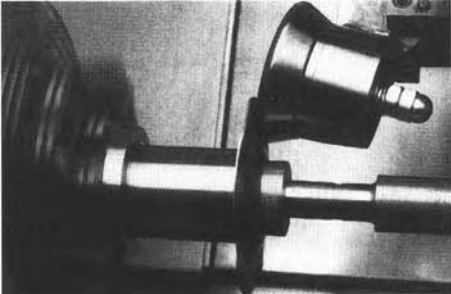
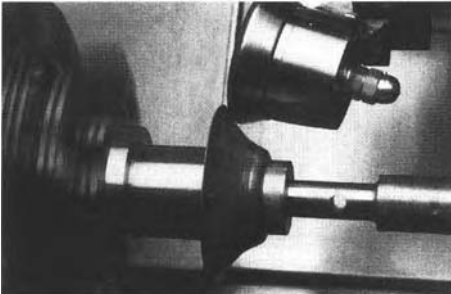
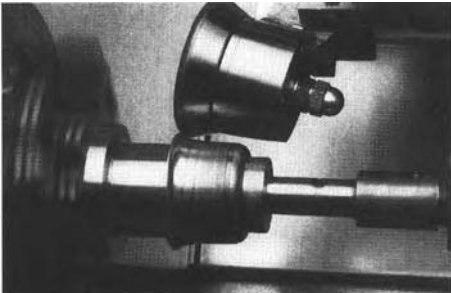
Spinning process steps	Photographs of the spinning process
<p>Initial state: The round blank is clamped tight by the tail-stock. The spinning roller is in the starting position.</p>	
<p>Intermediate state 1: The blank rotates with a rotation speed of 1000 rpm and the spinning roller starts to form the blank. Wrinkling occurs due to the tangential compressive stresses</p>	
<p>Intermediate state 2: The material is gradually fed onto the mandrel by the controlled movement of the roller. The wrinkles are removed by being rolled over.</p>	
<p>Final state: A cup with flange is produced.</p>	

Figure 15.6 Spinning process steps (photographer: Sebb, Dresden University of Applied Sciences, Germany)



Figure 15.7 High-performance hdm 45/90 spinning machine (Photograph: hdm-Metalldrückmaschinen GmbH works, Ahlen, Germany)

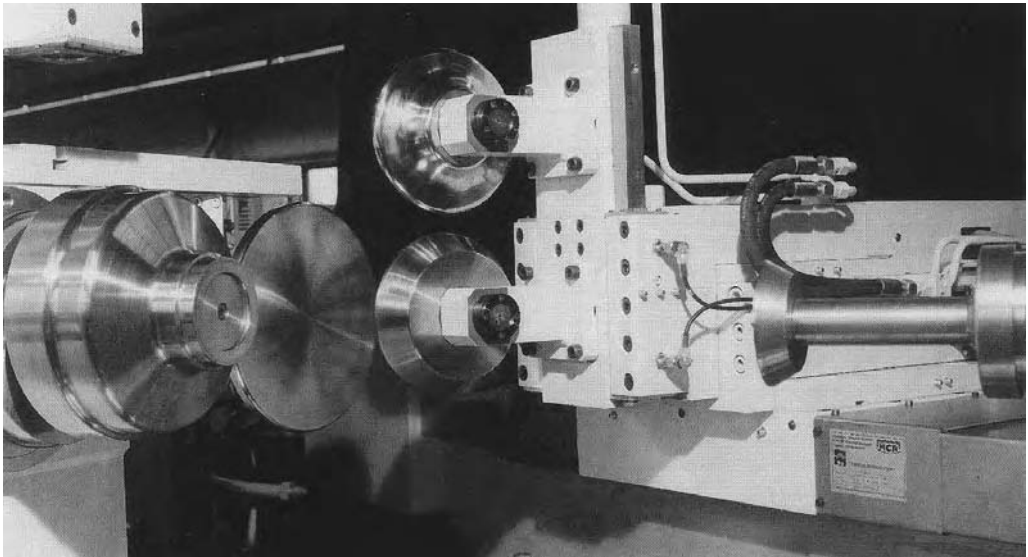


Figure 15.8 Working area of the HDM 45/90 (Photograph: hdm-Metalldrückmaschinen GmbH works, Ahlen, Germany)

15.2.4 Limits of spinning

Similarly to deep drawing, the spinning ratio β is calculated from the blank diameter D and the spinning mandrel diameter d as follows:

$$\beta = D/d$$

Depending upon the material to be formed, the maximum spinning ratios in the following table can be achieved (without annealing).

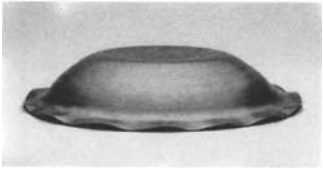

Table 15.3 Maximum spinning ratio β_{\max}


Material	β_{\max}	Material	β_{\max}
Structural steel sheet	1.40	Al and Al alloys	1.55
Deep drawing steel sheet	2.00	Cu and Cu alloys	2.00
High-alloy steel sheet	1.27	Ni	1.27

15.2.5 Defects during spinning

Defects during spinning result on one hand from the particular process and on the other from failing to comply with the optimal technological parameters, as can be seen from the following table.

Table 15.4 Typical defects during spinning (Photographer: Sebb, Dresden University of Applied Sciences, Germany)

Defect	Photograph	Cause	Corrective action
Buckling of the flange due to the formation of waves and wrinkles		<ul style="list-style-type: none"> – Compressive stresses – Spinning ratio β too high – Feed too fast 	<ul style="list-style-type: none"> – β Reduce β – Reduce speed of feed
Radial cracks on the outer area of the cup		<ul style="list-style-type: none"> – Bend fatigue strength of the material exceeded by constant removal of wrinkles 	<ul style="list-style-type: none"> – β Reduce β – Raise feed speed

Cracks in a tangential direction at the junction of the flange and the wall		<ul style="list-style-type: none"> - Tensile stresses - Change from one step to next too high 	<ul style="list-style-type: none"> - Reduce difference between steps
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15.2.6 Comparison of the economic efficiency of spinning hollow parts and deep drawing

Table 15.5 lists a qualitative comparison of the processes of spinning hollow parts and deep drawing, both from the point of view of engineering and of economics.

Table 15.5 Comparison of deep drawing and spinning

	Deep drawing	Spinning
Workpiece shape	<ul style="list-style-type: none"> • nearly any 	<ul style="list-style-type: none"> • only rotationally symmetric
Properties of the workpieces; material used	<ul style="list-style-type: none"> • good surfaces • low to medium tolerances • sheet steel of drawing quality • nonferrous sheet 	<ul style="list-style-type: none"> • bright surfaces • low tolerances • steel sheet may be of lower quality • nonferrous sheet
Tooling and machines	<ul style="list-style-type: none"> • One tool set required per step • hydraulic or mechanical presses • generally multi-step process 	<ul style="list-style-type: none"> • simpler tooling • (universal spinning rollers and spinning mandrels adapted to the workpiece shape) • spinning machines, for simple parts also on turning lathes • single- or multi-step process
Unit costs	<ul style="list-style-type: none"> • low 	<ul style="list-style-type: none"> • higher
Unit times	<ul style="list-style-type: none"> • low – mass production 	<ul style="list-style-type: none"> • medium – manufacture of single parts or lots
Preparation time	<ul style="list-style-type: none"> • medium – high, according to the amount of automation 	<ul style="list-style-type: none"> • low
Cost-efficient unit quantities	<ul style="list-style-type: none"> • very high 	<ul style="list-style-type: none"> • cost-efficient manufacture from smaller lots to single parts (large diameter) • unrivalled for very large diameters (parabolic mirrors, aircraft parts)

15.3 Exercise

1. Compare the limits and possibilities of the deep drawing and spinning processes in producing different numbers of rotationally symmetric hollow parts in various sizes.
2. What stress conditions are there during spinning?
3. How is the spinning ratio calculated and what limits it?
4. Name typical defects and their causes during spinning.

15.4 Incremental sheet forming

Incremental sheet forming is an example of the latest innovation in the field of flexible sheet metal forming. This technology allows prototypes or small lots to be manufactured from steel, stainless steel and aluminium directly from a 3D CAD model without using conventional tools, expanding the possibilities of spinning to include non-rotationally symmetric parts.

15.4.1 Definition

Incremental sheet forming is a form of stretch drawing as concerns stresses, and partly a form of spinning. The cyclical, localised deformation is characteristic for the process, with the final form created entirely from the original sheet thickness.

15.4.2 Description of the process

The deformation takes place incrementally by moving a simple, universal CNC-controlled indenter. The sheet being formed is held in a clamping device on the machine used. During forming, the indenter moves along the X and Y co-ordinates of the contour at the programmed level; when each level is completed it is moved by small amounts in the Z direction. At the same time, the indenter can be moved slightly around its axis and the geometry of the product is gradually formed. There are various approaches to carrying out the process; for example, during processing the sheet metal may be supported by a second, full die or a partly active male die (Amino company, Japan), formed with a second, controlled indenter or with no other tool, as in the photograph. To reduce friction and improve the surface of the workpiece, a liquid lubricant is used.



Figure 15.9 Test facility in Hermle C 500 V HSC milling machine



Figure 15.10 Workpiece (sized-down bathtub) (Photograph HTW Dresden)

15.4.3 Application of the process

The process is particularly suitable for manufacturing prototypes (design verification) and small lots, as tooling costs are considerably lower than with deep drawing and new designs can be produced straight from 3D CAD. However, series of identical components such as those produced with deep drawing can not be produced using this process. Special machines made by the Japanese firm Amino are available on the market which can be used to manufacture very complex components with dimensions up to 2 m x 6 m. The automobile industry and many other fields of application are open to these prototypes, as far higher degrees of deformation can be achieved than with deep drawing, and at the same time their mechanical properties are good and their surfaces smoother. A more comprehensive description is reserved for the next edition of this textbook (see also: [http: www.htw-dresden.de/~manufact](http://www.htw-dresden.de/~manufact)).

16 Bending

16.1 Definition

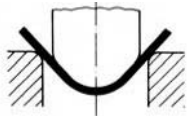
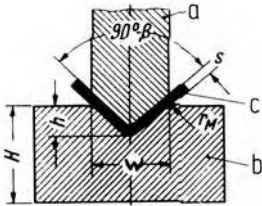
Bending is the forming of solid parts, where angled or ring-shaped workpieces are produced from sheet or strip metal. In bending, the plastic state is brought about by a bending load.

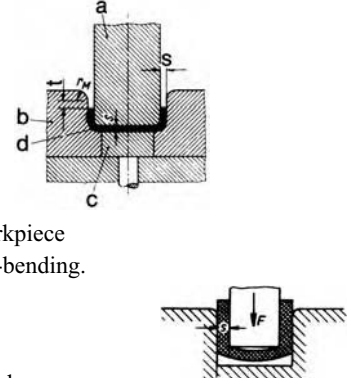
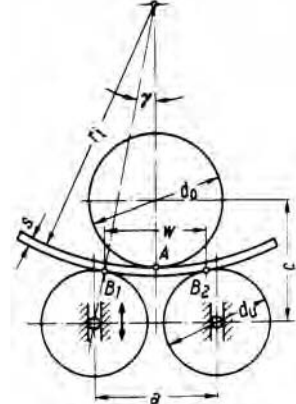
16.2 Application of the process

Bending is used as a sheet metal forming process to produce angled parts, sheet profiles, tubes and workpieces for shipbuilding and apparatus manufacturing. Apart from these parts, profile stock is also used to make rings for various fields of application.

16.3 The bending process

Table 16.1 The bending process

<p>1. <i>Air bending</i></p> <p>In air bending, the tooling, punch and die, are used only to convey energy. The workpiece rests on two points. The punch carries out the bending movement. A curvature sets in, growing in the centre. Air bending is used mainly to straighten workpieces.</p>	 <p>The principle of air bending</p>
<p>2. <i>Die bending (bottom bending)</i></p> <p>In die bending, the bending punch presses the workpiece into the bending die. The deformation ends with a localized compressive stress in the die (bottoming the punch). Here, a difference is made between V-bending and U-bending.</p> <p>2.1 <i>V-bending</i></p> <p>The bending punch and die are V-shaped. In the initial phase, air bending takes place, with the workpiece radius constantly changing. It is only when it reaches the last phase that the final form is imparted by bottoming the punch.</p>	 <p>Tooling and workpiece layout during V-bending.</p> <p>a) punch, b) bottom die, c) workpiece</p>

<p>2.2 U-bending</p> <p>In U-bending the workpiece is also given its final shape by bottoming the punch.</p> <p>In this case, to prevent the bottom from bulging out during bending, a backing pad is often used. During the bending process it already starts pressing against the bottom of the workpiece.</p>	 <p>Tooling and workpiece layout during U-bending.</p> <ul style="list-style-type: none"> a) punch, b) bottom die c) backing pad, d) workpiece
<p>3. Roll bending</p> <p>During roll bending, the bending moment is created by three rolls.</p> <p>The top roll can be moved around the angle γ and the height of both lower rolls can be adjusted. Both are driven by a motor. By adjusting the relative positions of the rolls, any diameters can be produced, with the smallest diameter limited by the size of the bending rolls and the largest diameter limited by the plasticity criterion.</p>	<p>The principle of roll bending with three rolls</p> 

16.4 Limits of bending deformation

16.4.1 Material stress

This varies within the cross-section of the bent part.

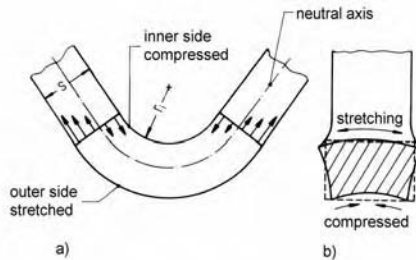


Figure 16.1 Material stress during bending, a) in the longitudinal direction, b) in the transverse direction, s is the sheet thickness.

- The *inner* side is *compressed* along the length of the workpiece, *stretched* across the direction of force.
- The *outer* side is *stretched* along the length of the workpiece, *compressed* across the workpiece.
- The *neutral* axis does not change in length. It is approximately in the centre, its position actually offset towards the small radius. It depends upon the thickness of the sheet, s , and the bend radius, r .

16.4.2 Die bending (bottom bending)

In die bending, the desired V- or U-shaped forms are produced with the most precision when enough pressure is applied in the die at the end of forming.

The smaller the bend radius r_1 (= punch radius), the better the accuracy of the included angle between the legs. However, the bend radius should not be smaller than $0.6 \cdot s$ and with harder materials it should be equal to the sheet thickness.

$$r_{1 \min} = s \cdot c$$

- $r_{1 \max}$ in mm smallest permissible bend radius
- s in mm sheet thickness
- c material coefficient from Table 16.2

The actual bend radius r_1 must be $\cong r_{1 \min}$.
For steel, $E = 2.1 \cdot 10^5 \text{ N/mm}^2$.

16.4.3 Roll bending

During roll bending, the limiting values of the bend radii arise from the plasticity criterion, and for the smallest radius they also come from the dimensions of the bending rolls.

$$r_{1 \max} = \frac{s \cdot E}{2 \cdot R_e}$$

- $r_{1 \max}$ in mm maximum bend radius
- E in N/mm^2 modulus of elasticity
- R_e in N/mm^2 yield strength
- s in mm sheet thickness

Table 16.2 Material coefficients c for die bending

Material	c values			
	soft annealed		hardened	
	Position of the bend axis relative to the rolling direction		Position of the bend axis relative to the rolling direction	
	transverse	longitudinal	transverse	longitudinal
Al	0.01	0.3	0.3	0.8
Cu	0.01	0.3	1.0	2.0
CuZn 37 (Ms 63)	0.01	0.3	0.4	0.8
St 13	0.01	0.4	0.4	0.8
C 15–C 25 St 37–St 42	0.1	0.5	0.5	1.0
C 35–C 45 St 50–St 70	0.3	0.8	0.8	1.5

16.5 Spring-back

In every bending operation spring-back occurs, i.e. there is a deviation from the planned bend angle.

The extent of the spring-back depends upon

elastic limit of the material formed

bending type (air bending or die bending)

bend radius (the smaller r is, the larger the plastic deformation zone is – and accordingly, the smaller the spring-back).

The result:

the bending dies are given a smaller angle than the finished part.

Correction of angle or bend radius

$$\beta = \gamma - \gamma^* \quad (\text{see Figure 16.2})$$

β in degrees spring-back angle
 s in mm sheet thickness
 γ^* in degrees actual angle

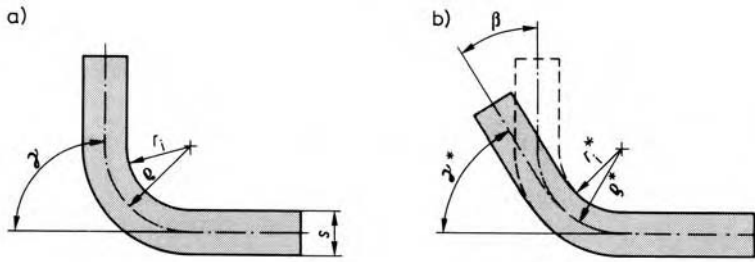


Figure 16.2 Spring-back of bent parts, a) before, b) after spring-back

Table 16.3 Spring-back angle $\beta = f(r_i, s)$ for St up to $R_m = 400 \text{ N/mm}^2$ and Ms up to $R_m = 300 \text{ N/mm}^2$

β in degrees	5	3	1
s in mm	0.1 to 0.7	0.8 to 1.9	2 to 4
r_i in mm	$1 \cdot s$ to $5 \cdot s$	$1 \cdot s$ to $5 \cdot s$	$1 \cdot s$ to $5 \cdot s$

16.6 Determining the blank length L

L = effective length,
= the sum of all straight and curved sections

$$L = l_1 + l_{cu} + l_2$$

L in mm effective length
 L_{cu} in mm length of the curve
 l_1 in mm length of the leg
 l_2 in mm length of the leg
 r_i in mm bend radius

$$L = l_1 + \frac{\pi \cdot \alpha}{180^\circ} \left(r_i + \frac{e \cdot s}{2} \right) + l_2$$

s in mm sheet thickness
 e correction value
 α in degrees bend angle

for $\alpha = 90^\circ$ then L is:

$$L = l_1 + 1.57 \left(r_i + \frac{e \cdot s}{2} \right) + l_2$$

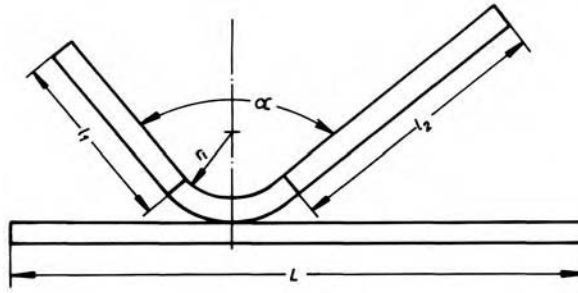


Figure 16.3 Measurements of the bent part for determining blank size

Table 16.4 Correction value $e = f(r_i/s)$

$\frac{r_i}{s}$	5.0	3.0	2.0	1.2	0.8	0.5
e	1.0	0.9	0.8	0.7	0.6	0.5

The correction value e takes into account the fact that the neutral axis is not exactly in the centre.

16.7 Bending force F_b

16.7.1 Bending in a V-shaped die

$$F_b = \frac{1.2 \cdot b \cdot s^2 \cdot R_m}{dw}$$

- F_b in N bending force
- w in mm width of the part
- s in mm thickness of the part
- R_m in N/mm² tensile strength
- dw in mm die width
- r_i in mm bend radius
- $r_{i \min}$ in mm smallest radius still permissible

$$l = 6 \cdot s$$

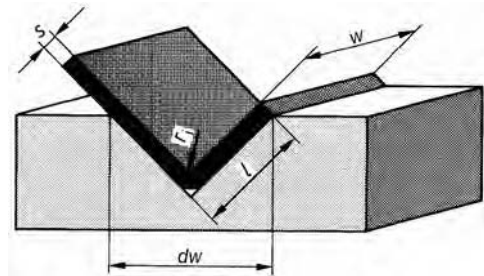


Figure 16.4 Size and shape of the V-shaped die

$$dw = 5 \cdot r_i$$

if $r_i > r_{i \min} \cong 2 \cdot s$ up to $5 \cdot s$

$$dw = 7 \cdot r_i$$

if $r_i = r_{i \min} \cong 1.3 \cdot s$

Bottoming force

$$F_{\text{bbot}} = n \cdot F_b$$

n	2	2	2.5	3.5
r_i/s	> 0.7	0.7	0.5	0.35

16.7.2 Bending in a U-shaped die

$$F_b = 0.4 \cdot s \cdot b \cdot R_m$$

Without backing pads in the die block.
For this reason the bottom bulges.

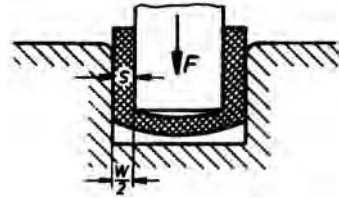


Figure 16.5 Bulging-out of the bottom during U-bending without a backing pad

16.7.3 Bending force for tooling with plate-shaped, spring-actuated ejector (backing pad)

$$F_{bT} \approx 1.25 \cdot F_b \quad F_{PP} = 0.25 \cdot F_b$$

$$F_{bT} = 0.5 \cdot s \cdot w \cdot R_m$$

- F_{bT} in N total bending force
- F_{PP} in N pressure pad force
- s in mm sheet thickness
- w in mm width of the bent part
- R_m in N/mm² tensile strength

The backing pad stops the bottom from bulging out.

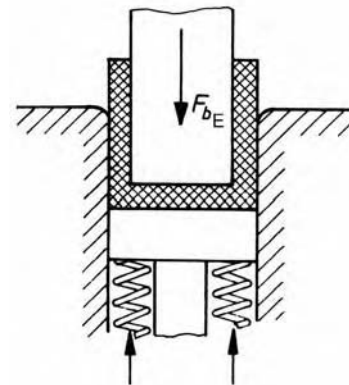


Figure 16.6 U-bending with a backing pad

16.7.4 Edge bending

$$F_b = 0.2 \cdot s \cdot w \cdot \sigma_B$$

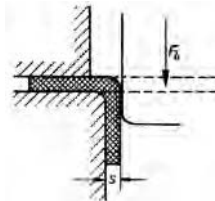


Figure 16.7 The principle of edge bending

16.7.5 Edge rolling

$$F_b = \frac{0.7 \cdot s^2 \cdot w \cdot R_m}{d_1}$$

d_i in mm external diameter of the roll

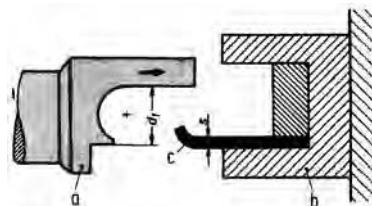


Figure 16.8 Tooling and workpiece during edge rolling. a) punch, b) die, c) workpiece

16.7.6 Collar forming

$$F_b = 0.7 \cdot s \cdot d_1 \cdot \delta \cdot R_m$$

$$d = D - 2(H - 0.43 \cdot r - 0.72 \cdot s)$$

$$H = \frac{D - d}{2} + 0.43 \cdot r + 0.72 \cdot s$$

F_b	in N	bending force
H	in mm	height of the collar, $H_{\max} \approx 0.12 \cdot d_1 + s$
D	in mm	mean collar diameter
s	in mm	sheet thickness
r	in mm	bend radius
d_1	in mm	bore diameter of the die, $d_1 \approx D + 0.3 \cdot s$
δ	in mm	hole opening value, $\delta = \frac{d_1 - d}{d_1}$
d	in mm	diameter of the punched-out hole
R_m	in N/mm ²	tensile strength

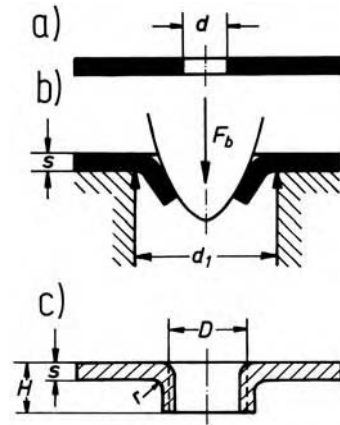


Figure 16.9 The principle of collar forming,
 a) workpiece before,
 b) during,
 c) after forming

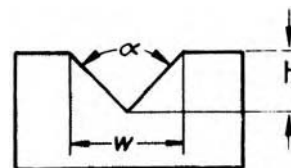
16.8 Bending work W

16.8.1 V-bending

$$W = x \cdot F_b \cdot h \quad \text{In general}$$

W	in N m	Bending work
x		process factor, $x = \frac{1}{3}$
F_b	in N	bending force
h	in m	punch displacement

$$W = \frac{1}{3} \cdot F_b \cdot h$$



16.8.2 U-bending

without a spring-actuated pressure pad (no final bottoming the punch)

$$W = x \cdot F_b \cdot h$$

W in N m	bending work
x	process factor; $x = \frac{2}{3}$
F_b in N	bending force
h in m	punch displacement; $h = 4 \cdot s$

$$W = 1.06 \cdot s^2 \cdot b \cdot R_m$$

W in N m	bending work
s in mm	sheet thickness
b in m	width of the bent part
R_m in N/mm ²	tensile strength

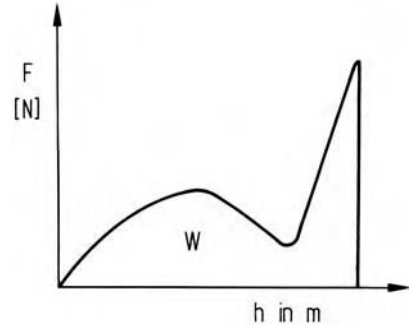


Figure 16.10 Force-displacement diagram

with sprung pressure pad

$$W = (x \cdot F_b + F_{PP}) \cdot h$$

W in N m	bending work
x	process factor; $x = \frac{2}{3}$
F_b in N	bending force
F_{PP} in N	pressure pad force;
$F_{PP} = 0.25 F_b$	
h in m	punch displacement; $h = 4 \cdot s$

$$W = 2.4 \cdot s^2 \cdot w \cdot R_m$$

W in N m	bending work
s in mm	sheet thickness
w in m	width of the bent part
R_m in N/mm ²	tensile strength

16.9 Bending tooling

16.9.1 V-shaped die

This assembly consists of:

punch and die (Figure 16.11)

die radius r_m

$$r_m = 2.5 \cdot s$$

r_m in mm die radius (mean value)

s in mm sheet thickness

curvature in die recess R

$$R = 0.7 (r + s)$$

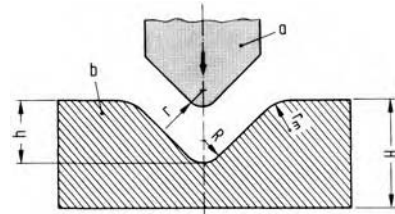


Figure 16.11 Constructional dimensions of a V-shaped die. a) punch, b) die

Table 16.5 Depth of the bottom die cavity h in mm

h	4	7	11	15	18	22	25	28
s	1	2	3	4	5	6	7	8
H	20	30	40	45	55	65	70	80

h in mm depth of the recess

s in mm sheet thickness

H in mm height of the bottom die

16.9.2 U-shaped die

This assembly consists of:

punch, die and sprung base.

Die radius r_m

$$r_m = 2.5 \cdot s$$

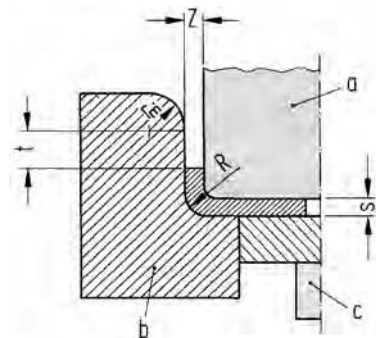


Figure 16.12 Constructional dimensions of a U-shaped die

Table 16.6 Size of t (space between die curvatures)

t	3	4	5	6	8	10	15	20	t in mm
s	1	2	3	4	5	6	7	8	s in mm

Width of gap Z in mm

$$Z_{\max} = s_{\max}$$

$$Z_{\min} = s_{\max} - s \cdot$$

s_{\max} in mm max. sheet thickness n

Table 16.7 n for side lengths of < 25 to 100 mm

n	0.15	0.10	0.10	0.08	0.08	0.07	0.07	0.06
s	1	2	3	4	5	6	7	8

s in mm sheet thickness

Curvature in die impression C

$$C = 0.7 (r + s)$$

or $C = 0$

Table 16.8 Tooling materials

Material no.	Designation	Assembly hardness HRC	Punch	Bottom die
1.1550	C 110 W 1	60	×	×
1.2056	90 Cr 3	64	×	×
1.2842	90 Mn V 8	62	×	×

16.10 Bending defects

Not all sheet metals are suited to bending, so the right choice of stock is extremely important. Suitability for producing a particular bent part can be determined by experimental bending and folding. As far as the tooling allows, the grain flow should be transverse to the bending edge. The bending edge and the grain direction should only be in the same direction in exceptional cases. The most common bending defect is material cracking at the outside edge (Figure 16.13).

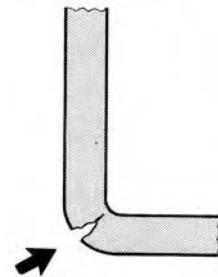


Figure 16.13 Bent part cracked on the outside edge

16.11 Example

The aim is to manufacture angled parts as in Figure 16.3 whose width $w = 35$ mm, sheet thickness $s = 2$ mm, lengths of the legs $l_1 = 20$ mm and $l_2 = 30$ mm with an inner bend radius $r_1 = 10$ mm and a bend angle of $\alpha = 90^\circ$, from the material St 1303 (soft annealed). The bend axis is transverse to the rolling direction.

$$R_m = 400 \text{ N/mm}^2, R_e = 280 \text{ N/mm}^2, A_{10} = 25 \%, E = 210\,000 \text{ N/mm}^2$$

Find:

1. Length of blank
2. Smallest permissible bend radius $r_{i \min}$
3. Die width dw
4. Bending force
5. Bending work

Solution:

$$1. \quad L = l_1 + \frac{\pi \cdot \alpha}{180^\circ} \left(r_1 + \frac{e \cdot s}{2} \right) + l_2$$

$$= 20 \text{ mm} + \frac{\pi \cdot 90^\circ}{180^\circ} \left(10 \text{ mm} + \frac{1 \cdot 2 \text{ mm}}{2} \right) + 30 \text{ mm} = 67.27 \text{ mm}$$

$$2. \quad r_{i \min} = c \cdot s = 0.01 \cdot 2 \text{ mm} = 0.02 \text{ mm} \quad c \text{ from Table 16.2}$$

$$r_{i \text{ actual}} > r_{i \min}$$

$$3. \quad dw = 5 \cdot r_1 = 5 \cdot 10 \text{ mm} = 50 \text{ mm}$$

$$4. \quad F_b = \frac{1.2 \cdot w \cdot s^2 \cdot R_m}{dw} = \frac{1.2 \cdot 35 \text{ mm} \cdot (2 \text{ mm})^2 \cdot 400 \text{ N/mm}^2}{50 \text{ mm}} = 1344 \text{ N}$$

$$5. \quad W = x \cdot F_b \cdot h = \frac{1}{3} \cdot 1344 \text{ N} \cdot 0.025 \text{ m} = 11.1 \text{ N m}$$

$$h = \frac{dw}{2} = \frac{50 \text{ mm}}{2} = 25 \text{ mm}$$

16.12 Bending machines

Bending machines are sorted according to their fields of application into machines:

1. *To produce folded profiles*
 - 1.1 Press brakes
 - 1.2 Folders (bending brakes)
2. *To produce rings and tubes*
 - 2.1 Three-roll bending machines
 - 2.2 Profile steel bending machines
3. *To produce sheet profiles*
 - 3.1 Beading machines

Table 16.9 Overview of bending machines

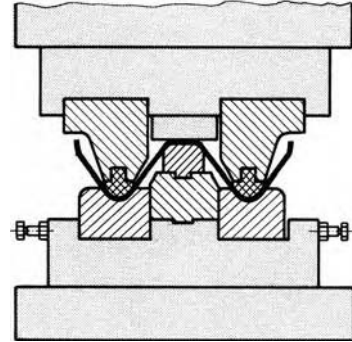
1.1 Press brakes

In press brakes, bent profiles are manufactured by forced bending in bending dies.

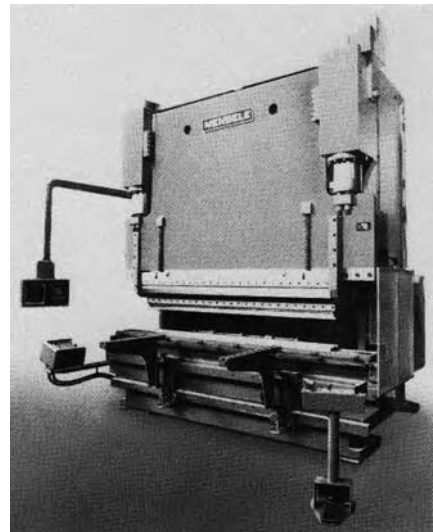
The shape of the die is that of the contour to be produced.

To keep spring-back on the workpiece as low as possible, the final impression (bottoming the punch) during bending must be deep. Press brakes are generally built in a fracture-proof steel plate construction. The CNC-controlled press brake shown here ($F_{\max} = 5000$ kN, max. workpiece length 4m) is driven hydraulically. The two press cylinders are electronically synchronised with non-contact measuring equipment. The press ram is guided in four-point guides, with no play. The machine is equipped with a CNC-controlled automatic tool change system. Five upper tools held on standby in a chain system on the crosshead can be activated with a specially-designed program and automatically positioned. The tools are clamped hydraulically in their working position. With four lower tools, which are moved laterally and can also be programmed, they form mating tool sets which can produce complicated profiles with no need for storage between operations.

With the freely programmable CNC system used here, orders are entered directly at the machine by the operator in a dialogue system. The data entered by this means are saved in the control system and can be retrieved at any time. The dimensions of 50 tools can be saved in a tool library and displayed in the form of a diagram on the screen.



Press bending die



CNC-controlled press brake with automatic tool change system (Photograph from Günzburger Werkzeugmaschinenfabrik works)

Table 16.9 (continued)**1.2 Folders (bending brakes)**

Bending on a bending brake uses a folder beam which grips the projecting workpiece and is turned with it around the die edge.

The main elements of the bending brake are: upper beam, lower beam and bending beam. The upper and lower beams are the tool holders.

A track with a curved edge is fixed in the upper beam; the sheet is bent around the track.

During the bending process the sheet being bent is first clamped between the upper and lower beams, then the bending beam, which can be swivelled around, bends the sheet to the desired angle.

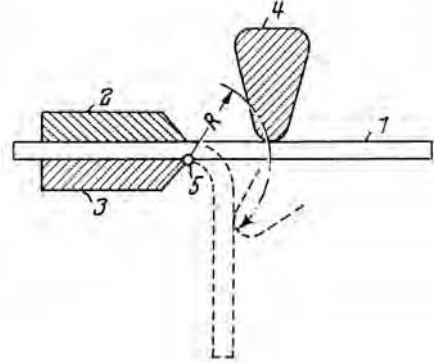
The bending brake shown here has a working width of 2–4 m and can be used for maximum sheet thicknesses of 3–5 mm. It is built as a welded steel construction. The upper beam is opened and closed by means of a hydraulic cylinder. The gripping pressure and the closing speed are adjustable. The lower beam is adjusted centrally and comes with a replaceable bar.

The bending wing, run on a servo-hydraulic system, ensures the bend angle is exact and there is highly accurate repeatability. The bending wing's special measuring system also means that extremely small angles can be produced.

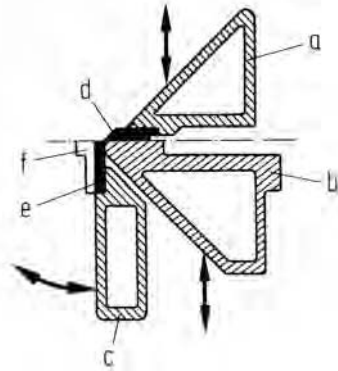
The machine can be delivered with various control systems, single-action program control or an MCNC program control. With the RAS Multibend 8000 MCNC control system, data are entered in a dialogue with the operator, using the screen. The values for the bend angle, the strike position and how far the upper wing opens can all be entered, as well as a large number of auxiliary functions.

The internal storage capacity can hold 99 program sequences.

RAS 74.20–74.40 bending brake with servo-hydraulic drive. (Photograph from Reinhardt Maschinenbau works, 7032 Sindelfingen, Germany)



Bending with folder beam (on a bending brake)



Cross-section of the beams of a bending brake, a) upper beam, b) lower beam, c) bending beam, d) three-sided track, e) flat track, f) reinforcing track



Figures 16.14 and 16.15 show working examples of the production of profiles.

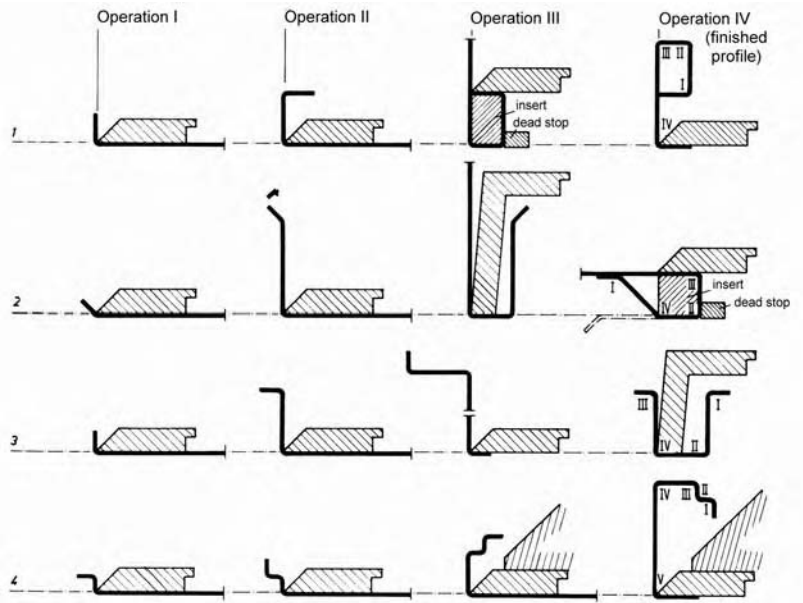


Figure 16.14 Working examples of the production of profiles with bending brakes

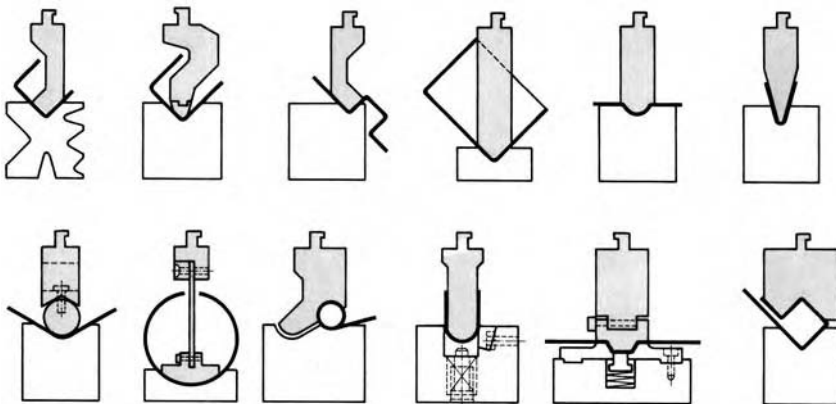
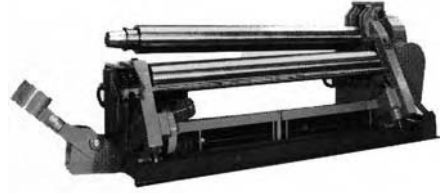


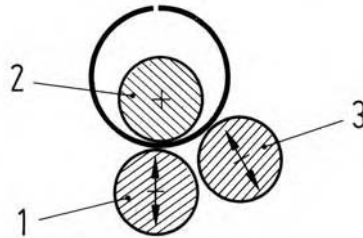
Figure 16.15 Working examples of the production of profiles with press brakes

Table 16.9 (continued)**2.1 Three-roll bending machines**

With three-roll bending machines the lower rolls (1 and 3) are driven mechanically. The top roll is idle, with no drive. To allow the finished length of pipe to be removed, one support for this roll can be swung open.



Type UH7 three-roll sheet bending machine with opened support (Herkules-Werke works)



Asymmetric roll layout 1 lower roll, 2 top roll, 3 bending roll

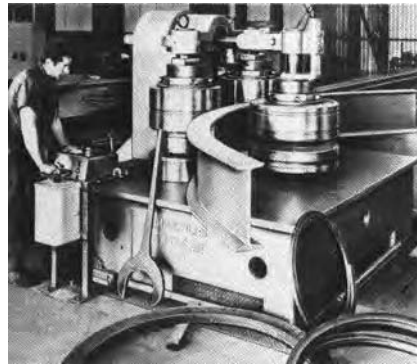
2.2 Profile steel bending machines

With these machines, the roll axes are arranged vertically.

The rolls consist of separate components. This means they can be adapted to the shape of the profile to be produced, using spacer rings.

The axes of the two motor-driven side rolls are supported in two places, once down in the machine body and once up in the crosshead.

The non-powered middle roll can be adjusted radially.



Profile bending machine (Herkules-Werke works)

Table 16.9 (continued)

3. *Beading machines*

The main elements of a beading machine are two shafts connected by a drive (gear).

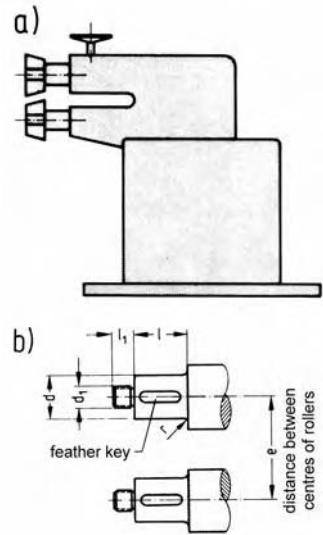
The ends of the shafts hold the dies; beading, seaming or flanging rolls.

The top roll can be adjusted vertically to set the spacing, e .

The lower roll can be adjusted axially; this means it can be aligned with the top roll according to the profile to be rolled.

The rolling dies are put on the ends of the shafts.

Figure 16.6 shows typical profiles produced on beading machines.



a) The principle of a beading machine
 b) Rough dimensions of the shaft journals to hold the dies

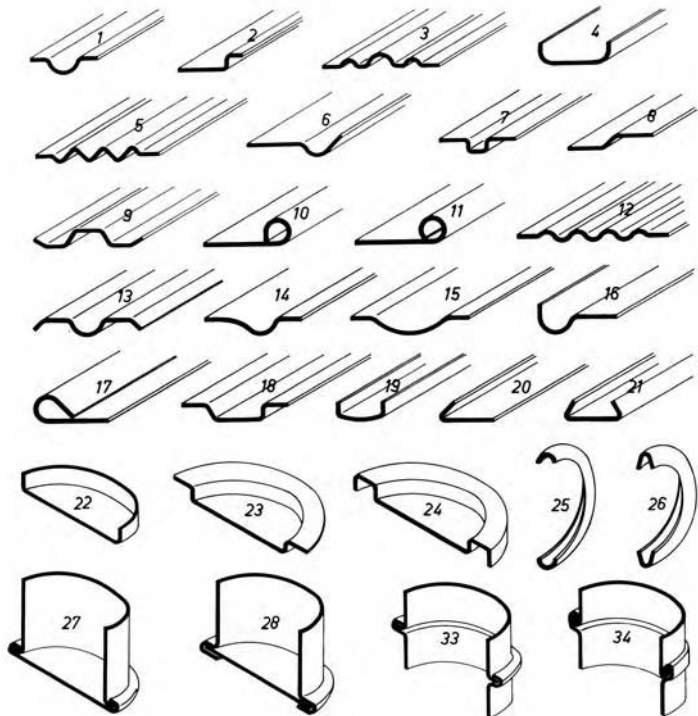


Figure 16.16 Profiles produced on beading machines (Illustration: Stückmann & Hillen works)

16.13 Exercise on Chapter 16

1. What different types of bending process are there?
2. How is the length of the blank determined?
3. What bending machines do you know?
4. Name the three main bending processes.
5. What kinds of workpieces are produced using roll bending?
6. What machines is roll bending carried out on?
7. What are beading machines used for?

17 Embossing

17.1 Definition

Embossing is a forming process where the surface of a workpiece is changed under the influence of high pressure. A difference is made between embossing and coining depending upon how the deformation is carried out.

In embossing, the material thickness of the initial blank remains the same after forming. An impression on one side is countered by a raised area on the other side of the workpiece (Figure 17.1).

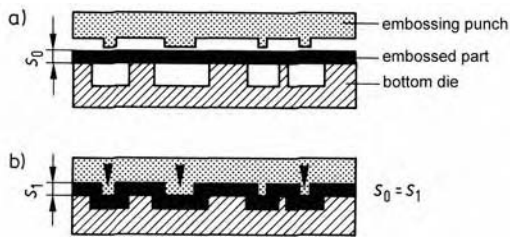


Figure 17.1 Embossing, a) starting stock before impression, b) after impression

17.2 Application of the process

Used to manufacture sheet parts of all kinds, e.g.

- a) indenting beading and local raised areas to stiffen sheet parts (Figure 17.2)
- b) badges made of thin sheet (Figure 17.3)
- c) jewellery
- d) planishing or straightening.

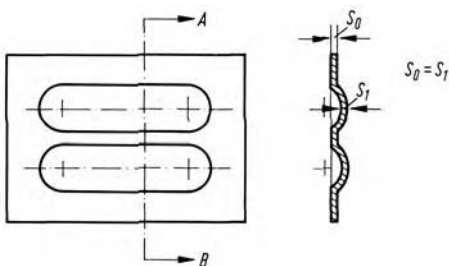


Figure 17.2 Beading to stiffen sheet parts

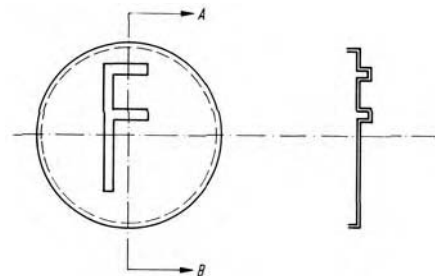


Figure 17.3 Embossed badge

Planishing is between embossing and coining. It is used to straighten twisted or warped stamped or sheared parts. By stamping a grid pattern (rough straightening) stresses can be relieved and the parts straightened out. Occasionally, straightening is also carried out between plane-parallel plates (Figure 17.4).

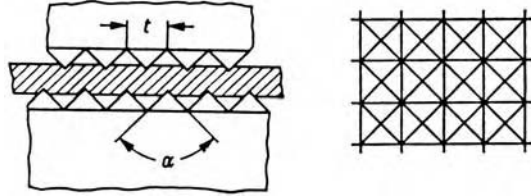


Figure 17.4 Grid pattern of a straightening die. α angle of the point, t spacing

17.3 Calculation of force and mechanical work

17.3.1 Embossing force F_e

In embossing, a difference is made depending upon the embossing force required between

- a) an impression where some material spring-back is possible at low limits without compromising the dimensions of the embossed part; the punch fits into the die with clearance, i.e.

$$b > a + 2 \cdot s \quad (\text{Figure 17.5})$$

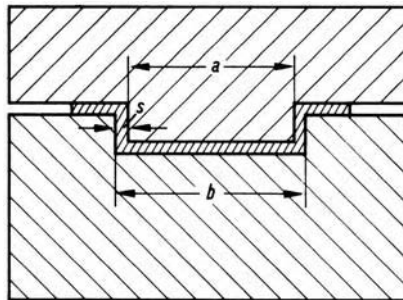


Figure 17.5 Embossing, s material thickness

- b) an impression where spring-back is not possible because of the tolerances which must be observed. Here, no clearance is allowed between the punch, the die and the material being formed. The punch must fit tightly into the die, i.e.

$$a + 2 \cdot s \cong b.$$

In borderline cases, the material to be formed may be stretched at the boundary point.

For these reasons, with loose and tightly-fitting punches different deformation resistances occur and thus different k_r values (see Table 17.1).

Deformation resistance k_r

The calculation values in Table 17.1 relate to forming with fly presses.

When knuckle-joint or crank presses are used, 50% higher values must be expected as the impact effect is “soft” compared to the “hard” impact of the fly presses.

Table 17.1 k_r values for embossing in N/mm^2

Material	R_m	loose punch k_r in N/mm^2	tight-fitting punch	
	in N/mm^2		sheet thickness in mm	k_r in N/mm^2
Aluminium 99 %	80 to 100	50 to 80	up to 0.4 0.4 to 0.7	80 to 120 60 to 100
Brass Ms 63	290 to 410	200 to 300	up to 0.4 0.4 to 0.7 > 0.7	1000 to 1200 700 to 1000 600 to 800
Copper, soft	210 to 240	100 to 250	up to 0.4 0.4 to 0.7 > 0.7	1000 to 1200 700 to 1000 600 to 800
Steel (deep drawing quality) St 12-3; St 13-3	280 to 420	350 to 400	up to 0.4 0.4 to 0.7 > 0.7	1800 to 2500 1250 to 1600 1000 to 1200
Stainless steel	600 to 750	600 to 900	up to 0.4 0.4 to 0.7 > 0.7	2200 to 3000 1600 to 2000 1200 to 1500

The deformation resistance depends upon

- the material to be formed,
- the surface of the material and the die,
- lubrication on the sliding surfaces,
- the shape of the workpiece and the impression,
- the strain rate and thus the machine used.

punch area A_e

$$A_e = w \cdot l$$

A_e in mm^2 projected area of the form actually to be impressed by the punch

max. embossing force F_e

$$F_e = k_r \cdot A_e$$

F_e in N embossing force
 k_r in N/mm^2 deformation resistance
 A_e in mm^2 punch area

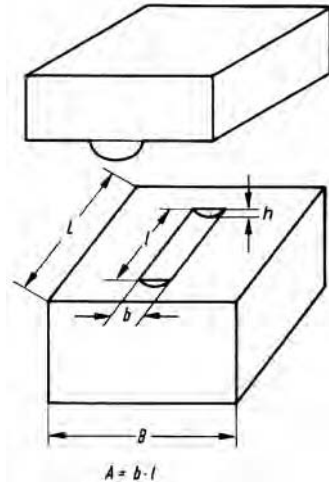


Figure 17.6 Basic dimensions during embossing

17.3.2 Embossing work W (embossing and coining)

The embossing work can be determined from the following equation:

$$W = F_m \cdot h$$

W in N m embossing work
 F_m in N mean embossing work effective across the entire deformation path
 h in m deformation path

In embossing, the deformation path h is equal to the deepest indentation. The mean force F_m comes from the force-displacement diagram which is roughly a triangular area in embossing. The area of the triangle formed by the force-displacement curve of the x-axis and the parallel lines to the y-axis at a distance h is the embossing work.

$$W = \frac{F_e \cdot h}{2}$$

In other words, for embossing the strain energy work W can also be presented as

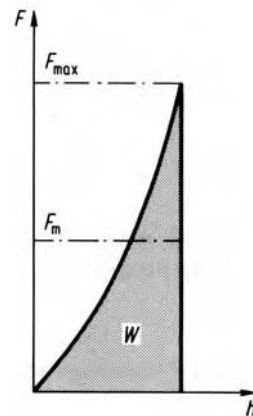


Figure 17.7 Force-displacement diagram during embossing

$$W = x \cdot F_e \cdot h$$

W	in N m	deformation work
F_e	in N	maximum embossing force
F_m	in N	mean embossing force
h	in m	deformation path
x		process factor, $x = F_m/F_{\max} \approx 0.5$ x can be determined from the work diagram

17.4 Embossing tooling

The main components of embossing tooling are the embossing punch and the die (Figure 17.8). For embossing tooling, the punch and the die have practically the same contour: the areas which are convex on the punch are concave on the die. The depth and width of the die are larger than the convex punch contour by the thickness of the sheet. To secure the tooling in place and to guide it during the work cycle, it is built into a pillar guide frame (Figure 17.8).

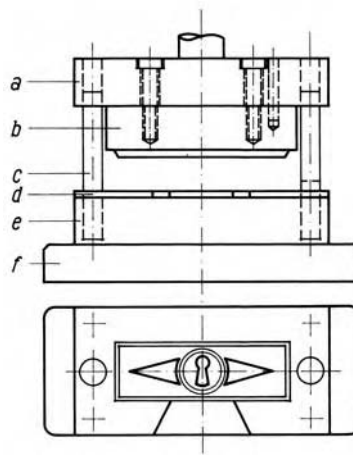


Figure 17.8 Embossing keyhole plates. a) punch head, b) embossing punch, c) guide pillar, d) holding fixture, e) die (bottom punch), f) base plate

17.4.1 Tooling materials

For tooling which is subject to low stresses, non-alloy steels such as the material C 110 W1 are used. For embossing tools subject to higher stresses and for coining and minting dies, alloy steels are mainly used.

Table 17.2 Materials for embossing punches and dies

Material	Material no.	Assembly hardness HRC
C 110 W1	1.1550	60
90 Cr 3	1.2056	62
90 Mn V 8	1.2842	62
50 Ni Cr 13	1.2721	58

17.5 Embossing defects

In embossing, cracks often form along the embossed edges, e.g. with beading (Figure 17.9) if the indentation has very sharp edges. This tendency to crack rises if the grain direction and the beading direction are parallel. For this reason, the grain direction is set transversely to the direction of the beading or indentation edge.

17.6 Example

The aim is to emboss a bead in a sheet as in Figure 17.9.

Material: St 12-03 (deep drawing steel), 1 mm thick.

Find: embossing force and embossing work.

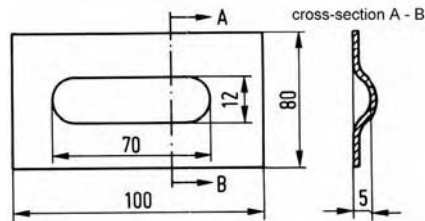


Figure 17.9 Embossed workpiece

$$F_e = A \cdot k_r = w \cdot l \cdot k_r = 12 \text{ mm} \cdot 70 \text{ mm} \cdot 1000 \text{ N/mm}^2 = 840\,000 \text{ N} = 840 \text{ kN}$$

$$k_r \text{ from Table 17.1} = 1000 \text{ N/mm}^2 \text{ selected}$$

$$W = F_e \cdot h \cdot x = 840 \text{ kN} \cdot 0.005 \text{ m} \cdot 0.5 = 2.1 \text{ kN m.}$$

17.7 Exercise on Chapter 17

1. What is meant by embossing?
2. How does embossing differ from coining?
3. What is planishing and what is it used for?
4. What elements is embossing tooling made up of?

18 Shearing

18.1 Definition

Shearing is cutting materials without producing chips. Shearing methods are sorted according to the shape of the blades (Figure 18.1)

In the kind of shearing used predominantly in industry, the material is cut by two blades with a large edge angle β .

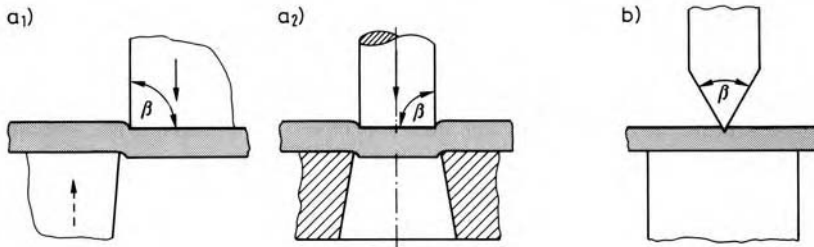


Figure 18.1 Shearing processes, a) shearing blade with large edge angle: a_1 shearing off an edge, a_2 piercing or blanking, b) shearing blade with small edge angle

18.2 Shearing process flow (Figure 18.2)

The punch touches the sheet. The blades press into the material until the pressure generated overcomes the shear resistance. Starting at the die block, a crack begins to form (known as an advancing crack). The cracking, which sets off the separation of the material, propagates through the sheet, splitting the material.

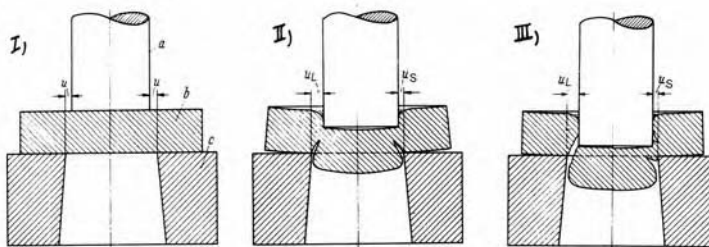


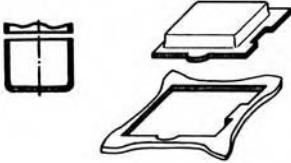
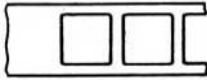


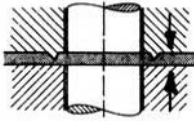
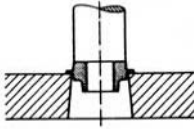


Figure 18.2 Shearing process flow. I) punch touches material, II) cracking in the shearing phase, III) break at the end of the shearing process, a) punch, b) sheet, c) die block, u_L) large break clearance, u_S) small break clearance, u) break clearance

18.3 Types of shearing process

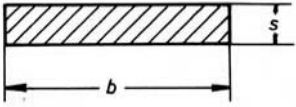
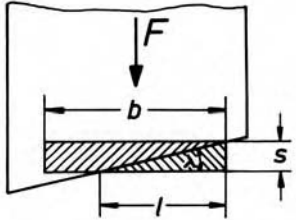
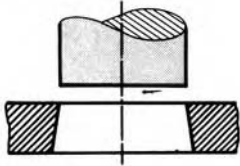
Table 18.1

	<p>1. <i>Shearing along an open-ended line</i></p> <p>1.1 <i>Parting (slitting)</i> Cutting off completely along a line whose two ends do not meet.</p>
	<p>1.2 <i>Lancing</i> Partly cutting along a line whose two ends do not meet.</p>
	<p>1.3 <i>Trimming (notching, cut-off)</i> Cutting off completely along a line whose two ends do or do not meet. Shearing off excess material from flat or concave parts.</p>
	<p>2. <i>Shearing along a closed-ended line</i></p> <p>2.1 <i>Blanking</i> Completely cutting off along a line whose two ends meet.</p>
	<p>2.2 <i>Piercing (punching)</i> Completely cutting off along a line whose two ends meet, from a component or from a strip.</p>
	<p>2.3 <i>Fine trimming</i> Final sizing after an initial operation, by shearing (shaving) material off e.g. a machining allowance.</p>
	<p>2.4 <i>Fine blanking</i> Blanking or piercing where the material is clamped down on all sides, producing the same quality in one operation as with trimming.</p>
	<p>2.5 <i>Deburring</i> Completely removing the burrs on cast parts, parts produced by closed- or open-die forging.</p>

18.4 Permissible deformation

The deformation limits arise mainly from the shape of the stamped parts. The shape and arrangement of the parts to be produced determine which tools are used and their design.

18.5 Calculation of force and mechanical work

<p>1. <i>Shearing along an open-ended line</i></p> <p>1.1 <i>with a straight blade</i></p> $A = w \cdot s$	 <p style="text-align: center;">Shearing area</p>
<p>1.2 <i>with an angled blade</i> (e.g. with sheet shears)</p> $A_{inc} = \frac{l \cdot s}{2} = \frac{s^2}{2 \cdot \tan \lambda}$ $l = \frac{2}{\tan \lambda}; \quad \lambda = 2^\circ \text{ to } 10^\circ$	 <p style="text-align: center;">Shearing area with an angled blade</p>
<p>2. <i>Shearing along a closed-ended line</i></p> <p>Shearing area</p> $A = C \cdot s$ <p>Shearing force</p> $F = A \cdot \tau_B$ <p>Shearing work</p> $W = F \cdot s \cdot x$	 <p style="text-align: center;">The principle of shearing along a closed-ended line</p>

$$x = \frac{F_m}{F_{max}}$$

Required machine power

$$P = \frac{F \cdot v}{\eta_M}$$

F in N shearing force
 A in mm² shearing area
 s in mm sheet thickness
 w in mm width
 l in mm length
 τ_B in N/mm² shear strength
 λ in degrees angle of inclination
 v in m/s shearing speed
 η_M machine efficiency; $\eta_M \approx 0.7$
 W in N m shearing work
 x process factor, results from force-displacement diagram; $x = 0.6$ for shearing
 P in W required machine power

Force-displacement diagram

The shear strength τ_B can be roughly calculated mathematically from the tensile strength R_m at:

$$\tau_B = c \cdot R_m$$

$c \approx 0.8$ (mean value)

For sheet metals with higher fracture resistance: $c = 0.7$

For sheet metal with lower fracture resistance and higher failure strain: $c = 0.9$

Table 18.2 Shear strengths τ_B of various materials

Material	Shear strength τ_B in N/mm ²	
	soft	hard
St 12	240	300
St 13	240	300
St 14	250	320
St 37	310	—

Material	Shear strength τ_B in N/mm ²	
	soft	hard
St 42	400	–
C10	280	340
C20	320	380
C30	400	500
C60	550	720
Stainless steel	400	600
Al 99.5	70	150
AlMgSi 1	200	250
AlCuMg cold cured	320	–
AlCuMg solution annealed	180	–
Ms 72 deep drawing quality	220 to 300	–
Ms 63	250 to 320	350 to 400

18.6 Resultant line of action (centroid of line)

The transfer of force from the ram to the workpiece should take place with no leverage and thus no pullout torque.

A torque effect of this kind would subject the press guides and the workpiece to further stresses and lower the precision of the stamped parts. For this reason it is important that the punch holder is in the correct position, in the central point (centre of gravity) of the force.

As the force is calculated from the circumference and the material thickness, the central point of the force is in the centre of gravity of the circumference line. This is why it is called the centroid.

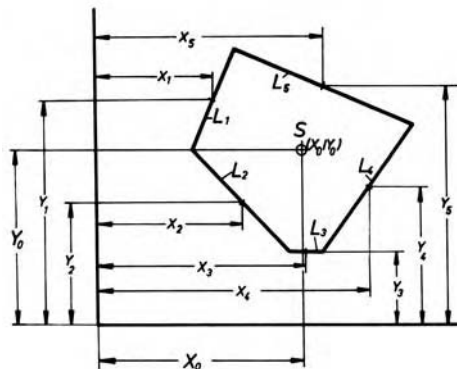


Figure 18.3 Determining the centroid using the separate lines

Determining the centroid

The circumference lines are divided into segments with known centroids. Then the product of the segment distances and the segment lengths is found, these products are added together and this sum is divided by the sum of all the segment lengths.

For all figures, a circumference line is always made up of the same basic elements. These basic elements are:

circles, arcs and straight lines.

The centroids of these basic elements must be known (see Table 18.3).

$$x_0 = \frac{L_1 \cdot x_1 + L_2 \cdot x_2 + L_3 \cdot x_3 + L_4 \cdot x_4 + L_5 \cdot x_5}{L_1 + L_2 + L_3 + L_4 + L_5}$$

$$y_0 = \frac{L_1 \cdot y_1 + L_2 \cdot y_2 + L_3 \cdot y_3 + L_4 \cdot y_4 + L_5 \cdot y_5}{L_1 + L_2 + L_3 + L_4 + L_5}$$

- L length of the segment
- x_n distance from the ordinates
- y_n distance from the abscissa
- $s(x_0/y_0)$ centroid

When piercing symmetric openings, the centroid is not determined from the centroids of the individual lines, but from the circumferences of the symmetrical figures and the centroid of the area.

Example:

Where: tooling arranged as in the sketch (Figure 18.4)

Find: force centroid

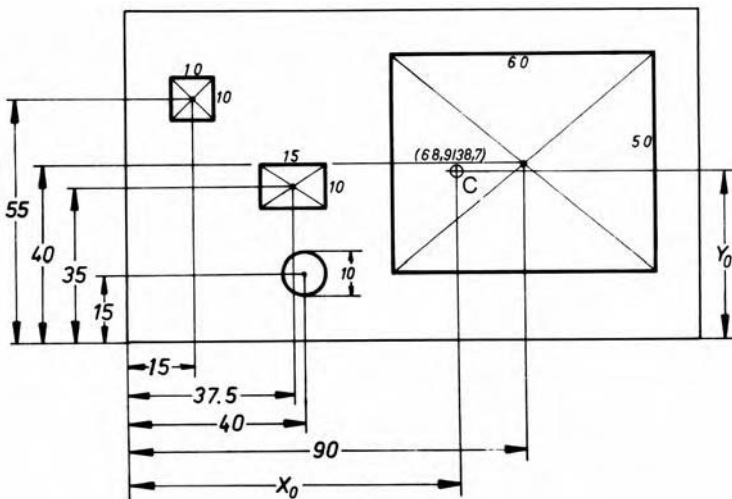


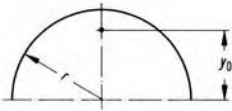
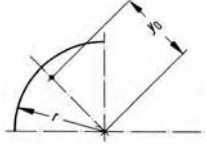
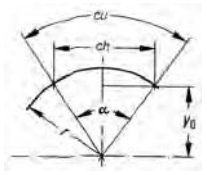
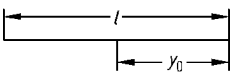
Figure 18.4
Determining the centroid of the line when piercing symmetrical openings

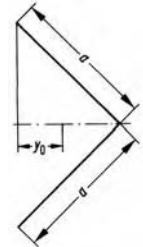
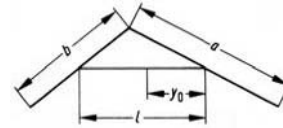
Solution:

$$\begin{aligned}
 1. \quad x_0 &= \frac{x_1 \cdot C_1 + x_2 \cdot C_2 + x_3 \cdot C_3 + x_4 \cdot C_4}{C_1 + C_2 + C_3 + C_4} \\
 &= \frac{15 \text{ mm} \cdot 40 \text{ mm} + 37.5 \text{ mm} \cdot 50 \text{ mm} + 40 \text{ mm} \cdot 31.4 \text{ mm} + 90 \text{ mm} \cdot 220 \text{ mm}}{40 \text{ mm} + 50 \text{ mm} + 31.4 \text{ mm} + 220 \text{ mm}} \\
 &= \frac{23531 \text{ mm}^2}{341.4 \text{ mm}} = 68.9 \text{ mm}
 \end{aligned}$$

$$\begin{aligned}
 2. \quad y_0 &= \frac{y_1 \cdot C_1 + y_2 \cdot C_2 + y_3 \cdot C_3 + y_4 \cdot C_4}{C_1 + C_2 + C_3 + C_4} \\
 &= \frac{55 \text{ mm} \cdot 40 \text{ mm} + 35 \text{ mm} \cdot 50 \text{ mm} + 15 \text{ mm} \cdot 31.4 \text{ mm} + 40 \text{ mm} \cdot 220 \text{ mm}}{40 \text{ mm} + 50 \text{ mm} + 31.4 \text{ mm} + 220 \text{ mm}} \\
 &= \frac{13221 \text{ mm}^2}{341.4 \text{ mm}} = 38.7 \text{ mm}
 \end{aligned}$$

Table 18.3 Line centroids

<p>Semicircle</p> <div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 10px auto;"> $y_0 = 0.637 \cdot r$ </div>	
<p>Quarter circle</p> <div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 10px auto;"> $y_0 = 0.9 \cdot r$ </div>	
<p>Any arc</p> <div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 10px auto;"> $y_0 = \frac{114.6 \cdot r \cdot \sin \alpha / 2}{\alpha^\circ} = \frac{r \cdot 2}{cu}$ </div> <p> $cu = \frac{2 \cdot r \cdot \pi \cdot \alpha^\circ}{360^\circ}$ $ch = 2 \cdot r \cdot \sin \alpha / 2$ $cu = \text{curve length}$ $ch = \text{chord length}$ </p>	
<p>Straight line</p> <div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 10px auto;"> $y_0 = \frac{l}{2}$ </div>	

<p><i>Right angle with legs of equal length</i></p> $y_0 = 0.707 \frac{a}{2}$ <p>y_0 is on the bisecting line of the angle.</p>	
<p><i>Angle with legs of unequal length</i></p> $y_0 = \frac{b \cdot l}{a + b}$	

18.7 Break clearance

Which measurement, that of the punch or the die, must be the same as the nominal size of the workpiece?

18.7.1 For blanking

The opening in the die block must be the same size as the nominal size of the workpiece. The punch then has the following dimensions:

$$\text{hole punch length } L_p = l - 2 \cdot u$$

$$\text{hole punch width } W_p = w - 2 \cdot u$$

The nominal measurements are l and w

The part which is punched out of the strip has the required dimensions.

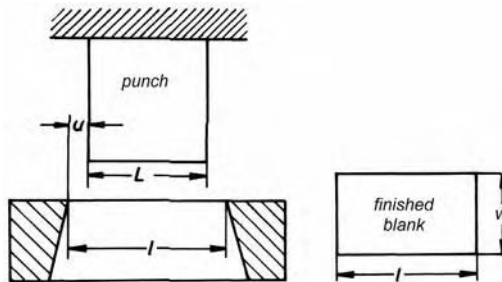


Figure 18.5 Dimensions of the punch and die block during blanking

18.7.2 For piercing (punching)

The punch must be the same size as the nominal size of the workpiece. Here, the diameter of the die measures:

$$d = \text{nominal size}$$

$$D = d + 2 \cdot u$$

The hole has the required dimensions.

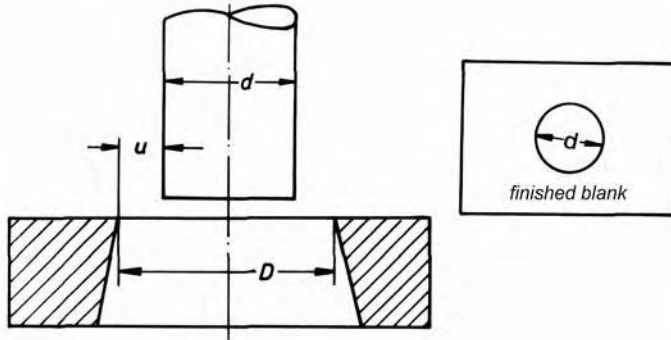


Figure 18.6 Dimensions of the punch and the die block during punching

18.7.3 Size of the break clearance u

For thin sheet up to 3 mm thick (empirical equation)

$$u = 0.007 \sqrt{\text{mm}^2 / N} \cdot s \cdot \sqrt{\tau_B}$$

u in mm break clearance
 s in mm sheet thickness
 τ_B in N/mm^2 shear strength

For sheet > 3 mm thick

$$u = (0.007 \cdot s - 0.005 \text{ mm}) \cdot \sqrt{\text{mm}^2 / N} \cdot \sqrt{\tau_B}$$

punch clearance c

$$c = 2 \cdot u$$

c in mm punch clearance

The break clearance influences the cleanness of the sheared surface, the shearing force and the shearing work.

With thinner sheet steels (< 2.5 mm), the proportion of the fracture surface is higher when the break clearance is larger. Too narrow break clearances, less than $u = 0.1 \cdot s$, lead to earing.

Choosing the right break clearance ensures that the cracks propagating from the edges of the blanking punch and the die (Figure 18.2) meet, creating a fracture surface with no earing.

18.8 Web and rim thickness

The web thickness e and the rim thickness a depend upon

- the sheet thickness
- the material
- the web length L_e
- the rim length L_a
- the width of the strip W

With round parts

$$L_e = L_a < 10 \text{ mm}$$

can be assumed.

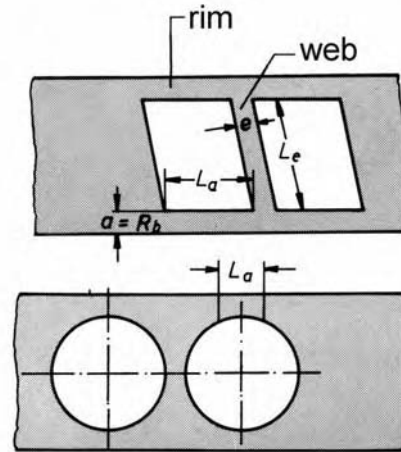


Figure 18.7 Web and rim thickness, a) for cut-outs with straight edges, b) for round cut-outs

Table 18.4 Web and rim thicknesses in mm

Material thickness s in mm	Web thickness e in mm; rim thickness a in mm	Width of strip W in mm							
		W up to 100				W above 100 – 200			
		Web length L_e or rim length L_a in mm							
		Up to 10	10 to 50	50 to 100	over 100	Up to 10	10 to 50	50 to 100	100 to 200
0.3	e	0.8	1.2	1.4	1.6	1.0	1.4	1.6	1.8
	a	0.9	1.5	1.7	1.9	1.1	1.7	1.9	2.2
0.5	e	0.8	0.9	1.0	1.2	1.0	1.0	1.2	1.4
	a	0.9	1.0	1.2	1.5	1.1	1.2	1.5	1.7
0.75	e/a	0.9	1.0	1.2	1.4	1.0	1.2	1.4	1.6
1.0	e/a	1.0	1.1	1.3	1.5	1.1	1.3	1.5	1.7
1.5	e/a	1.3	1.4	1.6	1.8	1.4	1.6	1.8	2.0
2.0	e/a	1.6	1.7	1.9	2.1	1.7	1.9	2.1	2.3

Web length L_e or rim length L_a in mm

18.9 Achievable precision

Tables 18.5, 18.6 and 18.7 show the tolerances which can be met when piercing or blanking. When piercing openings, higher precision can generally be achieved than with blanking. The values in the table can be halved when higher precision is required by using especially precisely-manufactured tooling. By additional trimming, the tolerances in Tables 18.5 and 18.6 can be reduced to one fifth of the values in the tables.

Table 18.5 Tolerances in mm when piercing openings

Material thickness s in mm	Size of the opening in mm			
	up to 10	11 to 30	31 to 50	51 to 100
0.3 to 1.0	0.05	0.07	0.08	0.12
1 to 2	0.06	0.08	0.10	0.14
2 to 4	0.08	0.10	0.12	0.15

Table 18.6 Tolerances in mm when blanking

Material thickness s in mm	Max. side length of the cut-out in mm				
	up to 10	11 to 30	31 to 50	51 to 100	101 to 200
0.3 to 1.0	0.10	0.14	0.16	0.20	0.25
1 to 2	0.18	0.20	0.22	0.28	0.40
2 to 4	0.24	0.26	0.28	0.34	0.60

Table 18.7 Tolerances in mm for the distance between the centres of the openings

Material thickness s in mm	Distance between the centres in mm		
	up to 50	51 to 100	101 to 200
0.3 to 1.0	± 0.1	± 0.15	± 0.20
1 to 2	± 0.12	± 0.20	± 0.25
2 to 4	± 0.15	± 0.25	± 0.30

18.10 Shearing tooling

Tooling for shearing is divided as follows:

1. According to the type of guide device

1.1 Unguided shearing

Shearing tooling with no additional guiding device.

1.2 Guided shearing

1.2.1 Directly guided *Pressure plate-guided shearing*

- a) Steel pressure plate
- b) Pressure plate lined with plastic (Duroplast)
- c) Pressure plate lined with Zamak (a zinc alloy)

1.2.2 Indirectly guided

Pillar guide shearing

Here, the pillar guide frame acts as a guide

2. According to how the tooling functions

2.1 Single-stage tooling

Can carry out only one function; either only piercing or only blanking.

2.2 Progressive tooling

In a certain order, the openings are first pierced in the part being stamped, then the pre-punched part is blanked.

2.3 Compound tooling

With compound tooling, the part is both pierced and blanked in one ram down-stroke.

18.10.1 Structural design of shearing tooling

1.1 Unguided shearing

With unguided shearing, the punch is not guided in the die itself. This means a machine with good guides is required. A stationary stripper fixed to the bottom of the die is used to strip the stamped strip from the punch. When shearing soft materials with this tooling only the punch is hardened. In small-scale production, the die block, made of St 60 or C100, remains soft. Unguided shearing is mainly used for small-scale production (Figure 18.8).

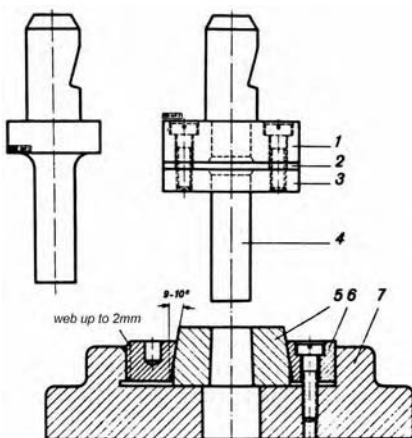


Figure 18.8

Unguided shearing.

1 punch (head) shoe, 2 hardened spacer, 3 punch carrier plate, 4 blanking punch, 5 bottom die, 6 tension ring, 7 die shoe

1.2 Guided shearing

1.2.1 Directly guided

Pressure plate-guided shearing (tooling with guided punch)

With this tooling, the punch is guided by a special guidance pressure plate above the die block. The guidance pressure plate has the same opening as the die block, but with no punch clearance. Between the die block and pressure plate there are spacers whose thickness depends upon the thickness of the material. The pressure plate also acts as the stripper plate (Figure 18.9). With this tooling, precise guidance is only possible up to a punch diameter of up to around 10 mm, as the guidance length is too short due to the limited thickness of the pressure plate.

This kind of plate-guided shearing is only used for medium- to large-scale production. Tooling of this kind can easily be installed in the machine because of the punch guidance.

Producing the pressure plate from steel is expensive, so with this guide system, three structural designs are used:

- a) pressure plate made of steel
- b) pressure plate with plastic-lined guide
- c) pressure plate with Zamak-lined guide (Zamak is the acronym for a zinc alloy).

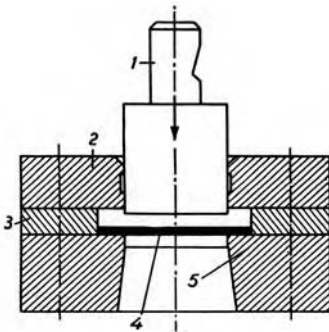


Figure 18.9 Pressure plate-guided shearing.

- 1 punch,
- 2 pressure plate,
- 3 spacer (strip guide),
- 4 workpiece, 5 die block

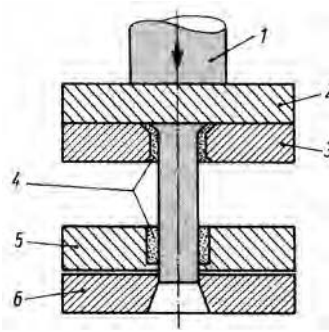


Figure 18.10 Plate-guided shearing with plastic-lined guide.

- 1 punch holder, 2 top plate,
- 3 punch carrier plate, 4 plastic or Zamak,
- 5 pressure plate, 6 die block

Pressure plate-guided shearing with plastic guide

For tooling which does not require very high precision and for medium-scale production, the punch-guiding openings can be lined with plastic or a zinc alloy (Zamak).

The openings in the metal pressure plate are then considerably larger than the punch to be guided, so it is less important how precisely they are arranged together. The punch shoe, with the punches precisely positioned, is put in the pressure plate with its enlarged openings (Figure 18.10).

Next, the punches in the pressure plate are lined with plastic, giving them their precise positioning. Epoxy is used as a plastic liner. Pressure plates produced in this way are considerably cheaper than solid steel plates; however, they also have a shorter lifetime and are therefore only used when the conditions described above make it possible.

1.2.2 Indirectly guided

Pillar guide shearing

With this tooling, the punch is guided directly, rather than indirectly as above. The tooling itself is an unguided shearing assembly. A pillar guide frame is installed (using screws and pins). The pillar guide frame guides extremely precisely, so no press guide is needed. The high guide precision lengthens the lifetime of the tooling (Figure 18.11).

This kind of guide device is made up of an upper and a lower part, the case-hardened pillars (St C 10.61; St C 16.61) and the sliding guide or ball bearing guide. When the tooling is installed, the guide can be on top or below, depending on the design of the tooling and the kind of guide. Pillar guide frames come in various structural designs.

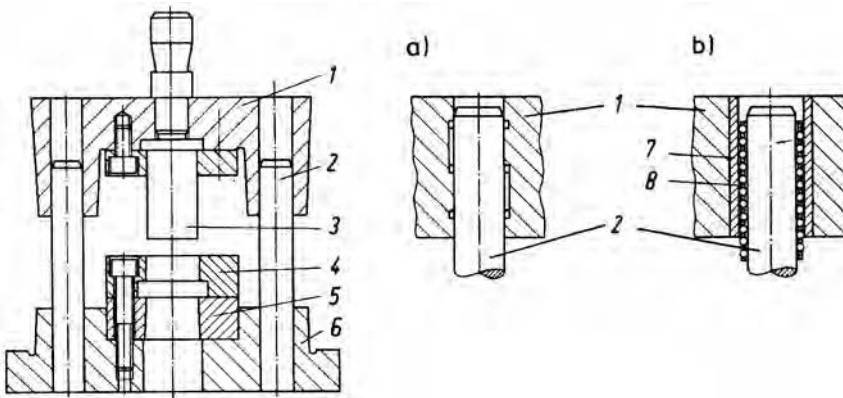


Figure 18.11 Pillar guide shearing, a) with guide bush, b) with ball bearing guide, 1 upper part of frame, 2 pillar guides, 3 punch, 4 stripper, 5 shearing die, 6 lower part of frame, 7 guide bush, 8 ball bearing cage

2.1 Single-stage tooling

This can carry out only one function; either only punching or only blanking. It can be designed as a guided or unguided shearing assembly.

2.2 Progressive tooling

With progressive tooling, several operations are carried out with the same tooling in a certain order. When the workpiece has openings, for example, first the openings are pierced and then the contour is blanked (Figure 18.12).

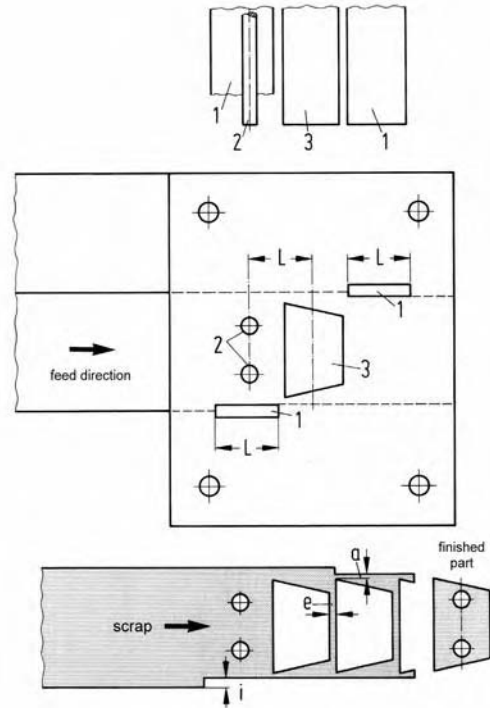


Figure 18.12 The principle of progressive tooling.
1 edge cutter, 2 pre-puncher,
3 blanking punch for the contour, a
rim thickness, e web thickness,
 i edge cutter cut width

2.3 Compound tooling

With compound tooling (Figure 18.13) the periphery and the cut-out are blanked and pierced simultaneously on one ram down-stroke.

For this reason, the accuracy of the comparative positioning of the contour and the openings in the workpiece can be extremely high with this tooling. When the strip is fed in irregularly this also has no effect on the preciseness of the workpiece positioning. Any positioning defects arise entirely from the accuracy with which the workpiece was manufactured.

In the compound assembly shown in Figure 18.13, the upper part of the frame 1 holds the die block 2 with the hole punch 3. The stripper 4 pushes the strip off the punch 3. The blanking punch 5, which blanks the contour, is in the lower part of the frame. The stripper 6 strips the scrap off the blanking punch 5. The piece punched out 3 falls out downwards. The blank is pressed back into the strip with the stripper 6 and carried out of the tooling along with the strip.

This kind of tooling is used to manufacture workpieces produced in large numbers with very low tolerances (up to 0.02 mm). Compound tooling is expensive: this kind of tooling costs about twice as much as shearing with two edge cutters, so it must always be checked in advance whether or not compound tooling is the most economical choice for the case in hand.

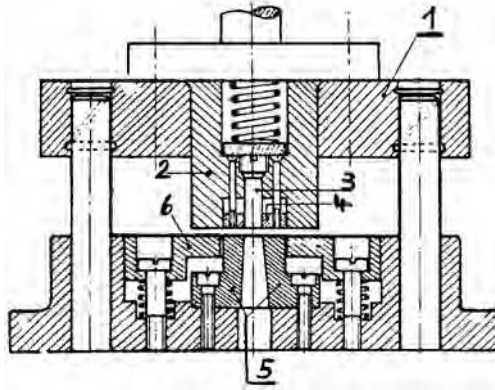


Figure 18.13 Compound tooling to manufacture a pierced disc

18.10.2 Feed regulation with shearing tooling

Pilot or stop pin

The pilot pin is the cheapest way to regulate the feed. It is a pin shaped like a mushroom or hook which is fixed in the die block. Instead of using a pilot pin, a bracket can also be added to the die block to stop the feed (Figure 18.14). When the blanking punch releases the strip of sheet as it moves up, the strip is lifted over the pilot pin by hand and pushed forward until the edge of the remaining section reaches the stop.

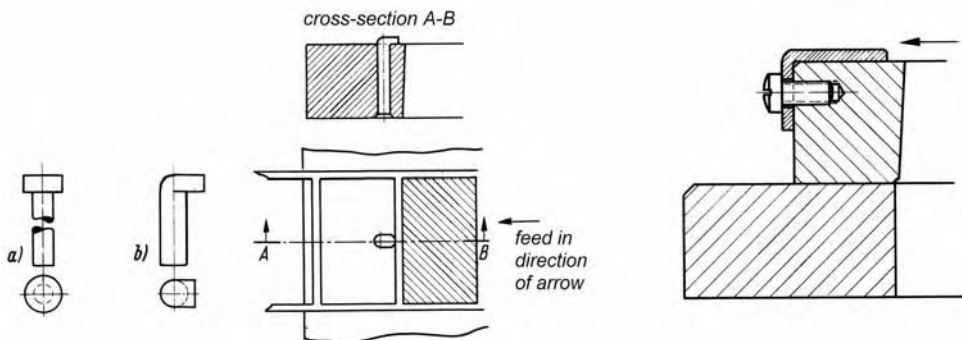


Figure 18.14 Different kinds of pilot pins, a) mushroom-shaped pilot pin, b) hook-shaped, c) bracket stop

Edge cutter

The edge cutter provides the most accurate feed control. It is an extra shearing punch which notches the edge of the strip of sheet. The sheet is pushed against the stopper in the tooling (Figure 18.15). When the ram moves downwards, the edge cutter notches a piece of stock of width b and length L at the edge of the strip. The sheet can now be pushed forwards by this length L (strip feed measurement).

Depending on the precision of the feed and material use of the strip (how it is used), one or two edge cutters are employed; when there are two, these are installed on the left and on the right, offset lengthwise (Figure 18.12). Edge cutters are divided into:

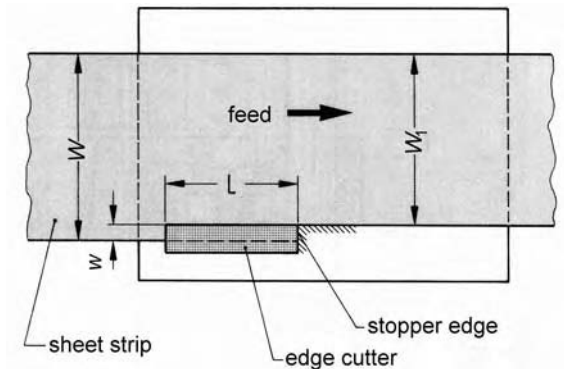


Figure 18.15

Edge cutter arrangement.
 W width of the strip before, W_1 width of the strip after being cut by the edge cutter, L length of the feed step, w width of notch

Straight edge cutter

Straight edge cutters have a straight cutting edge. When the stopper in the tooling becomes worn, burring develops on the strip. This burring stops the strip from being fed onwards and often also causes finger injuries (Figure 18.16).

Recessed edge cutters

These have advantages but are expensive to manufacture. The recessed edge cutter stamps impressions into the sheet being fed in.

Here, if burring accumulates between the indentations, it can be bent into the indentations as the strip is fed forwards. This means that the strip feed is no longer obstructed (Figure 18.16)

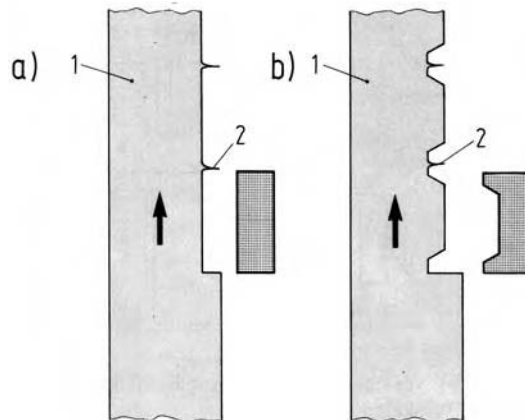


Figure 18.16

Types of edge cutter.
 a) straight edge cutter,
 b) recessed edge cutter,
 1 strip, 2 burring

18.10.3 Strip guides

To balance out the tolerance of the strip width and the strip guide, guides are usually spring-actuated (Figure 18.17).

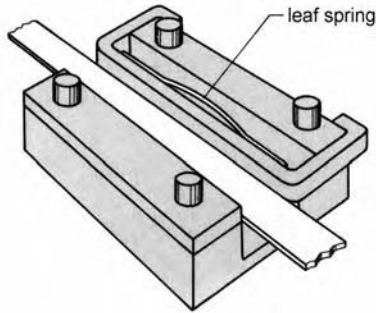


Figure 18.17 Spring-actuated strip guide

18.10.4 Piercing punch (hole punch)

With piercing punches, both the surface pressure acting on the punch shoe and the unsupported length must be taken into particular consideration. The surface pressure p on the punch shoe must not exceed the value $p = 25 \text{ kN/cm}^2$; otherwise, a hardened pressure plate (Figure 18.18) must be inserted between the punch carrier plate and the punch shoe plate. If this is left out, the punch presses into the top plate.

$$p = \frac{F_s}{A_k}$$

p in kN/cm^2 surface pressure
 F_s in kN shearing force
 A_{hd} in cm^2 cross-sectional area of punch

For example, when the cross-sectional diameter of the punch is 8.2 mm and the stamping force is $F_s = 30 \text{ kN}$ the resulting surface pressure is:

$$p = \frac{30 \text{ kN}}{0.528 \text{ cm}^2} = 56.8 \text{ kN/cm}^2$$

i.e. a hardened distance plate is required. As a rule of thumb it can be said of the danger of buckling with hole punches that: the unsupported length l of punches which are not guided should be less than

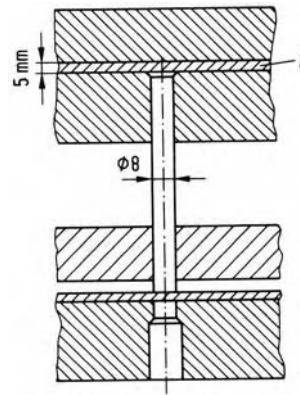


Figure 18.18 Layout of hardened intermediate plate 1

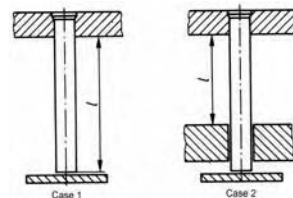


Figure 18.19 Unsupported length l
 Case 1: unguided,
 Case 2: guided

$$l \leq 8 \cdot d$$

and with punches which are guided (Figure 18.19) less than

$$l \leq 12 \cdot d$$

In borderline cases the permissible unsupported length can be determined with Euler's formula:

$$l_{\max} = \sqrt{\frac{\pi^2 \cdot E \cdot I}{F_s \cdot \nu}}$$

$$\left. \begin{array}{l} \nu = 4 \text{ unguided} \\ \nu = 0.5 \text{ guided} \end{array} \right\} \text{ safety factor}$$

$$E_p = 210000 \text{ N/mm}^2$$

$$I = \text{area moment of inertia}$$

$$F_s = \text{shearing force}$$

18.10.5 Types of opening in shearing dies

The two types of opening used the most often are shown in Figure 18.20. With design b, the opening is made larger by regrinding, hence with small tolerances, design a is mainly chosen. The size of the cone angle and the height h of the cylindrical opening depend mainly upon the sheet thickness.

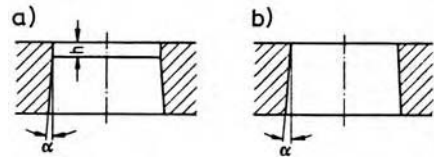


Figure 18.20
Types of shearing die opening

Table 18.8 Standard values for cone angle and the height of the cylindrical part of shearing dies

Sheet thickness s in mm	Design b	Design a	
	cone angle α	Height of the cylindrical opening h in mm	α
0.5 – 1	15' – 20'	5 – 10	3° – 5°
1.1 – 2	20' – 30'		
2.1 – 4	30' – 45'		
4.1 – 8	45' – 1°		

18.10.6 Punch holder

The upper part of the die is generally connected to the press ram by the punch holder. The following methods of construction are used (Figure 18.21):

- A: Rivet into the top plate
- B: Screw in with spreader lock by a tapered pin
- C: Screw in with sealing run and locking pin to prevent twisting
- D: Interference fit between holder and plate with turned groove for gripping.

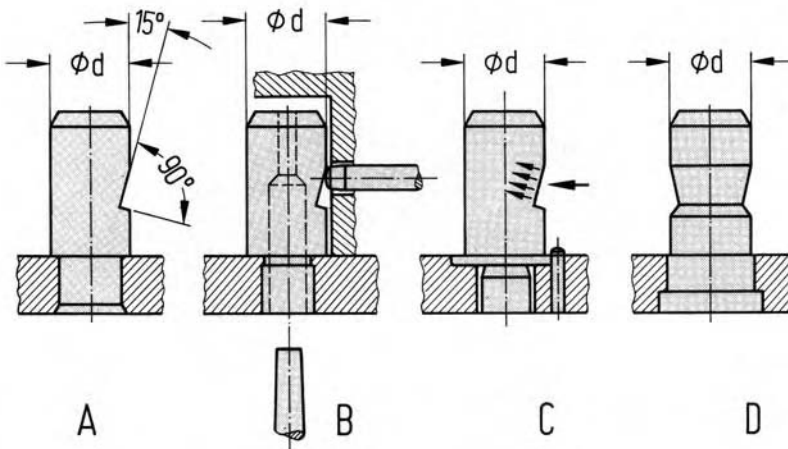


Figure 18.21 Ways of fixing the punch holder

18.10.7 Tooling materials

Table 18.9 Steels suitable for blanking punch and die blocks

Material to be cut		Material no.	Assembly hardness in HRC
Type of material	Material thickness in mm		
Sheets and strips of steel and nonferrous metal alloys	up to 4	1.2080, 1.2436	58 – 62
	up to 6	1.2379, 1.2363, 1.2842	56 – 60
	up to 12	1.2550	54 – 58
	above 12	1.2767	48 – 52
Transformer sheet and silicon steel sheet and strips	up to 2	1.2379, 1.2436	60 – 63
	up to 6	1.2379	58 – 62

Table 18.9 continued

Material to be cut		Material no.	Assembly hardness in HRC
Type of material	Material thickness in mm		
Sheets and strips from austenitic steels	up to 4	1.2379, 1.3343	60-64
	up to 6	1.2379, 1.3343	58-62
	up to 12	1.2550	54-58
	above 12	1.2767	50-54
Precision tooling for sheets and strips made of metallic materials	up to 4	1.2379,1.3343	60 – 63
	up to 6	1.2379, 1.3343	58 – 62
	up to 12	1.2379,1.3343	56 – 60
Plastics, wood, rubber, leather, textiles, paper		1.2080, 1.2379, 1.2436, 1.2842	58 – 63
		1.2550	54 – 58

18.11 Example

The aim is to stamp 2mm-thick discs with a diameter of 40mm made of St 1303 with $\tau_B = 240$ N/mm². Find the force and mechanical work.

$$F = C \cdot s \cdot \tau_B = d \cdot \pi \cdot s \cdot \tau_B = 40 \text{ mm} \cdot \pi \cdot 2 \text{ mm} \cdot 240 \text{ N/mm}^2 = 60288 \text{ N}$$

$$F = 60.3 \text{ kN}$$

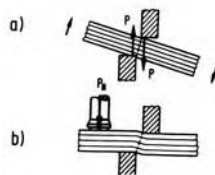
$$W = F \cdot s \cdot x = 60.3 \text{ kN} \cdot 0.002 \text{ m} \cdot 0.6 = 0.072 \text{ kNm} = 72 \text{ N m}$$

Table 18.10 Machines for shearing along an open-ended line

1. Plate shears

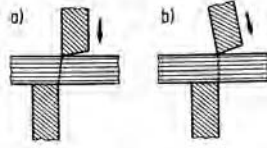
These are for shearing strips from plate stock.

The sheet must be held down with a blank holder so that a burr-free, right-angled cut is produced during shearing. Moreover, the motion from the upper blade to the lower blade must be adjusted so that the line of action of the shearing force runs vertically. This is achieved by angling the upper blade or rocking it (swinging it around a centre of rotation).



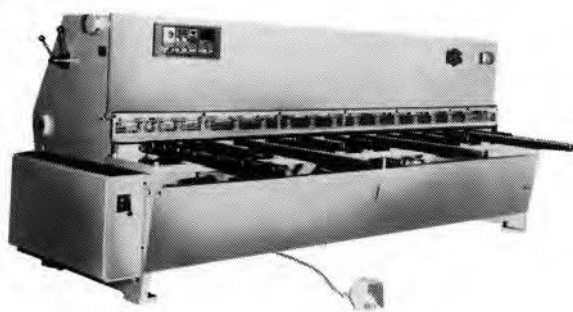
The principle of the shearing process,
 a) without a blank holder,
 b) with a blank holder

The plate shear pictured here is a swing beam type, i.e. the upper cutting bar is tilted electrohydraulically around a centre of rotation.



Line of action of shearing force during the shearing process, a) parallel shearing, b) angled or tilted shearing

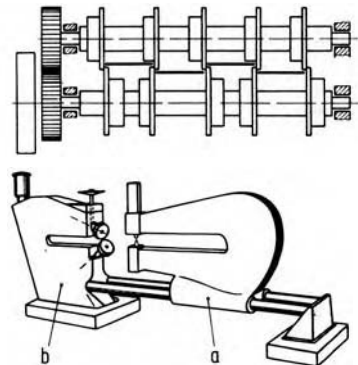
The blank holder has separate hydraulically-controlled rams which automatically adapt to the shearing force.



Hydraulic swing beam plate shear (Photograph from Reinhardt works, Sindelfingen, Germany)

2. Strip shears

Strip shears are shears which continuously cut strips of a defined width from wide rolling strips. The smallest width, which is determined by the smallest distance between the blades, is 40 mm. The maximum sheet thickness which can be cut using strip shears is around 6.5 mm. The ring-shaped tooling is mounted on the cutter shaft and is adjusted to the width of the strip to be cut using spacers. The two shafts, set up parallel to one another, are driven by a motor via a transmission gear, and turn in opposite directions.



Curve shears with centring device, a) centring clamp for round blanks, b) curve shear

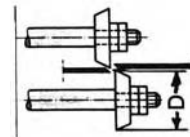
3. Circular and curve shears

These shears can be used to cut curved lines. For this reason they are used to cut sheet metal parts and produce round blanks. The main elements of circular and curve shears are rotating blades. The diameter of these blades must enable them to follow curved contours.

$$D \approx 120 \cdot s$$

D in mm blade diameter

s in mm sheet thickness



18.12 Exercise on Chapter 18

1. What are the different types of shearing process?
2. Describe the different phases of the shearing process.
3. Why is the movable upper blade of sheet cutting shears tilted towards the table area?
4. In shearing assemblies, why must the punch holder be in the centroid of the blanking punch?
5. What is meant by “break clearance”, “web thickness” and “rim thickness”?
6. What kinds of shearing tooling are there?
7. What is progressive tooling and what stamped parts is it used for?
8. How does compound shearing tooling work?
9. What is an edge cutter and what is its function?
10. Why is a recessed edge cutter better than a straight edge cutter?
11. What must be taken into consideration for guiding the strip?
12. Why must the blanking punch not be too long?
13. What are the following needed for:
 - a plate shear
 - a strip shear
 - a circular shear?

19 Fine blanking (precision blanking)

19.1 Definition

Fine blanking is a shearing process which produces very highly precise workpieces with completely smooth, tear-free sheared surfaces.

19.2 Fields of application

One typical field of application is manufacturing gear wheels with modules of 0.2 to 10 mm and sheet thicknesses of 1 to 10 mm. Toothed racks and other precise parts such as catches for automobile doors are also produced with fine blanking and no further working (Figure 19.1).

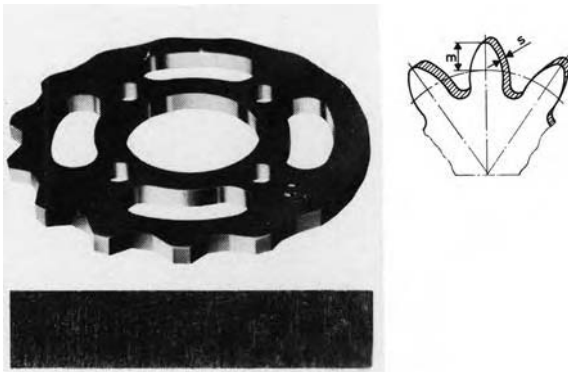


Figure 19.1

Fine blanked part and fine blanked surface
(Photograph from Feintool AG works,
Lyss, Switzerland)

19.3 Shearing process flow

During fine blanking, the material is:

1. Pressed firmly against the die block before the shearing operation, using a tooling element with a V-ring (impingement ring) incorporated into it (Figure 19.2).

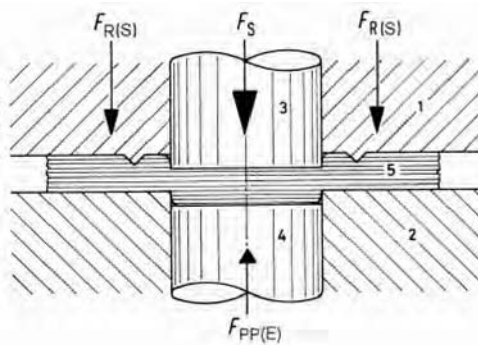


Figure 19.2 The principle of fine blanking.

F_S shearing force, F_{PP} pressure pad force,
 F_R V-ring force, $F_{PP(E)}$ ejector force,
 $F_{R(S)}$ stripper force (Illustration from Feintool
AG works, Lyss, Switzerland)

2. During the shearing process

The workpiece to be cut out is held tightly in place on the shearing plane from below by an opposing punch (Figure 19.2) with a force F_G . The shearing operation is carried out in this state of tension.

3. After the shearing process

3.1 The V-ring element acts as a stripper which strips the scrap from the punch.

3.2 The opposing punch acts as an ejector, ejecting the cut-out upwards, from below.

As can be seen from the sequence of operations, special presses are required for fine blanking (triple-action automatic blanking presses).

19.4 Fine blanking tooling design

Figure 19.3 shows the schematic construction of a fine blanking assembly.

A distinctive feature of this assembly is the V-ring plate which is moved with the upper part of the frame by the outer press ram. The blanking punch is operated by the inner press ram, independently of the movement of the V-ring plate.

The opposing punch is operated by the triple-action press ejector.

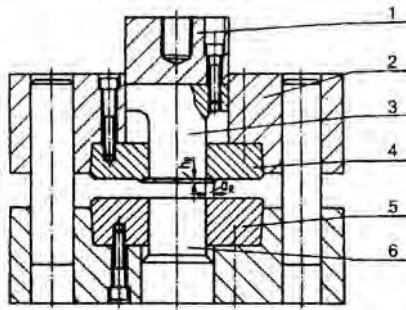


Figure 19.3 The main elements of a fine blanking assembly. 1 punch shoe, 2 upper part of frame, 3 blanking punch, 4 V-ring plate, 5 die block, 6 opposing punch

19.5 Break clearance

As well as the V-ring, another special feature of fine blanking assemblies is their small break clearance. This is what produces the smooth shearing surface. The size of the break clearance depends upon the sheet thickness and the ratio of the punch diameter to the sheet thickness.

Table 19.1 Break clearance u subject to the sheet thickness s and the punch diameter to sheet thickness ratio d/s

s in mm	1	2	3	4	5	8
u in mm for $q = 0.7$	0.012	0.024	0.036	0.048	0.06	0.095
u in mm for $q = 1.0$	0.01	0.02	0.03	0.04	0.05	0.08
u in mm for $q = 1.2$	0.005	0.01	0.015	0.02	0.025	0.04

$q = \frac{d}{s}$; d in mm punch diameter, s in mm sheet thickness

19.6 Forces during fine blanking

Shearing force

$$F_s = C \cdot s \cdot \tau_B$$

- F_s in N shearing force
- C in mm circumference of the blanking punch
- s in mm sheet thickness
- τ_B in N/mm² shear strength (see Table 18.2 Chapter 18.5).

V-ring force (Figure 19.4)

$$F_R = 4 \cdot L \cdot h \cdot R_m$$

- L in mm length of the V-ring
- h in mm V-ring height (Figure 19.4)
- R_m in N/mm² tensile strength
- F_R in N V-ring force

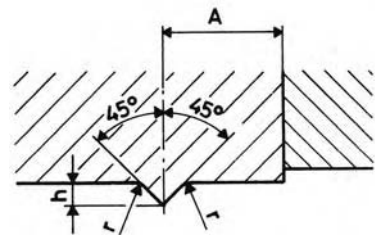


Figure 19.4 Shape of the V-ring

Table 19.2 V-ring height h subject to the sheet thickness s

h in mm	0.3	0.5	0.7	0.8	1.0
s in mm	1 – 2	2.1 – 3	3.1 – 6	6.1 – 9	9.1 – 11

Opposing force

$$F_{\text{opp}} = A \cdot p$$

$p = 20 \text{ N/mm}^2$ to 70 N/mm^2

$p = 20$ for thin parts with a small area

F_{opp} in N opposing force

A in mm^2 area of the fine-blanked part (top view of the part being blanked)

p in N/mm^2 specific contact pressure

Stripper force or ejector force

$$F_E = 0.12 \cdot F_s$$

F_E in N stripper force / ejector force

The V-ring plate strips the scrap from the blanking punch (stripper force) and the opposing punch pushes the part out of the die block (ejector force).

19.7 Fine blanking presses

Fine blanking presses are triple-action mechanically-driven presses with up to 2500 kN press force or hydraulically-driven presses with up to 14000 kN press force. These CNC-controlled machines have a ram which operates vertically from below to above; the sequence of movements is regulated with a precise upper ram reversal point; the ram is precisely guided and the columns are very rigid.

Feintool mechanical fine blanking presses (Figure 19.5) are driven by a fully variable DC motor via the flywheel, a multi-plate clutch and a worm gear on two synchronously-running crankshafts of different eccentricity. These crankshafts drive a double knuckle-joint system which produces the controlled sequence of movements.

Feintool hydraulic fine blanking presses (Figure 19.6) are fitted with an accumulator drive. The hydraulic pump continually charges a high-pressure accumulator, storing energy – something like the flywheel of a mechanical fine blanking press. During the shearing process, this accumulator powers the main ram cylinder. This means that unlike a direct drive, the shearing speed does not depend upon the pump capacity. At the same time, the hydraulic pump also powers the low-pressure accumulator which powers the high-speed closing cylinder. As a result, each phase of the movement can be tailored to any kind of tooling depending upon the path, the pressure and the speed. At the end of the shearing process, the ram comes up against a mechanically adjustable positive stop at the upper reversal point.

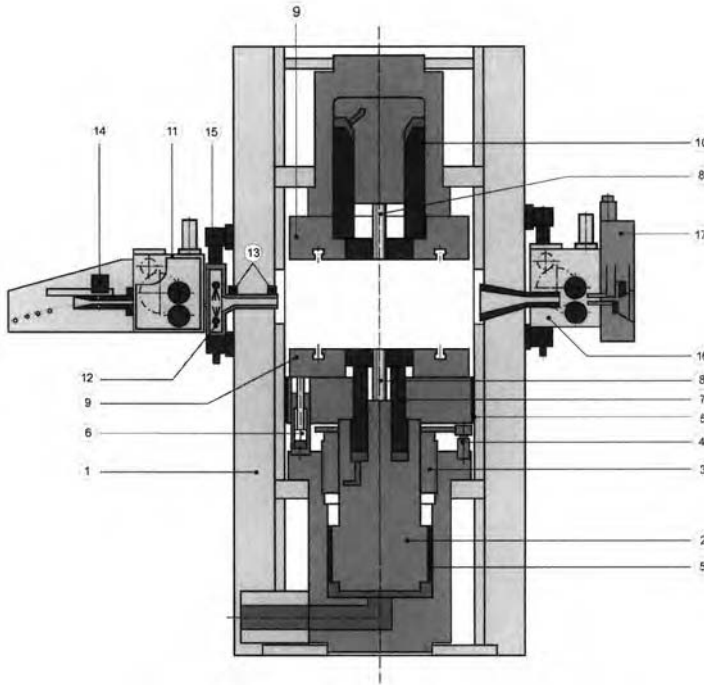


Figure 19.5 Construction of a hydraulic fine blanking press

Machine elements

Feed system elements

- | | | | |
|-------------------------------|-------------------------------|-----------------------------|---------------------------|
| 1 Four-pillar press frame | 6 high-speed closing cylinder | 10 V-ring cylinder | 15 feed height adjustment |
| 2 main working cylinder / ram | 7 pressure pad cylinder | 11 infeed | 16 outfeed |
| 3 positive stop for ram | 8 central support | 12 strip sprayer | 17 scrap cutter |
| 4 servomotor (stroke setting) | 9 tooling positioners | 13 automated initial cutter | |
| 5 ram guide | | 14 testing end of strip | |

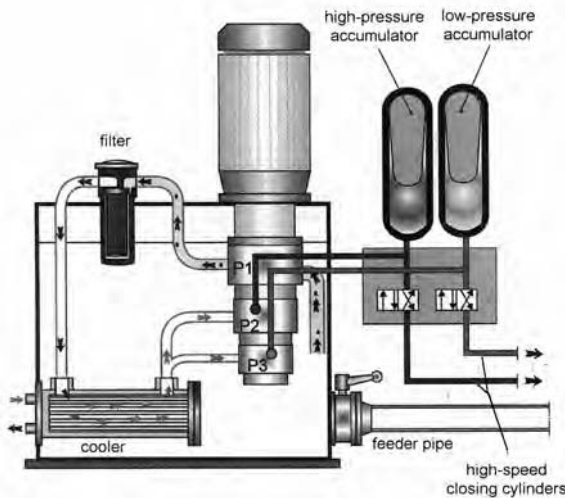


Figure 19.5a Hydraulic unit (Illustration from Feintool Technologie AG works, Lyss, Switzerland)

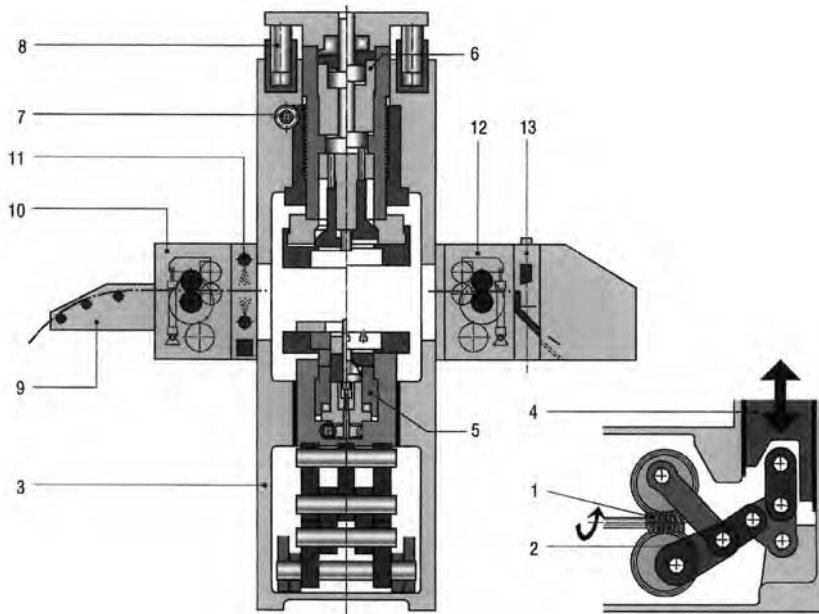


Figure 19.6 Structure of a mechanical fine blanking press (Illustration from Feintool Technologie AG works, Lyss, Switzerland)

Machine elements

- 1 gears
- 2 double knuckle joint
- 3 four-pillar press frame
- 4 ram
- 5 pressure pad piston
- 6 V-ring piston
- 7 tooling height adjustment

Feed system elements

- 8 infeed roller cage
- 9 infeed
- 10 sprayer
- 11 outfeed
- 12 scrap cutter

19.8 Exercise on Chapter 19

1. What is meant by fine blanking?
2. What is this process used for?
3. Describe the flow of the shearing process with fine blanking.
4. How is fine blanking tooling constructed?
5. What values does the selected break clearance depend upon?

19.9 Laser cutters

The Trumatic 600 Laser Press shown in Figure 19.7 is a combination of:

- an electrohydraulic blanking press
- and a laser cutter.

With its punching head, the ram driven electrohydraulically, standard contours such as round and square openings are blanked on a single stroke. The stroke path and the blanking force are variable with this punching unit. Both are optimised with a control system according to the tooling and the material. All the tooling can be rotated by 360°, reducing the number of tools needed to a minimum. The tooling is retrieved from the linear storage unit and changed within a few seconds.

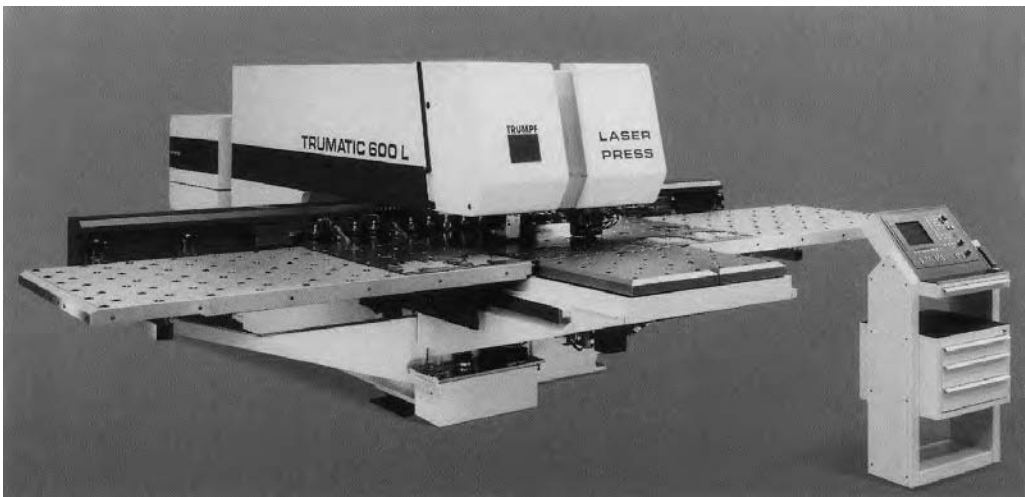


Figure 19.7 Trumpf Trumatic 600 Laser Press CNC sheet processing unit (Photograph from Trumpf GmbH works, Ditzingen, Germany)

With the Trumatic 600 Laser Press laser cutting and removing unit (CO₂ gas laser, high-frequency generated), the workpiece is finely machined after the blanking process. For example, the laser beam can produce extremely small openings (Figure 19.8) which could not be produced at all with a blanking punch as a punch that narrow would break.

The workpiece is pushed from the blanking unit to the laser head in the same clamping device.

The non-contact DIAS capacitive height sensor keeps the cutting nozzle and the workpiece at a constant distance. This means that the laser can even cut on pre-formed areas (e.g. bulges).

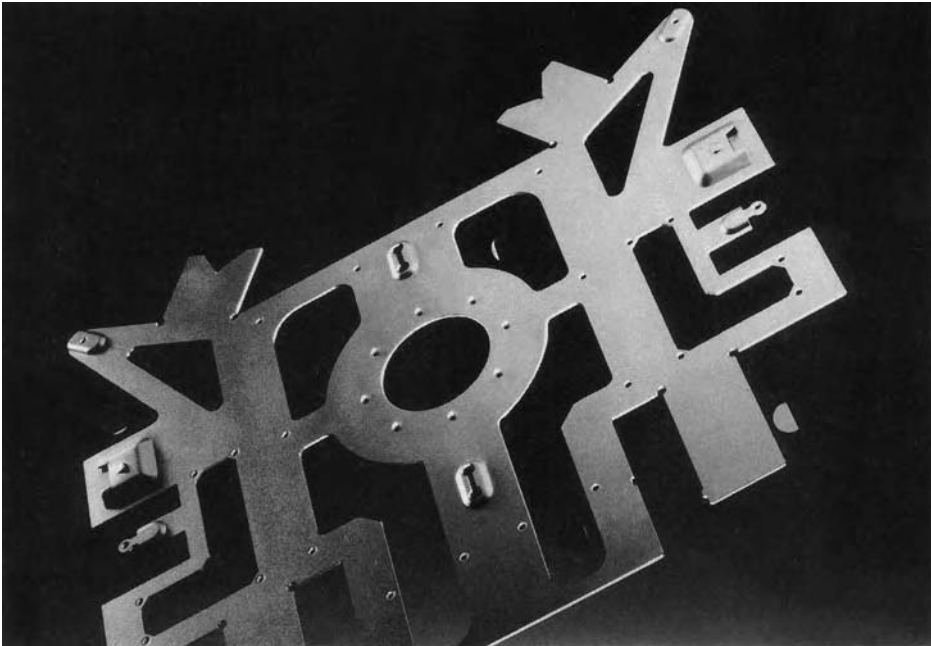


Figure 19.8 Fully processed workpiece (laser cutting, blanking and embossing) (Photograph from Trumpf GmbH works, Ditzingen, Germany)

The fast change system means that a laser head can be changed in only a few seconds. The machine comes with a Trumpf CNC system which is operated in a thoroughly user-friendly way. The graphic user interface meets the Windows standard. As the operational structure is geared towards production, processing can begin in only a small number of steps. Again, only three steps are required to programme it:

1. read in drawing;
2. lay out the sheet and the processing is automatically defined (the integrated processing software automatically calculates the ideal pattern which will use the least material);
3. automatically generate NC program.

Table 19.3 Technical data for the unit

Working range (X,Y) combined laser and blanking function	2585 × 1600 mm
Laser capacity	1800 – 3000 W
Max. blanking force	220 kN
Max. sheet thickness	8 mm
Achievable precision	+ 0.1 mm

20 Joining by forming

Joining by forming includes all processes where parts being joined or involved in the joining are formed locally, sometimes also completely. The deformation forces may be generated mechanically, electromagnetically or in another way e.g. by an explosion. Generally, the joint is kept from unintentionally coming undone by positive locking. With joining, a difference is made between

- forming wire-shaped bodies (e.g. braiding)
- forming sheet, tube and profiled parts (flanging, bending, clinching) and
- riveting processes (hollow riveting, punch riveting).

This chapter deals with clinching and punch riveting with no pre-punching, as these methods have been growing in importance since the mid-1990s. The advantages they confer in automobile production mean that they can largely replace conventional resistance spot welding.

Their economic advantages are in the joinability of differing materials (e.g. aluminium with steel), the longer tooling life and avoiding heat input. With higher-strength sheet in particular, the latter means that better use can be made of its strength, as the original properties of the material are not changed thermally.

At the point of joining, the deformation is carried out by deliberately changing the thickness of the semi-finished product. This is a bulk forming operation made up of different, overlapping processes, e.g. pushing through, compressing, extrusion.

Difficulties still arise when calculating theoretical values such as the required force and work, or describing process limits (joinable sheet thicknesses, joinable strengths) due to the complex triaxial changes in the states of tension and deformation involved. For this reason, until now development has been shaped by experiments. In future, the increasing use of numerical simulation will reduce the number of experiments needed.

20.1 Clinching

20.1.1 Principle

Four steps in clinching with a fixed die are laid out schematically in Figure 20.1. Once the sheets have been positioned using the blank holder (view 1) the material below the punch is pushed through and compressed (view 2). The material, pressed outwards radially, forms a button (undercut) between the sheets (view 3). As well as this positive lock, at the same time residual radial compressive stresses develop which create a non-positive lock (view 4).

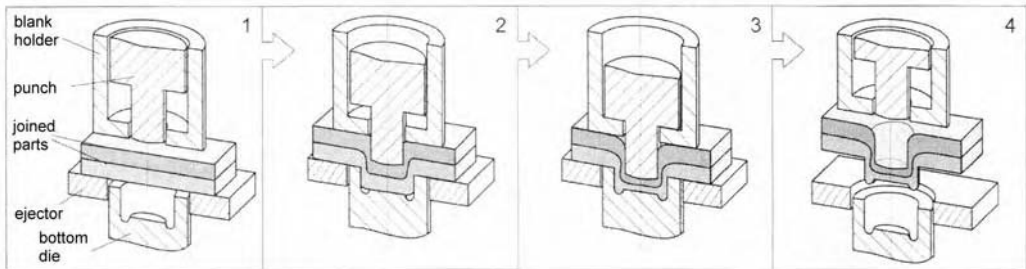


Figure 20.1 The principle of the clinching process with a fixed die (LWF Paderborn, Germany)

Figure 20.2 shows a cross-section of a joint clinched with a movable die. The base is visible where, because of the axial movement of the punch, the light-coloured aluminium has formed the button by a radial flow of material. The movable die plates passively spread apart, helping to form the button.



Figure 20.2 Cross-section of a joint clinched using movable die segments; connecting aluminium (above) and steel (below) (Fraunhofer Institute for Machine Tools and Forming Technology, IWU, Chemnitz, Germany)

20.1.2 Application of the process

The main advantage of clinching is its low cost. The process can be used to connect sheet, profiles and die-cast parts, the main range of use being around $s = 1.2\text{--}4$ mm total sheet thickness.

Materials can be joined with an R_m of up to 1000 Mpa, the general rule for combination being that the thicker and/or harder semi is placed on the punch side. One constraint is the required deformability. With low failure strains (below 10%) cracking appears, mainly on the die side which is under tensile strain.

Some areas where clinching is used include the automobile industry (Figures 20.3 and 20.4), white goods (household appliances), ventilation and air conditioning, electronics, medical appliances and sheet processing in general (Figure 20.4).

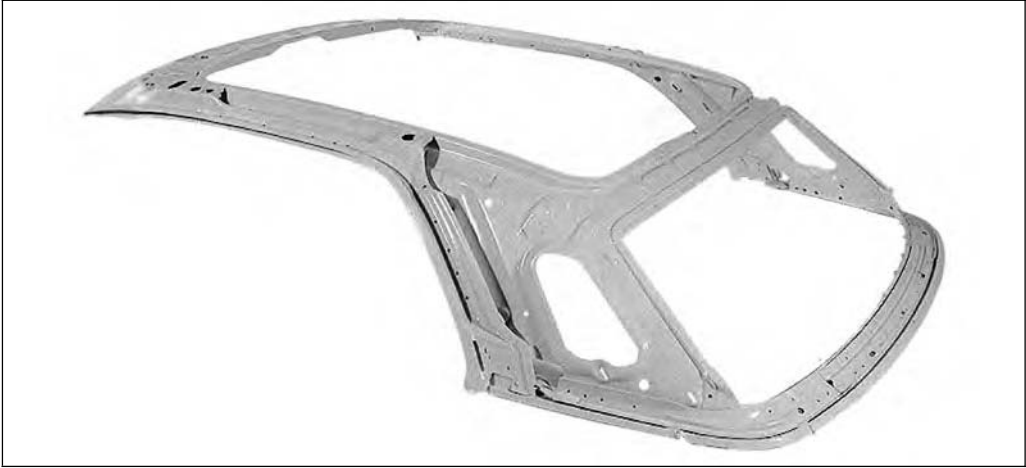


Figure 20.3 Hardtop BMW 3 series with 125 clinched joints (Eckold GmbH & Co. KG)

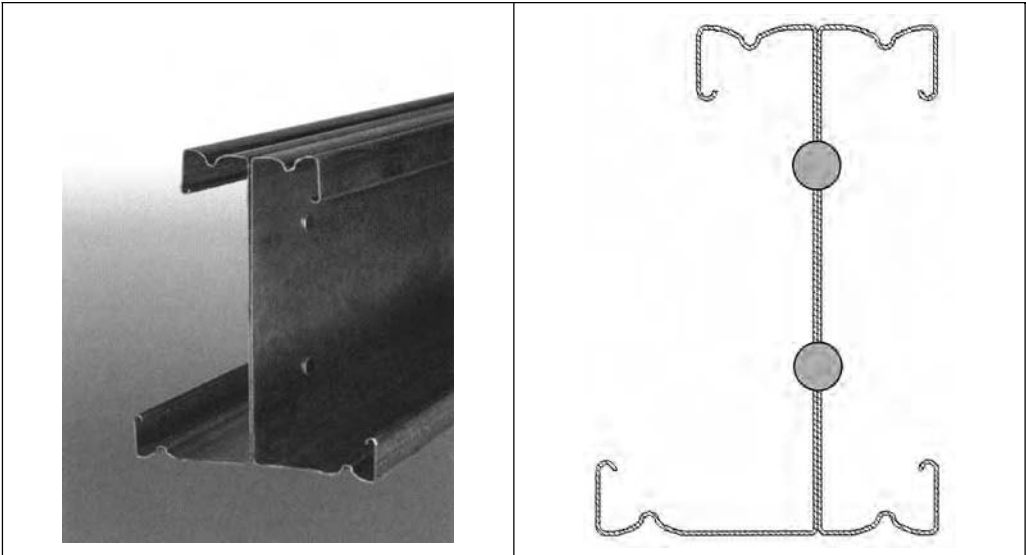


Figure 20.4 Roof rack (Eckold GmbH & Co. KG)

20.1.3 Tooling and equipment

Figure 20.5 shows active tooling components with a diagram of their accessibility.

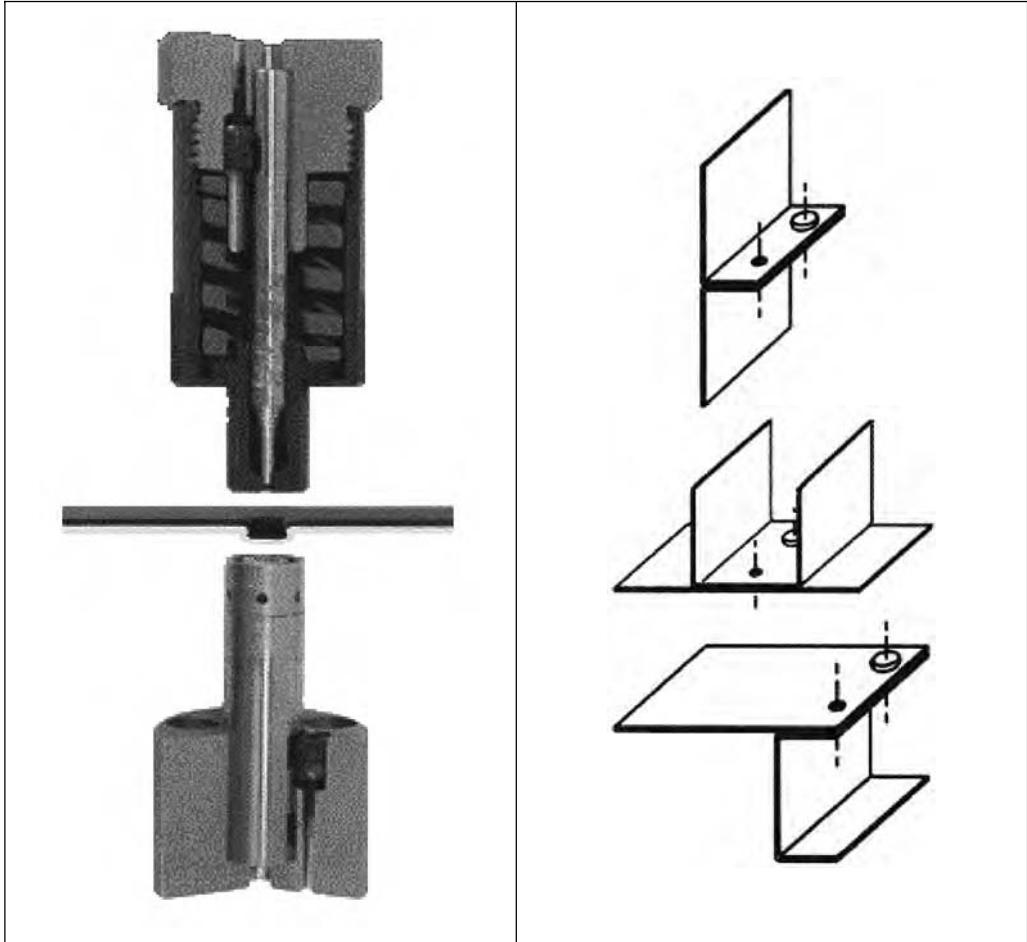


Figure 20.5 left: tooling; right: problem with accessibility (BTM Europe GmbH)

Figure 20.6 shows stationary use; a framing (joining) cell with ten clinching mechanisms for producing automotive bonnets. At 30 – 100 kN, the forces required for clinching are considerably higher than with spot welding; they require sturdier C-frames.

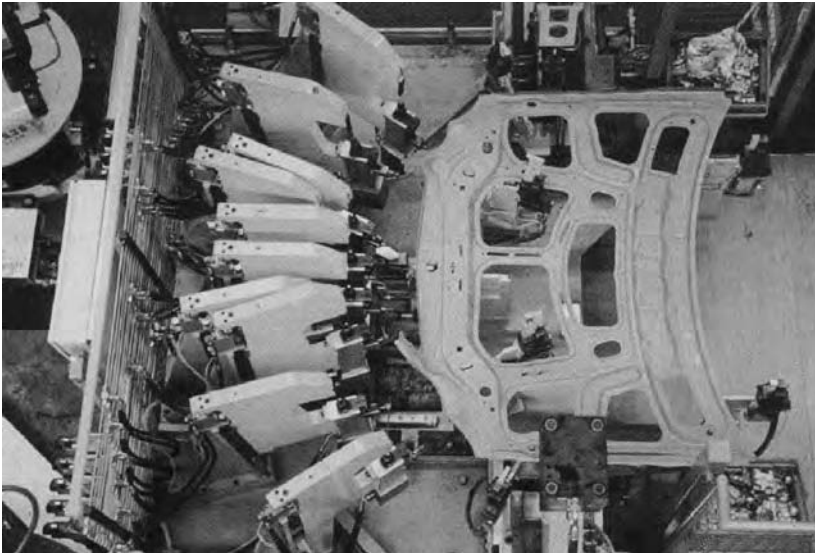


Figure 20.6 Joining cell (Eckold GmbH & Co. KG)

20.1.4 Trends in development

Future applications will require advances in quality, e.g.:

- lower tooling and equipment costs (e.g. Figure 20.7 point joined without a shaping die)
- lower joining forces (e.g. clinching with inclined rotating punch)
- better deformability for brittle materials
- combination with other processes (hybrid joining by clinching and adhesive; internal high-pressure forming and clinching with the fluid as an active joining tool)

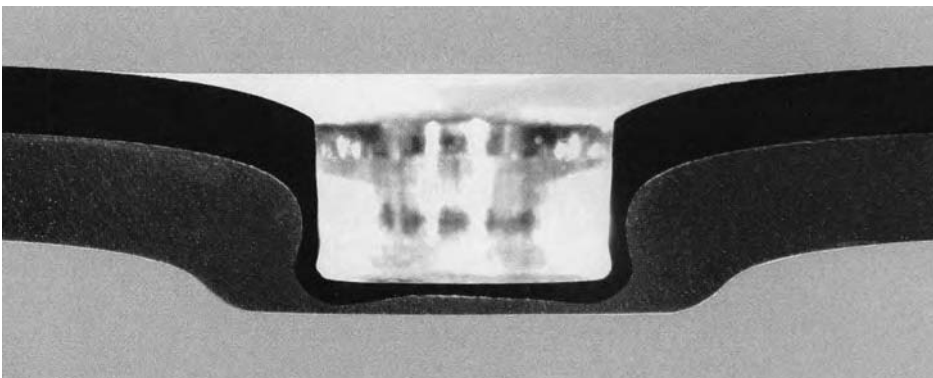


Figure 20.7 Dieless clinching (Fraunhofer Institute for Machine Tools and Forming Technology, IWU, Chemnitz, Germany)

20.2 Punch riveting

20.2.1 Principle

Figure 20.8 shows the riveting process with a punch rivet in four steps. First, the parts to be joined are fixed by the blank holder (view 1). As the punch moves down, the punch rivet penetrates both sheet layers and the scrap is ejected (view 2). As the punch moves on, the conical head of the rivet begins to mould into the upper sheet layer (view 3). Once the head is fully moulded in, the ring on the face of the die presses the lower layer of sheet material into the groove in the rivet shank, creating a positive lock (form closure) overlaid by non-positive radial compressive stresses (view 4).

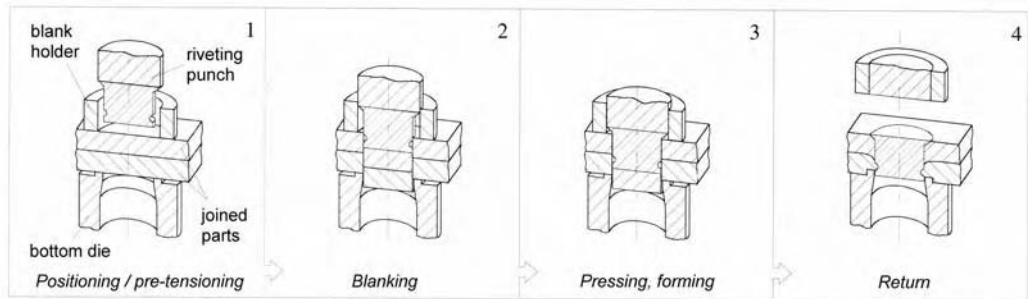


Figure 20.8 Illustration of the principle of punch riveting (LWF, Paderborn University, Germany)

In Figure 20.9 the groove can be seen in the rivet shank of a punch riveted joint. To join different total sheet thicknesses, there is a multi-range rivet with several grooves.

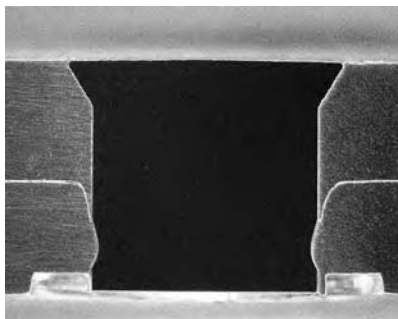


Figure 20.9 Cross-section of a punch riveted joint (Fraunhofer IWU, Chemnitz, Germany)

20.2.2 Application of the process

Figure 20.9 shows the smoothness of the joint at the head area and its flush fit on both sides. These advantages are often a criterion for its use. The main range of application for this joint is

between $s = 1.5$ and 5 mm total sheet thickness, the lower layer requiring a minimum thickness of around 1 mm in order to fill the groove in the shank.

Even materials of $R_m > 1000$ MPa can be joined. In the upper layer, very thin materials (< 1 mm) and non-metals can also be used. Deformability is not a major constraint. The shearing process results in a very restricted local deformation, meaning that materials with low failure strain, e.g. Magnesium, can also be processed.

The main areas of application for solid punch riveting are the automobile industry (Figure 20.10) and the rail vehicle industry.



Figure 20.10 Punch-riveted thermal shield for the Audi TT (produced by Kerb-Konus-Vertriebs-GmbH)

20.2.3 Tooling and equipment

Figure 20.11 shows a punch-riveting unit consisting of a robot and a C-frame (also known as a gap frame). The rivets are processed using a magazine; the drive is a hydraulic cylinder.

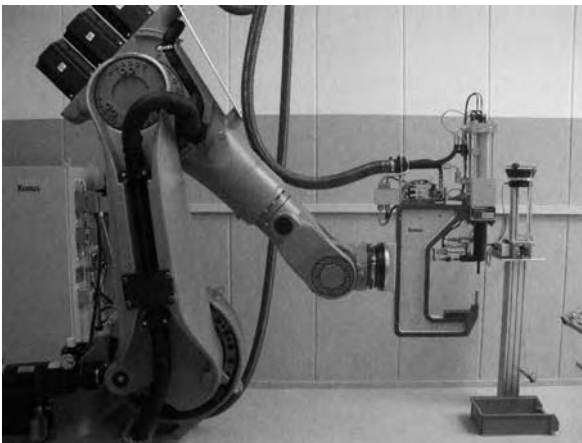


Figure 20.11
Punch-riveting unit (Kerb-Konus-Vertriebs-GmbH)

20.2.4 Trends in development

Future development is heading in the following directions:

- lower-cost rivets (manufactured by deformation instead of a chip-producing method), tools and equipment
- FEM calculation (Figure 20.12)
- lower joining forces; accessibility from one side (e.g. high speed)
- wider spectrum of uses (new rivet shapes or tooling concepts, e.g. split dies)
- corrosion-resistant joint (e.g. ceramic rivets)
- combination with other methods (clinching and adhesion).

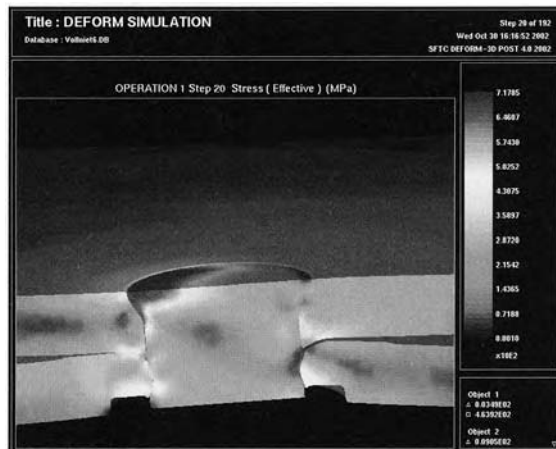
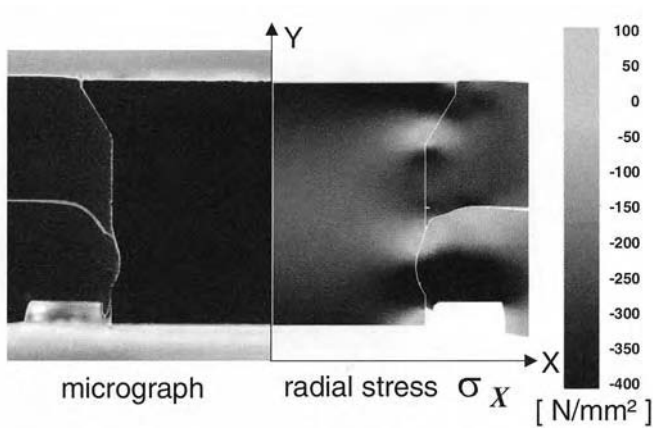


Figure 20.12 a) Cross-section and 2D joining simulation; b) 3D stress simulation for punch-riveted joint (Fraunhofer IWU, Chemnitz, Germany)

End-to-end numerical solutions offer a huge advantage in terms of time and expense. However, they must cover the individual steps of sheet forming, joining and stressing in all their complexity and the deformation history produced in each case. The simulation of the joining method shown in Figure 20.12 (final state) can be calculated axisymmetrically (2D). The shear tension stress, on the other hand, creates a complex stress condition which must be considered spatially (3D).

20.3 Self-piercing riveting with semi-tubular rivets

20.3.1 Principle

Figure 20.13 shows the riveting process with a self-piercing semi-tubular rivet in four steps. First, the parts to be joined are fixed by the blank holder (view 1). As the punch moves down (view 2) the rivet pierces only the upper sheet layer nearest the punch and the punched scrap is taken up into the cavity of the semi-tubular rivet. As the punch moves on, the lower part of the self-piercing semi-tubular rivet splits open and the undercut is formed (view 3). Again, with this positive lock, radial compressive stresses remain which create the non-positive lock important for cyclic resilience (view 4).

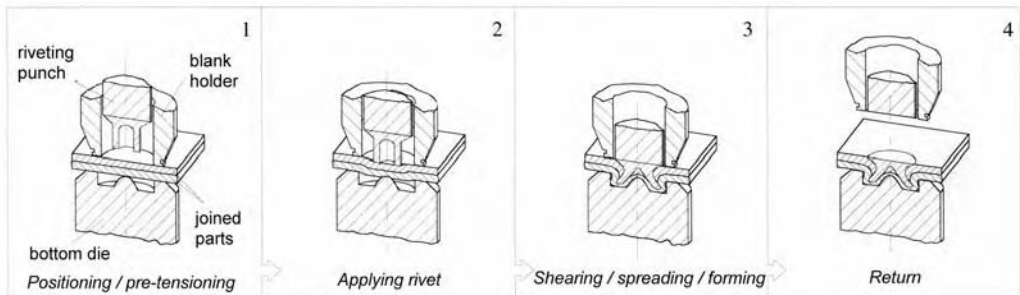


Figure 20.13 Diagram of the principle of self-piercing semi-tubular riveting (LWF, Paderborn University, Germany)

Figure 20.14 shows a self-piercing semi-tubular rivet joint. The pierced upper sheet layer and the undercut in the lower layer can be clearly seen. In the lower part, the contour of the die is clearly visible.

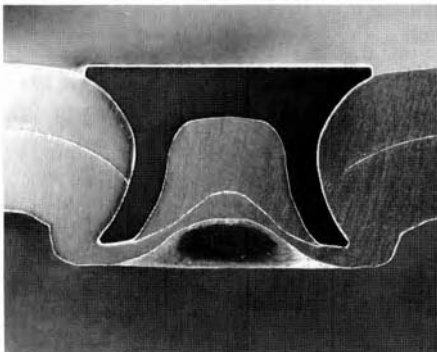


Figure 20.14 Cross-section of a self-piercing semi-tubular rivet joint (Fraunhofer IWU, Chemnitz, Germany)

20.3.2 Application of the process

The self-piercing semi-tubular rivet joint has the highest strength of all such joints, especially compared with spot welding. This advantage is the reason why these joints are permitted for use in the parts of an automobile subjected to most stress in a crash.

The joint is mainly used in the range of $s = 1.5 - 4$ mm total sheet thickness. Materials can be joined with an R_m of up to 1000 MPa, the general rule for combination being, unlike clinching, that the thinner and/or softer semi is placed on the punch side.

As with clinching, the required deformability is a constraint, meaning that it is better to place brittle materials such as die-cast aluminium on the punch side.

The main area of application for self-piercing semi-tubular riveting is the automobile industry (Figure 20.15).

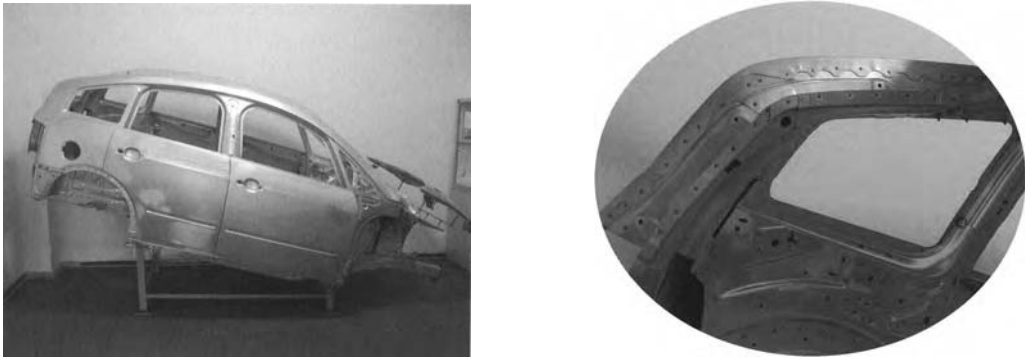


Figure 20.15 left: Audi A2 with 1800 semi-tubular rivet joints, right: close-up (Photographs from Dresden University of Applied Sciences, Germany)

20.3.3 Tooling and equipment

The active components in Figure 20.16 (blank holder, punch and die) demonstrate the basic layout generally used for all joining processes without pre-punching.

As well as the hydraulic drives used for riveting systems, which usually feature a positive stop at the bottom dead centre, electrically-driven spindles are also starting to coming into increasing use in production (Figure 20.17). This completely different concept means that different types of regulation and monitoring are needed and can be used.

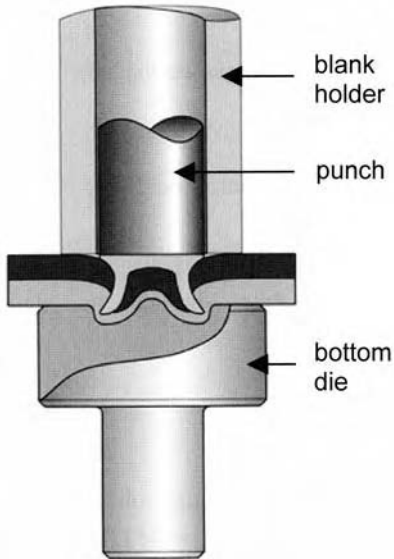


Figure 20.16
Schematic cross-section of the active components during semi-tubular riveting (Böllhoff GmbH)

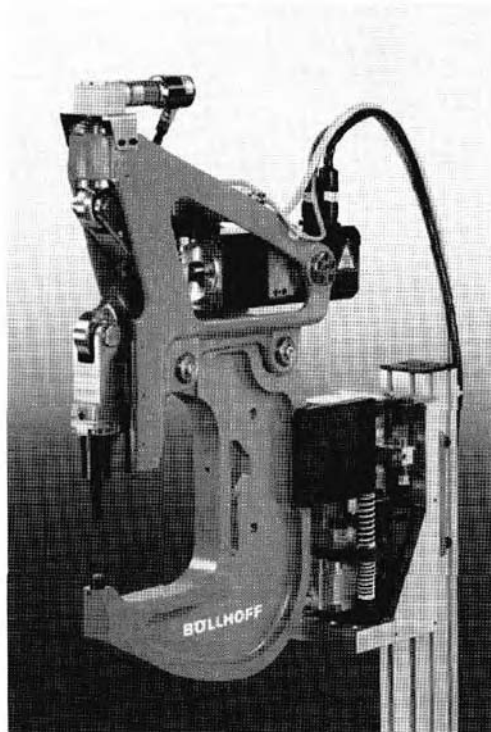


Figure 20.17 C-frame on knuckle-joint basis and spindle motor (without rivet feed; Böllhoff GmbH works)

20.3.4 Trends in development

Similarly to clinching and punch riveting, again the problems to be solved concern

- cost reduction
- improved joinability for high-strength sheet (use of high-strength rivets, workpiece heating)
- raised process stability (tolerance for process fluctuations)
- monitoring (monitoring of force is the standard; other possible methods are the analysis of distance or impact sound)
- realistic calculation of the processes
- reduction of joining force
- accessibility from one side
- raised resistance to corrosion (e.g. new kind of coating in a vacuum)
- combination with other methods (punch riveting and adhesion; internal high-pressure forming and self-piercing semi-tubular riveting with the fluid as an opposing force)

The method described above with clinching, with a single, flat opposing die with no shaping die, can be used for riveting following the same principle (Figure 20.18) with the following aims:

- no more concentricity required between punch and die, no outlay for setup, low tooling wear, high process stability; better accessibility during joining
- bump on underside flatter (good for structural space requirement, appearance, cleaning, lacquering, hybrid joining with displacement of adhesive in the undercut area)

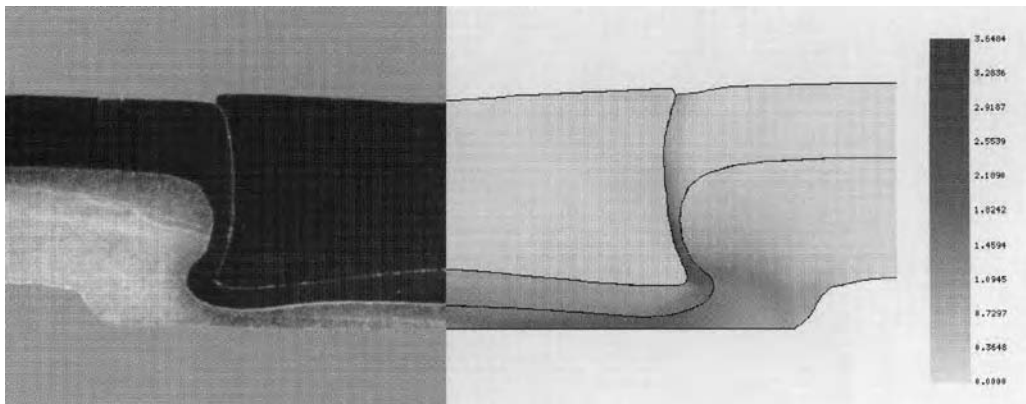


Figure 20.18 Dieless rivet clinching; left: experiment, right: calculation (Fraunhofer IWU, Chemnitz, Germany)

Part II: Presses

21 Types of press

According to their characteristics, presses can be classified into those controlled mainly by work (energy), the ram path or force.

21.1 Presses controlled by work

Hammers and screw presses are machines whose main characteristic is their work capacity (energy). A hammer's work capacity is determined from the ram mass and drop height. With screw presses, the work capacity is stored in the rotating masses (mainly in the flywheel), therefore it depends upon the angular velocity and the mass moment of inertia. The two kinds of machine are similar in that the work capacity can be influenced or adjusted.

The force, on the other hand, can not be directly adjusted, but depends upon the kind of work-piece and the deformation distance.

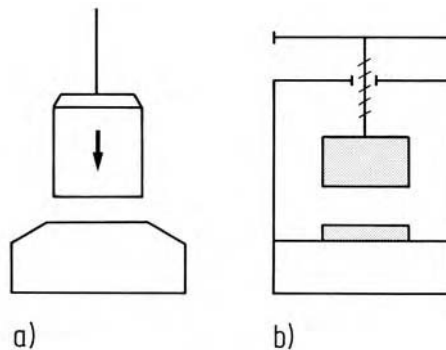


Figure 21.1 The principle of presses controlled by work, a) drop hammer, b) screw press

21.2 Presses controlled by the ram path

These include crank presses and knuckle-joint presses. With these presses, the deformation is complete when the ram has reached its lowest position (bottom dead centre – BDC). This means their characteristic value is the ram path limit, which comes from the crank radius r in crank presses and from the leverage with knuckle-joint presses (Figure 21.2).

With crank presses the nominal force of the press is available at a crank angle of 30° before BDC up to BDC, whereas with a knuckle-joint press, the nominal press force (depending on the leverage) is only available within a range of 3 to 4 mm before BDC.

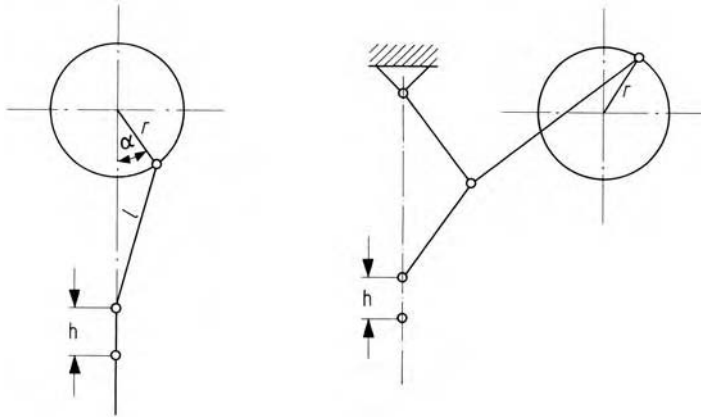


Figure 21.2 Drive layout of presses controlled by the ram path, a) crank press, b) knuckle-joint press

21.3 Presses controlled by force

The operation of hydraulic presses depends upon force, as the only thing which can be adjusted about them is the force (via the operating pressure).

As the deformation forces fluctuate within certain limits (differences in material strength, blank tolerances, lubrication and condition of the tooling), a dimensionally accurate part can only be produced on a hydraulic press if the deformation distance is limited. This can be carried out in the press itself using positive stops, or in the die.

This kind of ram path limit is also needed for presses controlled by work.

21.4 Question on Chapter 21

How are presses classified?

22 Hammers

22.1 Columns and frames

Figure 22.1 shows the most important types of hammer column.

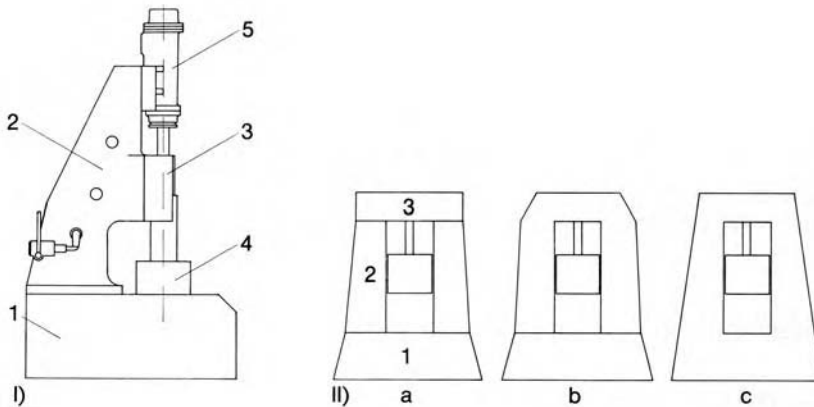


Figure 22.1 Hammer frame designs. I) Single-column frame, 1 anvil, 2 column, 3 ram guide, 4 ram, 5 air cylinder; II) structural designs of two-column frames, a) anvil 1, side column 2 and head 3, separate, b) side columns and head in one piece, c) anvil, side columns and head in one piece

22.2 Types of hammer

Hammers are classified according to the drive design into:

- drop hammers
- double-acting hammers
- counterblow hammers.

With drop hammers, the ram drops freely. The impact energy comes from the mass of the ram and the drop height. Belts, chains or with hydraulic drives the piston rod are used to lift the ram.

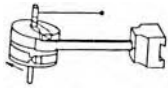
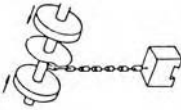
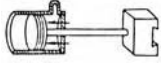
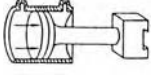
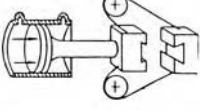
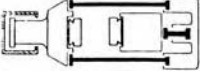
At present, hydraulic lifting devices are mainly used for reasons of cost-efficiency.

$$W = m \cdot g \cdot H$$

With double-acting hammers a pressure medium (air or compressed oil) is used as well as the drop energy to further accelerate the ram. This means that higher ram impact velocities can be achieved, thus raising the impact energy.

$$W = \frac{m}{2} \cdot v^2$$

Table 22.1 Types of hammer

Elements and parameters	Hammers with anvil block				Hammers without anvil block			
	Drop hammers		Double-acting hammers		Counterblow hammers		with hydraulics	
	Coupling with belt	with chain	with hydraulics		with bands			
Lifting mechanism								
Pressure mechanism	Belt	Chain	Piston rod	Piston rod	Piston	Differential piston		
Energy for working movement	Free fall	–	–	Air Compressed oil	Air Compressed oil	Compressed oil		
Max. drop height in m	2	1.3	1.3	1.3	–	–		
Ram acceleration a (m/s)		$a < g$		$a > g$				
Impact velocity v_A (m/s)		approx. 5		6	6–8	8–14		
Work capacity $W = m \cdot v^2/2$		$m \cdot g \cdot h$		$m \cdot g \cdot H + P \cdot 10^{-1} \cdot A \cdot H$	$\frac{(m_1 + m_2)}{2} \cdot v^2$			
Max. work capacity W (kJ/m)	80	100	160	200	1000	1000		1000

With double-acting hammers, in order to have the same available impact energy as with a drop hammer, the following is needed:

smaller stroke heights

smaller ram masses.

This results in a higher number of blows per time unit and more economical processing during the forging operation.

From the point of view of the drive, counterblow hammers are double-acting hammers with no extra drop energy. Only the upper ram is driven. The lower ram is driven indirectly by means of a mechanical coupling using strip steel or a hydraulic coupling.

At present only hammers with hydraulic couplings are built. Table 22.1 (previous page) shows how hammers are classified.

22.3 Constructional design

22.3.1 Drop hammers (Figure 22.2)

$$W = m \cdot g \cdot H \cdot \eta_F$$

(potential energy)

W	in Nm	impact energy
W_e	in Nm	effective work
m	in kg	ram mass
H	in m	drop height
v	in m/s	ram impact velocity
g	in m/s ²	drop acceleration
η_F	–	drop efficiency
η_i	–	impact efficiency ($\eta_i = 0.5 - 0.8$).

$$W = \frac{m \cdot v^2}{2}$$

(kinetic energy)

$$W_e = \eta_i \cdot W$$

$$v = \sqrt{2 \cdot g \cdot H}$$

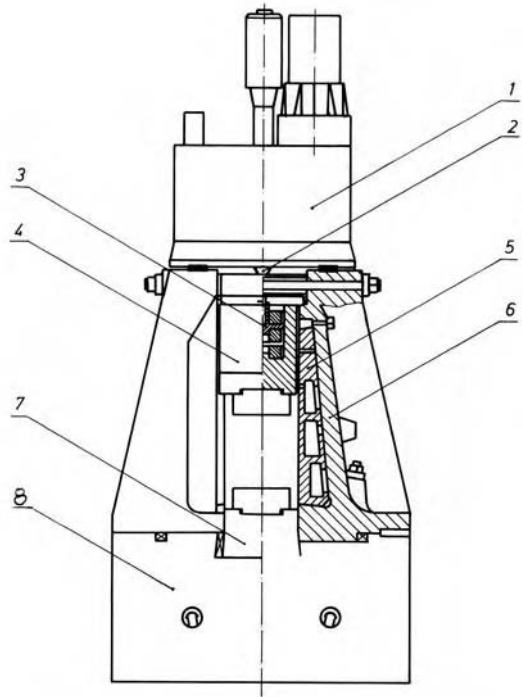


Figure 22.2 Electro/oil-hydraulic drop hammer
1 hydraulic drive, 2 con rod guide, 3 ram lock, 4 ram, 5 guides, 6 columns, 7 anvil bolster, 8 anvil block (Illustration from LASCO Umformtechnik works, Coburg, Germany)

The hydraulic drop hammer shown in Figure 22.2 has a three-part frame. The materials used are:

- a) Anvil and side columns: grey cast iron with added steel.
This special cast iron is a better damper and has a more homogeneous structure than cast steel.
- b) Ram: high-alloy, hardened and tempered cast electric steel or quenched and tempered steel.
- c) Guides: hardened, ground steel prism guides.

For hammers with an anvil block, the impact effect depends upon the ratio of

$$\frac{\text{impact energy}}{\text{mass of the anvil}}$$

Modern hammers have values of $Q = 1.0 - 1.2$.

$$Q = \frac{W(\text{Nm})}{m_a(\text{kg})}$$

The impact efficiency of a hammer is determined by this value. In the past, the following ratio was used to measure the impact effect:

$$\frac{\text{anvil mass (kg)}}{\text{ram mass (kg)}} = \frac{10}{1} \text{ to } \frac{20}{1}$$

However, as the anvil mass remains relatively small with small ram masses, this mass ratio can not be used to measure the impact effect.

22.3.2 Double-acting hammers

With double-acting hammers the work capacity of the falling ram is raised further by a propellant (air or compressed oil).

$$W = m \cdot g \cdot H + p \cdot 10^{-1} \cdot A \cdot H$$

$$W = H \cdot (m \cdot g + p \cdot 10^{-1} \cdot A)$$

W	in Nm	impact energy
m	in kg	ram mass
g	in m/s ²	drop acceleration
H	in mm	drop height
p	in bar	operating pressure
A	in cm ²	piston area
10^{-1}		conversion from bar to N/cm ²

With air-powered hammers, pressures are used of $p = 6 - 7$ bar.

Double-acting hammers are built as both single- and double-column hammers. The advantage of double-column hammers is the better ram guide and the more rigid self-contained column.

The hydraulic double-acting hammer shown in Figure 22.3, with fully electronic controls, is a development of this kind of hammer. The hydraulic pressure from above means that the ram reaches its impact velocity of around 5 m/s in the shortest distance possible. Thus, the impact frequency is considerably higher than with a drop hammer.

The result is short tooling contact times, lengthening tooling lives. These LASCO hammers are built with an impact energy of 6.3 - 400 kJ (63,000 - 400,000 Nm). Up to about 150 kJ (150,000 Nm) work capacity, the hammer is built with what is known as a U frame. When the work capacity is higher, a segmented frame construction is used because of the higher anvil weight and the transport problems this involves.

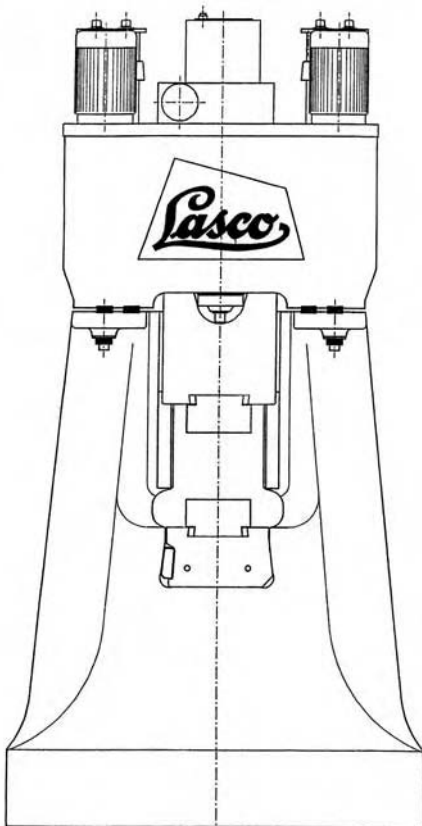


Figure 22.3
HO-type hydraulic double-acting hammer
(Illustration from LASCO Umformtechnik works,
Coburg, Germany)

The U-frame shape is ideal, with optimum mass distribution. It stands out for its high rigidity. The stress-optical characteristics of the most crucial cross-sectional transitions are optimised. The frame material is specially heat-treated alloyed cast steel. The weight of the frame and the base area are set up to accommodate spring dampers (Figure 22.3). A well-dimensioned bolster to hold the die, made of quenched and tempered steel, is wedged in the U frame.

The ram, made of forged quenched and tempered steel, is a block ram. The guides are in an X arrangement. The ram is guided precisely, with as little play as possible, in adjustable guide bars made of hardened steel mounted in the U frame.

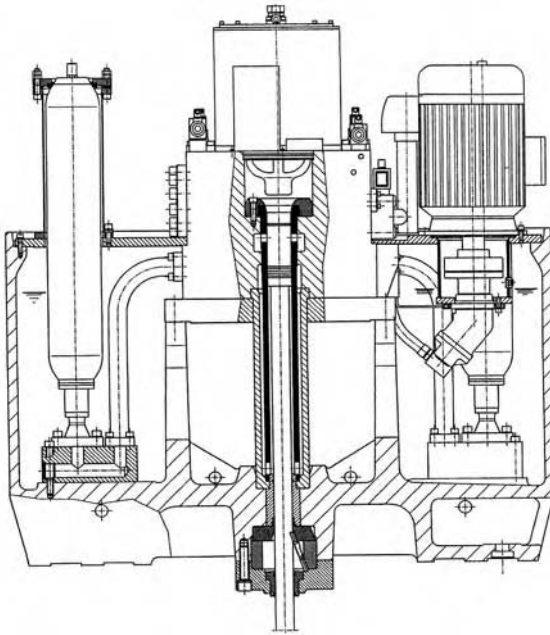


Figure 22.4
Double-acting hammer hydraulic drive
(Illustration from LASCO Umformtechnik
works, Coburg, Germany)

The drive system (Figure 22.4) is fully enclosed and cast in a modular design. It is installed in the head of the hammer which also serves as an oil chamber. In the forged control block, where the main control elements are combined in an integral hydraulic lift system, there are as few failure-prone pipes as possible.

At the heart of the hydraulic unit are long-lasting axial piston pumps, driven by special rotary current motors via elastic couplings, in connection with hydraulic accumulators.

Figure 22.5 again compares various structural designs of double-acting hammers.

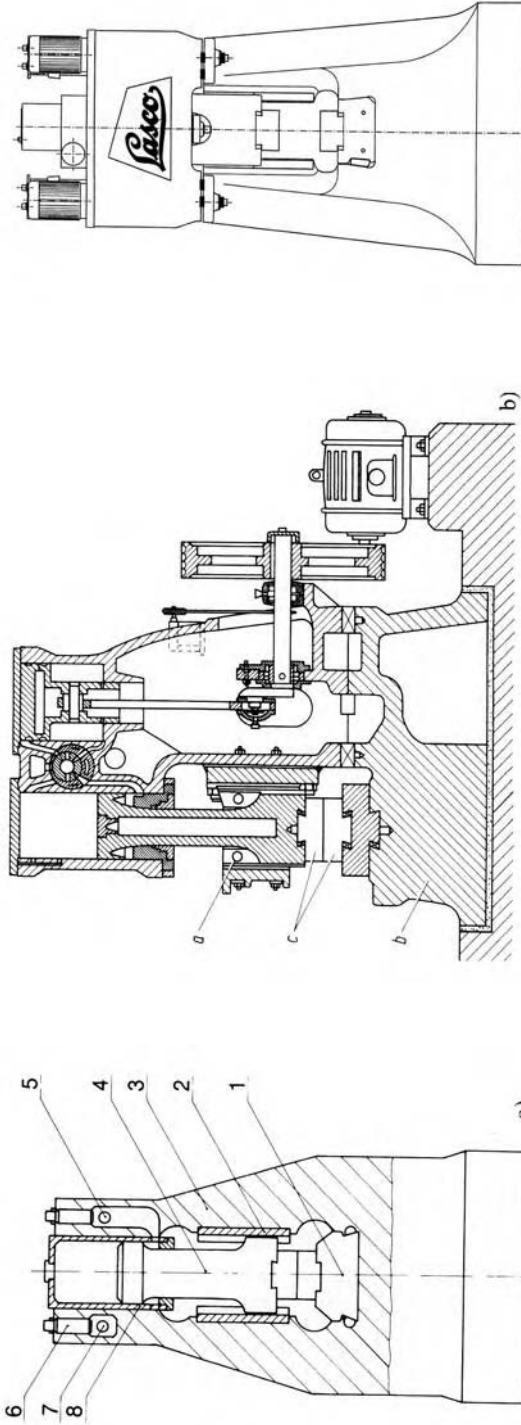


Figure 22.5
Structural designs of double-acting hammers, a) double-column double-acting hammer with pneumatic or hydraulic drive (Banning principle), 1 anvil bolster, 2 ram guide, 3 hammer body, 4 ram, 5 propellant feed, 6 pilot valve, 7 propellant outlet, 8 cylinder liner

b) Single-column air drop hammer (Béché & Grohs principle).
a extra ram guide, b anvil, c dies

c) Hydraulic U-frame design double-acting hammer (LASCO Umformtechnik)

22.3.3 Counterblow hammers

Counterblow hammers have two rams which strike one another. By this means the forces in the frame are reduced as much as possible, so these hammers need no bed or only a small one.

The construction mass of a counterblow hammer is only one-third of that of a hammer with an anvil block which has the same work capacity. From the point of view of the drive, the counterblow hammer is a double-acting hammer with a powered upper ram.

The lower ram is moved by a coupling with the upper ram; this coupling is mechanical (steel bands, Figure 22.6) or hydraulic (Figure 22.7)

Today, hammers with mechanical couplings (Figure 22.6) are no longer built.

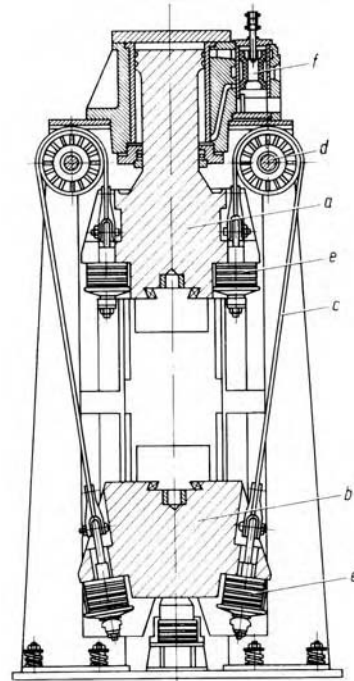
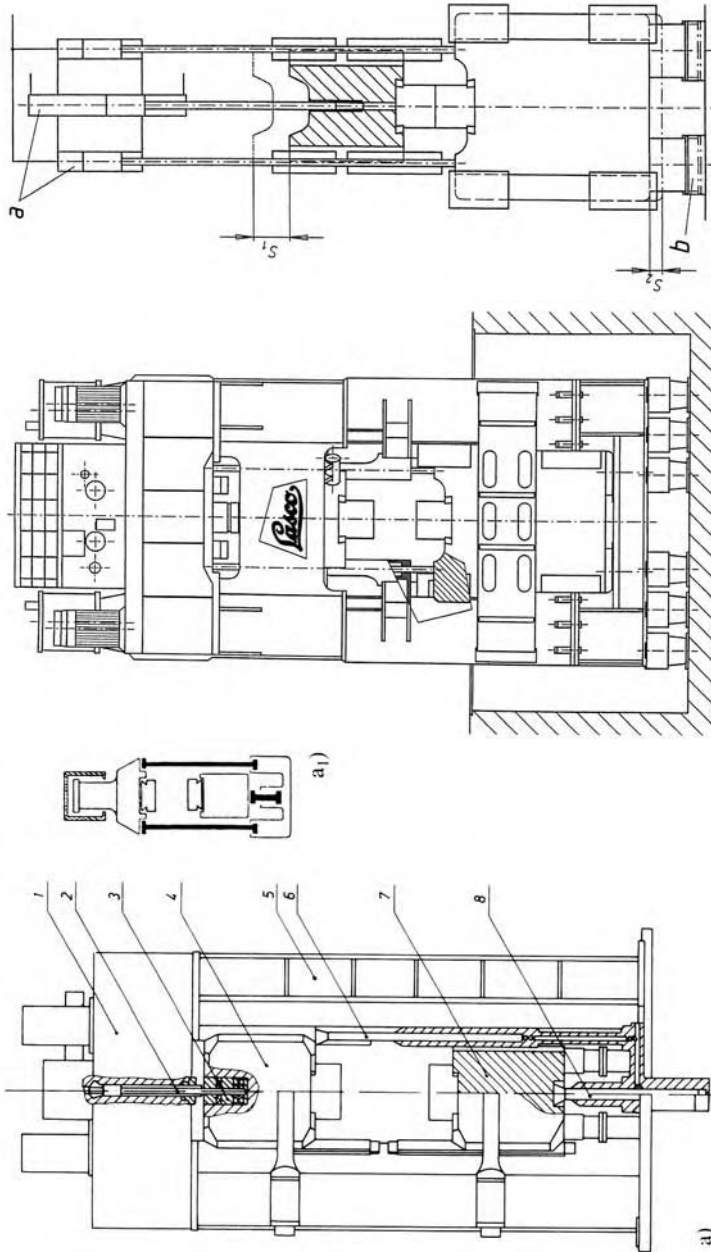


Figure 22.6 Counterblow hammer (Bêché & Grohs) with steel band coupling, a) upper ram with piston rod, b) lower ram, c) steel bands, d) pulley, e) rubber buffer, f) pilot valve

The counterblow hammer (Figure 22.7a, Bêché & Grohs system) is built with both pneumatic and hydraulic drives. With this hammer, the upper and lower rams are connected by a hydraulic coupling. It basically consists of two coupling pistons acting on the upper ram; on the hammer stroke, these power the pistons acting on the lower ram via a column of oil (Figure 22.7a). The pistons are linked directly to the rams without any elastic connectors. The system is low on maintenance due to its simple construction. The coupling cylinder below the lower ram is fitted with a hydraulic brake. On the return stroke the lower ram is braked before reaching the end of travel and is gently intercepted by the impact buffers, meaning that the bed only has low forces (stresses) to absorb.

With the LASCO principle counterblow hammer (Figure 22.7b) both rams are driven towards one another. The upper ram is accelerated as with a normal double-acting hammer. The lower ram is driven by means of pre-stressed air buffers. As the rams have different masses (the upper ram to lower ram mass ratio being around 1 : 5) the ram strokes and ram speeds are also different. When the impact begins the upper ram piston is hydraulically actuated. At the same time, the same valve is used to disengage the hydraulic cylinder via the upper ram and accelerate the lower ram using the gas energy from the lower stressed air buffer. When the rams meet, the cylinder of the upper ram is disengaged by the main valve and driven into its initial position by the constant retreat of the upper ram. In parallel, the pistons above the lower ram are actuated via the same valve and the lower ram is also brought into its initial position. The air buffers under the lower ram are stretched in this process.



b 1) Principle of the LASCO counterblow hammer drive with hydraulic and pneumatic coupling
 a) hydraulic cylinder
 b) air cylinder
 s_1 upper ram stroke
 s_2 lower ram stroke

b) LASCO Umformtechnik counterblow hammer

Figure 22.7
 Drive systems of hydraulic counterblow hammers.
 a) Bêché & Grohs principle, 1 hydraulic drive, 2 piston rod, 3 ram lock, 4 upper ram, 5 hammer frame, 6 and 8 piston rods (hydraulic coupling), 7 lower ram: a_1 plan of the hydraulic coupling.

As the ram drive is controlled by a single valve, the impact plane (forging plane) is precisely fixed. The lower ram stroke is about 120 – 150 mm. Its low impact velocity of around 1.2 m/s means that both flat and complicated forgings lie steady in the die on impact. The resultant impact velocity is around 6 – 8 m/s.

With these hammers the maximum ram impact velocity is around 8 to 14 m/s. The impact energy can be determined from the resultant impact velocity of the rams and the ram masses.

Impact energy:

$$W = \frac{m \cdot v^2}{2} = \frac{(m_1 + m_2)v^2}{2}$$

W in Nm impact energy
 m_1 in kg mass of the upper ram
 m_2 in kg mass of the lower ram
 v in m/s final velocity before impact.

In order for the counterblow hammer to open automatically when the machine stops, the lower ram mass is set about 5 % higher than that of the upper ram. Thus, for hammers with band couplings

$$W = \frac{2.05 \cdot m_1 \cdot v^2}{2}$$

22.4 Fields of application for hammers

Table 22.2 shows which kinds of hammers are used with different types of impression-die forging.

Table 22.2 Uses for hammer types

Hammer type	Application
Drop hammers	small to medium-sized impression-die forgings, e.g. wrenches, levers, coupling components
Double-acting hammers (double-column)	medium to large-sized impression-die forgings, e.g. camshafts, flanges
Counterblow hammers	difficult and extremely difficult impression-die forgings, e.g. large crankshafts, levers which are hard to form, large coupling components

22.5 Example

Where:

Drop height $H = 1.6$ m

Ram mass $m = 500$ kg

Drop efficiency $\eta_F = 0.7$

Impact efficiency $\eta_i = 0.8$.

Find: theoretical ram impact velocity v , effective work.

Solution:

Ram impact velocity:

$$v = \sqrt{2 \cdot g \cdot H} = \sqrt{2 \cdot 9.81 \text{ m/s}^2 \cdot 1.6 \text{ m}} = \underline{\underline{5.6 \text{ m/s}}}$$

The actual impact velocity is lower due to friction losses in the guides.

$$v_{\text{actual}} = \eta_{\text{fr}} \cdot v \quad \eta_{\text{fr}} = 0.8 - 0.9$$

Impact energy:

$$W = m \cdot g \cdot H \cdot \eta_F = 500 \text{ kg} \cdot 9.81 \text{ m/s}^2 \cdot 1.6 \text{ m} \cdot 0.7$$

$$W = 5493.6 \text{ N m} \cong \underline{\underline{5.5 \text{ kN m}}}$$

Effective work:

$$W_e = \eta_i \cdot W = 0.8 \cdot 5.5 \text{ kN m} = \underline{\underline{4.4 \text{ kN m}}}$$

If the actual impact velocity is known then the impact energy can also be determined thus:

$$v_{\text{actual}} = \eta_{\text{fr}} \cdot v = 0.84 \cdot 5.6 \text{ m/s} = 4.7 \text{ m/s}$$

$$\eta_{\text{fr}} = 0.84 \text{ selected.}$$

$$W = \frac{m \cdot v^2}{2} = \frac{500 \text{ kg} \cdot 4.7^2 \text{ m}^2/\text{s}^2}{2 \cdot 10^3} = \underline{\underline{5.5 \text{ kN m}}}$$

22.6 Exercise on Chapter 22

1. What kinds of hammer frame construction are there?
2. How are hammers classified?
3. What advantages do double-acting hammers have over drop hammers?
4. When are counterblow hammers used?

23 Screw presses

Screw presses are mechanical presses where the ram is moved up and down by a threaded spindle (usually three-gear). These presses are controlled by energy; the work capacity (available energy) is the only thing about them which can be directly adjusted. The work capacity stored in the flywheel comes from its dimensions and rotation speed.

$$W = \frac{\omega^2}{2} \cdot I_d = \left(\frac{\pi \cdot n_s}{30} \right) \cdot \frac{I_d}{2}$$

W in Nm work capacity

n_f in min^{-1} flywheel rotation speed

I_d in kg m^2 mass moment of inertia

30 in s/min conversion of the rotation speed from minutes to seconds

ω in s^{-1} angular velocity

23.1 Forms of structural design

Flywheel construction is categorised:

1. *According to the way the flywheel is accelerated:*

- friction wheel with disc drive
- hydraulic drive
- direct electric motor drive
- wedge drive

2. *According to the way the ram is moved vertically:*

- ram moves up and down with spindle and flywheel
- spindle fixed in place with flywheel. Only the ram, shaped like a nut, moves vertically.

This construction is called a Vincent press.

23.2 Functions of the individual styles of construction

23.2.1 By friction, spindle can be moved axially

The driving discs, turning at a constant speed (Figure 23.1), can be moved in the direction of the shaft axis. Thus, one driving disc at a time can be pressed against the flywheel using a rod, by hand, with electro-pneumatics or hydraulics. By friction, one driving disc pushes the flywheel with the threaded spindle and the ram downwards, while the other disc, turning the opposite way, pushes them back up. The press column, made of grey cast iron, is steadied by steel (e.g. St 60) tie rods. The flywheel, also made of grey cast iron, has a chrome leather bracket around it to ensure that energy is transferred smoothly. The material generally used for the press ram is cast steel.

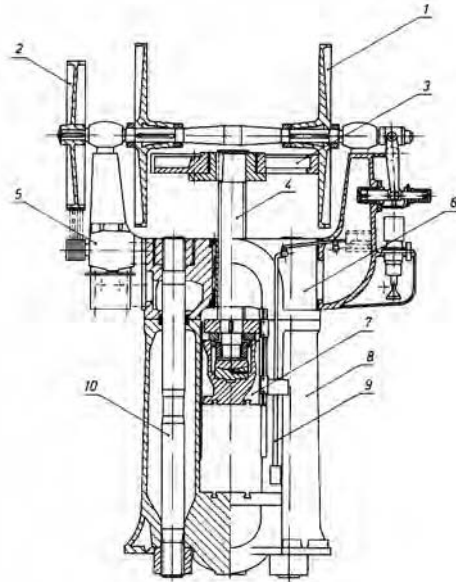


Figure 23.1

23.2.2 With friction wheel, spindle in fixed position – Vincent presses

Here (Figure 23.2) the spindle is fixed in place, meaning that the press ram, shaped like a nut, moves alone axially. With this Vincent press, the driving discs run on rolling bearings and are connected by movable tubes coupled to one another (Figure 23.3) in such a way that although the driving discs act together in the direction of rotation, each disc can be moved independently laterally. With this press the driving discs can also be moved laterally by an adjustment disc to maintain an ideal clearance between the driving discs and the flywheel even when the bracket wears down.

If the clearance between the driving disc and the flywheel was too great, the press would jerk when started up.

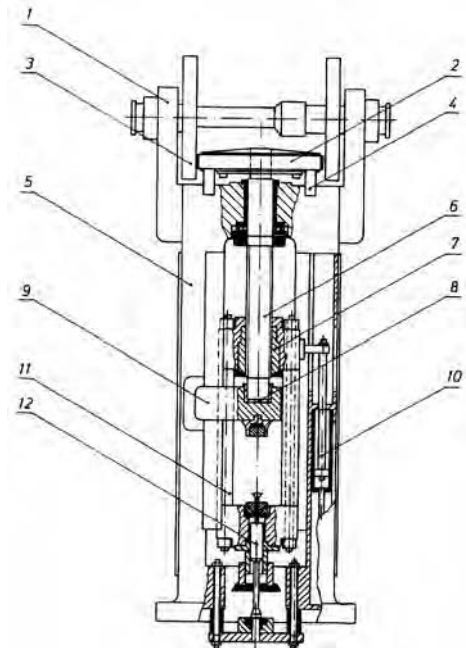


Figure 23.2

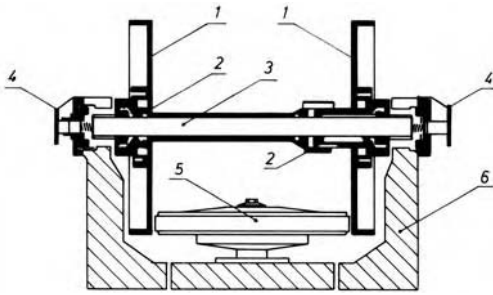


Figure 23.3 Cylinder friction disc gearing on a Vincent press, 1 driving discs, 2 rolling bearing, 3 fixed axle, 4 adjusting device, 5 flywheel, 6 press frame (Illustration from Hasenclever works, Düsseldorf, Germany)

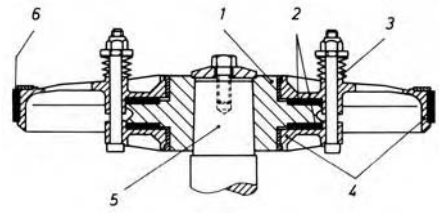


Figure 23.4 Cross-section of a flywheel with slip clutch (Hasenclever principle) 1 fixed section, 2 friction lining, 3 springs, 4 loose section, 5 spindle, 6 bracket

In modern Vincent presses the flywheel (Figure 23.4) is usually designed as a slip wheel. It contains a spring-loaded slip clutch.

As the press force which occurs is proportional to the moment, the maximum press force can be limited by adjusting the slip moment optimally (load-limiting device).

$$M = F \cdot r \cdot \tan(\alpha + \rho)$$

M in Nm moment

F in N press force

r in m spindle flank radius

α in deg. pitch angle of the thread

ρ in deg. angle of friction (about 6° equals $\mu = 0.1$ for steel on bronze).

On screw presses, maximum $2 \cdot F_N$ (F_N = nominal press force) is allowed for blows with recoil.

The press elements (column, spindle etc) are set up for this value.

With a slip wheel, the work capacity can be around twice as much as without, so as not to exceed this limiting value of $2 F_N$. Curve 1 (Figure 23.5) shows the possible energy supply required not to exceed $2 F_N$ on a press without a slip wheel (37%); Curve 2 shows the same value for the same press with a slip wheel (100%).

Figure 23.1 (above left) Screw press with three-disc cylinder gears (Kießlering & Albrecht principle) 1 driving disc, 2 wedge-belt pulley, 3 flywheel, 4 spindle, 5 driving motor, 6 head, 7 ram, 8 press column, 9 switch rods, 10 tie rod

Figure 23.2 (below left) Vincent press with three-disc cylinder drive. 1 air pressure cylinder to press the driving discs, 2 flywheel, 3 driving disc, 4 electro-pneumatic brake, 5 press frame, 6 spindle, 7 spindle nut, 8 bearing ring, 9 counter-bearing for the upper die, 10 counterweight, 11 ram, 12 ejector (Illustration: Hasenclever works, Düsseldorf, Germany)

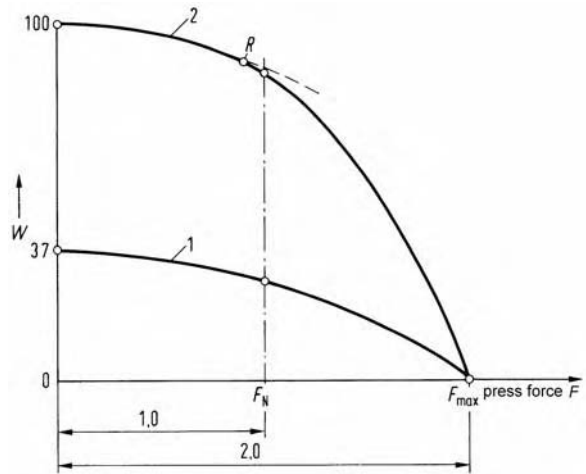


Figure 23.5

Maximum press force $2 F_N$ subject to the available forming energy W . Curve 1: press without slip wheel (W only around $\frac{1}{3}$ of Curve 2) Curve 2: press with slip wheel

23.2.3 Hydraulically-driven screw presses

On the press shown in Figure 23.6 the flywheel F is a helical gear wheel. The plastic pinions P (min. 2, max. 8), driven by hydraulic axial piston motors M , mesh with this helical gearing and accelerate the flywheel to the required speed. The oil motors are fixed in the press frame. As the toothed flywheel moves up and down with the spindle as far as the stroke length, the pinions slide lengthwise along the teeth in the flywheel tooth system. For this reason the flywheel thickness is at least

press stroke + pinion width.

For the return stroke, the oil motors' rotation direction is reversed. The pressurised oil for the oil motors (210 bar) is prepared in a pumping set with axial piston pumps and stored ready for the next stroke in a hydraulic storage system. The spindle nut SN is fixed in the press frame. The spindle S is fixed to the toothed flywheel F and mounted in the ram R so that it is able to turn. In this press, the flywheel is again designed as a slip wheel.

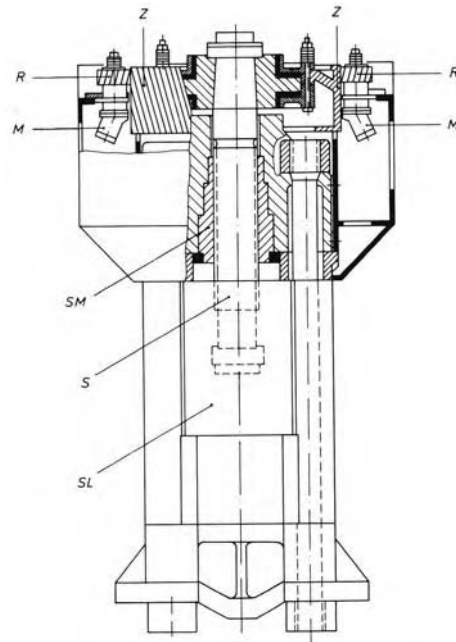


Figure 23.6 Hydraulically-driven screw press. F flywheel, P pinion, M axial piston motors, SN spindle nut, S spindle, R ram (Illustration from Hasenclever works, Düsseldorf, Germany)

23.2.4 Clutch screw press

In the clutch screw press shown in Figure 23.7 the flywheel turns constantly in one direction only. It is powered using a flat belt by a three-phase asynchronous motor. For every stroke the flywheel is loaded on to the spindle and unloaded immediately after the down stroke. When loaded, the spindle turns and the spindle nut moves the ram down until the upper die comes into contact with the material and forms it. The flywheel supplies the required forming energy, losing rotation speed. As soon as the selected pressure between the upper and lower dies has been reached, the flywheel is unloaded. Two hydraulic cylinders bring the ram back to its starting position. At the same time they act as a braking device, stopping the ram at the upper dead centre or in any other stroke position. Furthermore, the cylinders act as counterweights, meaning that the press can also carry out light blows with only 10% of the nominal press force.

Constructional design

The press frame is a split cast construction held together by four tie rods made of quenched and tempered steel. The cast steel ram has especially long guides to prevent tipping. The spindle is made of high-alloy quenched and tempered steel. The spindle bearing is a collar bearing (Figure 23.7a). The spindle nut is made of special bronze. The flywheel is supported hydrostatically on the press frame.

The clutch between the flywheel and the spindle is a single-disc friction clutch. It is actuated hydraulically by means of a ring piston. The oil pressure is regulated electronically. When the selected moment is exceeded the clutch slips out. As the press force is proportional to the spindle moment, the press can also be protected against overload by adjusting the moment.

$$M = F \cdot r \cdot \tan \alpha + \rho$$

M in Nm moment

F in N press force

r in m spindle flank radius

α in deg. pitch angle of the thread

ρ in deg. angle of friction (about 6° equals $\mu = 0.1$ for steel on bronze)

The main characteristics of these presses are:

- Low acceleration mass.
Only a light clutch disc and the spindle need to be set into action.
- Short acceleration distance.
Because of the small acceleration mass, the maximum ram velocity is reached after only 1/10 of the stroke.
- Full power is reached after only one-third of the stroke length.

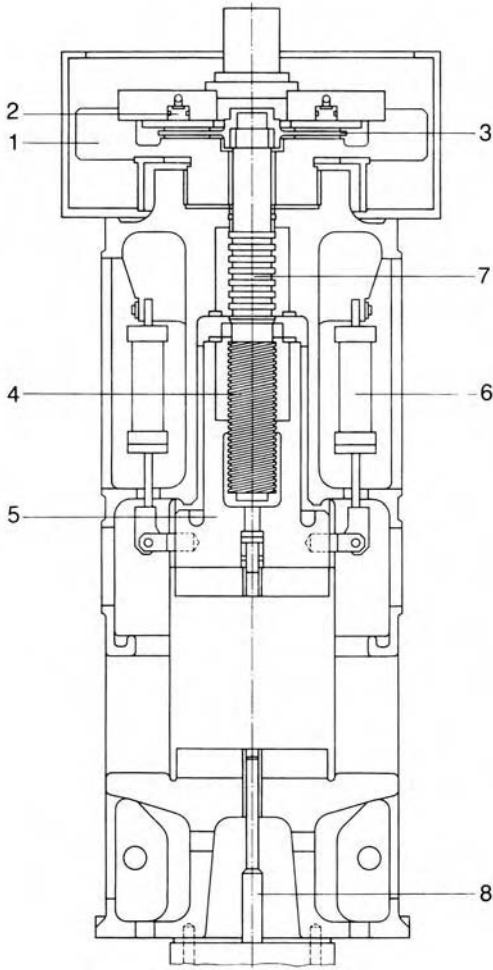


Figure 23.7
SPK-type clutch screw press

- 1 flywheel,
- 2 hydraulic ring piston
- 3 clutch disc
- 4 spindle
- 5 ram
- 6 return stroke cylinder
- 7 spindle collar bearing
- 8 ejector

(Illustration: Hasenclever works, Düsseldorf, Germany)

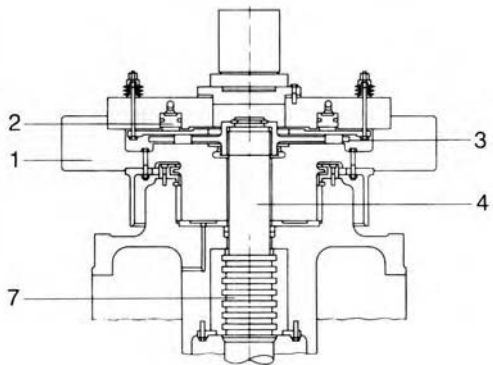


Figure 23.7a
Flywheel and spindle clutch

- 1 flywheel
- 2 hydraulic ring piston
- 3 clutch disc
- 4 spindle
- 7 spindle collar bearing

(Illustration: SMS Hasenclever works, Düsseldorf, Germany)

23.2.5 Screw presses with direct electric motor drive

The percussion press (Vincent press) shown in Figure 23.8 is powered in a non-contact manner by a reversible motor (electric motor which can be run in two rotation directions). In this press, the reversible motor rotor is positioned directly on the threaded spindle and the stator is on the press frame. The moment required to accelerate the flywheel is generated without contact by the magnetic field between the rotor and the stator. The direct electric drive means there are no parts which are subject to wear in the drive system. As there is no slip or other mechanical loss apart from electrical slip and losses in the linear (thread) drive itself, the mechanical efficiency of this press is very high ($\mu_M = 0.7 - 0.8$).

The work capacity can be precisely controlled by the speed of the rotor. Up to a nominal press force of 3150 kN, the press frame is built as a one-piece cast-plate construction made of fine-grained steel. For larger presses with a nominal press force of up to 23000 kN, a split press frame is used, held together by two hydraulically-retracted pre-stressed steel tie rods.

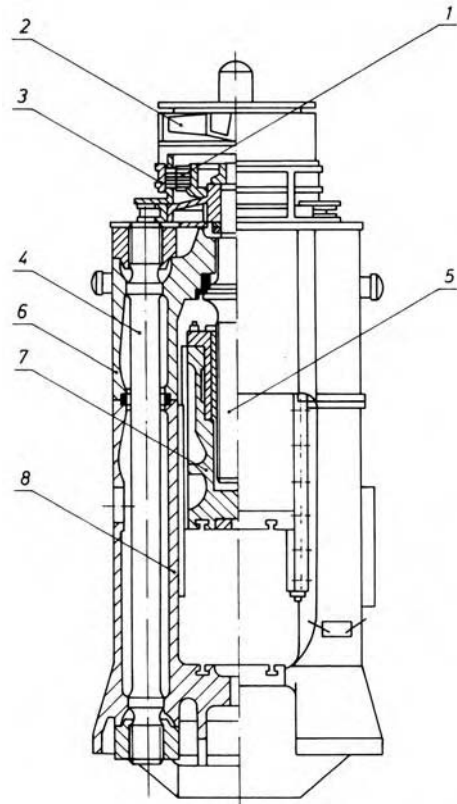


Figure 23.8

Screw press with direct electric motor drive.

1 rotor = flywheel, 2 ventilation wheel, 3 stator, 4 tie rod, 5 spindle, 6 column, 7 ram, 8 ram guide. (Illustration: Müller-Weingarten works, Weingarten, Germany)

For screw presses with a direct electric motor drive (Figure 23.9), small presses up to 6300 kN press force, mainly used in forging, are powered with a reversible three-phase asynchronous motor.

Because of their poor energy balance, for larger presses from 10,000 kN press force

direct electric drives with frequency converters

are mainly used.

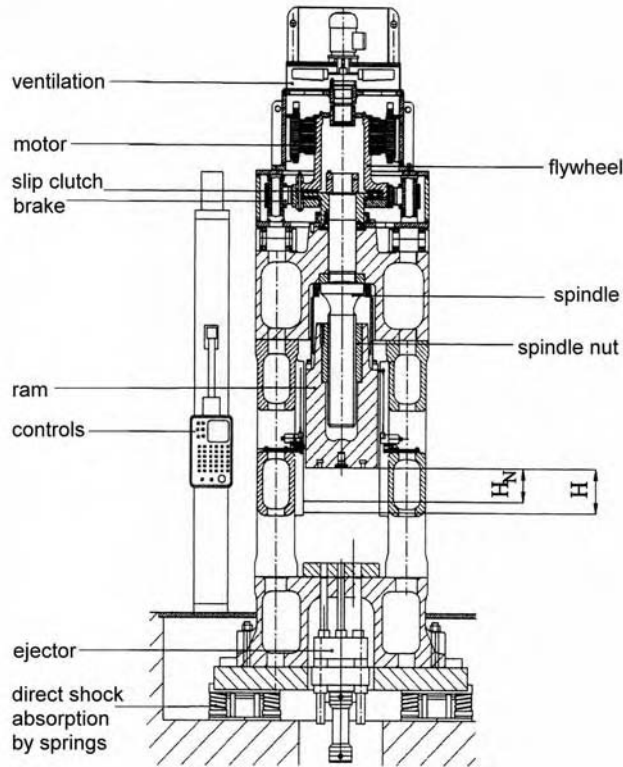


Figure 23.9 SPR/SPP screw press with direct electric drive
(Illustration from LASCO Umformtechnik works, Coburg, Germany)

The frequency converter raises the electrical efficiency of the screw press by a factor of three. As the drive accelerates, when the moment is constant the stress and frequency rise at the same proportion until the pre-selected rotation speed is reached. If the rotation speed and thus the energy stored in the flywheel is higher than that required for forming, then the generator is used as a brake. The generator effect then means that the excess energy is fed back into the network as electric energy.

On the return stroke this process is then repeated in the opposite direction. The upward acceleration and the generator braking are co-ordinated so that the mechanical brake only locks in at the upper dead centre, meaning that there is no braking heat or wear.

The following energy diagrams, Figures 23.10a and b, show the energy balance of both types of drive. Comparing the energy balances, it can be seen that when the drive is equipped with a frequency converter, around 80% of the energy required for the return stroke can be reclaimed in the form of electricity, in particular for the return stroke.

The energy for mechanical braking approaches zero, i.e. in practice, the mechanical brake is only needed as a retainer.

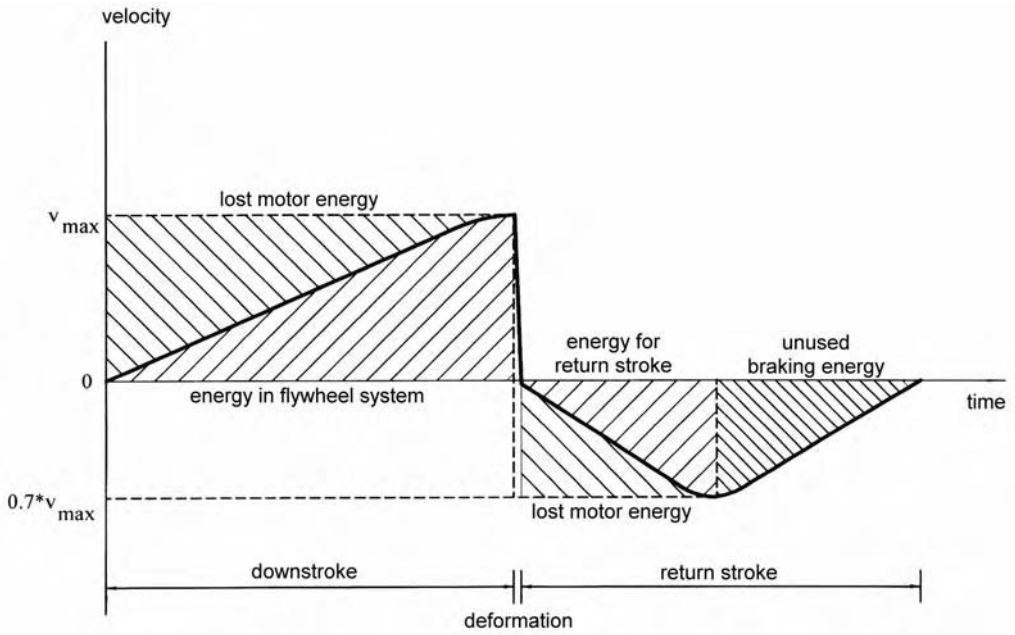


Figure 23.10a Energy path for a screw press with resistance motor

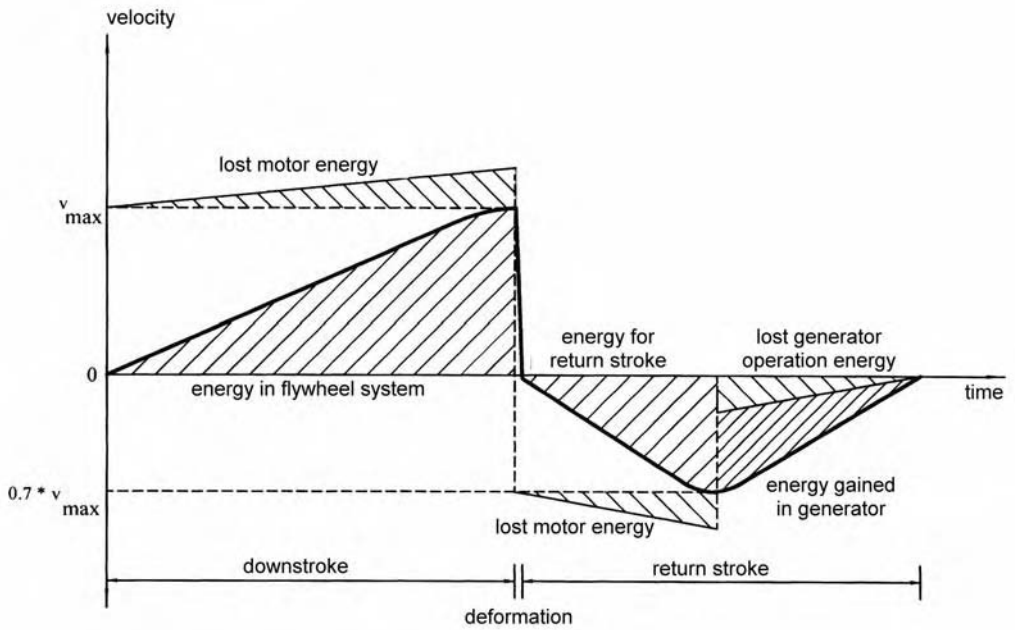


Figure 23.10b Energy path for a screw press with frequency-regulated drive

The energy from the electricity network (useful energy) is equal to the gross energy of the press plus electric and mechanical losses.

With a frequency-regulated drive the total energy is reduced by the amount of energy which flows back into the network due to the generator effect during braking. With the resistance rotor this energy is lost as heat.

The advantages of the frequency-regulated drive with reactive current compensation are:

- lower load on electricity network
- lower energy costs
- low wear in clutch and brake
- lower maintenance costs
- shorter cycle times with reduced impact energy
- higher efficiency.

Table 23.1 below shows the energy balance in figures, taking as an example a screw press with 10,000 kN nominal press force and 130 kW gross energy.

Table 23.1 Energy balance

	Resistance rotor [kW]	Frequency-regulated drive [kW]
Total energy loss	480.0	161.0
Mechanical work	130.0	130.0
Energy from the network	610.0	291.0
Generator gain	0.0	49.1
Energy from the network, taking into account the generator gain	610.0	241.9

Constructional design

The press frame is a multi-part cast construction whose elements (table, side columns and head) are joined to the press frame by four pre-stressed tie rods.

The bronze spindle nut is held in a steel casing, thus lengthening the guide. The threaded spindle is forged and made of high-alloy CrNiMo steel. The shape of the thread is optimised to have an extremely high fatigue strength. The cast steel flywheel is made up of several parts with an independent load-limiting device. The ram is also made of cast steel. The extremely long, heat-neutral guide system, mounted below 45°, has nitrated guide bars. Plastic-coated support blocks, which can be adjusted from any direction, allow a very small guide clearance.

By mounting the press on spring dampers to insulate it against vibration and structure-borne sound, press-induced vibrations can be almost completely avoided.

Controls

LASCO screw presses come with an electronic stored-programme control system which enables the process to be controlled fully automatically. All process data are shown on the screen.

Figure 23.11 shows a complete screw press with automatic feed system and a two-jaw robot. Among other things, this machine is used to manufacture automobile steering shafts.

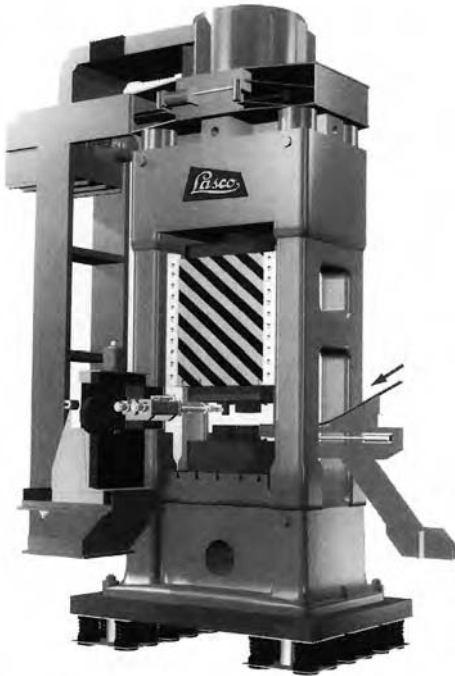
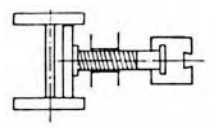
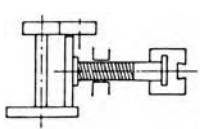
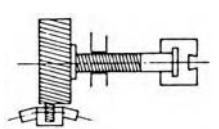
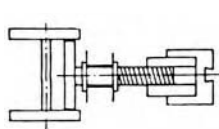
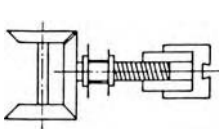
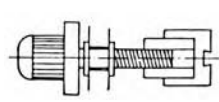
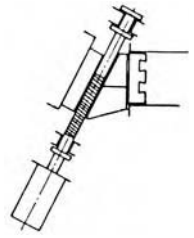


Figure 23.11
SPR 800 fully-automatic screw press
(Photograph from LASCO Umformtechnik
works, Coburg, Germany)

Table 23.2 Types of screw press

		Screw presses with spindle moved axially by friction				Screw presses with fixed spindles (Vincent presses)		
		Three-disc screw press	Four-disc screw press	Hydraulically-driven screw press	Three-disc screw press	Conical disc screw press	Screw press with direct electro-magnetic drive	Wedge screw press
Energy transmission		Friction-driven	Friction-driven	Pinion	Friction-driven	Friction-driven	Direct	Wedge
Max. work capacity (kNm)		800	no longer built	7 500	800	no longer built	7 000	800
Nominal press force (max.) (kN)		31 500		140 000	20 000		125 000	31 500
Recoil impact force (max.) (kN)		63 000		300 000	40 000		250 000	63 000
Impact velocity v in m/s		0.7 to 1 m/s						
Work capacity (kNm)		$W = \frac{\omega^2 \cdot I_d}{2} = \left(\frac{\pi \cdot n_f}{30} \right)^2 \cdot \frac{I_d}{2}$						
Required rotation speed n_f for W_1 (n_f in min^{-1})		$n_f = \sqrt{\frac{182 \cdot W_1}{I_d}} \quad W_1 = \text{work capacity required for forming}$						



23.3 Calculating the parameters for screw presses

23.3.1 Work capacity

$$W = \frac{\omega^2}{2} \cdot I_d = \left(\frac{\pi \cdot n_s}{30} \right) \cdot \frac{I_d}{2}$$

W	in Nm	work capacity (stored in the flywheel)
n_f	in min^{-1}	flywheel rotation speed
I_d	in kg m^2	mass moment of inertia
30	in s/min	conversion figure for the rotation speed from minutes to seconds
ω	in s^{-1}	angular velocity.

23.3.2 Mass moment of inertia

With the most common flywheel forms (Figure 23.12), the mass moment of inertia is made up of several elements.

$$I_{d \text{ tot}} = I_{d \text{ crown}} + I_{d \text{ web}} + I_{d \text{ hub}}$$

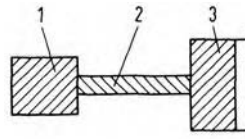


Figure 23.12
Flywheel made up of three hollow cylinders

The mass moment of inertia for a solid cylinder can be determined as follows:

$$I_d = \frac{m}{2} \cdot r^2$$

I_d	in kg m^2	mass moment of inertia
r	in m	radius of the solid cylinder
m	in kg	mass of the cylinder
g	in kg/m^3	density
h	in m	height / length of the cylinder.

The mass m is:

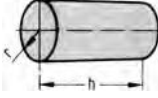
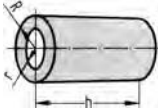
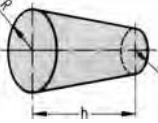
$$m = r^2 \cdot \pi \cdot h \cdot \rho$$

For cast iron, which is the material mainly used for flywheels, the expression $\rho \cdot \pi/2$ can be condensed into a constant, z .

$$z = \frac{\rho \cdot \pi}{2} = \frac{7250 \cdot \pi}{2} \text{ kg/m}^3 \qquad z = 11382 \text{ kg/m}^3$$

With this constant, z , it is easy to determine the mass moments of inertia. For the most common forms, this results in:

Table 23.3 Formulae for calculating mass moments of inertia.

<p><i>Solid cylinder</i></p> $I_d = z \cdot h \cdot r^4$	
<p><i>Hollow cylinder</i></p> $I_d = z \cdot h \cdot (R^4 - r^4)$	
<p><i>Obtuse cone</i></p> $I_d = z \cdot h \cdot \frac{R^5 - r^5}{5(R - r)}$	

h, r, R in m; $z = 11\,382 \text{ kg/m}^3$ for cast iron, e.g. GG 18

23.3.3 Required flywheel rotation speed

The operator of a screw press knows which workpieces the press is to be used for and thus the work capacity required for forming, as well as the press force. Depending on the press force, the nominal press force of the machine is selected and the spindle or flywheel speed is set according to the work capacity required.

The calculation is as follows:

$$n_f = \sqrt{\frac{182 \cdot W_1}{I_d}}$$

n_f	in min^{-1}	required flywheel speed
W_1	in N m	work capacity required for forming
I_d	in kg m^2	mass moment of inertia of the flywheel
182	in s^2/min^2	constants integrating all individual factors from Eq. 1.

This speed must be calculated for all screw presses of the Vincent construction type. For friction screw presses as in Figure 23.13, the driving disc radius r_{dd} is sought. Up until this point, r_{dd} , the friction must be kept up between the flywheel and the driving disc so that the energy required for forming is stored in the flywheel.

23.3.4 Required driving disc radius

This results from the assumption (Figure 23.13) that the peripheral speeds of the driving disc and the flywheel are equal at a driving disc radius of r_{dd} . Thus:

$$v_f = v_{dd}$$

$$d_f \cdot \pi \cdot n_f = 2 \cdot r_{dd} \cdot \pi \cdot n_{dd}$$

$$r_{dd} = \frac{d_f \cdot n_f}{2 \cdot n_{dd}}$$

If n_f – from Equation 2 – is inserted into Equation 3, the driving disc radius r_{dd} can be calculated up to which friction must be maintained (Eq. 4) in order to save the work capacity W_1 required for forming in the flywheel.

$$r_{dd} = \frac{d_f \cdot \sqrt{182 \cdot W_1}}{2 \cdot n_{dd} \cdot \sqrt{I_d}}$$

r_{dd} in mm	required driving disc radius
d_f in mm	flywheel diameter
n_{dd} in mm^{-1}	driving disc rotation speed
n_f in min^{-1}	flywheel rotation speed
I_d in kg/m^2	mass moment of inertia of the flywheel
W_1 in Nm	work capacity required for forming

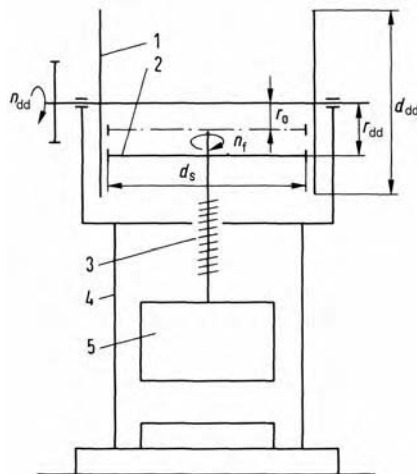


Figure 23.13 Layout of a friction screw press.

r_0 initial radius, r_{dd} radius at which there is no more friction, d_f flywheel diameter, d_{dd} driving disc diameter, n_f flywheel speed, n_{dd} driving disc rotation speed: 1 driving disc, 2 flywheel, 3 spindle, 4 frame, 5 ram

23.3.5 Ram impact velocity

The ram impact velocity can be determined from the spindle pitch and rotation speed.

Spindle pitch:

$$h = d_0 \cdot \pi \cdot \tan \alpha$$

h in m spindle pitch
 d_0 in m pitch diameter of the thread
 α in deg. pitch angle.

Impact velocity:

$$v = \frac{h \cdot n_s}{60 \text{ s/min}}$$

v in m/s ram impact velocity
 n_s in min^{-1} spindle rotation speed.

With screw presses, impact velocities are between 0.7 and 1.0 m/s, much lower than with hammers (5 – 14 m/s).

If the calculation of the required radius r as well as that of the work capacity and the values this produces for the rotation speed n take into account the press efficiency η_M then:

$$\text{Eq.1a} \quad W_e = \frac{W^2}{2} \cdot I_d \cdot \eta_M = \left(\frac{\pi \cdot n_s}{30} \right)^2 \cdot \frac{I_d}{2} \cdot \eta_M$$

$$\text{Eq.2a} \quad \eta_M = \sqrt{\frac{182 \cdot W_1}{I_d \cdot \eta_M}}$$

$$\text{Eq.3a} \quad r_M = \frac{d_f}{2 \cdot n_{dd}} \sqrt{\frac{182 \cdot W_1}{I_d \cdot \eta_M}}$$

W_e in Nm available effective work
 η_M press efficiency (0.7 – 0.9)
 n_M in min required effective rotation speed
 r_M in m required effective diameter
 W_1 in Nm work capacity required for forming

23.4 Advantages of screw presses (compared to hammers and crank presses)

1. Screw presses require only a small base.
2. The noise level is far lower than with hammers.
3. Screw presses are high-energy machines. For this reason, workpieces which require a lot of energy can be formed with them.
4. The dwell periods (the time during which the workpiece is being forged) are short. This means that tool life is improved.
5. The spindle thread is not self-locking. This means that a screw press can not block under stress.
6. Screw presses convert their energy abruptly, similarly to hammers. Because of the lower ram impact velocity ($v = 0.7 - 1.0$ m/s) the deformation resistance during hot forming is lower than with hammers ($v = 5 - 14$ m/s).
7. Like hammers, screw presses have no kinetically-fixed bottom dead centre. It is no longer necessary to adjust the height of the tooling. Forging can also take place in a closed die, as the excess material can be balanced out in the height of the workpiece.

23.5 Typical fields of application of screw presses

1. *Embossing work*

Because of their hard impact, screw presses are ideal for embossing work, e.g. embossing and shaping cutlery, clutch cases made of sheet metal, etc.

2. *Calibration*

For example, finishing gears with tolerances of around ± 0.02 mm.

3. *Precision forging*

Forging where a hard final impression is required to ensure that the workpiece stays still and there is no spring-back. e.g. manufacturing turbine blades. These are produced to high dimensional accuracy on screw presses with no reworking apart from a polishing operation.

4. *Workpieces with high energy requirements*

Here, impression-die forgings are involved which require high work capacity (up to 6000 kN m) for forming.

23.6 Examples

Example 1

In order to manufacture a workpiece, a work capacity of $W_1 = 8000 \text{ Nm}$ is required. A screw press with the following specifications is available:

1. Flywheel dimensions
2. Driving disc diameter $d_{dd} = 1200 \text{ mm}$
3. Driving disc rotation speed $n_{dd} = 125 \text{ min}^{-1}$

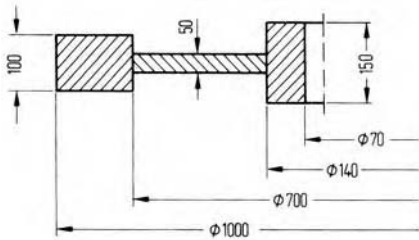


Figure 23.14 Flywheel

Find:

Can the workpiece be manufactured on this screw press?

Solution:

1. Determining the mass moment of inertia

$$I_{d_{\text{tot}}} = I_{d1} + I_{d2} + I_{d3}$$

$$I_{d1} = z \cdot h (R^4 - r^4) = 11382 \text{ kg/m}^3 \cdot 0.1 \text{ m} (0.8^4 \text{ m}^4 - 0.7^4 \text{ m}^4)$$

$$I_{d1} = 192.92 \text{ kg m}^2$$

$$I_{d2} = 11382 \text{ kg/m}^3 \cdot 0.05 \text{ m} (0.7^4 \text{ m}^4 - 0.2^4 \text{ m}^4)$$

$$I_{d2} = 135.73 \text{ kg m}^2$$

$$I_{d3} = 11382 \text{ kg/m}^3 \cdot 0.15 \text{ m} (0.2^4 \text{ m}^4 - 0.04^4 \text{ m}^4)$$

$$I_{d3} = 2.73 \text{ kg m}^2$$

$$I_{d_{\text{tot}}} = 331.38 \text{ kg m}^2$$

2. Maximum press work capacity

$$n_{f_{\text{max}}} = \frac{d_{dd} \cdot n_{dd}}{d_f} = \frac{1200 \text{ mm} \cdot 125 \text{ min}^{-1}}{1600 \text{ mm}} = 93.75 \text{ min}^{-1}$$

$$W_{\text{max}} = \left(\frac{\pi \cdot n_f}{30} \right)^2 \cdot \frac{I_d}{2} = \left(\frac{\pi \cdot 93.75 \text{ min}^{-1}}{30} \right)^2 \cdot \frac{331.38 \text{ kg m}^2}{2}$$

$$W_{\text{max}} = \underline{\underline{15970 \text{ Nm}}}$$

As $W_{\text{max}} > W_1$, the press can be used for this deformation.

Example 2

In a workshop there is a screw press (Figure 22.12) with the following specifications:

Mass moment of inertia of the flywheel	$I_d = 80 \text{ kg/m}^2$
Driving disc diameter	$d_{dd} = 1.6 \text{ m}$
Flywheel diameter	$d_f = 2.0 \text{ m}$
Driving disc rotation speed	$n_{dd} = 125 \text{ min}^{-1}$
nominal press force	$F_n = 1000 \text{ kN}$

Find:

1. Can the press be used if the following data are needed to manufacture a workpiece?

press force	$F = 700 \text{ kN}$
work capacity	$W = 4200 \text{ Nm}$

2. What flywheel rotation speed is needed to store a work capacity of 4200 Nm?

Solution:

- 1.1 As the nominal press force $F_n = 1000 \text{ kN}$ is higher than the force needed for the deformation, $F = 700 \text{ kN}$, the press can be used from the point of view of the force required.

- 1.2 Max. press work capacity

from Eq. 3:

$$n_{f \text{ max}} = \frac{2 \cdot r_{dd} \cdot n_{dd}}{d_f} = \frac{d_{dd} \cdot n_{dd}}{d_f} = \frac{1.6 \text{ m} \cdot 125 \text{ min}^{-1}}{2.0 \text{ m}} = \underline{\underline{100 \text{ min}^{-1}}}$$

from Eq. 1:

$$W = \left(\frac{\pi \cdot n_s}{30} \right)^2 \cdot \frac{I_d}{2}$$

$$W = \left(\frac{\pi \cdot 100 \text{ min}^{-1}}{30 \text{ s/min}} \right)^2 \cdot \frac{80 \text{ kg m}^2}{2} = \underline{\underline{4386.5 \text{ Nm}}}$$

As the max. work capacity of the press is also higher than that required for the deformation, the press can be used for this work.

2. Required flywheel rotation speed

from Eq. 2:

$$n_f = \sqrt{\frac{182 \cdot W_1}{I_d}} = \sqrt{\frac{182 \text{ s}^2 / \text{min}^2 \cdot 4200 \text{ Nm}}{80 \text{ kg m}^2}} = \underline{\underline{97.7 \text{ min}^{-1}}}$$

A comparison of the parameters for hammers, screw and crank presses once more provides some indications for these machines' fields of application.

Table 23.4 Parameters of hammers and presses

	Hammer	Screw press	Crank press
Impact velocity	4 – 6	0.6 – 0.8	0.3 – 0.7
Recoil time (m/s)	2 – 3	30 – 60	30 – 60
Deformation time (m/s)	5 – 15	30 – 150	80 – 120

23.7 Exercise on Chapter 23

1. Explain the structure of the main screw press construction types and how they work.
2. Why is the flywheel of most screw presses made with a slip clutch?
3. Why is it that on screw presses, the force can not be adjusted or only to a limited extent?
4. What are the advantages of screw presses compared to hammers?
5. What is meant by a percussion screw press ?
6. How is the impact energy produced by a screw press?
7. How is the work capacity required for forming on a screw press adjusted?
8. Why are screw presses commonly used for embossing work?

24 Eccentric and crank presses

Eccentric and crank presses are controlled by the ram path.

24.1 Types of these presses

These presses are categorised according to the design of the press frame (Figure 24.1) into:

- a) gap-frame presses
- b) open-back presses
- c) straight-side presses.

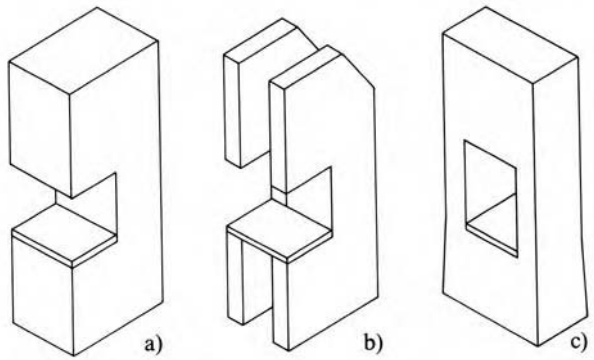


Figure 24.1 Press frames.

- a) gap frame,
- b) open-back frame,
- c) straight-side frame

Gap-frame presses

In these presses, the press frame is made in one piece and is shaped like a C. This is why this kind of frame is also known as a C frame or overhanger. The dimensions of gap-frame eccentric presses are listed in Table 24.1.

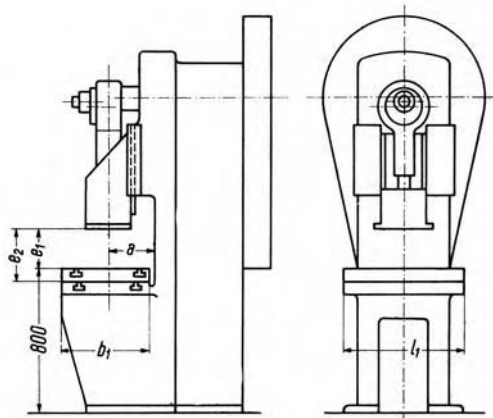


Figure 24.2 Gap-frame eccentric press with fixed table

Table 24.1 Dimensions of gap-frame eccentric presses

Dimensions	Press force in kN	100	160	250	400	630	1000	1600	2500	4000
Throat (gap)	a	160	180	200	280	315	280	400	315	450
Area	width · length $w_1 \cdot l_1$	315 400	355 450	400 500	560 710	630 800	560 710	800 1000	900 1120	1000 1250
Platen	Distance from ram with bolster plate e_1 without bolster plate e_2	135 200	150 220	175 250	200 280	180 315	190 355	215 400	275 450	310 500
Ram	Stroke adjustment range from – to	6 – 60	8 – 68	8 – 80	8 – 88	8 – 100	8 – 112	20 – 120	32 – 132	40 – 140
	Height adjustment	40	50	50	63	63	80	100	125	160

All measurements in mm

Table 23.2 Dimensions of open-back eccentric presses

Dimensions	Press force in kN	160	250	400	630	1000	1600	2500	4000	
Throat (gap)		180	200	220	250	280	400	315	450	
Platen	Area width · length $w_1 \cdot l_1$	355 500	400 560	450 630	500 710	560 800	800 1000	800 1120	900 1250	1000 1400
	Distance from ram without bolster plate e_2	220	250	280	315	355	400	450	500	
Ram	Stroke adjustment range from – to	8 – 68	8 – 80	8 – 88	8 – 100	8 – 112	20 – 120	32 – 132	40 – 140	
	Height adjustment	50	50	63	63	80	100	125	160	

All measurements in mm

Open-back presses

These are characterised by their double-sided frame. Two parallel side columns are permanently connected with one another, above at the press head and below at the bottom platen. The crankshaft is mounted parallel to the front edge and supported on both sides in the walls of the columns. The ram drive is between the walls of the columns (Figure 24.3).

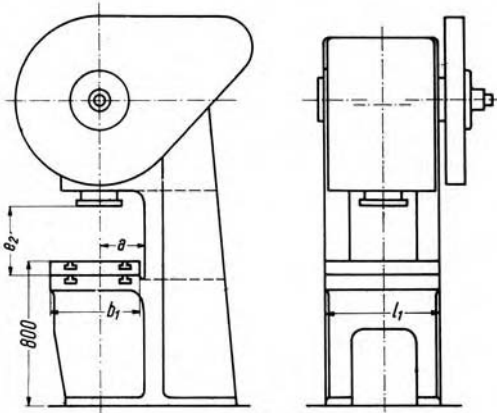


Figure 24.3
Open-back eccentric press

Straight-side presses

These are characterised by their double-sided frame, also known as an O frame. In this kind of frame design, for small presses the side columns and the head are permanently connected (welded). For large presses the separate parts – side columns, head and bottom platen – are held together with tie rods.

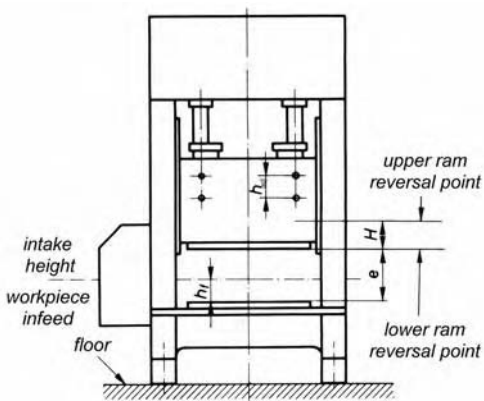


Figure 24.4
Straight-side eccentric press. Mechanical double-sided high-speed press with a nominal press force of $F_N = 1000$ kN.

Table 24.3 Dimensions of straight-side presses

Nominal force F_n in kN	250	400	630	(800)	1000	(1250)	1600	(2000)	2500	(3150)	4000
Normal ram stroke H in mm	20	20	25	25	25	25	30	30	30	35	35
Maximum ram stroke H_{\max} in mm	50	50	50	50	50	50	60	60	60	60	60
Ram setting range h_{adj} in mm	50	60	60	60	60	60	60	80	80	100	100
Daylight e in mm	275	300	325	350	350	375	375	400	400	450	500
Ram and bolster plate width (from left to right) x_0 in mm	630	710	800	900	1000	1120	1250	1400	1600	1800	2000
Bolster plate depth (from front to back) y_0 in mm	530	650	600	630	670	710	800	900	1000	1120	1250
Further press construction specifications must be arranged when an order is placed. Values not in brackets to be used first.											

24.2 Press frame materials

Grey cast iron (e.g. GG 26, GG 30)

and special cast iron which has a higher strength and failure strain, such as Meehanite or spheroidal cast iron (spherical-shaped graphite formation).

Advantages of grey cast iron frames

- ribs and cross-sectional transitions of different thicknesses are easy to construct with cast iron frames,
- elegant design which fulfils its purpose,
- good processability,
- good shock absorption.

For the above reasons, grey cast iron frames are often used in the serial production of smaller presses.

Disadvantages of grey cast iron frames

The lower strength of cast iron frames means they have larger cross sections and thus larger masses than steel frames.

Cast steel (e.g. GS 45, GS 52)

is used most often in presses with a higher ultimate power which can easily be overloaded (forging presses) because of its good malleability and weldability, higher strength and failure strain.

Steel (e.g. constructional steel St 42)

is used with frames built in a framework or steel-plate design. The advantages of steel construction over a cast iron design are:

- a) higher modulus of elasticity,
- b) higher strength,
- c) due to a) and b), smaller cross-sections and lighter frames,
- d) no pattern costs, meaning that steel constructions are commonly used for single-part and small lot production.

The disadvantages of a steel construction is the poor shock absorption and the complex stress-relief annealing which has to be carried out after welding.

24.3 Frame deflection and deflection energy

On every stroke, the press frame must absorb deflection energy W_d . When the press force F rises, the press frame stretches by the frame deflection f , thus acquiring a potential energy of

$$W_d = \frac{1}{2} \frac{F \cdot f}{10^3 \text{ mm/m}} = F \cdot f \cdot 5 \cdot 10^{-4} \text{ m/mm}$$

W_d in Nm potential energy

F in N press force

f in mm frame deflection.

The resistance to deflection C of a press frame is defined as

$$C = \frac{F}{f}$$

C in kN/mm resistance to deflection

F in kN press force

f in mm frame deflection.

Accordingly, a difference is made between rigid presses (with a high C) non-rigid presses (with a low C).

Permissible frame deflections for medium-sized machines are around $f_{\text{perm}} \cong 0.1 \text{ mm}/100 \text{ mm}$ throat a (Figure 24.5).

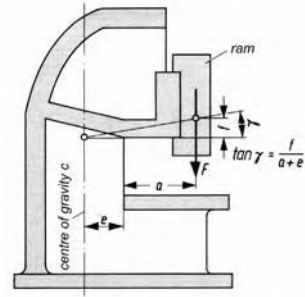


Figure 24.5 Press column deflection,
a) press throat, f deflection

24.4 Eccentric and crank press drives

In the eccentric press shown in Figure 24.6, the motor drives the flywheel by means of a belt drive. The energy is transferred from the flywheel via the combined clutch/brake system to the eccentric shaft. The connecting rod mounted on the eccentric bush, with the round-headed bolt fitted in it, transforms the circular movement into a linear one.

The head of the round-headed bolt fits in the ball socket in the ram. Below the ball socket the press safety device (shearing member) is mounted which is broken when the press is overloaded, abruptly cutting off the force.

To produce a higher work capacity the drive (Figure 24.7) is fitted with a transmission gear. The transmission gear then acts as a further energy storer. Figure 24.8 shows the simplified drive plan of a crank press.

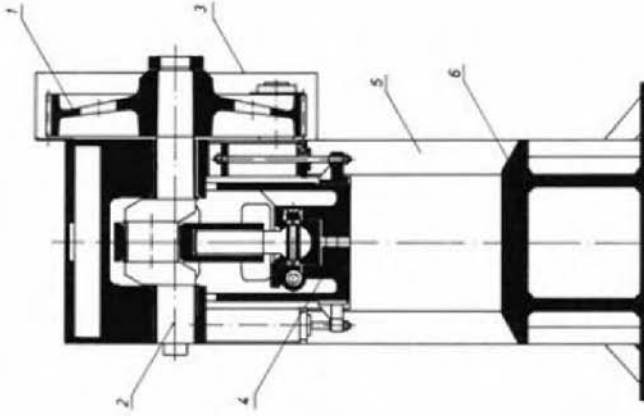


Figure 24.8 Crank press.
 1 flywheel, 2 crankshaft,
 3 protective cover, 4 ram,
 5 press column, 6 bottom
 platen

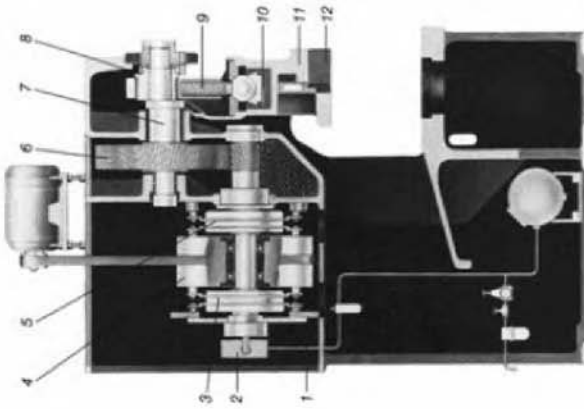


Figure 24.7 Drive of a gap-frame eccentric press with transmission gear. 1 press frame, 2 valve, 3 and 5 clutch and brake, 4 flywheel, 6 transmission gear, 7 electric shaft, 8 eccentric bush for stroke length adjustment, 9 round-headed bolt to adjust stroke position, 10 load-limiting device, 11 ram, 12 cover (Illustration from Weingarten works, Weingarten, Germany)

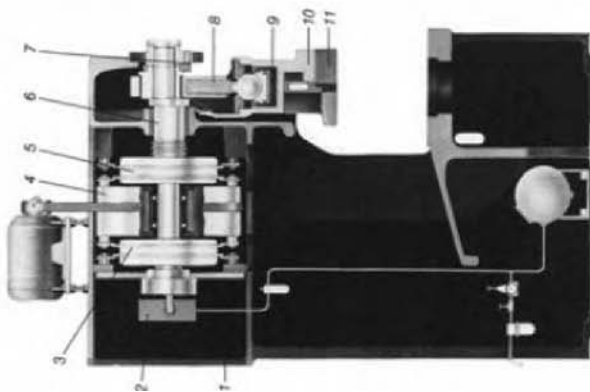


Figure 24.6 Drive of a gap-frame eccentric press. 1 press frame, 2 valve, 3 and 5 clutch and brake, 4 flywheel, 6 eccentric shaft, 7 stroke adjustment (stroke length adjustment), 8 round-headed bolt to adjust stroke position, 9 load-limiting device, 10 ram, 11 cover to clamp tooling in place (Illustration from Weingarten works, Weingarten, Germany)

24.4.1 Clutches

Clutches are very important to keep the press and operator safe. When the press is deactivated, the clutch must disconnect the connection between the flywheel and the eccentric shaft or crankshaft. In order for this shaft to stop *immediately*, the clutch is coupled to a brake.

Clutches are categorised either as (form-closed, positive) driving clutches or (force-closed, non-positive) friction clutches.

1. Driving clutches

These clutches are named after the type of driver:

- bolt clutch
- rolling key clutch
- tangential key clutch.

The clutch used the most in older machines was the rolling key clutch. As all positive clutches run very roughly and have long operating times, today non-positive friction clutches are mainly used.

2. Friction clutches

All clutches of this kind (Figure 24.10) run quietly and stand out for their short operating times. The contact pressure force is supplied either pneumatically or hydraulically.

These clutches are safe against overload as they transmit a very precise, adjustable limiting moment M .

$$F = \frac{M}{r \cdot \sin \alpha}$$

F ram force, M moment set on the clutch,
 r crank radius, α crank angle

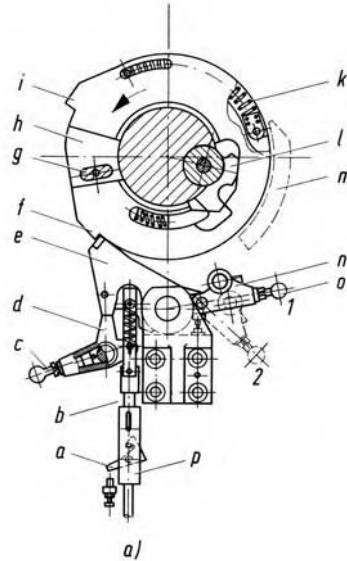


Figure 24.9 Rolling key clutch (clutch disengaged), a) pawl, b) threaded bush, c) fastening bolt, d) supporting lever, e) locking lever, f) 1 latch, g) feather key, h) locking ring, i) 2 latch, k) tension spring, l) nose of rolling key, m) cam, n) release lever, o) locking bolt, p) shift linkage

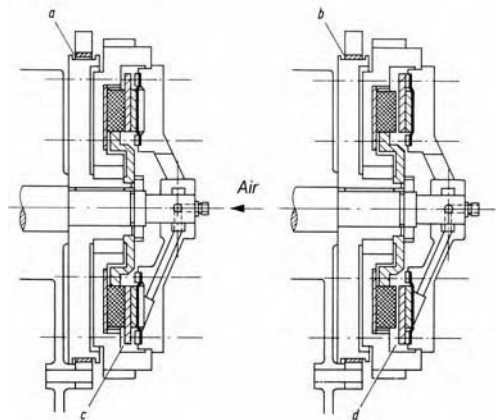


Figure 24.10 Single-disc functional clutch with brake, a) brake open, b) brake closed, c) clutch engaged, d) clutch disengaged

Figure 24.11 shows a modern disc clutch/brake system.

This drive construction has an integrated safety lock to halt the press. The two independently-operating brakes ensure that if one brake fails, the second dynamically halts the press cycle. The particular advantages of this kind of construction are:

- lower ram deceleration path
- fast single-stroke operating cycles.

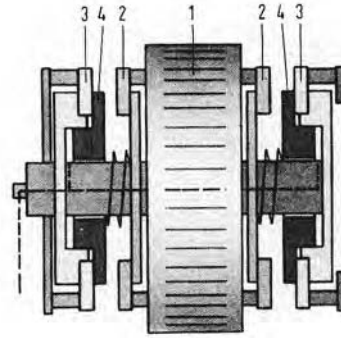


Figure 24.11

Pneumatic single-disc clutch/brake system.

1 flywheel, 2 clutch, 3 brake, 4 pneumatic piston

24.4.2 Load-limiting safety elements on the press frame

Apart from the clutch, which as well as activating and deactivating is mainly intended to protect the drive elements against overload, other elements are necessary to protect the press frame against overload. These load-limiting elements must fulfil the following requirements:

- fast response on overload,
- precise load limit setting must be possible,
- load limit must be independent of the frequency of the load (must not be prone to failure when subjected to continuous load),
- it must be possible to quickly replace the fail-safe element.

Different types of load-limiting device

1. Mechanical safety devices

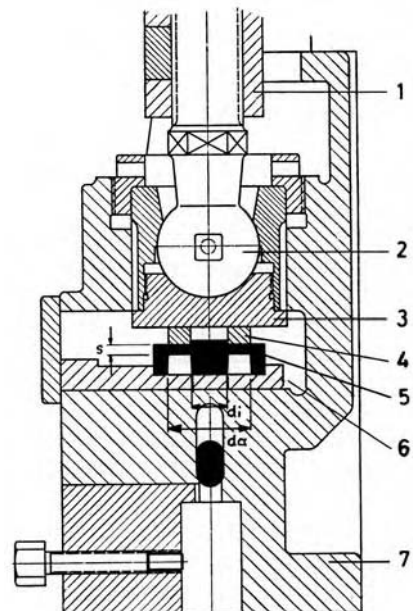
These elements are built into the ram unit below the ball socket in the ram (Figure 24.12). For example:

- shear plates
- steel shear plates
- spring releases.

1.1 Safety device with shear plate

Here, the shearing force at which the safety device reacts (Figure 24.13) can be calculated from the shearing area and the shear strength of the plate material:

Figure 24.2 Shearing member load-limiting device in press ram, 1 connecting rod, 2 round-headed bolt, 3 ball socket, 4 shear ring, 5 shearing member made of grey cast iron, shearing member holder, 7 press ram



$$F = A \cdot \tau_s$$

$$A = d \cdot \pi \cdot s$$

F in N shearing force
 s in mm thickness of the shearing
 plate at the shear-off point
 τ_s in N/mm² shear strength
 A in mm² shearing area.

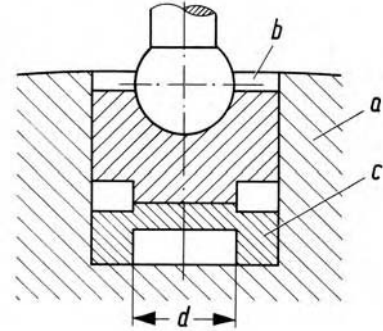


Figure 24.13 Shear plate safety device, a) ram, b) ball socket, c) shear plate

One disadvantage of shear plate safety devices is their susceptibility to fatigue fracture. An advantage is that the shear plates can be quickly replaced.

1.2 Spring releases

A pivotable lever (Figure 24.14) presses against a dog which is mounted on a bolt pre-tensioned by disc springs. When there is an overload the dog moves out of the horizontal position and the pivoted lever is released.

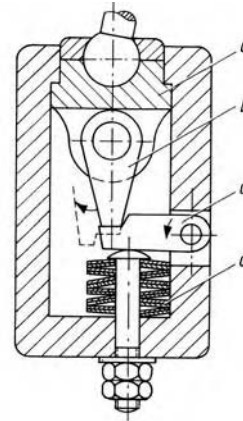


Figure 24.14
Release lock.
a) ball socket
b) pivoted lever
c) dog, d) disc springs

2. Hydropneumatic and hydraulic safety devices

2.1 Pneumatic safety devices in the ram

In this design (Figure 24.15) a piston is mounted in the ram, the interior of which is a cylinder; the lower end of this piston is connected to the die bolster plate. The piston is actuated with compressed air, so the safety force can be calculated from the pressure times the area. When there is an overload the piston is pushed out of the zero position. In doing so it deactivates the machine by means of an electronic limit switch.

2.2 Hydraulic safety device in the bottom platen

Here, with a similar principle to the pneumatic safety device, a hydraulic piston is built into the bottom platen.

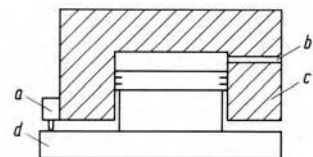


Figure 24.15
The principle of a pneumatic press safety device, a) limit switch, b) air inlet, c) ram, d) bolster plate

24.4.3 Stroke setting

1. Length of the stroke

– Presses with a fixed stroke

For presses with a fixed, unadjustable stroke, the stroke length results from:

$$H = 2 \cdot x$$

H in mm stroke

x in mm eccentricity between the pin and the shaft in eccentric presses; $x = r$ in mm, crank radius in crank presses

– Presses with an adjustable stroke

Presses with an adjustable stroke have an adjustable eccentric bush (Figure 24.17) on the crank web (crank presses) or on the eccentric pin (eccentric presses). With this kind of machine the stroke results from the sum of the two eccentricities.

$$H_{\max} = 2(x + y)$$

$$H_{\min} = 2(x - y)$$

y in mm eccentricity of the bush bore

x in mm eccentricity of the eccentric pin.

2. Stroke position

In order to set up the tooling precisely it must be possible to adjust the height of the ram. As the tools have different overall heights, the stroke position must be adjusted according to the overall height of the tooling. This adjustment is especially important with embossing work as the embossing force is strongly influenced by height differences and the machine may be overloaded. With smaller machines the stroke position is adjusted using round-headed bolts (Figure 24.12).

With larger machines the ball socket in the ram is adjusted.

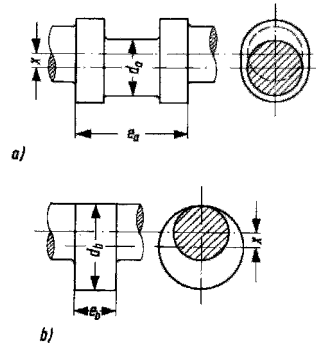


Figure 24.16 Drive shafts a) crankshaft, b) eccentric shaft

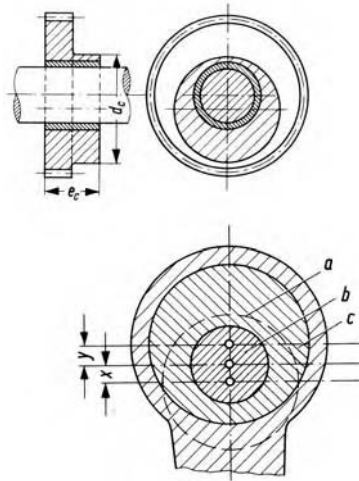


Figure 24.17 Layout of eccentric bush and eccentric pin on presses with adjustable stroke. a) eccentric shaft, b) eccentric pin, c) eccentric bush, y eccentricity of the eccentric bush, x eccentricity between the eccentric pin and the shaft

24.5 Calculating the parameters

24.5.1 Clutch moment

$$M = \frac{9554 \cdot P_{\text{def}} \cdot \eta_M}{n}$$

$$P_{\text{def}} = P \frac{(360^\circ - \alpha^\circ)}{\alpha^\circ}$$

α	in deg.	crank angle
M	in Nm	moment
n	in min^{-1}	strokes per minute
P	in kW	motor power
P_{def}	in kW	short-term capacity available for forming between α and BDC
α	in deg.	angle at which the energy is released until BDC
η_M	–	press efficiency.

Because the energy stored in the flywheel is released between α and the BDC (bottom dead centre), in this range a short-term power of P_{def} is available.

24.5.2 Tangential force

– Dynamic tangential force

The dynamic tangential force results from:

$$P_{\text{def}} = M \cdot \omega = T_d \cdot r_c \cdot \frac{\pi \cdot n}{30}$$

$$T_d = \frac{P_{\text{def}} \cdot 30}{r_c \cdot \pi \cdot n}$$

T_d	in N	dynamic tangential force
T	in N	static tangential force
r_k	in m	effective radius on the clutch.

– Static tangential force

The static tangential force results from:

$$T = \frac{P \cdot 30}{r_c \cdot n}$$

With a known crank radius, the following then results from the constant moment:

$$T = \frac{M}{r} \quad r \text{ in m} \quad \text{crank radius.}$$

24.5.3 Permissible press force

For the permissible force in a crank press a difference is made between nominal press force,
permissible press force from the drive moment,
permissible press force from the work capacity.

From the point of view of press force, the press can only be used for a certain forming operation if the force required for the deformation is smaller than, or at most equal to, the permissible forces mentioned above.

Nominal press force (Figure 24.18)

When the work capacity is provided, and assuming that the tangential force T on the drive is always available, it can be said, on condition that r/l is very small, that:

$$\frac{T}{F} = \sin \alpha$$

- T in kN tangential force
- F in kN press force
- α in deg. crank angle
- r in m crank radius
- l in m length of the connecting rod.

$$M = F \cdot a = F \cdot r \cdot \sin \alpha$$

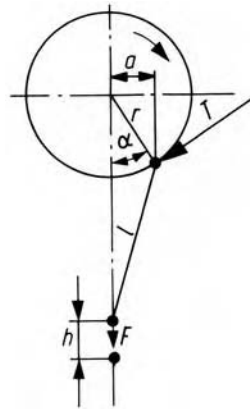


Figure 24.18 Crank press drive layout.

For a normal crank press, a value of 0.5 is fixed for the T/F ratio. This is equal to a crank angle of 30° . Thus:

$$F_n = \frac{T}{\sin 30^\circ}$$

F in kN nominal press force.

In other words, the nominal press force is available from a crank angle of 30° before BDC. The press force is smaller when $\alpha > 30^\circ$. It reaches a minimum at $\alpha = 90^\circ$ ($\sin 90^\circ = 1$).

The maximum is at the BDC at $\alpha = 0^\circ$ ($\sin 0^\circ = 0$), i.e. at the BDC the force approaches infinity. The permissible press frame load (press frame strength) is set to the nominal press force. **For this reason the nominal press force must not be exceeded.**

Permissible press force from the drive moment

This can be determined from the values which are always known about a press, using the following equation:

$$F_M = \frac{F_n \cdot H_{\max}}{4 \cdot \sqrt{H_{\text{adj}} \cdot h - h^2}}$$

- F_M in kN permissible press force from the drive moment
 F_n in kN nominal press force
 H_{\max} in mm max. stroke ($H = 2 \cdot r$)
 H_{adj} in mm set stroke
 h in mm ram displacement.

This force F_M is the limiting force from $\alpha = 30 - 90^\circ$.

Permissible press force from the work capacity

This limiting force results from the press work capacity (or its centrifugal masses).

If it is exceeded then the press stops. As the limiting force $F_{W_{\text{ct}}}$ resulting from the work capacity is always lower than F_n , it can not cause the machine to break if exceeded.

$$F_{W_{\text{ct}}} = \frac{W_{\text{ct}}}{h}$$

- $F_{W_{\text{ct}}}$ in N permissible press force from the continuous work capacity
 W_{ct} in Nm continuous work capacity
 h in m ram displacement.

The following table shows once more which forces at which crank angle limit the operation of a crank press.

Table 24.4 Limits on the press force of a crank press

Crank angle α	Force is limited by:	Force
$0^\circ - 30^\circ$ before BDC	the strength of the press frame	F_n
$30^\circ - 90^\circ$ before BDC	<i>the drive moment</i>	F_M
	the work capacity	$F_{W_{\text{ct}}}$

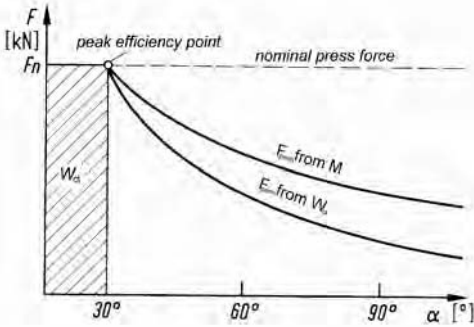


Figure 24.19
Characteristic curves of a crank press

If the three limiting forces are put together in a diagram (Figure 24.19) then it can be seen that until $\alpha = 30^\circ$ the force of a crank press is limited by F_n and when α is higher than 30° by the drive moment or the work capacity of the press.

The point where all three limiting forces reach a maximum is the peak efficiency point.

The ideal press load would be if the press was run in the peak efficiency range.

However, depending upon the operating process, this is only possible to a limited extent. Apart from checking the three permissible forces – compared with the maximum force occurring with a particular operating process – the work capacity of the process and the operating process must also be checked. This kind of press can only be cleared for use for a certain operation if all forces and the work capacity are within the permissible range.

24.5.4 Ram displacement

The ram displacement can be determined from the crank radius and the crank angle.

$$h = r(1 - \cos \alpha)$$

- h in m ram displacement
- r in m crank radius
- α in deg. crank angle
- H in m press stroke ($H = 2r$)

For $\alpha = 30^\circ$ h is:

$$h \approx \frac{H}{15}$$

24.5.5 Work capacity

1. Continuous work capacity

This means the work capacity of a press in continuous mode, i.e. if the press runs without interruption.

The continuous mode requires an automatic material and workpiece feed system.

$$W_{ct} = \frac{F_n \cdot H}{15}$$

W_{ct}	in Nm	work capacity in continuous mode
W_{si}	in Nm	work capacity in single-stroke mode
H	in m	press stroke ($H = 2r$)
r	in m	crank radius
F_n	in N	nominal press force.

2. Work capacity in single-stroke mode

$$W_{si} = 2 \cdot W_{ct}$$

Single-stroke mode is when the press stops after every stroke and needs to be initiated again (clutch engaged). When workpieces need to be inserted by hand, presses are run in single-stroke mode. As the flywheel speed, which drops on the working stroke, can be fully recovered during the insertion period (unlike in automatic mode), the work capacity in single-stroke mode is around double that of continuous mode.

24.6 Example

The following must be found for an extrusion:

max. press force $F = 1200$ kN with a ram displacement of $h = 20$ mm.

A crank press is available with a

nominal press force of $F_n = 2000$ kN and a stroke of $H = H_{adj} = 200$ mm (not adjustable).

Can the press be used for this operation?

Solution:

1. Determining the extrusion work

$$W_{F1} = F \cdot h \cdot x = 1200 \text{ kN} \cdot 20 \text{ mm} \cdot 1 = 24\,000 \text{ kNm}$$

2. Work capacity of the press in continuous mode W_{ct}

$$W_{ct} = \frac{F_n \cdot H}{15} = \frac{20\,000 \text{ kN} \cdot 200 \text{ mm}}{15} = 26\,666.7 \text{ kN mm}$$

3. Comparison of both work capacities.

The work capacity of the press in continuous mode, W_{ct} , is higher than that required for the deformation, W_{F1}

$$W_{ct} > W_{F1}$$

$$26\,666.7 \text{ kN mm} > 24\,000 \text{ kN mm}$$

i.e. the press can be used for this operation in continuous mode.

4. Assessing the forces.

4.1. Nominal press force F_n

The nominal press force is higher than the force required for the deformation

$$F_n > F_{F1}$$

$$2000 \text{ kN} > 1200 \text{ kN}$$

For this reason, the press can be used for this operation from the point of view of the nominal press force.

4.2. Determining the permissible press force F_M from the drive moment

$$F_M = \frac{F_n \cdot H_{\max}}{4 \cdot \sqrt{H_{\text{adj}} \cdot h - h^2}} = \frac{2000 \text{ kN} \cdot 200 \text{ mm}}{4 \cdot \sqrt{200 \cdot 20 \text{ mm} - 20^2 \text{ mm}^2}} = 1\,666.7 \text{ kN}$$

The permissible press force resulting from the drive moment and taking into account the stroke is higher than the extrusion force,

$$F_M > F_{F1}$$

$$1666.7 \text{ kN} > 1200 \text{ kN}$$

meaning that the press can also be used from this point of view.

4.3. Determining the permissible press force from the continuous work capacity of the press

$$F_{W_{ct}} = \frac{W_{ct}}{h} = \frac{26\,666.7 \text{ kN}}{20 \text{ mm}} = 1\,333.3 \text{ kN}$$

$$F_{W_{ct}} > F_{F1} \text{ so it can be used.}$$

Decision: As the permissible forces and the continuous work capacity of the press are higher under the given conditions than the deformation forces and the work capacity required for the deformation, the press can be used.

24.7 Application of eccentric and crank presses

Eccentric presses

are mainly used for blanking, embossing and bending, as long as only small displacements are required, as the eccentric demands.

Crank presses

are used for all chipless forming methods where the deformation force does not have to be constant over a long distance, i.e. for the forward extrusion of short components, deep drawing, bending and impression-die forging on heavy forging presses.

24.8 Exercise on Chapter 24

1. What kinds of frame construction are there for eccentric and crank presses?
2. Why is the press frame's resistance to deflection of great importance?
3. What kinds of drive are there for eccentric and crank presses?
4. What kinds of clutches are there for crank presses?
5. What load-limiting safety devices do you know?
6. How is the ram stroke length adjusted on an eccentric press?
7. How is an eccentric press protected against overload?
8. What different types of eccentric and crank press construction are there?

25 Knuckle-joint and toggle presses

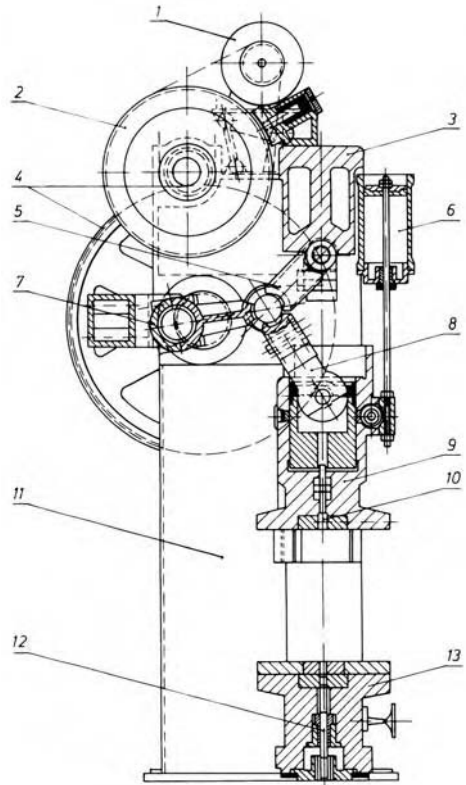
25.1 Single-point knuckle-joint presses

Knuckle-joint presses (Figure 25.1) are a special kind of crank press where the crank force is produced via a (knuckle joint) joint system. In principle, the rules which govern a crank press apply here, both as concerns the construction design and the way it works.

The ram velocity path depending upon the crank angle, and the force-displacement diagram, are unlike a crank press (Figure 25.2). The nominal press force on a knuckle-joint press only appears at 3 to 4 mm before BDC (at $\alpha_n = 32^\circ$ nominal crank angle). When the punch displacement is higher the force drops steeply (hyperbolically).

Figure 25.1

Drive layout of a knuckle-joint press. 1 driving motor, 2 flywheel, 3 head, 4 gear drive, 5 rocker arm, 6 cylinder to counterbalance the ram mass, 7 connecting rod, 8 push rod, 9 ram, 10 ejector, 11 column, 12 ejector, 13 platen (Illustration: Kieserling & Albrecht works, Solingen, Germany)



This is particularly important to know for a works engineer as the operation of these presses results from the shape of the force-displacement curve. They are used for operations which require high press forces over a short deformation distance. Typical fields of application for knuckle-joint presses are sizing, pancaking, coining and backward extrusion (of tubes).

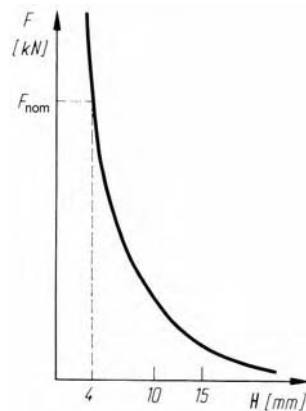


Figure 25.2 Force-displacement diagram for a knuckle-joint press

25.2 Toggle presses – modified knuckle-joint presses

Because of the poor force-displacement path with conventional knuckle-joint presses with one joint, the toggle press was developed, with a modified drive by means of two joints (Figure 25.3).

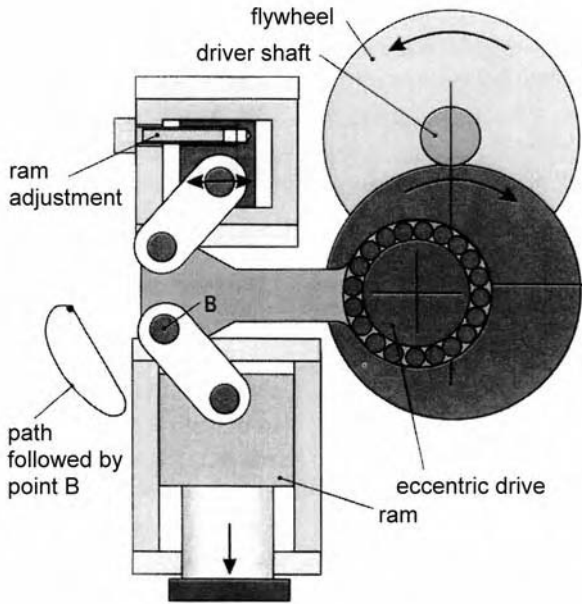


Figure 25.3
Toggle press (Illustration: Schuler works, Göppingen, Germany)

The toggle press is anchored in the head. The upper joint pivots in this anchor while the lower joint follows an curved path. This means that the ram path changes. This path (Figure 25.4) can be modified by changing the arrangement of the joints.

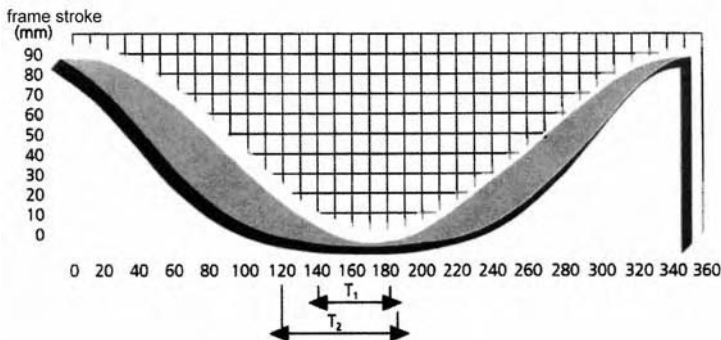


Figure 25.4 Time-displacement diagram for a toggle press
Crank angle α_c (degrees); time until plastic flow:
 T_1 for knuckle joint or eccentric presses
 T_2 for toggle drives

As a rule, the aim is to reduce the velocity of the ram in the operating range (e.g. reduce the impact velocity of the ram). Another advantage for bulk forming is the ram displacement which can be achieved on this drive system when the operational speed and drive moment are constant, which is three to four times longer than that of eccentric presses. The time-displacement diagram (Figure 25.4) shows the slower movement of the ram with a toggle press. This leaves the material near the bottom dead centre with enough time to reach plastic flow.

Figure 25.5 shows a vertical cold extrusion transfer press with a toggle drive. A two-piece welded press frame calculated by FEM is pre-tensioned using tie rods. One distinctive feature is the cross-shaped eight-part ram guide system with no play (Figure 25.6). This construction makes the system highly sway-resistant, guaranteeing high workpiece quality and optimum tool lives.

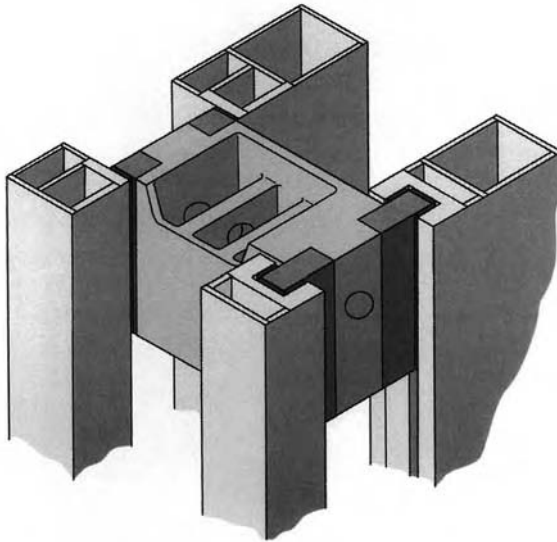


Figure 25.5

The principle of a cross-shaped eight-part ram guide
(Illustration: Schuler works, Göppingen, Germany)

The following table contains the dimensions of this press.

Table 25.1 Technical specifications of a cold extrusion transfer press.

Nominal press force	in kN	4.000	to	16.000
Nominal force distance	in mm	10	to	25
Ram stroke	in mm	180	to	520
Strokes per minute	in l/min	30	to	60
Work capacity	in kJ	50	to	270
Drive power	in kN	90	to	300

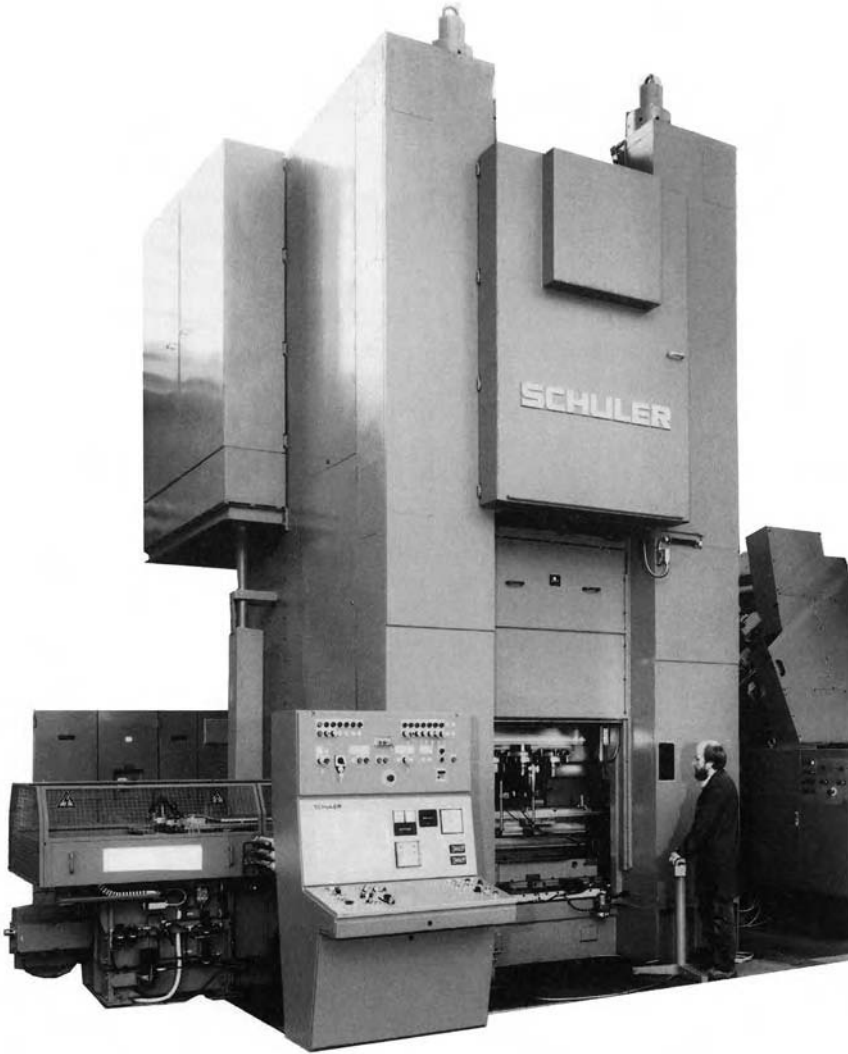


Figure 25.6 Vertical cold extrusion transfer press with toggle drive (Photograph: Schuler works, Göppingen, Germany)

These presses have a generously-sized housing to hold tooling for up to six operations. These presses are powered with variable-speed DC motors. The clutch and brakes are operated electropneumatically, and are mounted apart for thermal reasons.

25.3 Horizontal knuckle-joint and toggle presses

To produce tubes and similar thin-walled hollow parts, presses are generally used with a horizontal layout (Figure 25.7) as it is easier to feed in the blanks and convey away the finished parts.

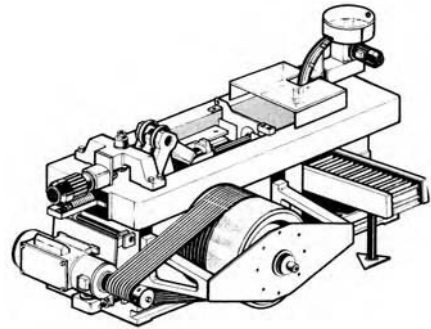



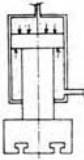


Figure 25.7
Horizontal toggle press to manufacture tubes (Illustration: Herlan & Co. works, Karlsruhe, Germany)

Table 25.2 Characteristics of eccentric, crank, knuckle joint / toggle and hydraulic presses. 1

Characteristic	Presses controlled by the ram path			Presses controlled by force
	Eccentric press	Crank press	Knuckle-joint or toggle press	Hydraulic press
Energy transmission	Con rod 	Con rod 	Con rod 	Piston rod 
Energy for movement	Energy storage – flywheel			Pressurised oil $p = 100$ to 315 bar
Effective stroke range (mm)	10 – 80	100 – 300	3 – 12	100 – 1000
Max. nominal press force F_N (kN)	1000 to 16 000		1000 to 16 000	1000 to 16 000
Number of continuous strokes n_{ct} in min^{-1}	10 to 100	10 to 100	20 to 200	5 to 60
Work capacity W (kNm)	$W = F_N \cdot h_N$			$F_{\max} \cdot h_{\max}$
Nominal press force F_N (kN)	$F_N = \frac{T}{\sin \alpha}$		graphical analysis	$F = p \cdot A - R$

25.4 Exercise on Chapter 25

1. What differences are there between a knuckle-joint or toggle press and a crank press?
2. When are horizontal knuckle-joint presses often used?

26 Hydraulic presses

The frames of hydraulic presses are mainly built as welded steel O-frames (straight-side frames) (Figure 26.1). In smaller presses the frame is built in one piece and in larger presses in three pieces. The three main elements (bottom platen, side columns and head) are held together with tie rods.

26.1 Hydraulic press drives

The ram movement (Figure 26.2) is produced by a differential piston. In small presses, the required amount of compressed oil is provided by means of constant feed pumps (gear or screw pumps) and in larger presses by adjustable axial or radial piston pumps. The operating pressure for hydraulic presses is between 200 and 300 bar. Too low a pressure would require an oversized piston and too high a pressure would mean leakage would be hard to control.

The most important technical data can be determined as follows:

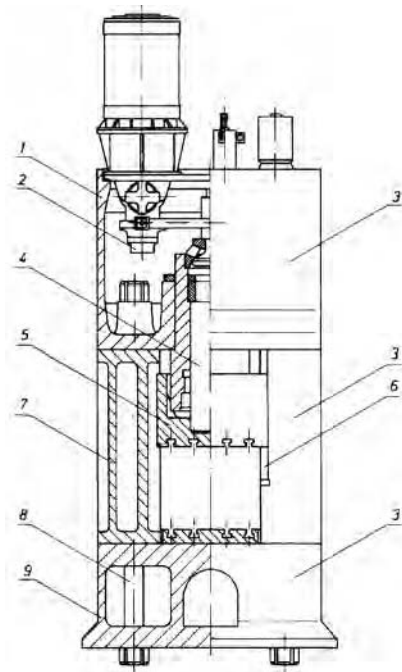


Figure 26.1 Three-part hydraulic press. 1 head, 2 pump, 3 side column, 4 press cylinder, 5 ram, 6 guide, 7 cross-section of side column, 8 tie rod, 9 bottom platen (Illustration from LASCO Umformtechnik works, Coburg, Germany)

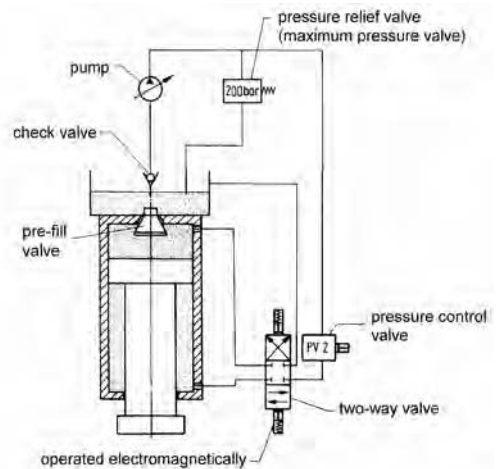


Figure 26.2 Highly simplified drive layout of a hydraulic press

1. Drive power:

$$Q_P = Q_{Pth} \cdot \eta_{Pvol}$$

Q_P in l/min actual pump capacity

Q_{Pth} in l/min theoretical pump capacity

P in kW drive power

p in bar pressure in the system

η_{Pvol} – volumetric efficiency of the pump

η_{Pm} – mechanical efficiency of the pump

η_M – machine (press) efficiency

$$P = \frac{Q_{th} \cdot p}{600 \cdot \eta_{Pm} \cdot \eta_M}$$

2. Piston speeds:

2.1 Forward stroke (working stroke):

$$Q_P = Q_{pi}$$

A_{pi} in cm^2 piston area during working stroke

d_1 in cm diameter of the piston

d_2 in cm diameter of the differential piston

$$v_A = \frac{Q_p \cdot 10 \cdot \eta_{pi_{vol}}}{A_{pi1}}$$

$$A_{pi1} = \frac{d_1^2 \cdot \pi}{4}$$

Q_{pi} in l/min actual piston inward oil flow

Q_p in l/min actual pump outflow

η_{ws} in m/min speed of piston on forward stroke

η_R in m/min speed of piston on return stroke

$\eta_{pi_{vol}}$ – volumetric efficiency of piston

2.2 Return stroke:

$$v_R = \frac{Q_p \cdot 10 \cdot \eta_{pi_{vol}}}{A_{pi2}}$$

$$A_{pi2} = (d_1^2 - d_2^2) \frac{\pi}{4}$$

A_{pi2} in cm^2 piston area on return stroke



Figure 26.3 Hydraulic cylinder with differential piston

3. Piston force (without considering piston own weight and friction)

3.1 Press force (working stroke)

$$F = \frac{p \cdot A_{pi1}}{10^2}$$

F in kN press force

p in bar operating pressure (as N/cm^2)

3.2 Ram retraction force

$$F_R = \frac{p \cdot A_{pi2}}{10^2}$$

F_R in kN retraction force.

26.2 Example

A constant feed pump providing a feed flow of $Q_p = 200 \text{ l}/\text{min}$ at an operating pressure of $p = 150 \text{ bar}$ is to be used to power a small hydraulic press.

Where:

diameter of the working piston $d_1 = 200 \text{ mm}$;

diameter of the differential piston $d_2 = 160 \text{ mm}$; $\eta_{pi\text{vol}} = 0.97$

Find:

1. press force
 2. retraction force
 3. speed of piston on forward stroke (operating speed)
 4. speed on return stroke.
- } without considering own weight and friction

Solution:

$$1. \quad F_{\text{def}} = \frac{p \cdot A_{pi1}}{10^2 \text{ N/kN}} = \frac{150 \text{ daN} \cdot (20 \text{ cm})^2 \cdot \pi}{\text{cm}^2 \cdot 10^2 \text{ N/kN} \cdot 4} = \underline{\underline{471.2 \text{ kN}}}$$

$$2. \quad F_R = \frac{p(d_1^2 - d_2^2)}{10^2 \cdot 4} = \frac{150 \text{ daN} \cdot (20^2 \text{ cm}^2 - 16^2 \text{ cm}^2) \cdot \pi}{\text{cm}^2 \cdot 10^2 \cdot 4} = \underline{\underline{159 \text{ kN}}}$$

$$3. \quad v_A = \frac{Q_p \cdot 10 \cdot \eta_{pi\text{vol}}}{A_{pi1}} = \frac{200 \text{ l} \cdot 10 \cdot 0.97}{\text{min } 20^2 \text{ cm}^2 \cdot \pi / 4} = \underline{\underline{6.17 \text{ m}/\text{min}}}$$

$$4. \quad v_R = \frac{Q_p \cdot 10 \cdot \eta_{pi\text{vol}}}{A_{pi2}} = \frac{200 \text{ l} \cdot 10 \cdot 0.97}{\text{min } (20^2 \text{ cm}^2 - 16^2 \text{ cm}^2) \cdot \pi / 4} = \underline{\underline{17.1 \text{ m}/\text{min}}}$$

26.3 Advantages of hydraulic presses

The advantages of hydraulic presses are:

- a) constant power all through the stroke,
- b) force can be finely regulated (so no extra load-limiting safety device required),
- c) work capacity unlimited until $W_{\max} = F_{\max} \cdot s_{\max}$.

One disadvantage is the lower operating speed compared with crank presses, which results in lower output (parts per time unit).

26.4 Practical application of hydraulic presses

26.4.1 Drawing presses

Generally wherever constant power along a long stroke depth is required:

forward extrusion of long parts,

ironing,

embossing and coining (here, there is enough time for material to flow),

deep drawing.

Triple-action drawing press

For deep drawing, triple-action presses are sometimes used (Figure 26.4). The press shown here consists of two main elements: the press frame and the blank holder, as well as an ejector or a die cushion in the bottom platen (Figure 26.4a).

The inner ram drawing depth is determined by the relative stroke setting which can also be used to link the blank holder and the inner ram. Once the blank holder and the inner ram move down, the blank holder builds up the required pressure. Then the actual drawing process is carried out by the inner ram. Finally, the drawn part is knocked out by the ejector (see also Chapter 14.9).

If the layout includes a die cushion in the bottom platen and the blank holder and inner ram are linked by the relative stroke setting, conventional drawing tooling can also be used on the press.

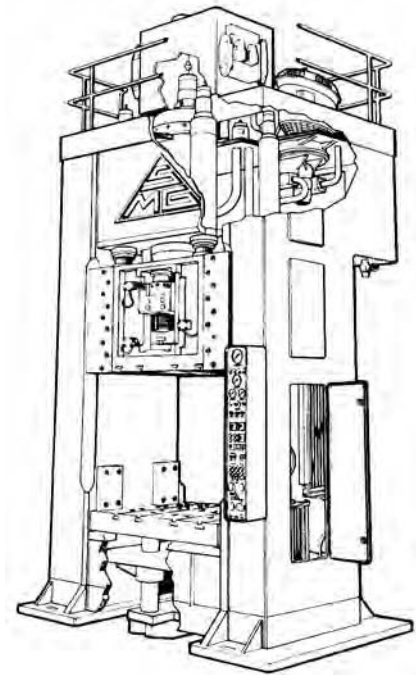
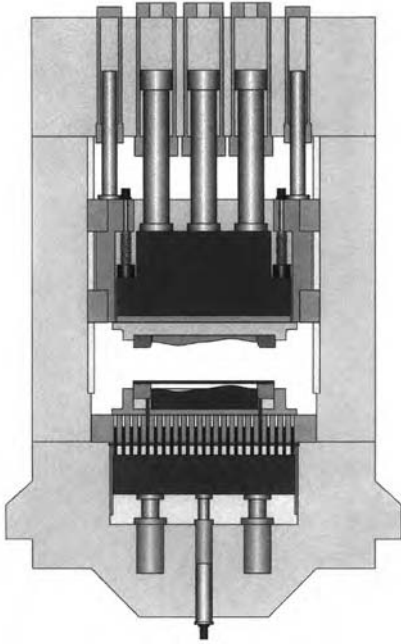
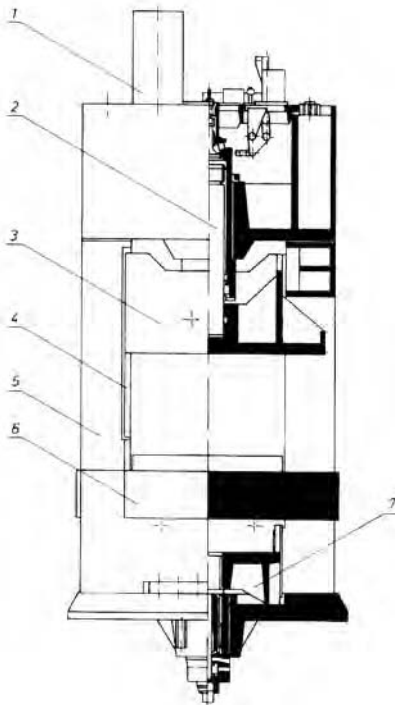


Figure 26.4 Cross-section of a triple-action hydraulic drawing press (Illustration from Schuler, SMG GmbH & Co. KG, Waghäusel, Germany)

**Figure 26.4a**

Layout of blank holder, drawing ram and ejector on the drawing press shown in Figure 26.4a (Illustration: Schuler, SMG GmbH & Co. KG, Waghäusel, Germany)



26.4.2 Deep drawing percussion presses

Deep drawing percussion presses are also double- or triple-action drawing presses which can work both as normal drawing presses and also as drop hammers. In the double-action hydraulic deep drawing percussion press shown in Figure 26.5, a drawing press is combined with a hammer. The die cushion to operate the blank holder is built into the lower part of this press, under the platen. It is driven separately, so the drawing ram and the die cushion can be controlled completely independently of one another.

The die cushion can also act as an ejector.

Figure 26.5

Electric/oil hydraulic deep drawing percussion press

1 axial piston pump, 2 press piston, 3 ram
4 ram guide, 5 press frame, 6 bottom platen,
7 deep drawing die cushion

(Illustration from LASCO Umformtechnik works, Coburg, Germany)

This press is equipped with a program control which can be used to pre-select the operating principle. For example:

1. deep drawing,
2. heavy bottom finishing with hammer (up to 5 hammer blows from different drop heights).

Highly accurate combined drawn and bottomed parts can be produced by bottoming with a hammer. Whereas the workpiece often springs back with a pure deep drawing operation, bottoming with a hammer can stop the material from moving. The forces which result from the bottoming can be calculated from the relationship

$$\text{Force} = \frac{\text{work}}{\text{deformation displacement}} .$$

As the deformation displacement is very small in bottoming, high forces result which form the workpiece very precisely. This outstanding characteristic makes the press ideal for manufacturing difficult drawn and bottomed parts.

26.4.3 Hydraulic extrusion presses

The hydraulic extrusion press shown in Figure 26.6, with a press force of 3,150 kN, stands out for its highly bend- and twist-resistant double-sided press frame. The eight-part ram guide system with no play is set out like a cross. This system gives the ram close directional accuracy and at the same time makes it very sway-resistant. Sway resistance is also increased by the high ratio of the ram length to the ram width, L/W.

Workpieces can be ejected from the lower or upper die as required thanks to hydraulic ejector pins in the platen and ram.

The machine comes with a fully programmable PC control system (PC-5000 type). It has menu navigation and can therefore be operated with little training by any worker familiar with CNC machines. Instead of the computer control system, another option is to use a CNC-50 type CNC control system with a disc drive.

Hydraulic extrusion presses are used for manufacturing larger workpieces using a cold forward extrusion method. This kind of workpiece requires constant force across a long distance. This is provided with a hydraulic extrusion press, as the available deformation force does not depend upon the deformation distance.

The ram guidance system described above offers optimum guidance, meaning that these presses can be used to produce very precise extrusions requiring no chip-producing finishing work.



Figure 26.6 Hydraulic double-sided extrusion press (Photograph: Dunkes GmbH works, Kirchheim unter Teck, Germany)

26.5 Exercise on Chapter 26

1. Explain the drive layout of a hydraulic press.
2. How is the ram speed raised on the return stroke?
3. Why is high speed on the return stroke desirable?
4. What is the difference between a double-action and a single-action press?
5. What kind of operations are double-action or triple-action presses needed for?

27 Special-purpose presses

Special purpose presses are those which are designed for very precise fields of application or operations.

These presses can be powered by hydraulic or crank drives. Some examples of special-purpose presses are:

- deep drawing transfer presses for sheet forming
- transfer presses for bulk forming
- forging presses for impression-die forging
- extrusion presses for hot and cold extrusion
- automatic punching presses for the automatic production of stamped parts.

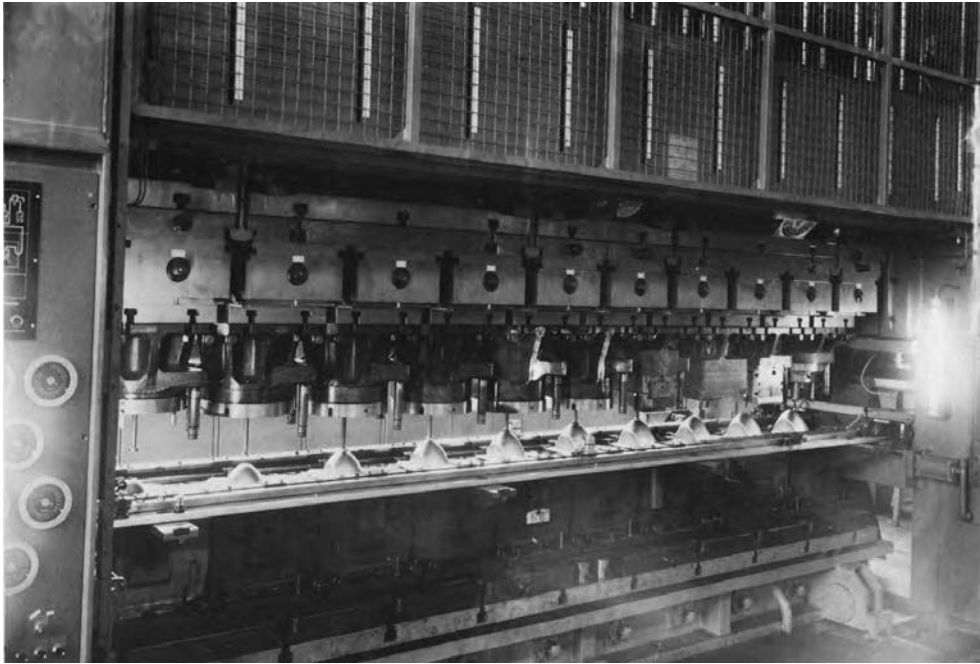
Of the special-purpose presses described above, three will now be described in more detail.

27.1 Deep drawing transfer presses

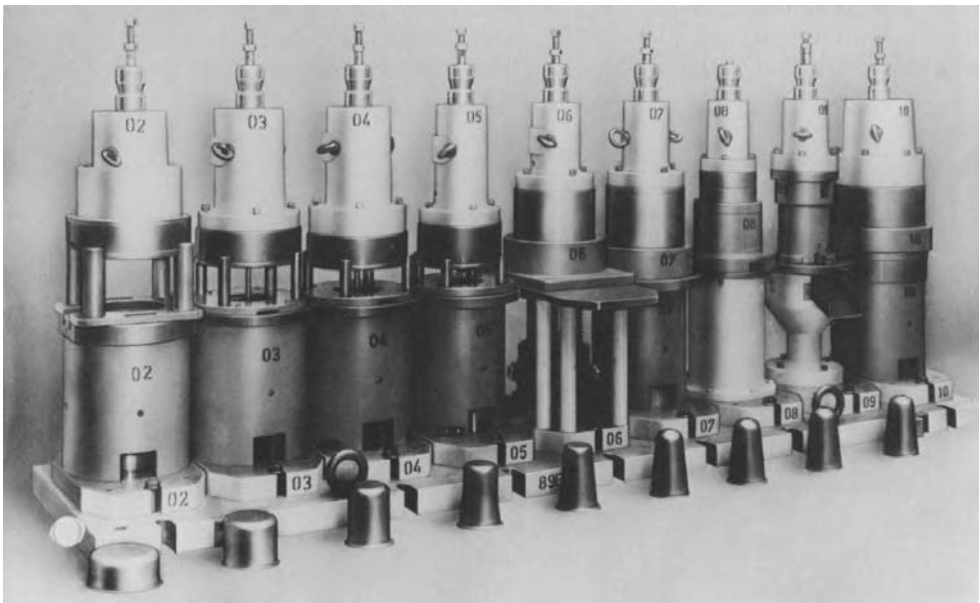
Transfer presses are special machines for workpieces requiring several operations. As they are mainly used to manufacture drawn sheet parts, their basic construction is that of a drawing press. They have a double-action ram. Whereas only one die set is mounted on a normal drawing press, a transfer press holds several. The number of die sets corresponds to the number of operations required to produce a drawn part. Figure 27.1 shows a drawn part of this kind, requiring 11 manufacturing operations. Figure 27.2 shows the Weingarten transfer press used for this workpiece with the die sets ready for use. The press frame is a steel-plate construction. It consists of the platen, the press columns and the head. These parts are joined using hydraulically pre-tensioned steel tie rods, forming a stable frame.



Figure 27.1 Sequence of operations for a drawn part



a)



b)

Figure 27.2 Tool space (Figure a) and tooling set (Figure b) of a deep drawing transfer press with 4500 kN press force (Photograph: Weingarten works, Weingarten, Germany)

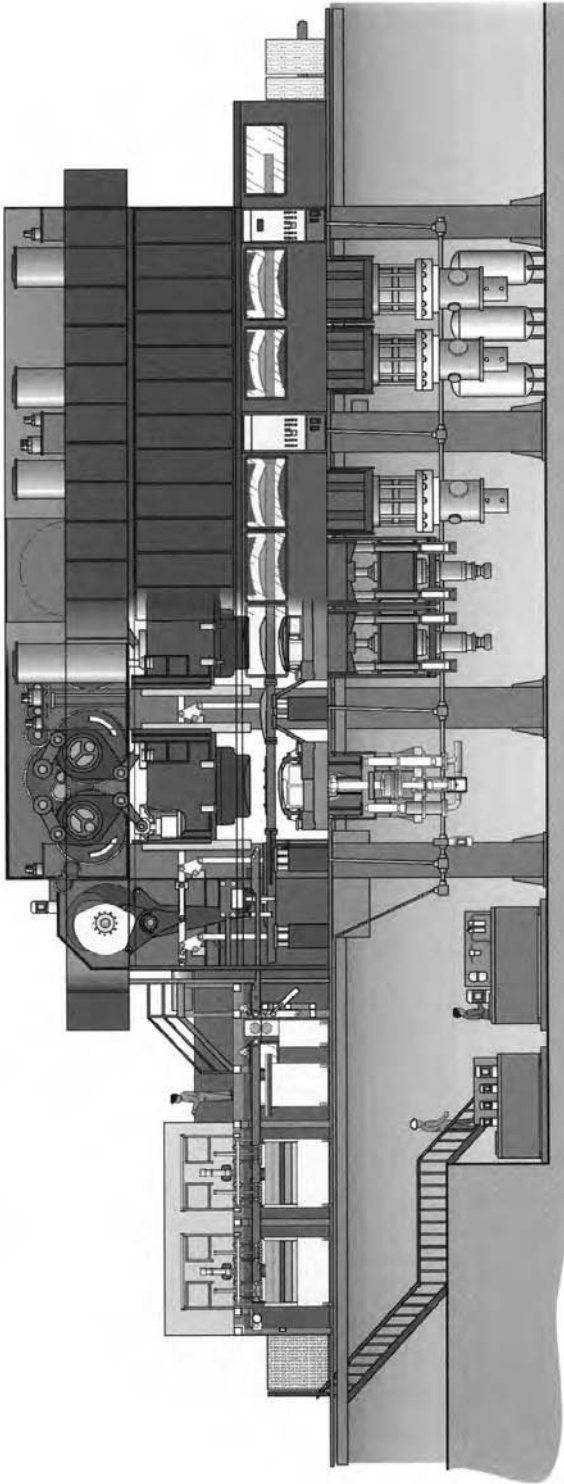


Figure 27.3 Set-up of a four-column bulk transfer press system with three rams, six forming stages and a press force of 38,000 kN. (Illustration: Müller-Weingarten works, Weingarten, Germany)

The principle of construction for a bulk transfer drawing press with a gripper rail transfer (Figure 27.3) is based on the press, transfer and stock feed working together as a unit. The design mainly depends upon the range of parts, the tooling dimensions these require and the deformation process.

Between four and six forming stages are required to produce car body parts, according to difficulty. As well as deep drawing operations, bending, flanging, stamping and embossing operations can also be carried out in a sequence of this kind. The number of rams is determined by the number of forming stages needed. The number of rams also determines the number of press columns which give the presses their name:

1 ram = 2 columns; 2 rams = 3 columns; 3 rams = 4 columns.

The press system shown in Figure 27.3 is therefore a four-column press with three rams and six deformation stages divided thus: 1 + 3 + 2. It is equipped with a hydraulic or pneumatic die cushion and has a maximum press force of 38,000 kN. The central drive moves not only the rams, together, but also the transfer system.

As the drive principle (Figure 27.4) shows, the moment is transmitted from the RPM-regulated motor (1) to the flywheel (2). As soon as the hydraulic clutch (3) is closed, the ram movement is initiated by means of the pinion (4) and the transmission gear (8), moving the pinion shaft (7). The eccentric herringbone gears (8) then move the crank arms of the ram kinematics, thus causing the ram to move.

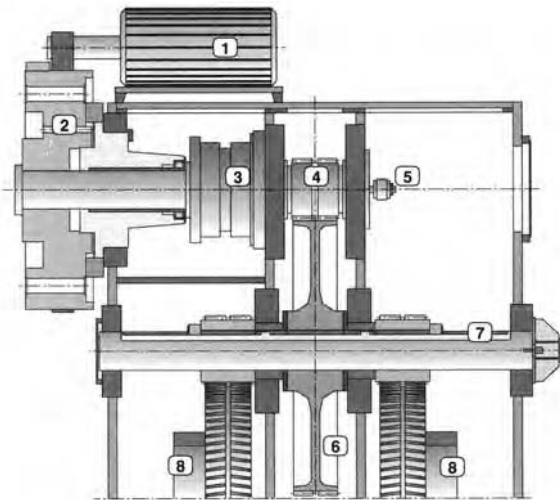


Figure 27.4

The principle of the drive on the bulk transfer press shown in Figure 26.3.

(Illustration: Müller-Weingarten works, Weingarten, Germany)

To ensure that the path of the movement is optimal, as a rule these presses are fitted with a drive with several joints (Figure 27.5) known as HiPro kinematics. The kinematics is constructed in such a way that in conjunction with a drawing device, even difficult parts can be produced with no difficulty.

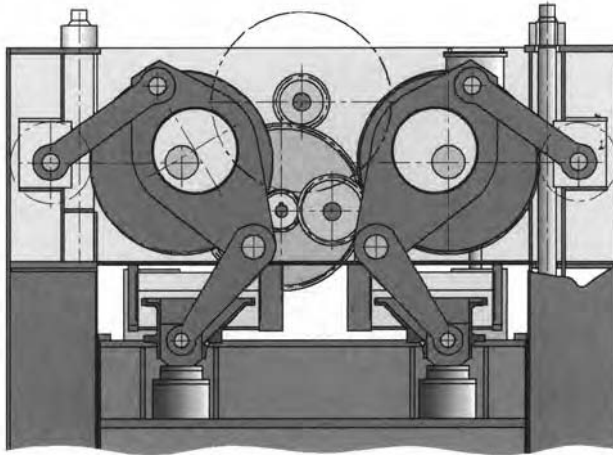


Figure 27.5 Ram kinematics with a multi-joint drive (HiPro kinematics) (Illustration: Müller-Weingarten works, Weingarten, Germany)

Parts are transported from one tooling station to the next by means of a gripper rail transfer system. The transfer system functions are divided into three axes.

Axis 1: gripper part; axis 2: lift part; axis 3: move part forwards.

In this system, the transfer system drive is connected directly to the press drive via a transmission gear. This ensures that the movements of the press and transfer system are precisely synchronised. The movements of the three transfer axes are initiated by cams. The profiles of the cams are traced by cam followers and transferred to a lever system.

Figure 27.6 shows a large-capacity transfer press from the Schuler company. The drive principle is comparable to the Müller-Weingarten transfer press described above. In both presses, the blanks are fed in (in Figure 27.6 front left) by stack systems (known as de-stackers) which automatically conduct the blanks into the press: from here the gripper transport system conveys the blanks into the working area. At the end of forming the finished parts are brought out of the press in the unloading station.

To ensure that tool changes are efficient, bulk transfer presses are fitted with sliding tables which move automatically (Figure 27.6 shows four sliding tables to the right of the press); the tooling which is about to be mounted is placed here. These sliding tables, which are powered by frequency-regulated motors, move in and out at right angles to the direction of production.

When the tooling is changed, the die sets are driven out of the preparation area into the press operation area. Here they are automatically located and clamped in place. In the past when assembly was carried out manually, it took one or two weeks to change to a new workpiece. Today, in the age of automation, only two or three hours are needed. The whole unit is operated by only three people and monitored on computer screens.

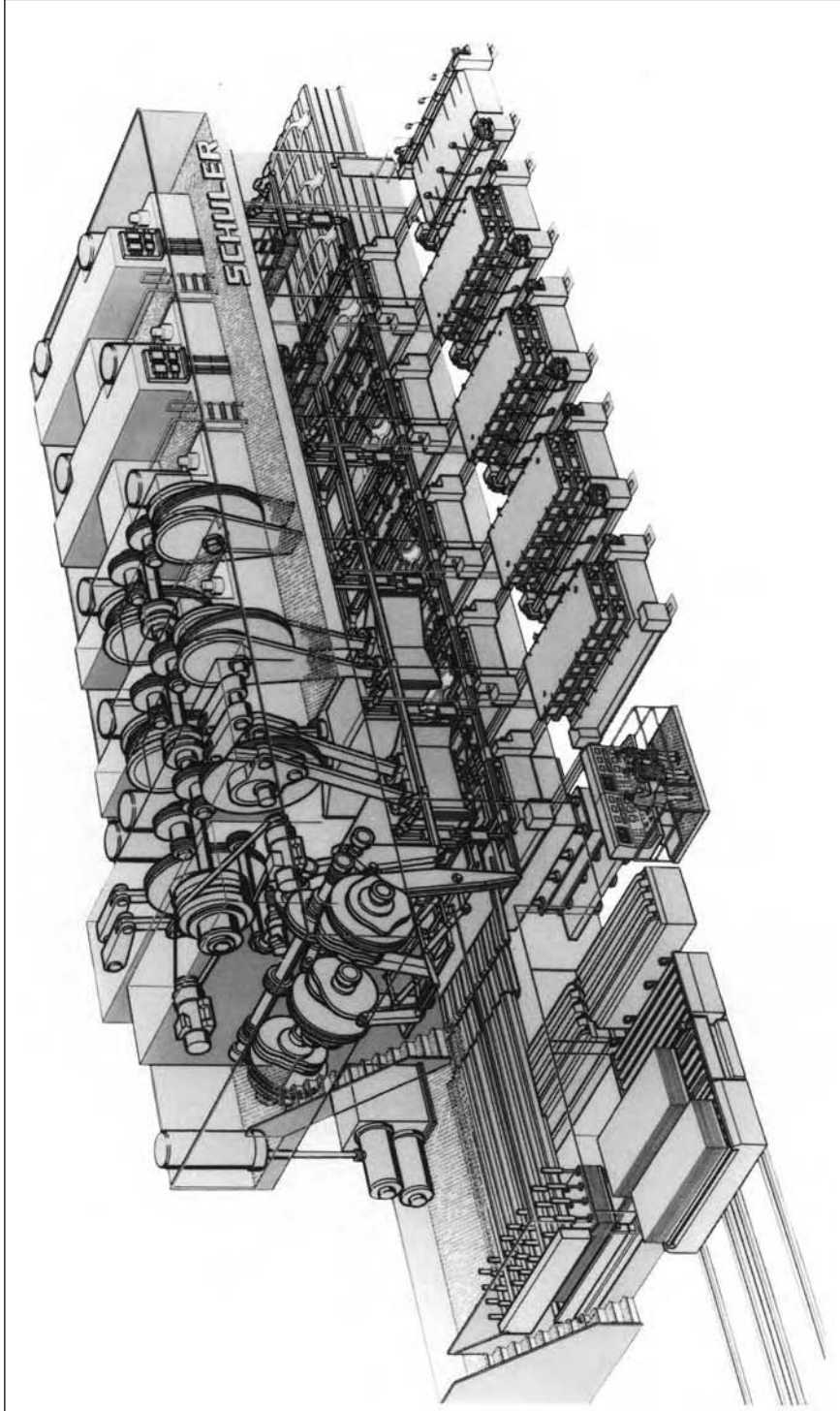


Figure 27.6 The drive of a large-capacity transfer press. Crank mechanism to drive the press; control discs to drive the workpiece transport system. (Illustration from Schuler works, Göppingen, Germany)

27.2 Transfer presses for bulk forming

Unlike vertical transfer presses, which are used mainly for sheet forming, horizontal transfer presses were developed for bulk forming.

They are cost-effective when workpieces requiring several working operations need to be produced in large quantities, and when the tooling can be controlled in terms of its useful life. After shearing, different manufacturing processes are carried out in the individual press stations (e.g. Station 1 upsetting, Station 2 extrusion, etc.). As the industry for standard parts (screws and bolts, nuts and rivets) always requires parts on a large scale, that is where presses of this kind first became established. Today transfer presses are used to manufacture all kinds of bulk-formed parts. These presses are categorised according to

1. the number of stations into two-stage, three-stage, four-stage and multi-stage presses,
2. tooling arranged horizontally or vertically,
3. fields of application
 - e.g. presses for screw and bolt manufacturing,
 - presses for nut manufacturing,
 - presses for formed parts of various kinds, e.g. valve spring retainers.

Figure 27.7 shows a two-stage press. This press has a shearing stage and two working stations.

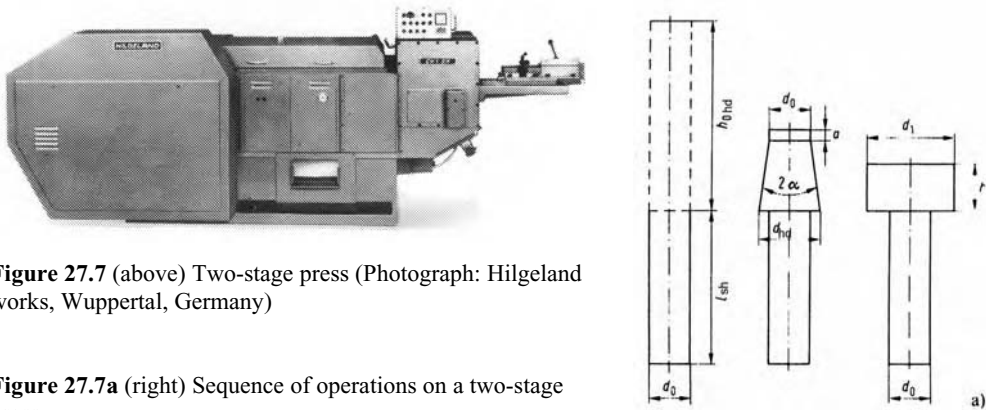


Figure 27.7 (above) Two-stage press (Photograph: Hilgeland works, Wuppertal, Germany)

Figure 27.7a (right) Sequence of operations on a two-stage press

The head of a screw, for example, can be upset and finished in the two working stations (see also Chapter 4 Figure 4.7). The front feed of the press guides the wire from the coil through a wire straightener and then pushes the straight wire on to the shearing stage. Here it is cut to the required length. A gripper brings the wire section to the press die set. After forming, the finished workpiece is automatically knocked out by the ejector.

Figure 27.8 shows the drive layout for this press:

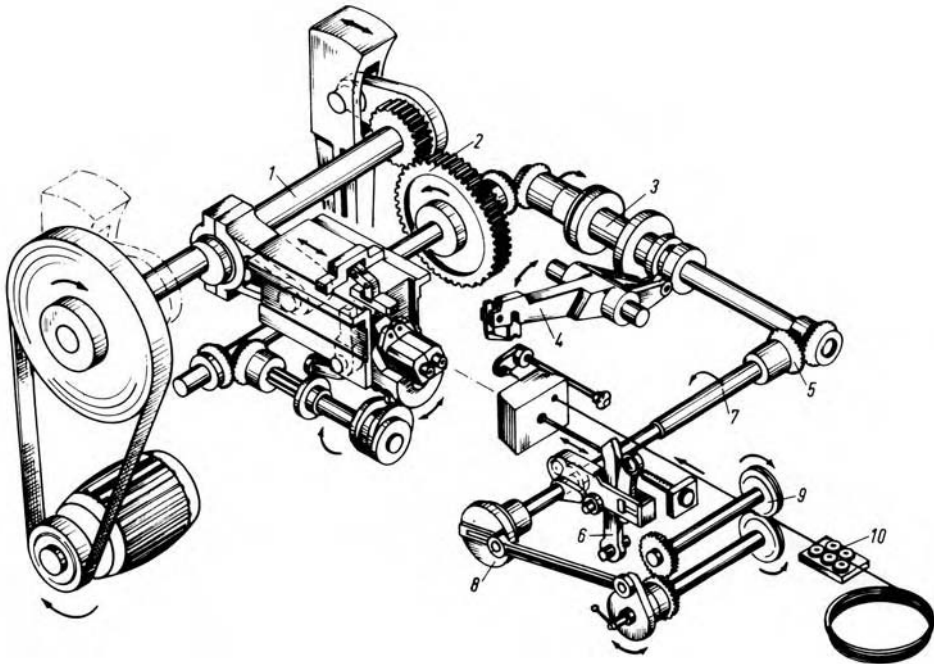


Figure 27.8 Drive layout of a CH 1 SH two-stage press (Illustration: Hilgeland works, Wuppertal, Germany)

The eccentric shaft 1 drives the slide stroke via the connecting rod, and at the same time powers the drive of the control shaft 3 via a transmission gear 2 and bevel gears.

The shearing system 4 is operated by means of cams from the control shaft, and the ejector is operated using more bevel gears 5 and a pivoted lever 6.

Via a link block 8, the same transverse shaft 7 drives the wire infeed rollers 9 which also pull the wire through the straightening rollers 10 and then push it into the shearing bush.

The “Formmaster FM-350” press shown in Figure 27.9 is a transfer press with a vertical tool layout.

The press body is a box frame which holds the gears and the ejector mechanism in a closed casing. This keeps the elements of the driving gear, running in an oil bath, safely separated from the tooling area. The highly rigid construction of the body was optimised using the Finite-Element Method. The ram, which holds the punch, is guided by rollers with no play at any level. In this press, the working stages are arranged one above the another and the die sets are set up vertically (Figure 27.10). This is a great advantage for tool changing as the tooling is easy to access. They can also be monitored well and maintenance is easy.

The punch holders on the front side of the ram can be adjusted at three levels as relates to the die axle.

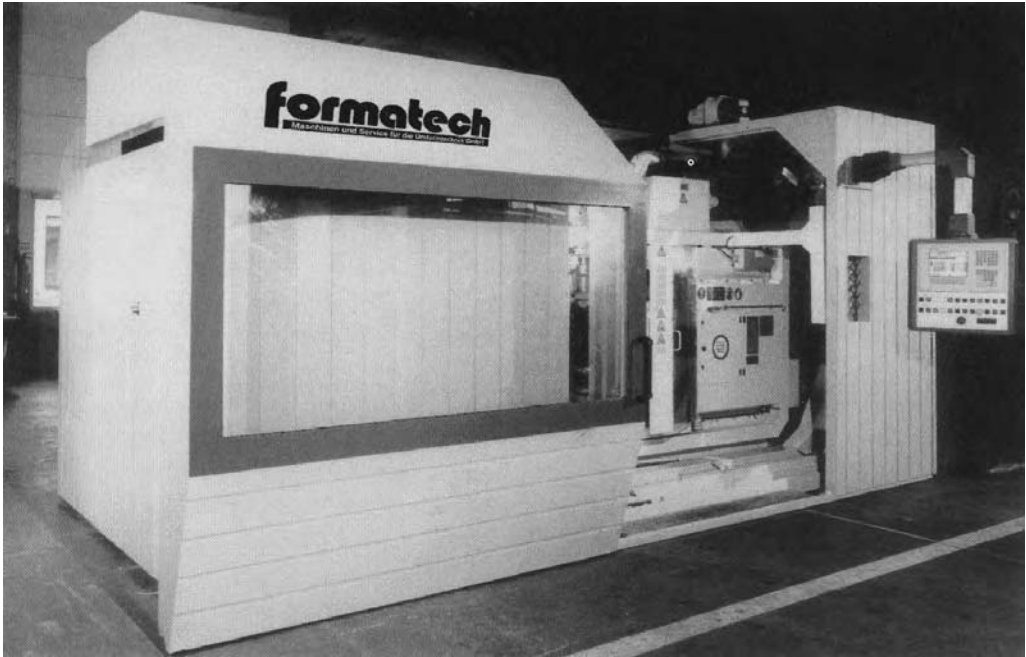


Figure 27.9 Formmaster FM-350 transfer press with five forming stages and one shearing stage (Photograph from Formatech GmbH works, Willich-Müncheide, Germany)

For the transfer press shown in Figure 27.9, a program-controlled tool-changing system is available, among other things.

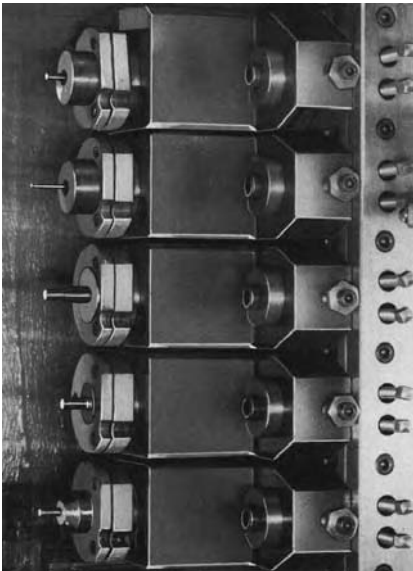


Figure 27.10 Vertical arrangement of the punch in adjustable tool holders (Photograph from Formatech GmbH works, Willich-Müncheide, Germany)

The fact that the punch holder and punch can be precisely adjusted and the ram is guided with no play guarantees consistently small tolerances in the finished part and long tool lives. The manufacturing plants typically used in bulk forming are capital-intensive, and their cost-efficiency depends crucially upon the percentage of the total production time taken up by non-productive time and set-up time. Here, tool changing and set-up systems can make a vital contribution to shortening these non-productive times and lengthening the time the press is in action.

As manufacturing structures can differ greatly as concerns part size, lot size, processing and the manufacturing sequence, various systems for fast tool changing are available on the market: the operator can choose a combination suited to the operation.

With this tool-changing system all the tooling is adjusted and changed fully automatically when the press set-up is changed. This reduces changeover times drastically. The result is flexible manufacturing which means these presses can also be used economically for smaller lot sizes.

The die block, shearing block and punch blocks, which are mounted on a single die plate, are changed as one unit. The press is equipped with a special device to help carry out the change. The die block and the die plate are clamped in place with quick-action hydraulic devices which can easily be released.

The shearing blade, shearing bush, punch and die can still be changed separately, independently of this fast tool-changing system.

The tooling being changed can be adjusted before it is mounted in the press. For this purpose the press has a tooling support area for adjusting tools, and a fixed holder for the die block and die plate, as well as appropriate adjustment devices.

The optimum settings for the X, Y and Z coordinates of a workpiece are determined once for every stage and then saved in the tooling databank. When the tooling is changed, these saved parameters can be called up at any time, even when the work is not being done on the press.

This makes tool changing faster, easier and safer. When the conditions of a process are the same, sound parts are produced right from the first strokes. With this system, a program adjusts peripheral units: this is fully automatic. The ejector stroke and return stroke are adjusted with a motor. The feed system is set up to fit a wide range of diameters so that the grippers do not need changing when production is switched over.

A *numerically* controlled transfer system (Figure 27.11) is used to transport the workpieces within the press. The transfer system and grippers are operated by individually-controlled electric servo drives. The settings are adjusted using a menu – it is no longer necessary to change camshafts or adjust cams. These settings are saved in a tooling databank and can be called up when needed within seconds.



Figure 27.11 NC transfer unit (Photograph from Formatech GmbH works, Willich-Münchheide, Germany)

When single gripper jaws are replaced, a complete magazine is changed which can be pre-adjusted outside the press using an adjustment gauge.

Another important way to reduce machine down time is to fit the press with the Coros Operator Panel operating system. With this system, operating and fault messages give the operator a comprehensive overview of the status of the unit. When he selects the Setup – Operation – Tool Change operating mode, the menu-driven user guide leads him through the process until the press is ready for operation.

All operating and fault messages are clearly worded and archived, making long-term failure analysis possible. The tooling data specific to each part are archived in the tooling databank and can be called up at any time.

Figure 27.12 shows typical workpieces which can be produced on this kind of transfer press.



Figure 27.12 Typical workpieces for transfer presses (Photograph: Formatech GmbH works, Willich-Münchheide, Germany)

Figure 27.13 shows a state-of-the-art transfer press with a shearing station and five forming stages.

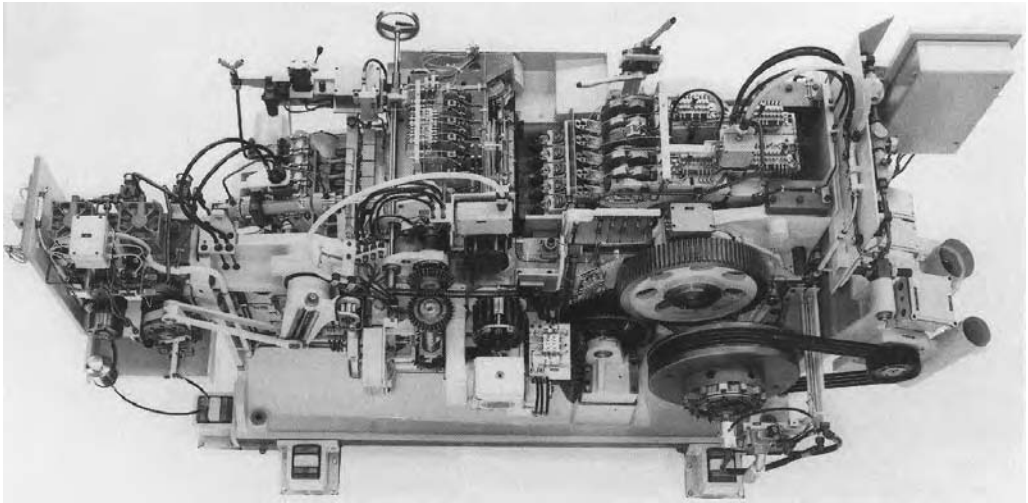


Figure 27.13 High-performance transfer press with five forming stages and an integrated shearing station (Photograph: Hatebur works, Reinach, Switzerland)

In this press, which works from a wire coil, the die sets are arranged horizontally. Four feed rollers draw the wire (14 to 27 mm diameter) into the press via a roller straightener which straightens the wire, until it reaches the stock feed stopper on the shearing machine. In the shearing station (Figure 27.14) the sections of wire are sheared without burring to the length required for the workpiece. The length of the sections is monitored electronically in the

press. The wire stopper, which determines the length of the section, can be adjusted during operation. When there is a deviation in the measurements, the press automatically turns off.



Figure 27.14 Tooling area of a transverse feed transfer press (Photograph: Hatebur works, Reinach, Switzerland)

In the destacker station, the sections are pushed out of the shearing bush and taken up by the first gripper (Figure 27.15) on the transverse transport system, which transports the blank as far as the first forming stage. In the following five forming stages, the blank is then formed by the five die sets (punch and die) until the workpiece is finished. The grippers transport the part in a straight line to the next forming stage. There, they rise up and, as the forming takes place, move back above the punch.

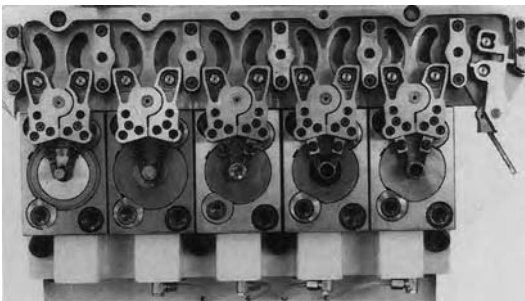


Figure 27.15
Gripper system on a five-stage transverse feed press
(Photograph from Hatebur works, Reinach, Switzerland)

In the last stage of forming, the finished part is then ejected. Depending upon the thickness of the wire, 80 to 210 workpieces per minute can be produced on this press.

Constructional design of the presses

The basic body of the press is a closed bend- and twist-resistant frame which is cast in one piece. The pressure pad the dies are mounted on is strengthened with hardened, replaceable armour plating. The press slide has long guides in front of and behind the crankshaft. The slight play is practically negated by a high-pressure oil circulation lubrication system, which presses the oil into the guide paths. Labyrinth seals protect the guides at the front of the working area against coolant, abrasion and particles from the workpiece.

The crankshaft throw is as wide as the whole slide. The H-shaped double connecting rod is also the same width. This means that the slide support across all five forming stages is such that even an asymmetrical press force does not impair the accuracy of the slide guidance.

The drive is fully variable. A safety stop can bring the press to a halt by means of an electro-pneumatic clutch/brake device within 90° of a shaft rotation. This protects the tooling against damage (fracture). The stroke depth and time of the ejectors which knock the workpiece out of the press can be adjusted separately for each die set.

The tooling can be changed within 60 minutes with the fast tool-change system. The tooling modules (Figure 27.16) are exchanged as a single block, meaning that only fine adjustments have to be made in the press.

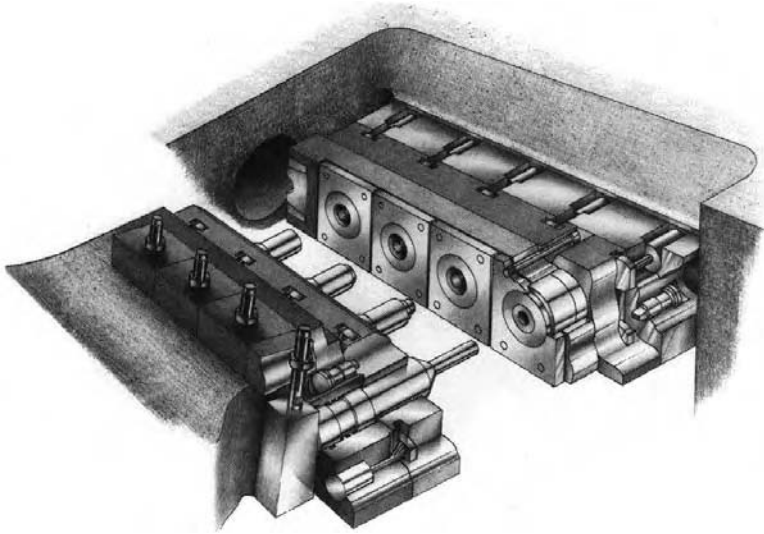


Figure 27.16 Interchangeable fast tool change block (Photograph from Hatebur works, Reinach, Switzerland)

The tooling blocks are prepared outside the press and preset so as not to cause machine downtime. Figure 27.17 shows typical parts produced on this press.



Figure 27.17 Sequence of operations for a spark plug barrel produced on a Coldmatic transfer press (Photograph from Hatebur works, Reinach, Switzerland)

The machine is controlled from a control desk combining all display and control devices. Operating errors are practically impossible as all the main switching functions are interdependently locked.

Table 27.1 Technical specifications

Max. wire diameter at 600 N/mm tensile strength	in mm	14 – 27
Section length	in mm	6 – 170
Number of strokes	in min^{-1}	80 – 120
Nominal press force	in kN	850 – 3500
Press force per step	in kN	350 – 1500
Drive power	in kW	35 – 110

27.3 Automatic punching presses

In Chapter 19, Figure 19.5, there is a description of an automatic fine punching press. This section presents an automatic punching press, Figure 27.18, designed for particularly high stroke rates. With these extreme stroke rates, large mass forces occur due to the bidirectional movement of the masses.

$$F_m = m \cdot \frac{H}{2} \cdot \left(\frac{n}{9.55} \right)^2$$

F_m in N mass force
 m in kg mass of the moving parts
 n in min^{-1} stroke rate
 H in m stroke length

These mass forces not only put a stress on the bearing and guides, they are also transmitted onto the floor of the hall.

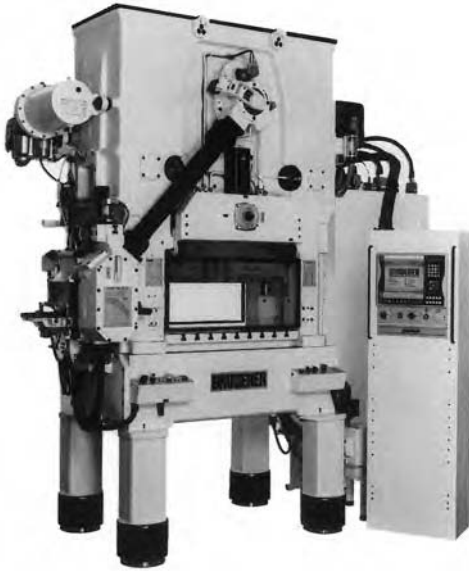


Figure 27.18

BSTA 50 automatic punching press with mass counterbalancing
(Photograph from Bruderer works, CH-9320 Frasnacht, Switzerland)

For these fast-running punching presses, mass counterbalancing is therefore needed if the total mass of the ram and the upper part of the die set exceeds 200 kg.

Table 27.2 Technical specifications for automatic punching presses

Press type		BSTA 20	BSTA 50	BSTA 110
Nominal press force	in kN	200	500	1100
Max. stroke rate	in min ⁻¹	1800	1200	850
Stroke length	in mm	8 – 38	16 – 51	16 – 75
Stroke adjustment	in mm	50	64	89

In the Bruderer mass counterbalancing system (Figure 27.19) the movement of the ram 1 is transferred relative to the tooling bolster plate 2, e.g. on the downwards working stroke; the force produced by the eccentric 6 is increasingly transmitted via the connecting rod 5 and the lever 4 to the column of oil 3 and so on to the ram 1. As a result of acceleration one mass force acts in an upward direction. At the same time the counterweights 9 carry out an upward movement by means of the rod 7 and the mass counterbalancing lever 8. These mass forces counteract and balance out the mass forces from the ram.

The horizontal mass forces from the eccentric parts must also be balanced out, or the press lurches. These mass forces are balanced out by a counterweight using rod 10 and lever 11, with the centre of gravity of the counterweights moving in an ellipse, every point of which corresponds to the resultant of both forces.

As well as the geometric accuracy of the bearing and guide elements, the arrangement of the ram guide system is a decisive factor in the accuracy of the punched parts and the tool lives. In this press, the ideal solution was found: the four-column guide system. The belt feed system consists of a combined gripper and roller feed – a Bruderer system – which can achieve feed accuracies of 0.01 to 0.02 mm.

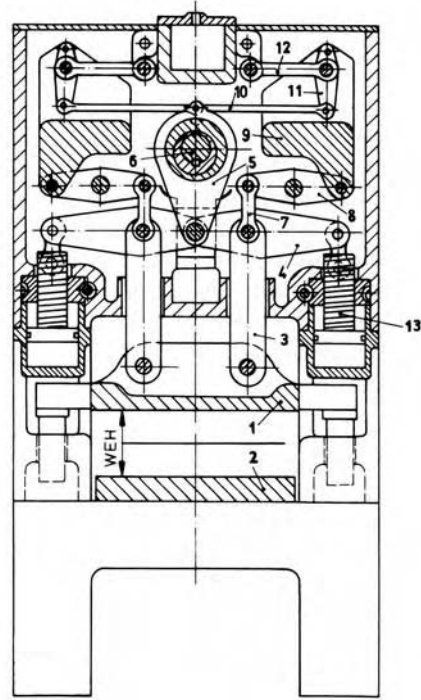


Figure 27.19 Operation of an automatic punching press with mass counterbalancing – Bruderer system – with four-column guide (Illustration from Bruderer works, Frasnacht, Switzerland)

Figure 27.20 is an automatic double-sided shearing / forming press from the HQR series, with a short belt conveyor and a numerically-controlled straightening and feeding device. This press was designed for press forces of 2000 –6300 kN. The frame is a welded steel construction.

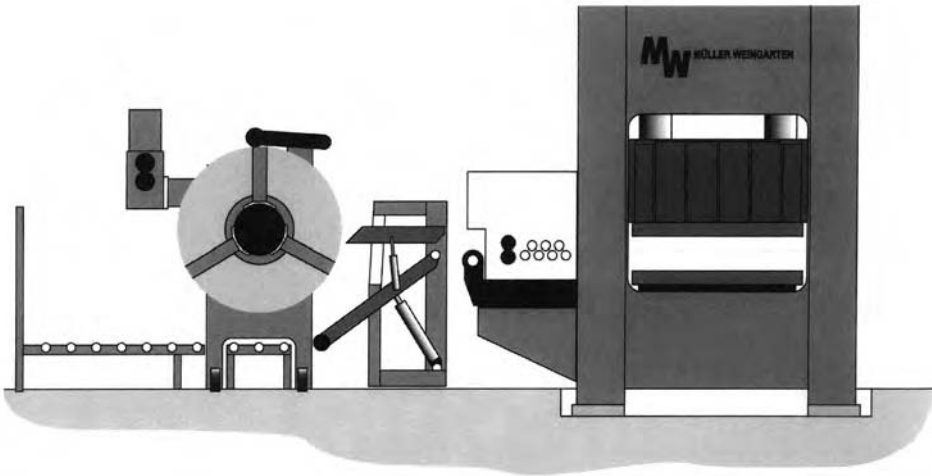


Figure 27.20 HQR-type automatic shearing and forming press with belt conveyor and numerically-controlled straightening and feeding device (Photograph: Müller Weingarten AG, Weingarten, Germany)

It is manufactured to order and so can be adapted to suit the vertical capacity of the customer's tooling. The frame construction has been optimised using the Finite-Element Method. The individual elements of the press and all the know-how were integrated using a building-block method.

The press is powered by a cross-shaft drive (Figure 27.21) with two connecting rods. The drive moment is transmitted from the driving motor, which has a variable stroke rate, by means of the flywheel and the pneumatic clutch/brake combination, to the pinion shaft. From here, half the power is carried to the left eccentric shaft and half to the right one by an intermediate gear.

In this drive principle, the two eccentric shafts turn in opposite directions, each thus compensating for the other's rotational forces without any extra mass. This means that the braking process, when set off by a safety function, for example, has the shortest possible brake angle.

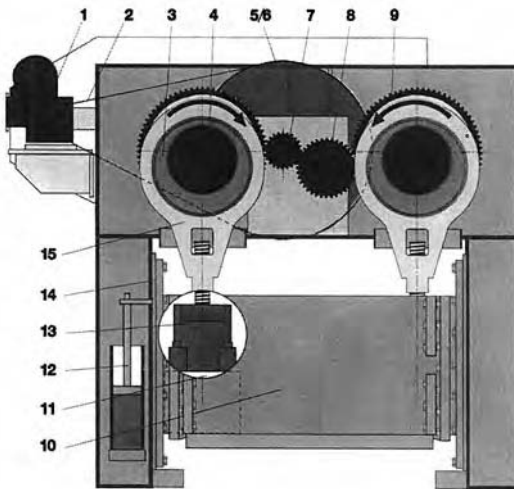


Figure 27.21

Cross-shaft drive

- 1 driving motor,
- 2 flat belt,
- 3 eccentric bush,
- 4 eccentric shaft,
- 5 flywheel,
- 6 clutch/brake combination,
- 7 driver shaft,
- 8 intermediate gear,
- 9 herringbone gear,
- 10 ram,
- 11 pneumatic cushion,
- 12 ram counterweight,
- 13 ram mounting,
- 14 slideway,
- 15 connecting rod

(Illustration: Müller-Weingarten AG works, Weingarten, Germany)

The ram stroke (Figure 27.22) can be automatically adjusted in steps. The required ram stroke is set by twisting the two eccentric bushes in relation to the eccentric shafts. To do this, the eccentric bushes are held in the locking device using synchronising discs and the eccentric shaft is twisted by moving the sliding sleeve, by means of the main drive. The sliding sleeve has inner dog teeth which form a friction lock between the eccentric bush and the eccentric shaft. The ram is adjusted (ram position) by turning the ball spindle (Figure 27.23) using worm gears. This changes the depth by which the ball spindle enters the connecting rod and thus the distance between the ram and the table. To stop the press from being overloaded, the ball spindle presses against a piston onto a cavity containing oil which is pressurised according to the nominal press force. When there is an overload the oil below the piston suddenly escapes, creating a space for overload relief.

The press is CNC controlled. An industrial computer controls all the functions of the press and furthermore all peripheral devices such as the sheet conveyor, the roller feed, the workpiece transporter and the device for ejecting finished parts. An extensive package of various software modules allows the computer system to be adapted to a task as needed. All necessary informa-

tion is visualised on the screen which at the same time acts as a programming interface for the stored-programme control system.

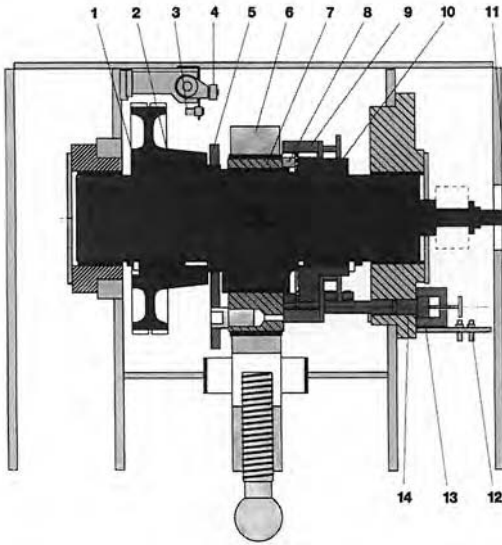


Figure 27.22

Stroke setting (stroke length)

- 1 herringbone gear,
- 2 eccentric shaft,
- 5 synchronising disc,
- 6 connecting rod,
- 7 eccentric bush,
- 8 ring gear,
- 9 sliding sleeve,
- 10 ring gear,
- 13 hydraulic cylinder,
- 14 hydraulic piston

(Illustration: Müller-Weingarten AG works, Weingarten, Germany)

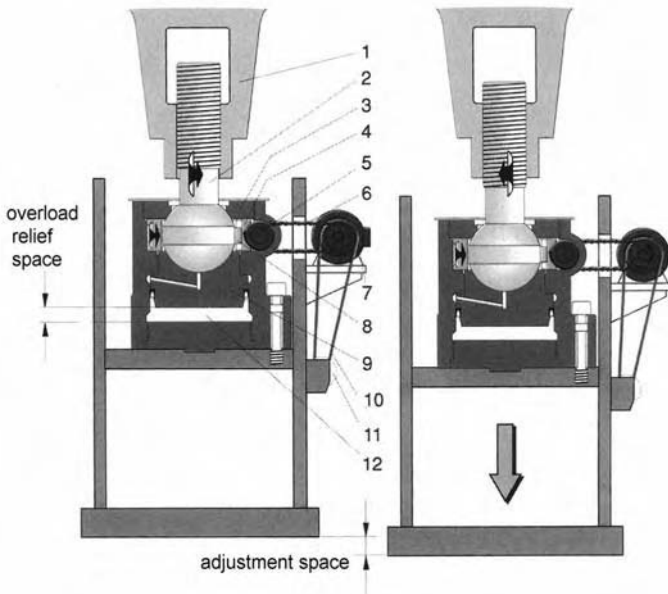


Figure 27.23 Elements for adjusting the ram (ram position)

- 1 connecting rod, 2 ball spindle, 3 ball flange, 4 worm gear, 5 worm shaft, 6 roller chain, 7 electric motor, 8 sliding block, 9 piston, 10 toothed belt, 11 angle encoder, 12 oil cavity (Illustration from Müller Weingarten AG works, Weingarten, Germany)

Table 27.3 Technical specifications for HQR automatic punching presses

Nominal press force	kN	2000 – 6300
Stroke rate	per min.	80 – 150
Ram stroke	mm	200 – 250
Bolster plate	mm	1900 – 2800
	Length	
	Depth	

27.4 Exercise on Chapter 27

1. What are the distinctive features of a transfer drawing press and what workpieces is it used for?
2. How do transfer presses for bulk forming differ and what are they used for?
3. What number of strokes per minute do automatic punching presses have?
4. Why do automatic punching presses require mass counterbalancing?
5. How is the stroke adjusted on an eccentric press?
6. Why are hydraulic extrusion presses used for long extruded workpieces?
7. What is the advantage of transfer presses?
8. What different types of transfer press construction are there?
9. Which workpieces are manufactured only on transfer presses?
10. Which elements of a transfer press transport the workpieces from die set to die set?
11. What is meant by a flexible manufacturing system?

28 Workpiece and stock feed systems

All presses which work automatically in continuous mode need automatic workpiece feed devices.

Some feed devices are powered indirectly from the press.

Others have their own drive. All of them, however, are controlled from the press.

Feed devices can be sorted according to their application into:

28.1 Feed devices for piercing or blanking operations

In automatic piercing and blanking, the operation is carried out from a metal strip. There are two strip feed systems: the roll feed and the gripper feed system.

28.1.1 Roll feed system

This consists of two pairs of rollers which move the stock by friction (Figure 28.1). The movement is derived from the eccentric shaft as a link drive. At the start of the feed process, the pusher rod is pulled upwards. This turns the lever l_1 anticlockwise. This direction of rotation activates the freewheeling clutch c_1 (roller clutch). This then drives the bottom roll clockwise by means of the gears g_1 and g_2 . This moves the strip stock from left to right. The link rod r transfers the infeed movement to the outfeed side. In another construction (Figure 28.2) the roller clutch is driven directly by the pusher rod, the lower part of which is designed as a toothed rod.

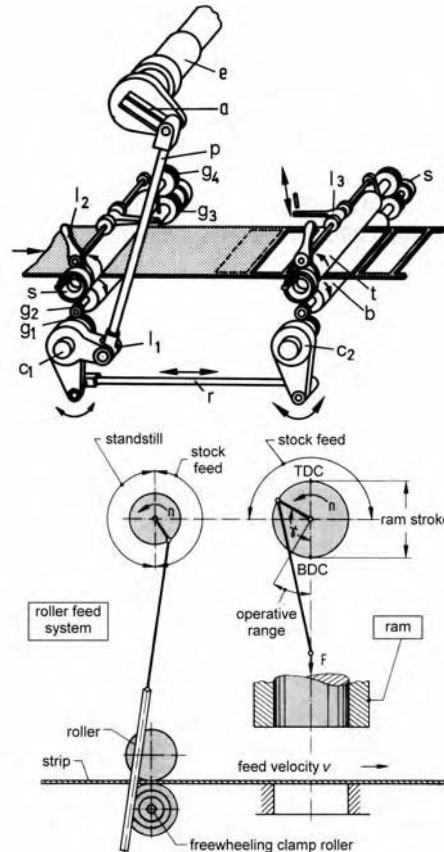


Figure 28.1 (above right) Plan of the roller feed system, e eccentric shaft, a crank arm, p pusher rod, g gears, c roller clutches, t top roll, b bottom roll, s spreader ring brake, l lever, r link rod

Figure 28.2 (below) Roller feed system with bottom roll drive by means of toothed rod

28.1.2 Gripper feed system

This is a feed system where the strip stock being moved is clamped between two pairs of gripper jaws. Here, the movement itself, as shown in Figure 28.3, can again be derived from a link drive, but there are also hydraulic and pneumatic drives. In Figure 28.3 the pusher rod swings round a crank lever which carries out the feed movement. The link rod transfers the gripper infeed movement to the clamping jaws on the outfeed side. The outer transport grippers are closed pneumatically. When the sheet is clamped tight, the feed movement takes place, controlled synchronously with the ram movement of the press.

Both inner clamping rods are opened during the feed phase. They are for holding the sheet tight during the working phase (blanking operation).

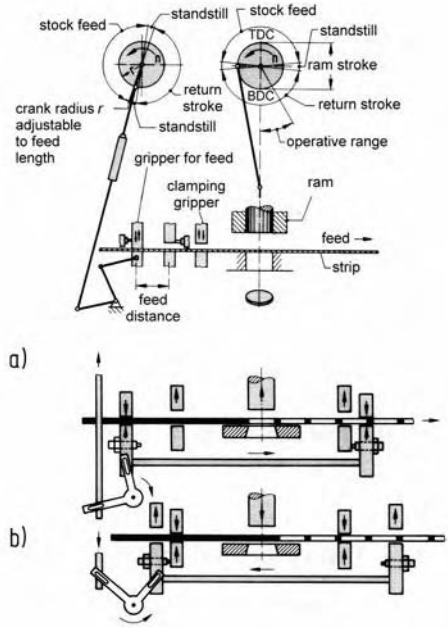


Figure 28.3 The principle of a gripper feed, a) clamping jaws open, b) shut

28.2 Transport devices in deep drawing transfer presses

In deep drawing transfer presses the workpieces are transported from stage to stage with gripper rail systems. These gripper devices consist of two rails which open and close laterally, moving in the direction of feed by one feed step. Gripper elements which are adapted to the workpiece shape at each stage are mounted on the gripper rails (Figure 28.4).

The working cycle consists of four movements:

1. close gripper rails and grasp workpieces;
2. gripper system moves one feed step to the right, carrying the workpieces;

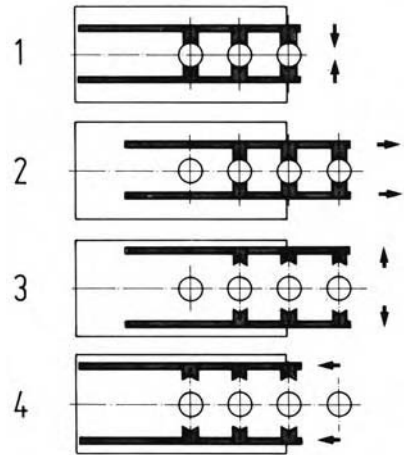


Figure 28.4
The operating principle of a gripper rail system.
1 close, 2 feed movement, 3 open, 4 return

3. the gripper rails open and deposit the conveyed workpieces in the operating position on the next processing die.
4. The open gripper rails drive back into their initial position during the working movement of the ram.

According to the shape of the initial blanks, they are fed to the first station of the gripper rails by stacking magazines, disc feed systems or other suitable conveyors.

28.3 Transport devices for transfer presses for bulk forming

On these machines, grippers are used to carry the workpieces from one forming stage to the next.

The grippers (Figure 28.5) are opened and moved linearly by means of cams. The jaws are closed by spring tension (Figure 28.6). There are some gripper jaws which pivot instead of moving linearly (Figure 28.7), allowing them to turn a workpiece 180°. Figure 28.8 shows a gripper system for a transverse feed press with four working stages.

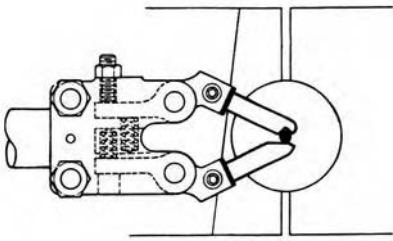


Figure 28.5 Transporting workpieces with simple spring-actuated jaws

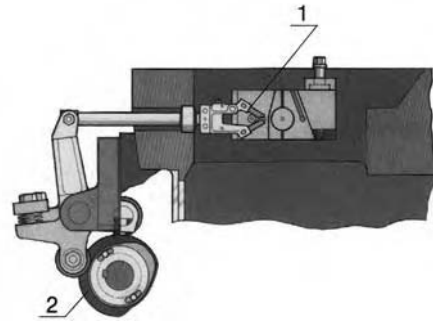


Figure 28.6 The drive of the gripper system to produce the linear movement. 1 gripper, 2 cam

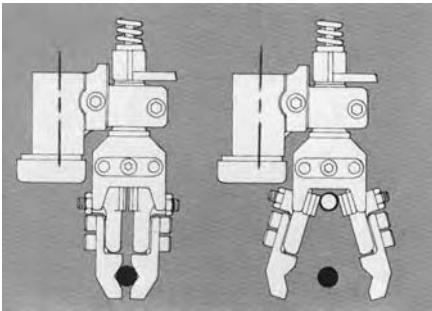


Figure 28.7 Pivotable grippers (180°)

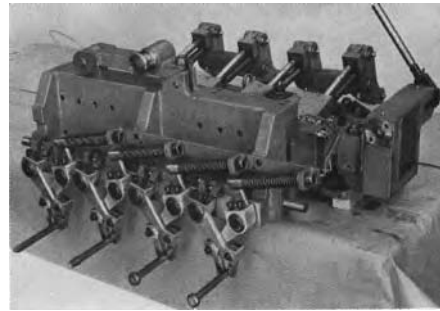


Figure 28.8 Grippers on a four-stage transverse feed press

28.4 Feed devices to supply round blanks for backward extrusion

This kind of device usually consists of three parts: a vibrating conveyor, a baffle (guide rails) and a pusher. The vibrating conveyor is for sorting the blanks. The vibrations of the container separate the parts and they move upwards in spiral grooves. From there they fall through a mechanism which is controlled synchronously with the ram of the press, falling into a chute with guide rails which they slide down due to gravity (Figure 28.9).

The pusher device then moves the blanks in front of the die. The formed parts are knocked out by an ejector which is part of the press. Stud-bolts, rivets and other shaped parts are conveyed in the same way.

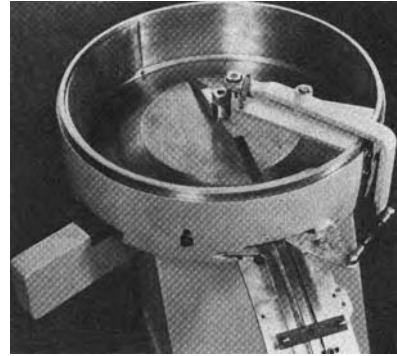


Figure 28.9 Vibrating conveyor

28.5 Feed devices to convey single workpieces in steps

To convey single workpieces, rotary indexing tables are also used. The workpieces are placed in the front area of the table, outside the danger zone, either manually or with a feed device. The rotation, in steps (one move per press stroke), is produced by a Geneva drive (Maltese Cross) and transmitted from the crankshaft by means of toothed and bevel gears. Figure 28.10 shows the drive layout of this kind of rotary indexing table.

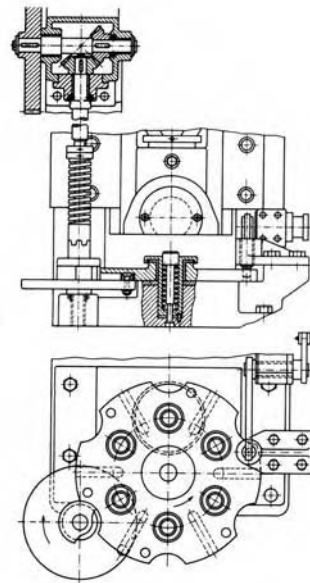


Figure 28.10
Drive layout of a rotary indexing table.

28.6 Feed devices to supply forging presses

Today, impression-die forging in forging lines is also often carried out fully automatically.

The blanks, heated to the forging temperature, are placed in the die using industrial robots (known as manipulators). The manipulator removes the finished or pre-formed forgings from the die after forming and conveys them to the next machine. These industrial robots (Figure 28.11) are built in various sizes (related to the weight they transport and the distance they move). According to requirement, they can carry out linear movements in three axes and also turn. The gripper elements are adapted to the shape of the workpiece.

The lengthwise movements are mainly pneumatic and the turning movements produced using electricity (an electric motor with a downstream gear drive). All the manipulators are NC controlled and can be programmed.

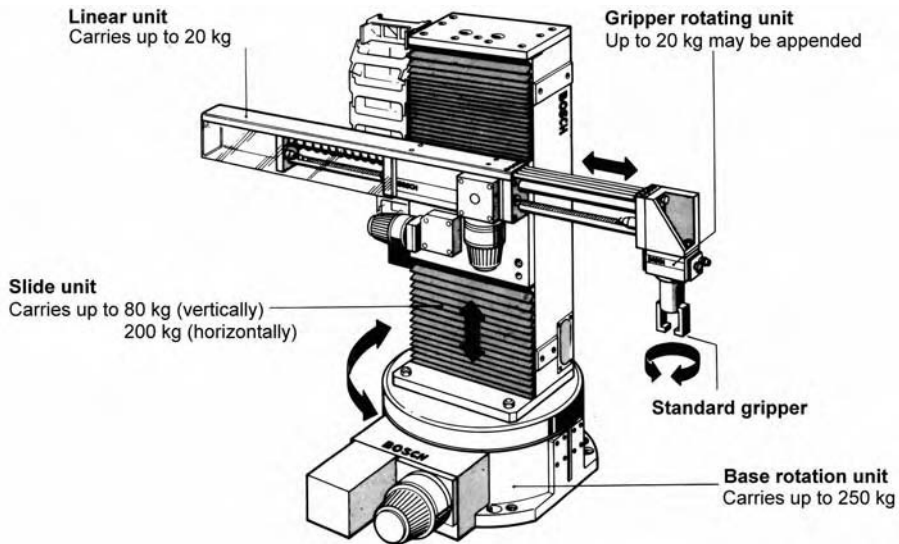


Figure 28.11 Industrial robot with two linear and two turning movements (Illustration from Bosch Material Handling Engineering, Stuttgart, Germany)

28.7 Exercise on Chapter 28

1. What material feeding systems do you know for piercing and blanking operations?
2. Which workpiece transport devices are used with drawing transfer presses?
3. Which workpiece transport devices are used with transfer presses for bulk forming?
4. Where are industrial robots used in metal forming?

29 Future developments in metal forming presses and tool changing systems

29.1 Flexible manufacturing systems in metal forming

29.1.1 Automatic forging lines

As elsewhere, the trend in metal forming is towards flexible manufacturing systems. These feature:

- automatic press feed,
- automatic tool changing,
- automatic control and monitoring of production sequence.

Figure 29.1 shows a fully automatic forging line. Sway bars are produced on this unit (Figure 29.1a) in five operations.

The overhead (gantry) manipulator (3) removes a blank from the storage magazine (4) and transports it in the feed device to the electric upsetting press (1). Here, the ball-shaped head is at first compressed on one side. Then the overhead manipulator transports the pre-compressed workpiece to the transfer press. There, the workpiece, still heated to forging temperature, is finished on one side in three operations (impression-die forging, deburring, piercing). Next, the rod is turned round 180° and taken back to the electric upsetting press. There, the production sequence is repeated for the second side.

While the first workpiece is being processed in the transfer press, the feed device inserts a new workpiece and the heating and upsetting process is started.

Thus, two workpieces are always processed at the same time in rotation. Cycle times of around 40 seconds are achieved by overlapping the working operations.

The unit is set up to process rods with a diameter of between 28 and 70 mm and between 1200 and 2500 mm in length.

It is controlled from a central desk using a Siemens S5 series electronic control system. This provides functions such as:

- user-led input of all data relevant to the manufacturing process on an operator terminal
- clear on-screen presentation of target and actual values
- plain text fault messages and process monitoring reports, automatic chain of events analysis
- savable process data.

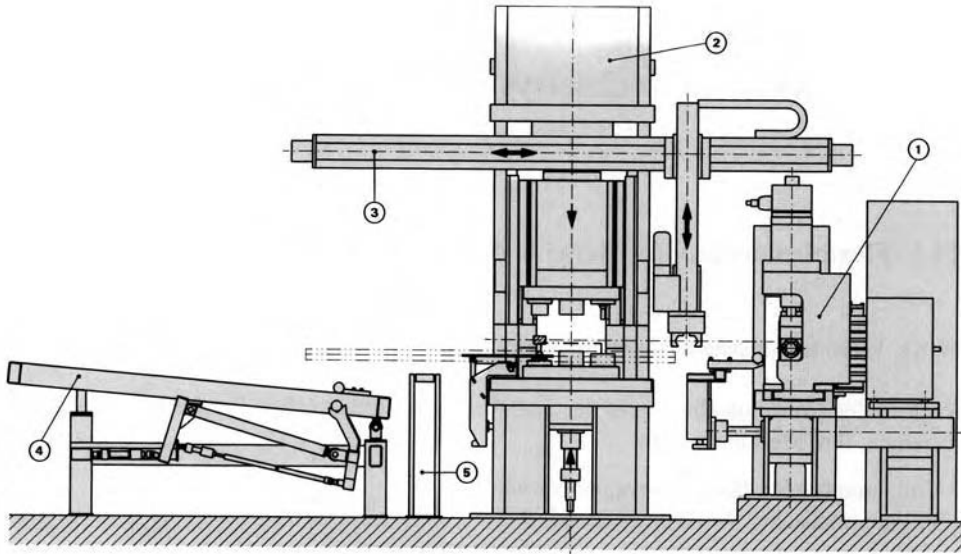


Figure 29.1 Automatic forging line consisting of:
 1 140 kVA electric upsetting press, 2 2000 kN press force transfer press, 3 overhead (gantry) manipulator, 4 storage magazine for rod stock, 5 conveyor for transporting finished workpieces. (Illustration from LASCO Umformtechnik works, Coburg, Germany)

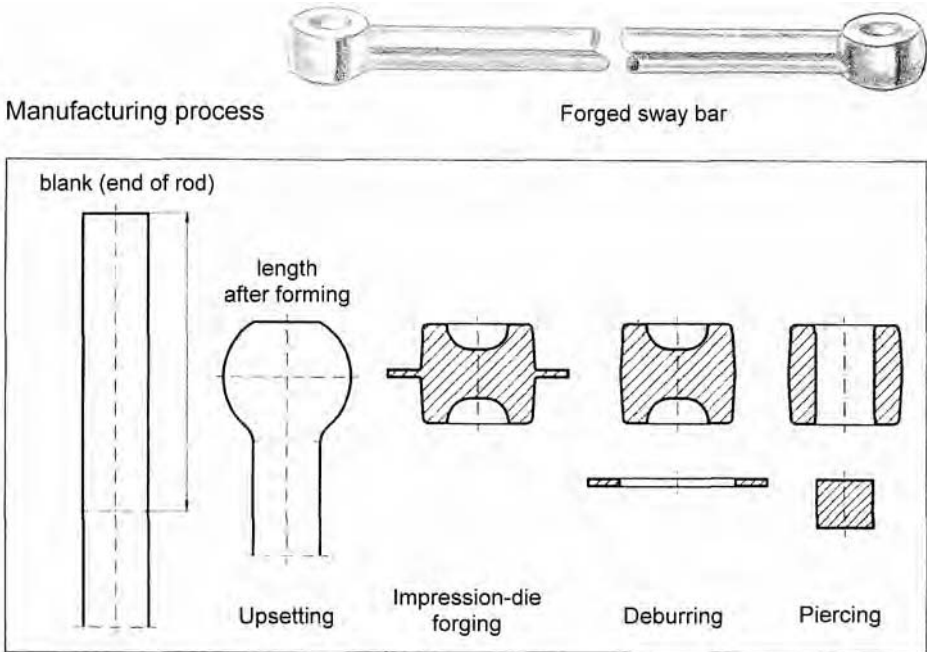


Figure 29.1a Sequence of operations diagram for the sway bar produced on this unit (Illustration: LASCO Umformtechnik works, Coburg, Germany)

29.1.2 Flexible manufacturing cells

One example of a flexible manufacturing cell (FMC) is an automatic hydraulic cold extrusion press unit. This consists of a four-stage cold extrusion transfer press (Figure 29.2) with a press force of 20,000 kN. Workpieces weighing up to 15 kg apiece are produced on this unit. Everything runs automatically, from the stock (rod sections) feed stage and their transfer onto the gripper system, to the output of the finished parts on a conveyor belt. The press force is also monitored at every station.

The active tooling is changed quickly with a hydraulic tool changing arm. The whole tooling set can be changed quickly by pressing a button.

The entire flow is controlled by a microprocessor with a memory capacity for more than 200 die sets.

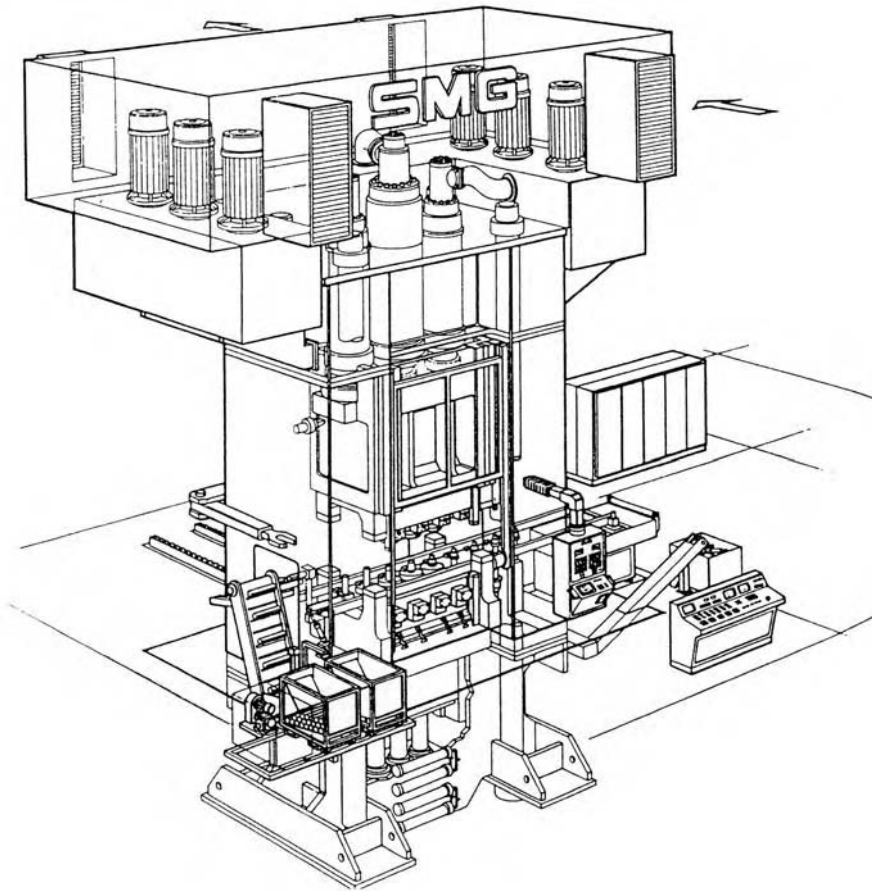


Figure 29.2 Four-stage transfer press with automatic infeed and outfeed of parts and automatic fast tool changing system.

(Illustration from Schuler SMG GmbH & Co. KG works, Waghäusel, Germany)

As well as the four main press stations, there is also a shearing station in the side column which means the blanks can be cut to length precisely. Tool changing is carried out fully automatically. Only the separate tooling cartridges are changed. A tool changer handles the tooling sets weighing up to 600 kg. These tooling cartridges are adjusted and tensioned automatically in the press.

The blanks are conveyed to the press in palette trucks and there transferred to the conveyor belt. A gripper system takes hold of the blank and takes it to the press stations. The finished pressed parts are ejected from the press and placed on a palette truck by the gripper.

29.1.3 Flexible manufacturing system

Figure 29.3 shows a flexible manufacturing system for manufacturing gas cylinders from sheet steel. All standard cylinder sizes on the world market are produced using this kind of unit. It has a production capacity of 3.5 million gas cylinders per year. On this unit, 1200 cylinder halves ($\text{Ø } 300 \times \text{H } 235$) are produced per hour. Both press lines consist of:

- | | |
|--------------------------------|--------------------------------|
| 1 stamping (embossing) press – | 1 twin-column trimming machine |
| 2 deep drawing presses | 1 piercing press. |

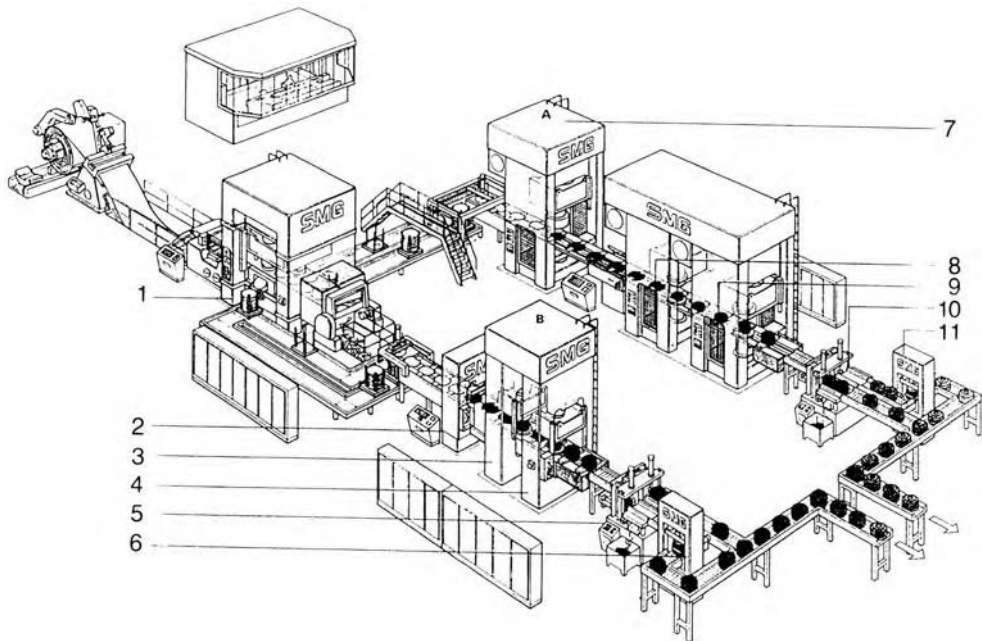


Figure 29.3 Flexible manufacturing unit for producing steel gas cylinders.

1 blanking unit, 2 stamping press, 3 and 4 deep drawing press, 5 trimming and beading machine, 6 piercing press, 7 stamping press, 8 and 9 deep drawing press, 10 trimming and beading machine, 11 piercing press

(Illustration from SMG Süddeutsche Maschinenbaugesellschaft works, Waghäusel, Germany)

The initial blanking unit provides both press lines with round blanks. They are blanked from strip stock (1300 mm wide and 1.5 – 3.5 mm thick), stacked and then conveyed to stacking magazines on the first press. There, gripper systems take on their transport to the press. A gripper transfer device transports them on from press to press fully automatically. After the last press, a roller conveyor transports them on to the wash station.

The first press in Unit B is a simple stamping press with a press force of 2000 kN; in Unit A the first press is a combined stamping and deep drawing press with a maximum deformation force of 4000 kN. The next presses are deep-drawing presses only, with deformation forces of 2500 kN and 1600 kN. The trimming machines have two stations each: on the left, the lower parts of the cylinders are trimmed and beaded, on the right the upper parts are trimmed. In the piercing press, the valves are pierced into the upper parts.

The numerical control system controls the process, monitors the tooling and reports weak spots in the production sequence.

EMP 800 transfer press unit as a flexible manufacturing system for medium-sized shaped sheet parts.

The demand for the low-budget manufacturing of extremely high-quality parts, both in small- and large-scale manufacture and with the variety of parts constantly rising, has led to flexible manufacturing systems being developed in many fields. In sheet forming, the construction of modern transfer press units is characteristic of this development trend (Figure 29.4).

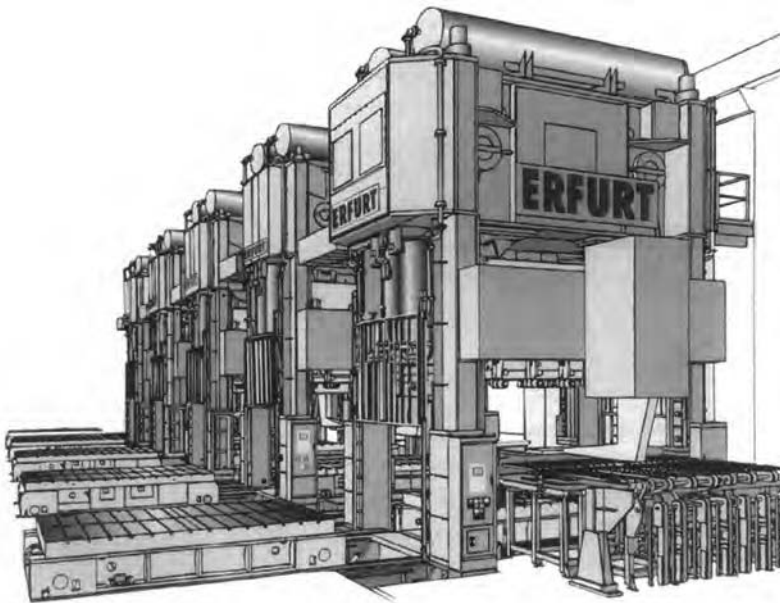


Figure 29.4 EMP 800 transfer press unit as a flexible manufacturing system (Illustration from Umformtechnik works, Erfurt, Germany)

The range of uses for these press units starts off with small parts, especially cup-shaped parts whose shape includes other elements. The main uses are medium-sized press units to produce

- car body parts for automobiles and other vehicles;
- deep drawn and stamped parts for various uses (Figure 29.5).

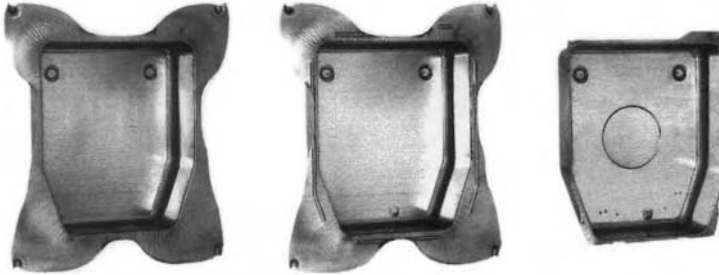


Figure 29.5 Deep drawn part produced on a medium-sized transfer press unit (Photograph from Umformtechnik works, Erfurt, Germany)

As tandem presses or multi-column presses, transfer press units are used to produce large parts such as car body parts, automobile side parts and truck body components.

Standard EMP series straight-side press as a transfer press

The basis for the flexible transfer press unit is the newly-developed series of mechanical straight-side presses (Figure 29.6). A range of presses, built from standard modules, can be delivered according to need. Equipped with specific modules depending upon the application, these are used as

- universal presses
- automotive body part presses (lead and following presses)
- transfer presses and
- shearing presses.

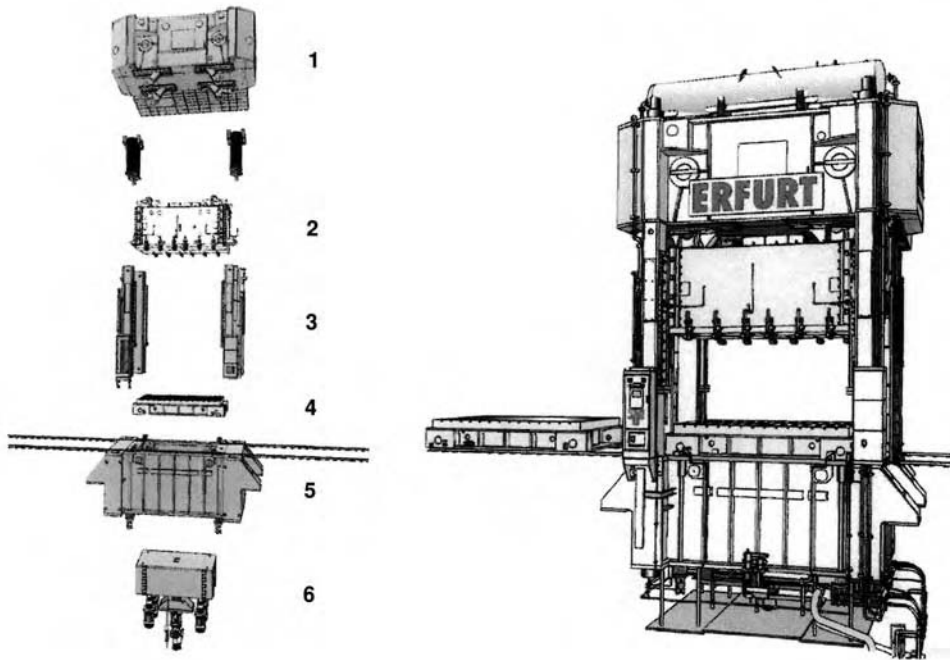


Figure 29.6 EMP series modular-construction mechanical straight-side press
 1 head, 2 press ram, 3 side column, 4 sliding table, 5 platen, 6 die cushion in platen
 (Illustration from Umformtechnik works, Erfurt, Germany)

Hybrid drive – Application of the innovative development for deep drawing

The operational principle of a hybrid drive is based on the relative hydraulic motion of the ram (Figure 29.7) superimposed upon the mechanical crank drive of the straight-side press. The relative motion is effected by means of the pressure points designed as synchronised cylinders (Figure 29.8). The braking stroke, initiated immediately before the upper die is set in place, reduces the impact velocity of the ram with the upper die to a minimum. Towards the end of the braking stroke and thus at the start of the deformation process, the ram velocity once more comes into synch with that of the crank drive. Once the deformation process is completed – i.e. at the TDC crank drive position – the relative motion of the ram is brought back to its starting position.

For the braking stroke, a graph of velocity-related target values is established and saved in the software. In particular, this is used to optimise the final sequence of the braking stroke. How the braking phase is adjusted with regard to the moment of impact is a decisive factor in the effectiveness of the hybrid drive.

Advantages of the hybrid drive:

- adapts flexibly to the geometry of the parts by adjusting the velocity reduction in each case
- usable stroke rate at maximum drawing speed – compare:
 - * without hybrid drive up to 16 min^{-1}
 - * with hybrid drive up to 28 min^{-1}

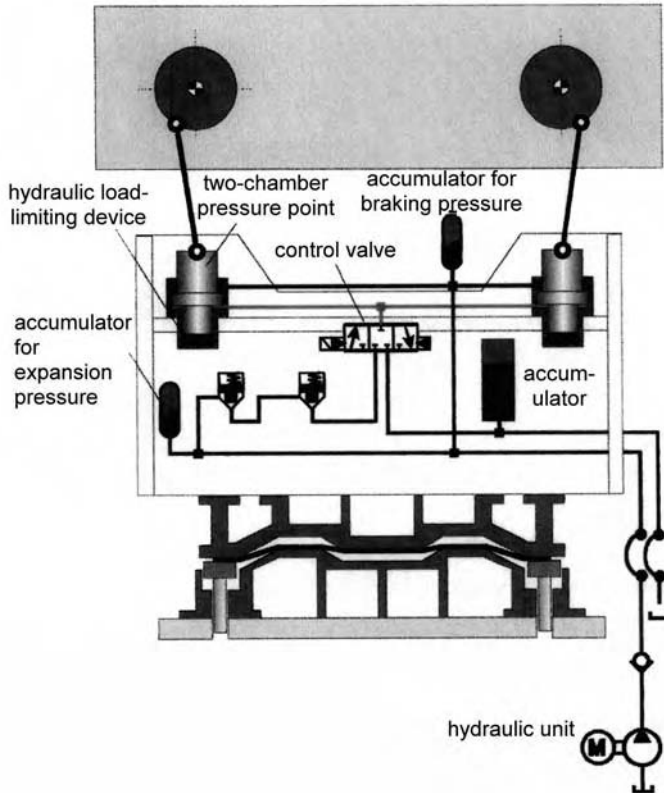


Figure 29.7 The principle of the hybrid drive (Illustration from Umformtechnik works, Erfurt, Germany).

Die cushions

Using several separate die cushions makes the range of applications extremely flexible. It means the functions of the die cushions can be adjusted to the requirements of each forming stage. Complicated adjustments and carefully fitting the pressure bolts – as needed with single die cushions – are no longer required (Figure 29.8).

The EMP 800 three-stage transfer press comes with a two-point hydraulic die cushion each in stages 1 and 3 and a single-point nitrogen die cushion in stage 2.

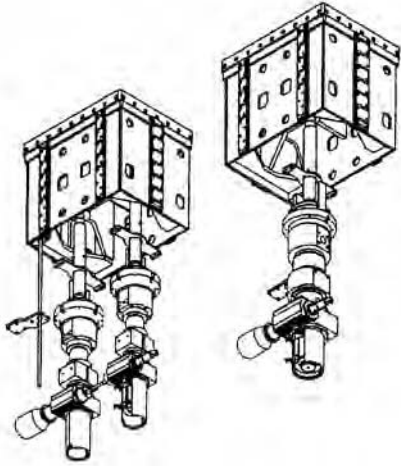


Figure 29.8
Die cushion in the EMP 800 transfer press
(Illustration from Umformtechnik works, Erfurt,
Germany)

The arrangement of the individual die cushions means that all bolt types can be dealt with in the same way as with a one-piece die cushion plate. This is also true for the three ejector cushions in the ram.

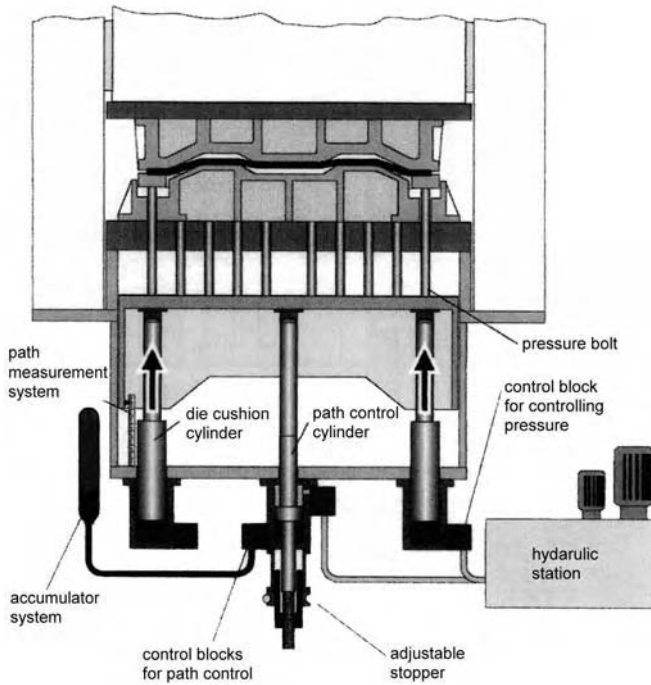


Figure 29.8a Hydraulic die cushions in the platen (Illustration from Umformtechnik works, Erfurt, Germany)

As well as the standard functions such as

- preacceleration of die cushion
- free-running ejector stroke and
- controlled and prolonged ejector stroke

the flow of the forces at the pressure point can also be individually programmed.

Flexibility features

Stock feed from strip or as round blanks

The basis for flexible automation is the options for feed, from the strip unit or by means of the blank destacker and CNC transfer. One example of the combined use of a strip unit and a blank destacker is shown in Figure 29.9.

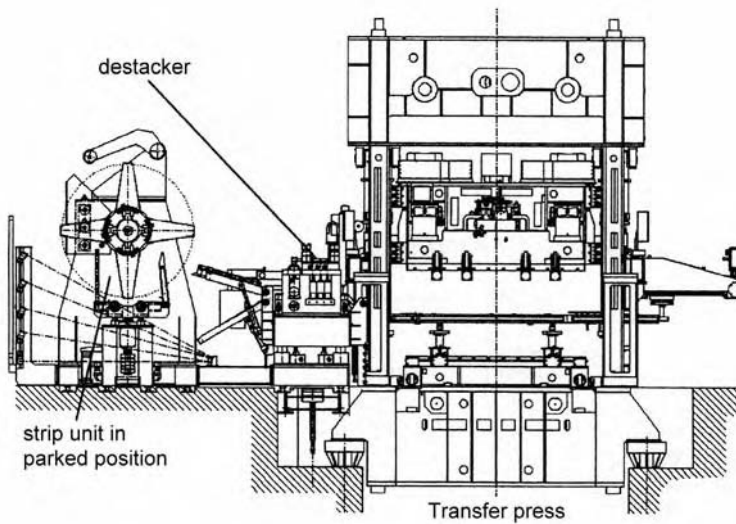


Figure 29.9 Transfer press with combined strip and blank feed system – side view (Illustration from Umformtechnik works, Erfurt, Germany)

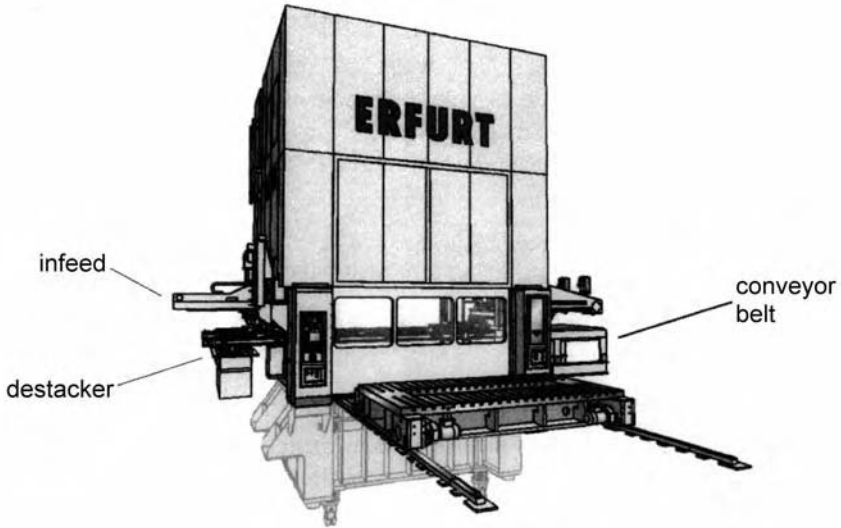
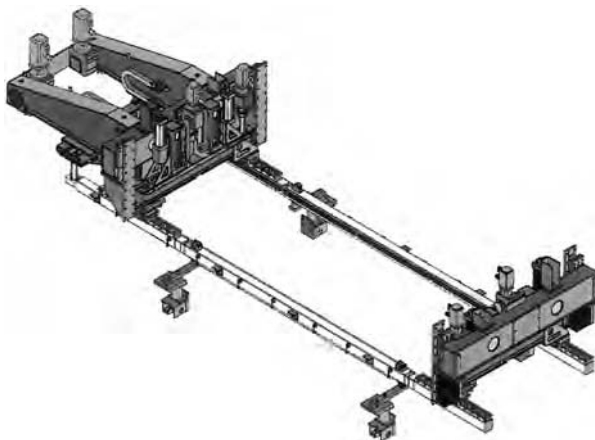


Figure 29.9a EMP 800 transfer press unit with workpiece and stock conveyor stations (Illustration from Umformtechnik works, Erfurt, Germany)

Flexibly programmable 3-D CNC transfer

This 3D CNC transfer system (Figure 29.10) is designed as a module. The transfer movements and the cycle times can be freely programmed within the limits of the values that apply. This construction is designed for a universal fit with different tooling demands.



Transfer distance at the stages	100 - 600 mm
	100 - 900 mm
	100 - 1200 mm
shut height	50 - 350 mm
– fully closed	500 mm
– fully opened	250 mm
lift height	0 - 200 mm
– adjustment range of lower stroke position	0 - 200 mm

Figure 29.10 3D CNC transfer (Illustration from Umformtechnik works, Erfurt, Germany)

Modular control system in an open, extendable structure

All necessary press control functions are fitted into a basic module according to the schematic design of the press control system. To add the many functions which make the transfer press unit fully automatic, and for a user-friendly display, each add-on module can be integrated as needed.

The most-used PLCs are:

- SIMATIC S7 for Europe and
- Allen Bradley PLC5 for the United States

Automatic tool changing reduces non-productive times

The press and transfer system adjustment data required for each die set can be saved in the press control system under a code number of the user's choice. When the code number is entered the separate steps of the automatic tool changing process are activated by the sequence control system.

The destacker and strip handling unit also come with automatic devices for fast blank or coil changes.

Integrating the controls of the destacker and the strip unit in the press control system reduces the changeover time for the whole press unit to a minimum.

29.2 Automatic tool change systems

One way to shorten tool changing times is to use cartridge-style tool holders (Figure 29.11). These cartridges are fixed in the working area of the press using quick-action hydraulic devices. These devices are released from the control desk, the cartridge is pulled onto a changeover table or changeover truck and replaced with a ready-to-install cartridge preheated to the operating temperature.

The sequence of events for tool changing is as follows:

1. Tooling cartridges are locked. The ram is moved down.
2. The lock is released and the ram is moved up.
3. The tool changing truck drives up to the press. The cartridge pack is lifted and coupled on to the changing truck.
4. The cartridge pack is pulled onto the changing truck and is ready to be taken away.

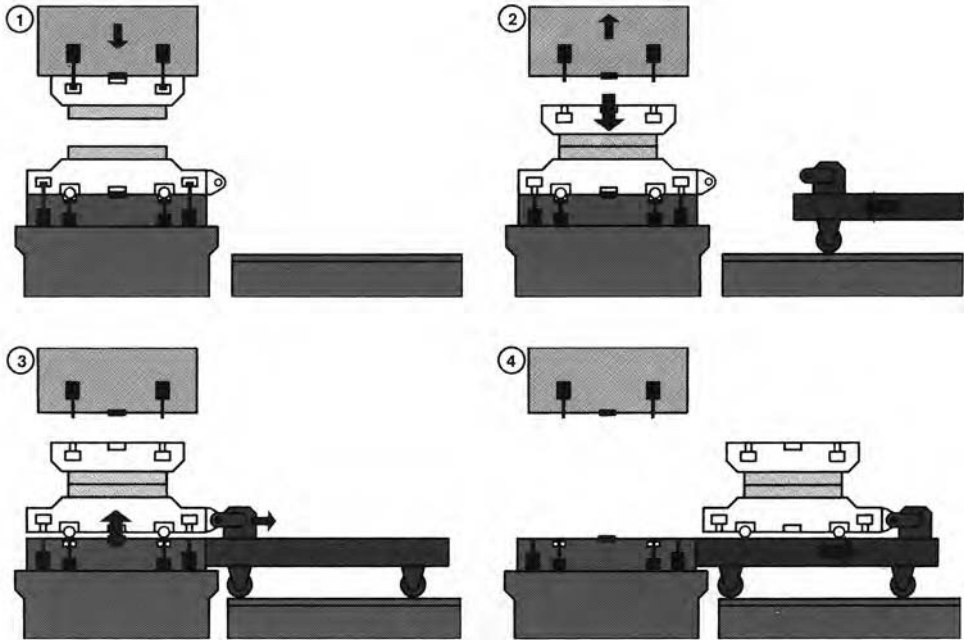


Figure 29.11 Automatic tool changing system (Illustration: Hasenclever SMS works, Düsseldorf, Germany)

The four-stage cold extrusion press shown in Figure 29.12, with the tooling arranged vertically, works completely automatically. Finished parts are produced in one shearing operation and four press operations, from straightening the wire to the finished screw, bolt or other shaped part.

Depending upon the size of the workpieces, 50 to 150 workpieces per minute can be produced on this press. The following table shows the technical specifications for these presses.

As manual changeover used to take around 8 to 10 hours on this kind of press, transfer presses of this type could only be used in a cost-effective way with large-scale manufacture.

It was only when automatic tool changing systems were developed that it became possible to substantially improve the efficiency of these capital-intensive manufacturing units.

This was the only way for these units to become flexible enough for small-scale production to be carried out economically.

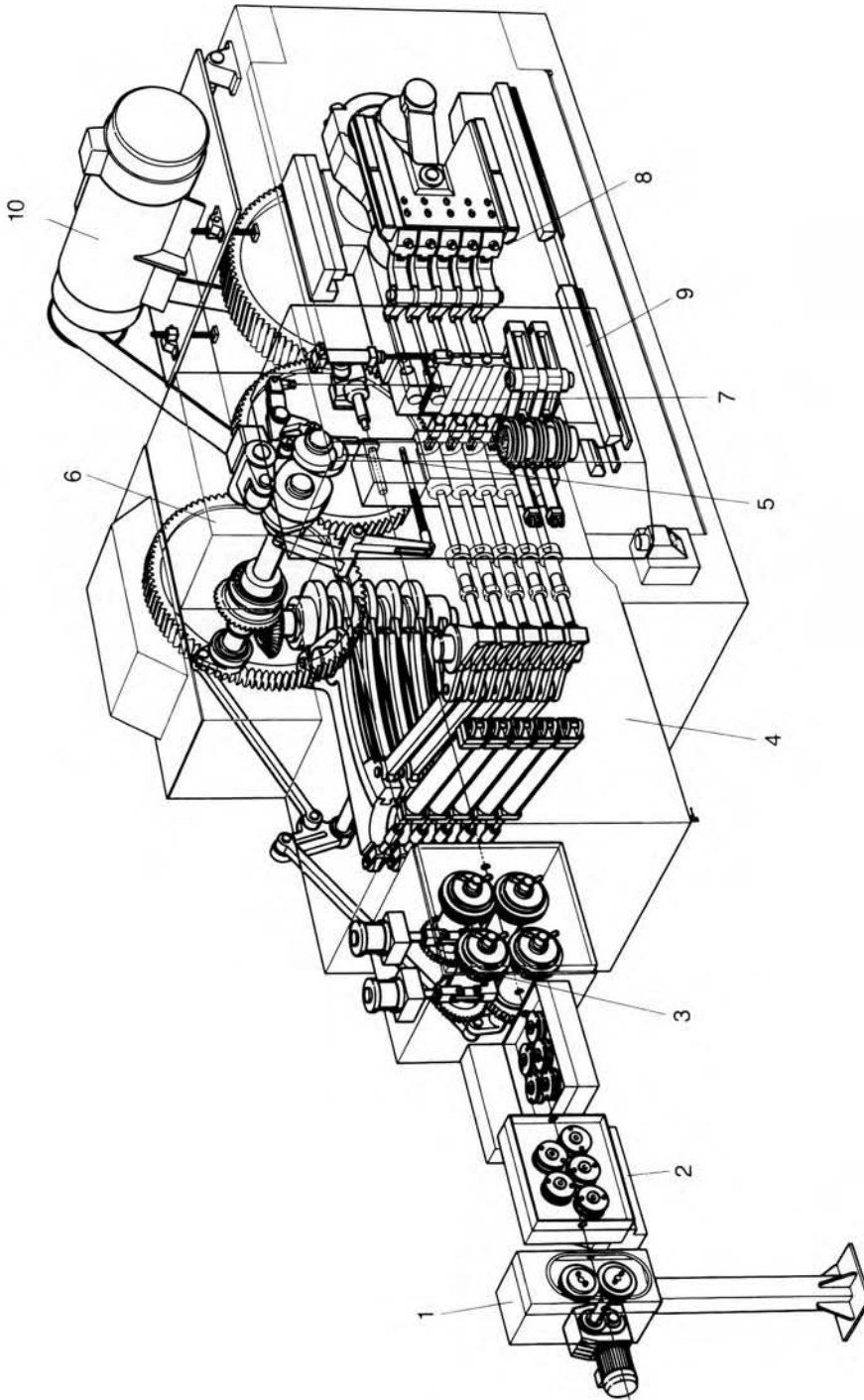


Figure 29.12 Formmaster GB 25 four-column cold extrusion press.

1 wire infeed, 2 straightening device, 3 conveyor device operated in time with the press, 4 ejectors in the dies, 5 shearing station, 6 central gear equipment, 7 transfer system for workpiece transport, 8 ejector in the punches, 9 ram, 10 main drive (Illustration from Schuler works, Göppingen, Germany)

Table 29.1 Technical data for the four-stage cold extrusion presses, Formmaster, GB series

Model	GB 15	GB 20	GB 25	GB 30	GB 36	GB 42	GB 52
Press force kN	1000	2000	3500	4500	6300	8500	14 500
Number of ram strokes depending on pressed part 1/min	110–150	95–125	80–100	60–80	50–70	35–55	30–45
Max. wire \varnothing at 600 N/mm ² wire strength mm	15	20	25(1")	30	36	42	52
Section length max. mm	140	180	205	260	290	345	425
\varnothing of the bottom die holder mm	90	110	130	150	175	215	260
\varnothing of the punch holder mm	75	90	110	130	145	175	215
Ram stroke without / with changer mm	180	220/250	250/300	300/360	360/420	420/500	520/600
Max. ejector stroke on the bottom die side mm	120	140	170	225	250	290	320
Ejector stroke on the punch side mm	40	45	55	70	75	85	100
Number of stages	4/5	4/5	4/5	4/5	4/5	4/5	4/5

The changeover time with the automatic tool changing system described below takes only two minutes for a punch or die pack and 50 minutes for the whole press with five stages. The automatic tool changer for transfer presses (Figure 28.13) can change five die sets (die and punch) weighing up to 75 kg per set. The tool changing system has five axes of movement.

Operating principle and sequence of functions:

After the tooling clamp is unlocked (Figure 29.13.1) the changer device drives from its standby position into the tooling area. There, the open gripper jaws are positioned above the collars of the sleeves holding the tooling so that the jaws can grip the slots. When the jaws close (Figure 29.13.2) the tooling sleeves are pulled out of their holders. Next, the changing device drives out of the tooling area and swings off the magazine. The double gripper arm then pivots 180° (Figure 29.13.3) and swings the magazine in again.

The tool changing device pushes both tooling sleeves in the tooling set and in the magazine into their holders. The jaws are then opened and the changing device drives back to its standby position.

High-performance presses with the tooling arranged horizontally (Figure 29.14) can also be equipped with this kind of automatic tool changing device.

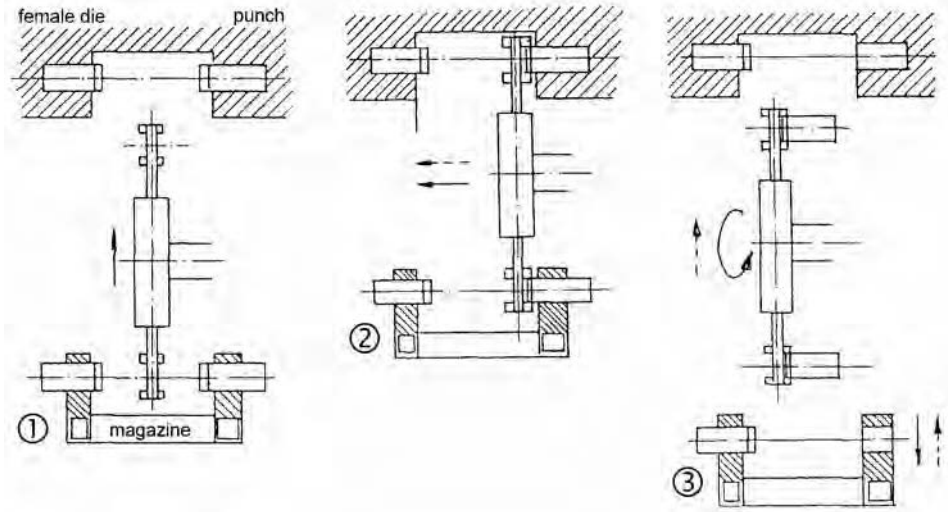


Figure 29.13 Automatic tool changing device for cold forming transfer presses.
 1 starting position, 2 tooling packs being gripped, 3 pivoting (180°) the tooling packs and driving back into standby position (Illustration from Schuler works, Göppingen)

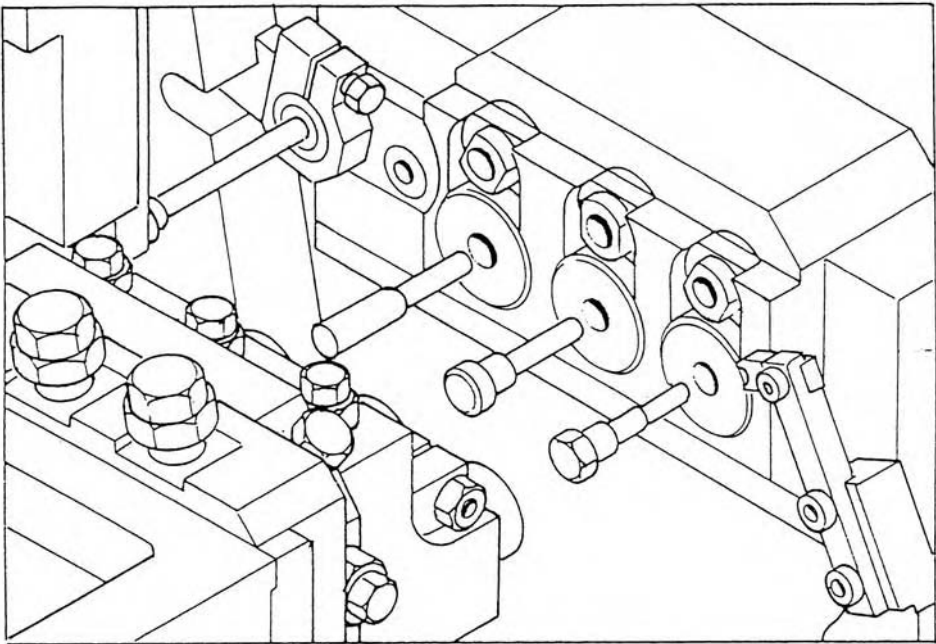


Figure 29.14 Forming stations on an M2/M3 high-performance cold forming press (Illustration from Hilgeland works, Wuppertal, Germany)

Part III: Technical tables

Table 1 $k_{fi} = f(\varphi_p)$ in N/mm² – soft annealed– cold forming –

Material	f_{k0}	$k_{fi} = f(\varphi_p)$														
		0.1	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	← φ_p			
QSt 32-3(Ma 8)	250	420	496	586	646	692	730	763	792	818	–	–	–	–		
Ck 10	260	450	523	607	663	706	740	770	796	819	–	–	–	–		
Cq 15/Ck 15	280	520	583	654	700	733	760	783	803	821	–	–	–	–		
Cq 22/Ck 22	320	530	591	658	702	734	760	782	801	818	–	–	–	–		
Cq 35/Ck 35	340	630	713	807	867	913	950	982	1008	1033	–	–	–	–		
Cq 45/Ck 45	390	680	764	858	918	963	1000	1031	1058	1082	–	–	–	–		
Cf 53	430	770	867	975	1049	1098	1140	1176	–	–	–	–	–	–		
15 CrNi 6	420	700	767	841	888	922	950	973	993	1011	–	–	–	–		
16 MnCr 5	380	630	702	780	832	869	900	926	948	968	–	–	–	–		
34 CrMo 4	410	730	808	893	947	998	1020	1048	1071	1092	–	–	–	–		
42 CrMo 4	420	780	865	959	1019	1064	1100	1130	1156	1180	–	–	–	–		
CuZn 37 (Ms 63)	280	325	438	592	706	799	880	952	1018	1078	1134	1188	–	–		
CuZn 30 (Ms 70)	250	280	395	558	682	788	880	964	1040	1112	1179	1242	–	–		
Ti 99.8	600	700	862	1062	1200	1309	1400	1479	1549	1612	–	–	–	–		
Al 99.8	60	90	105	122	134	143	150	156	162	166	171	175	–	–		
AlMgSi 1	130	165	189	217	235	249	260	270	278	285	292	298	–	–		
Continued AL		2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.5	5.0	← φ_p			
Al 99.8	60	182	185	188	191	194	196	200	202	204	210	214	–	–		
Al MgSi 1	130	309	314	318	323	327	331	335	338	342	–	–	–	–		

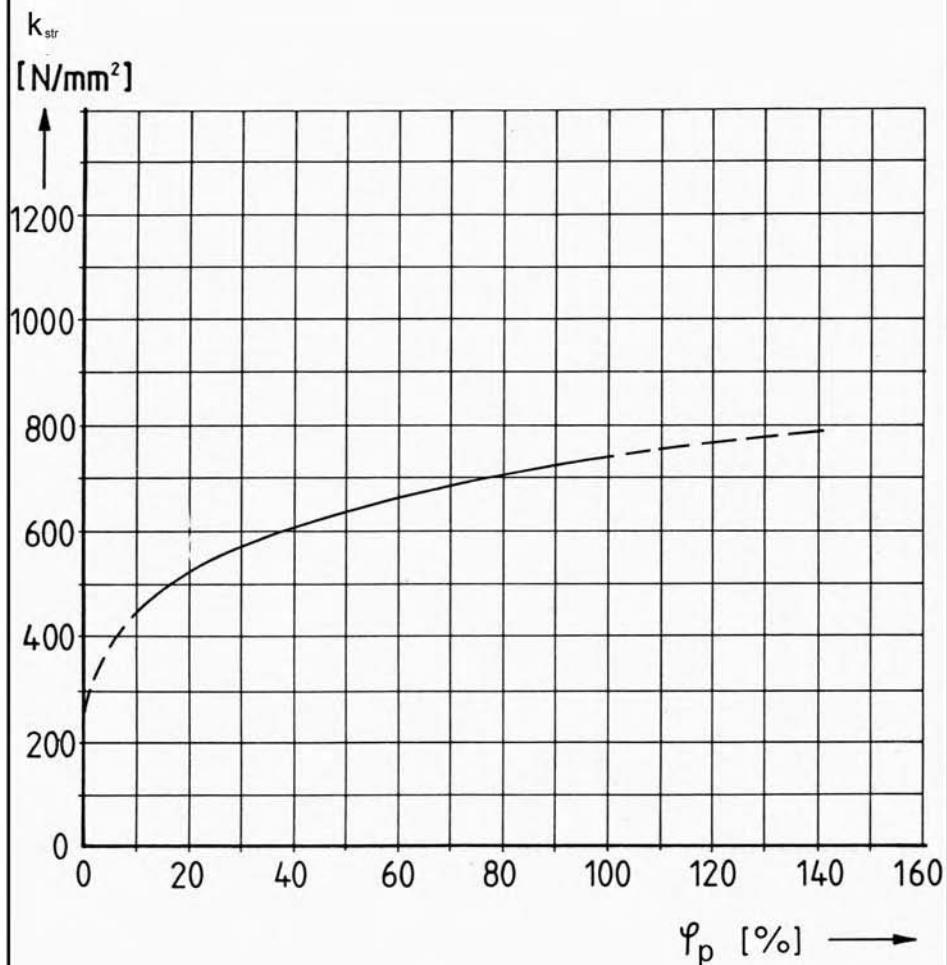
Flow stress curve

Material: Ck 10

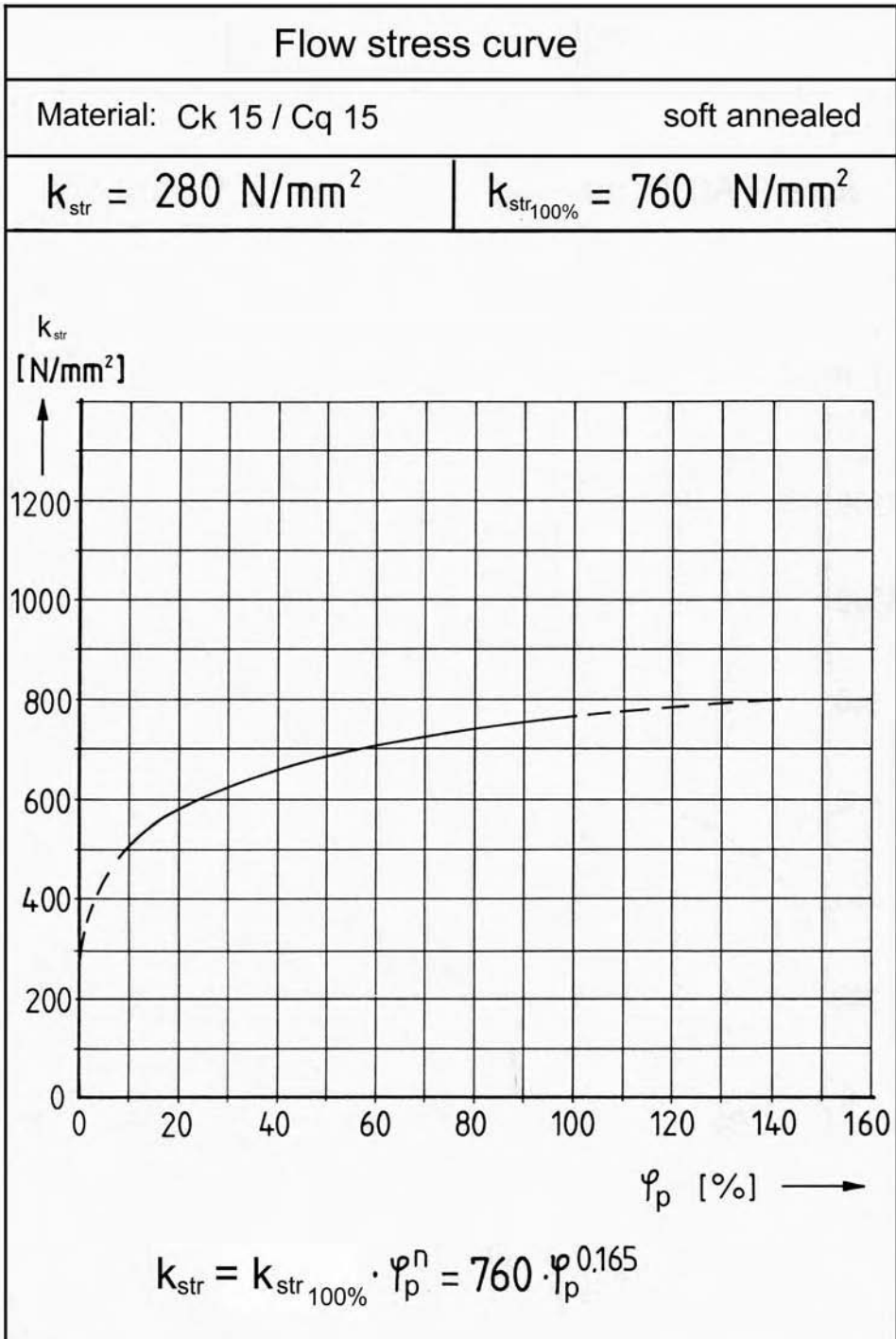
soft annealed

$$k_{\text{str}} = 260 \text{ N/mm}^2$$

$$k_{\text{str}100\%} = 740 \text{ N/mm}^2$$



$$k_{\text{str}} = k_{\text{str}100\%} \cdot \varphi_p^n = 740 \cdot \varphi_p^{0.216}$$



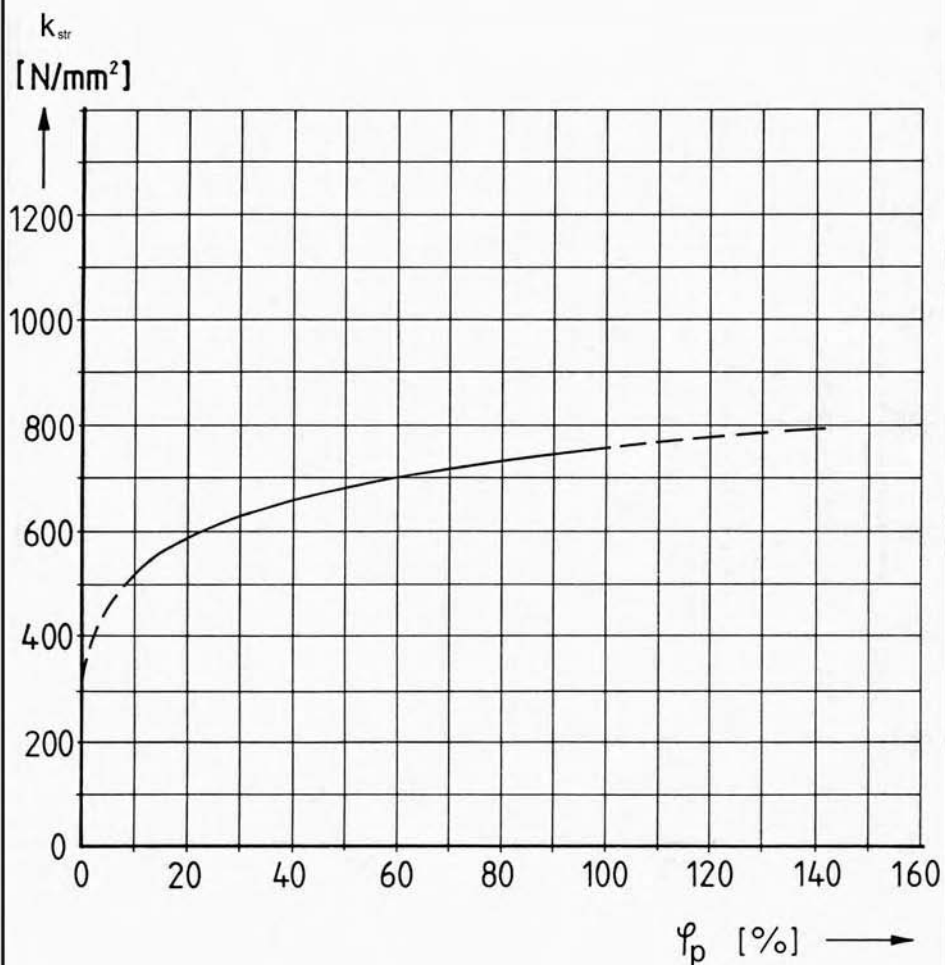
Flow stress curve

Material: Ck 22 / Cq 22

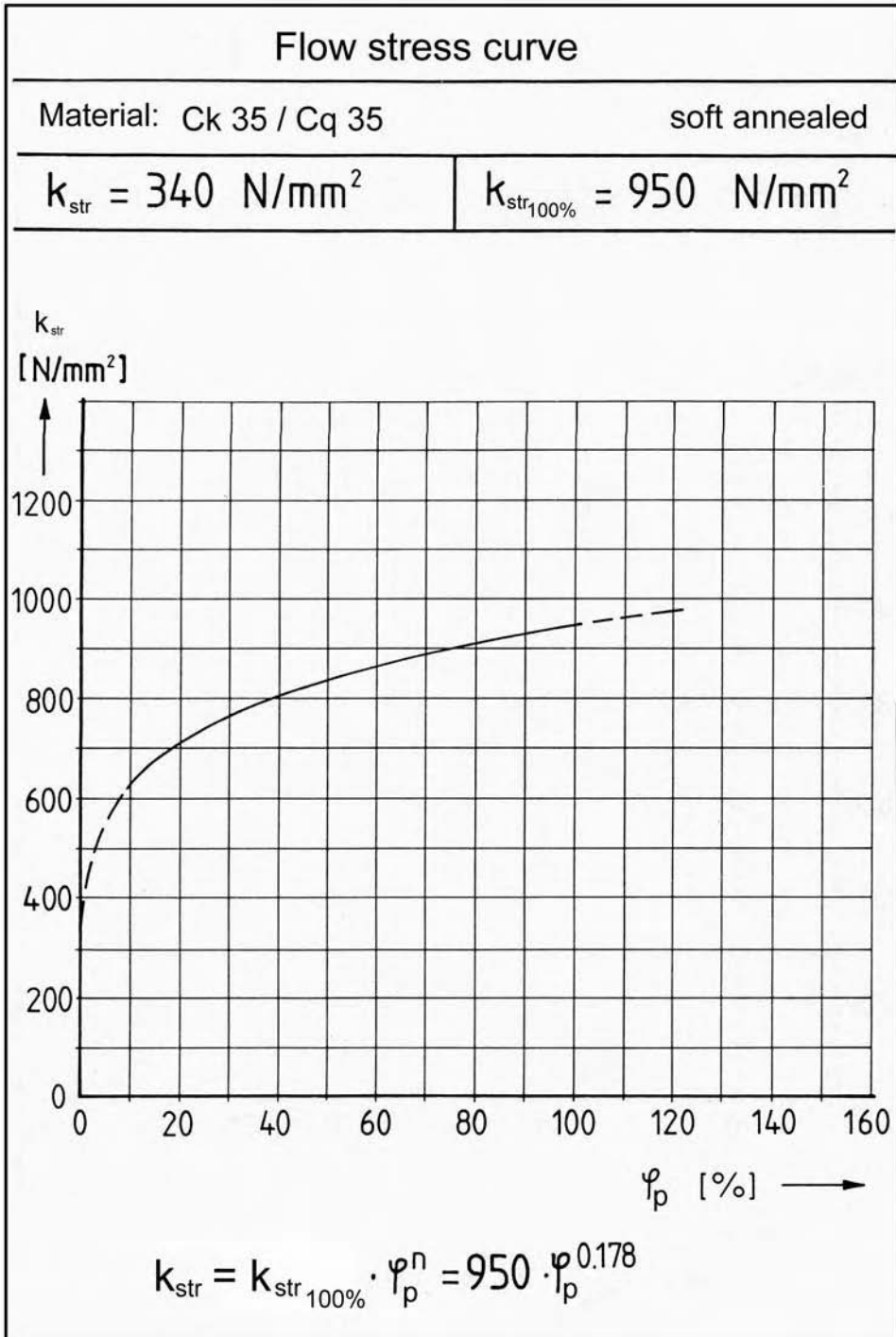
soft annealed

$$k_{str} = 320 \text{ N/mm}^2$$

$$k_{str_{100\%}} = 760 \text{ N/mm}^2$$



$$k_{str} = k_{str_{100\%}} \cdot \varphi_p^n = 760 \cdot \varphi_p^{0.157}$$



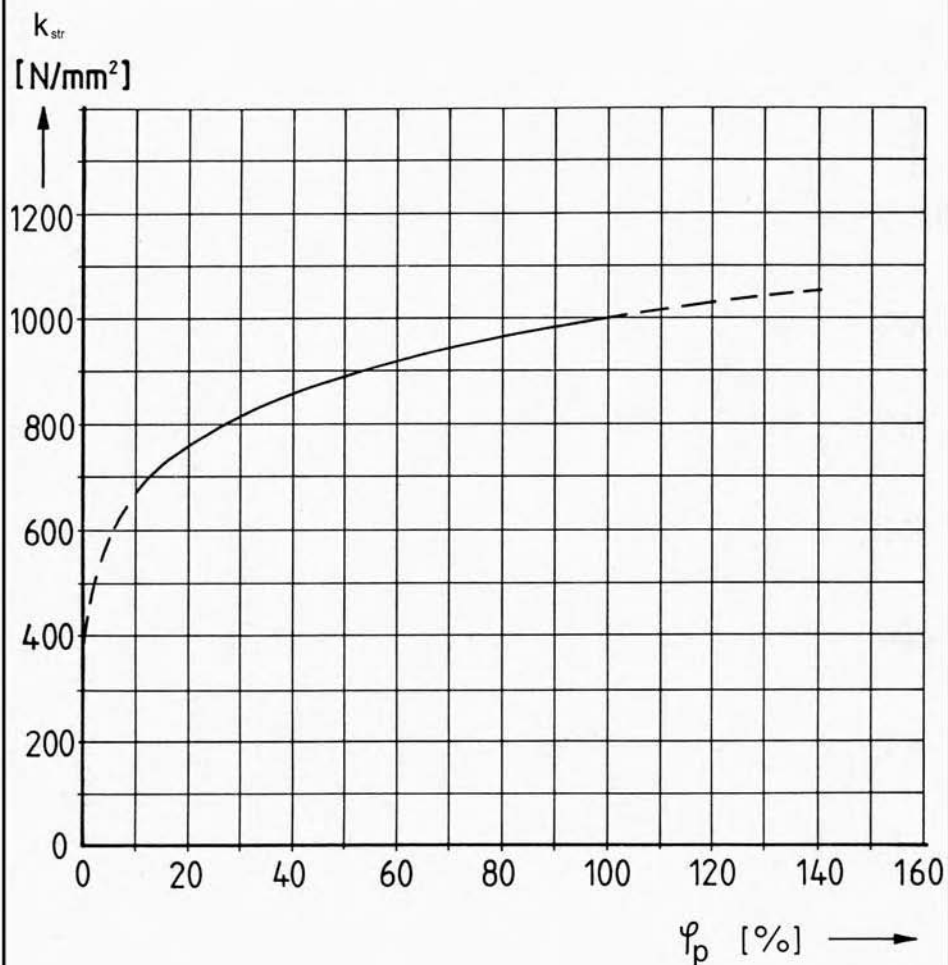
Flow stress curve

Material: Ck 45 / Cq 45

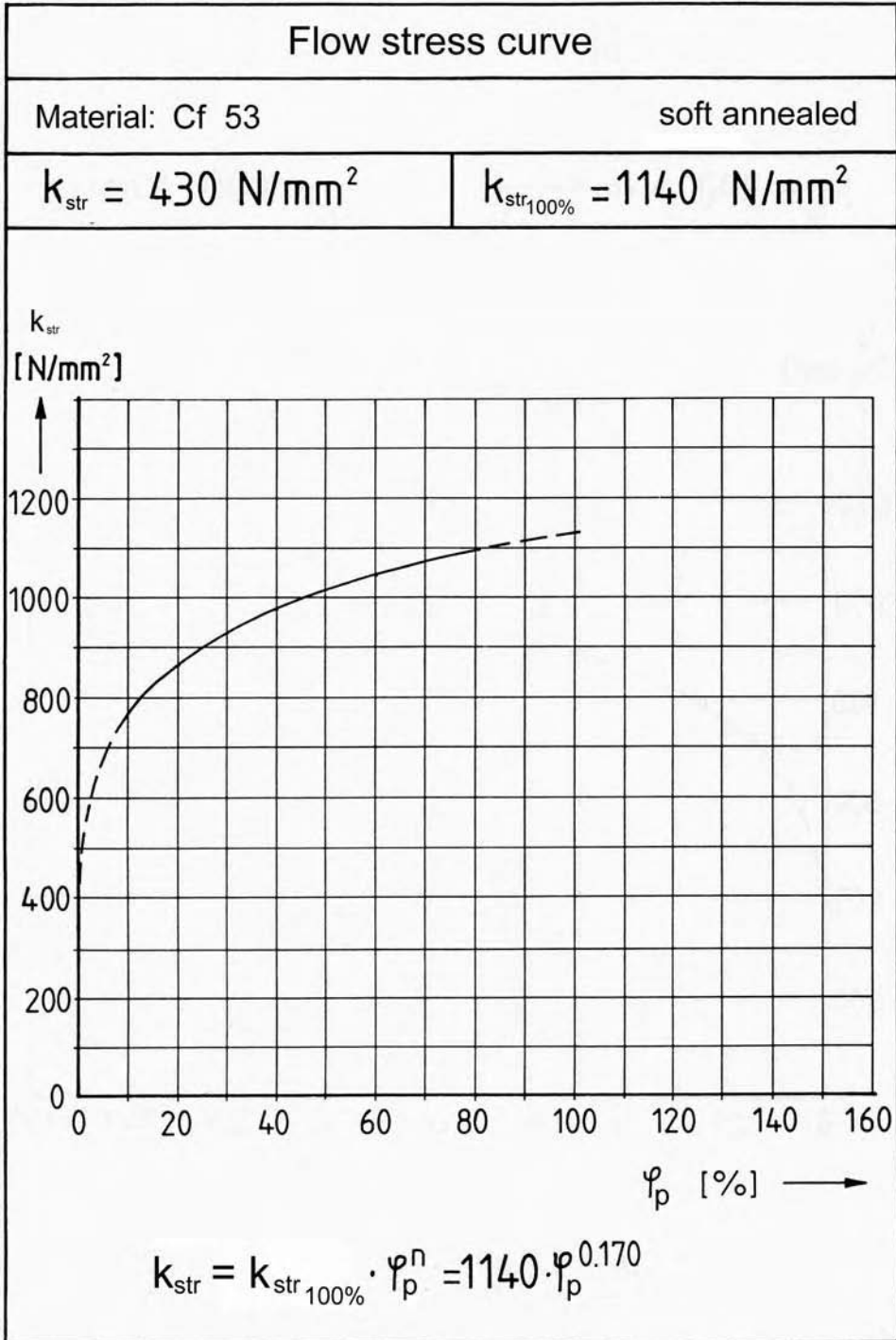
soft annealed

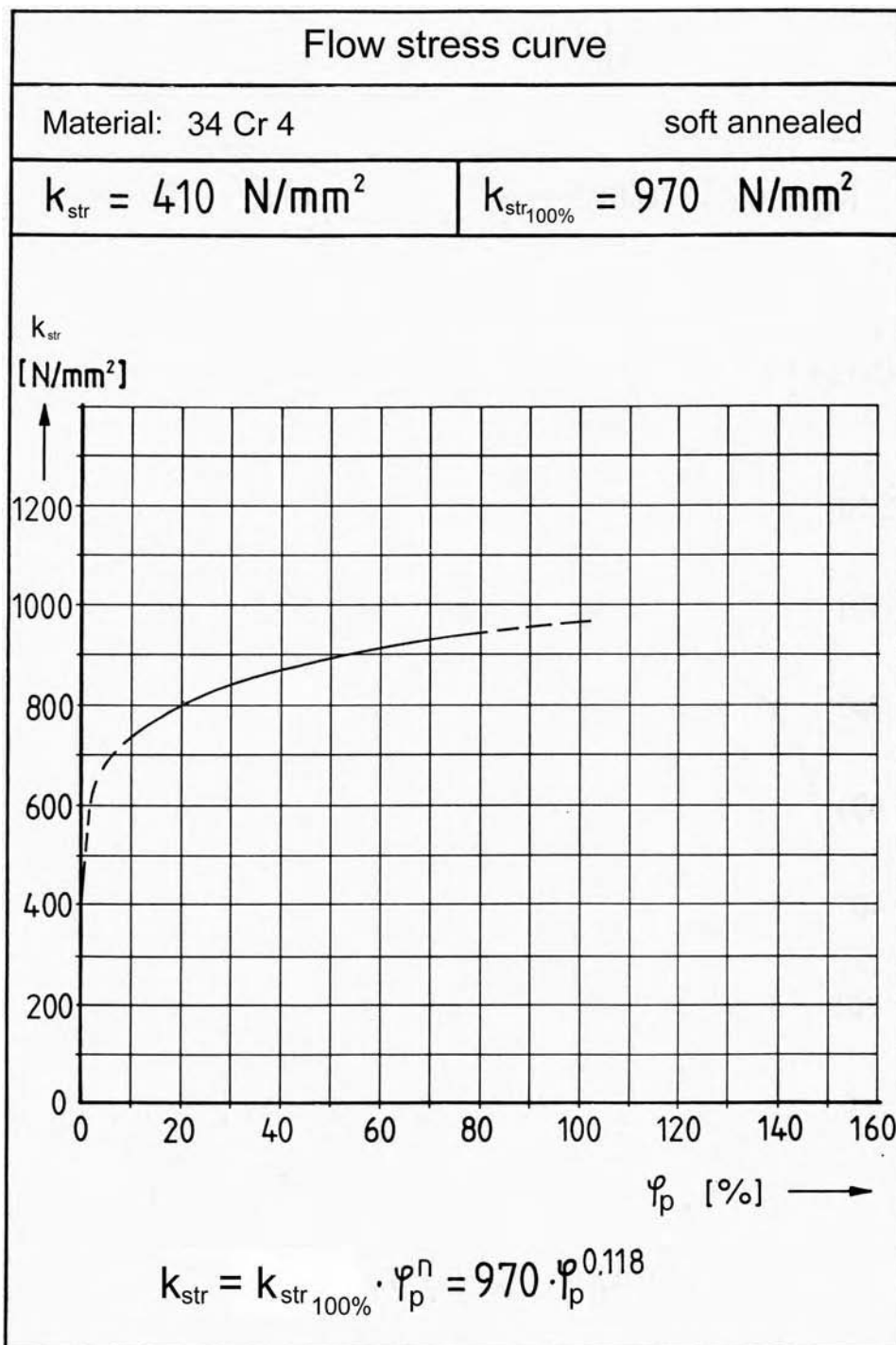
$$k_{\text{str}} = 390 \text{ N/mm}^2$$

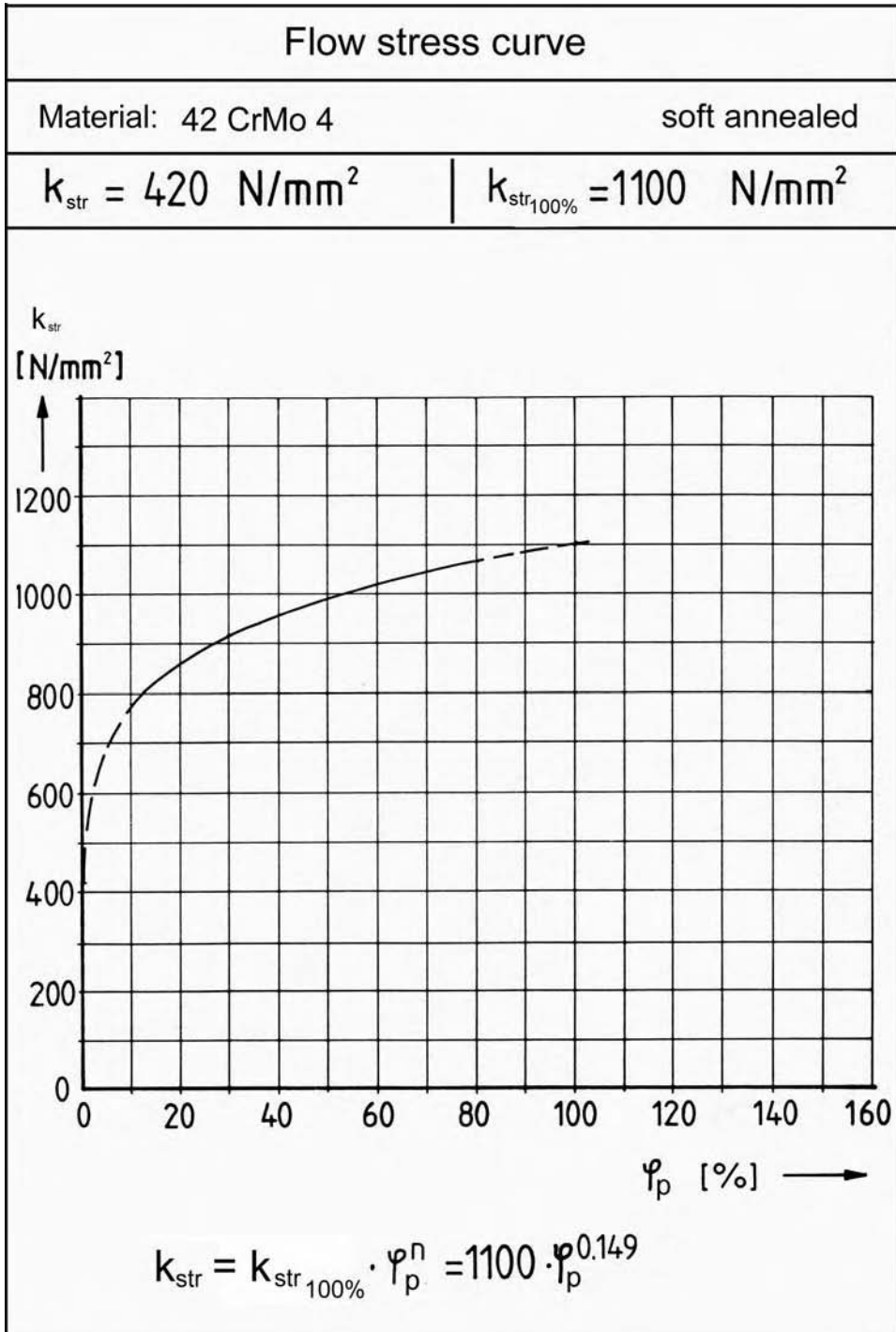
$$k_{\text{str}_{100\%}} = 1000 \text{ N/mm}^2$$

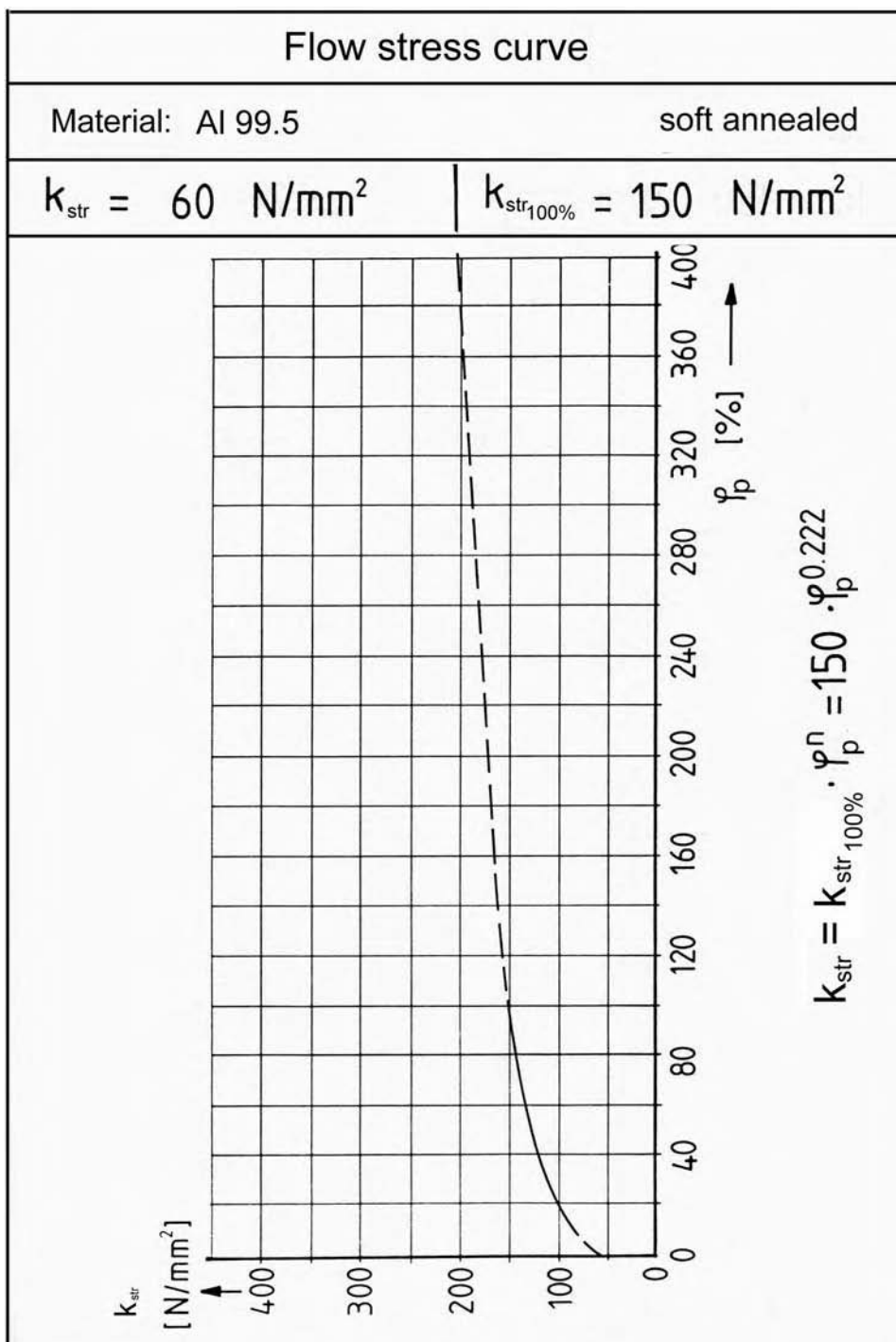


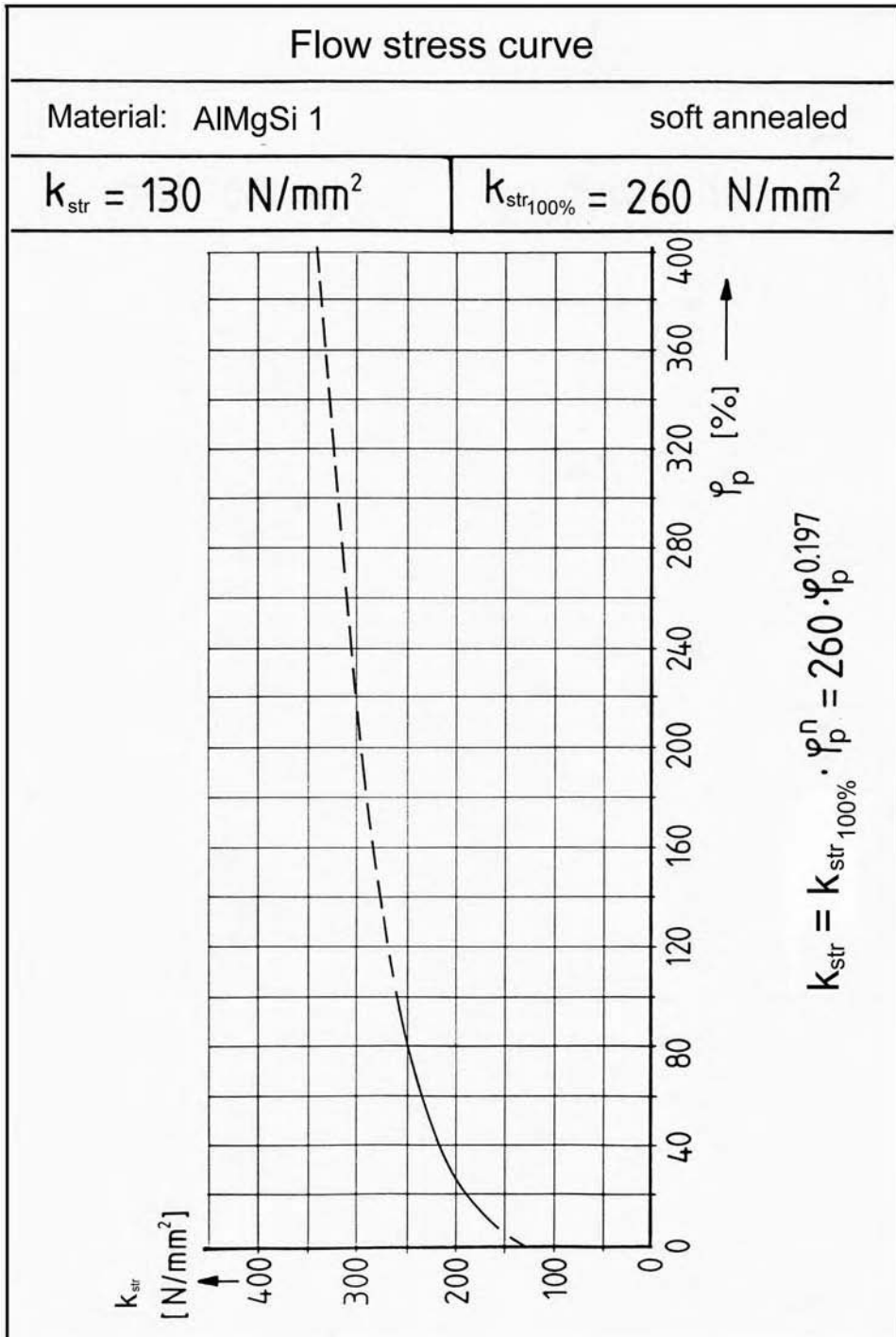
$$k_{\text{str}} = k_{\text{str}_{100\%}} \cdot \varphi_p^n = 1000 \cdot \varphi_p^{0.167}$$

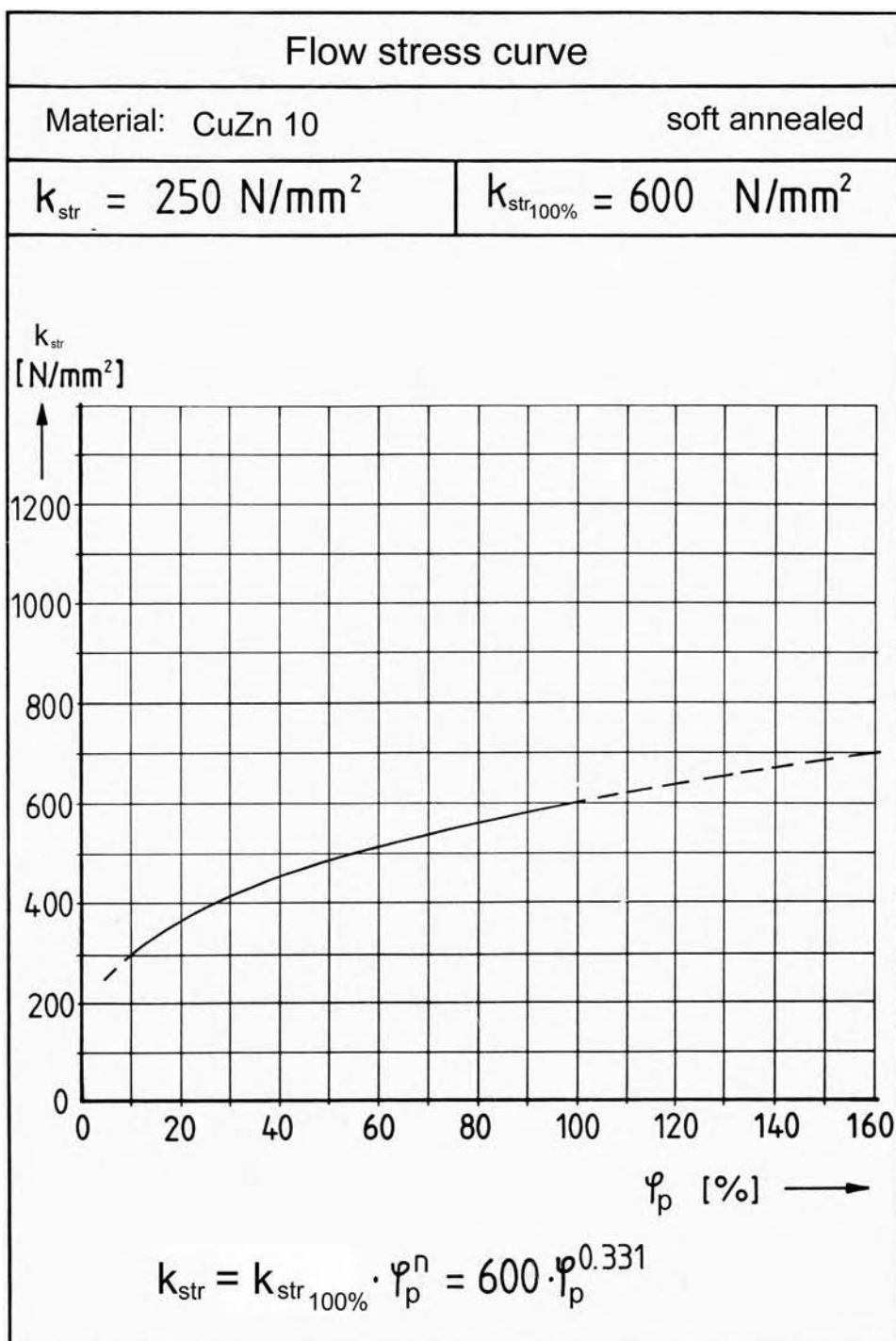


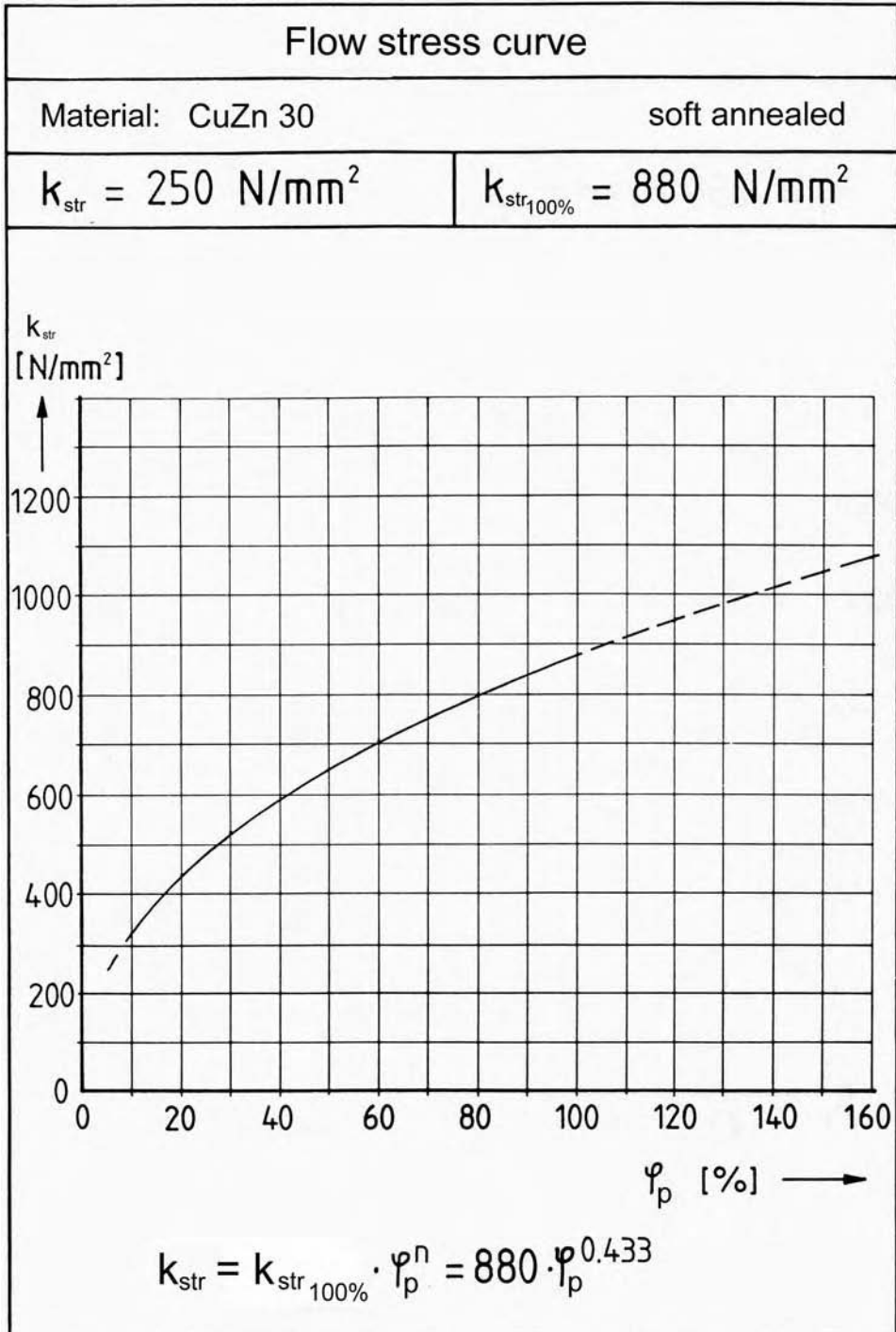










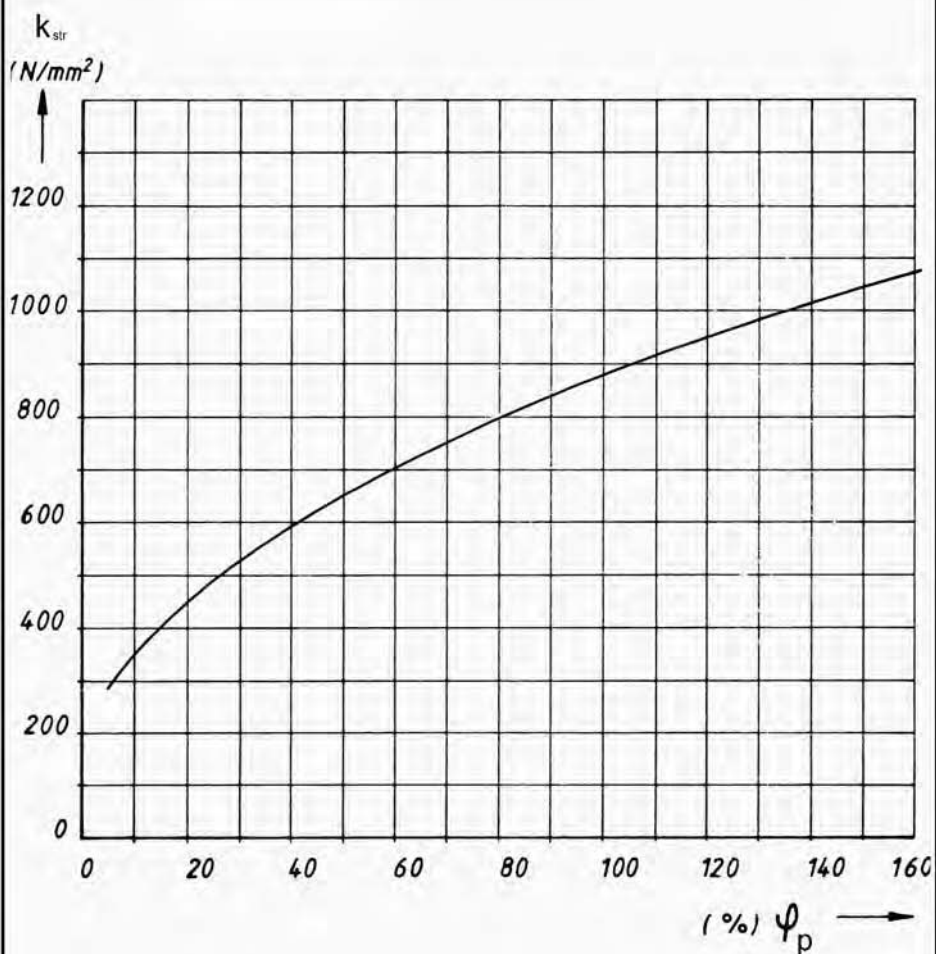


Flow stress curve

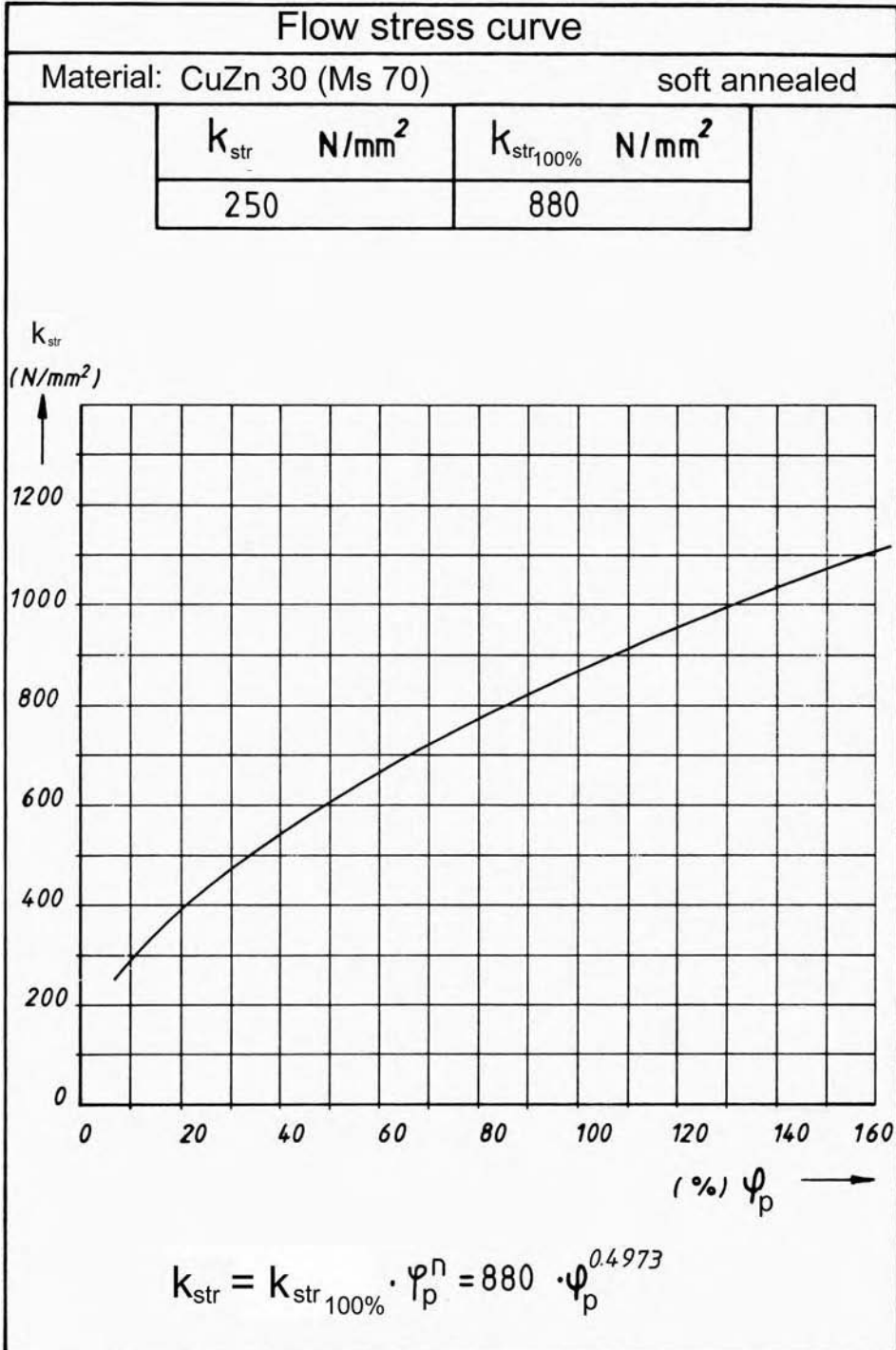
Material: CuZn 37 (Ms 63)

soft annealed

k_{str}	N/mm^2	$k_{\text{str}100\%}$	N/mm^2
280		880	



$$k_{\text{str}} = k_{\text{str}100\%} \cdot \phi_p^n = 880 \cdot \phi_p^{0.4326}$$

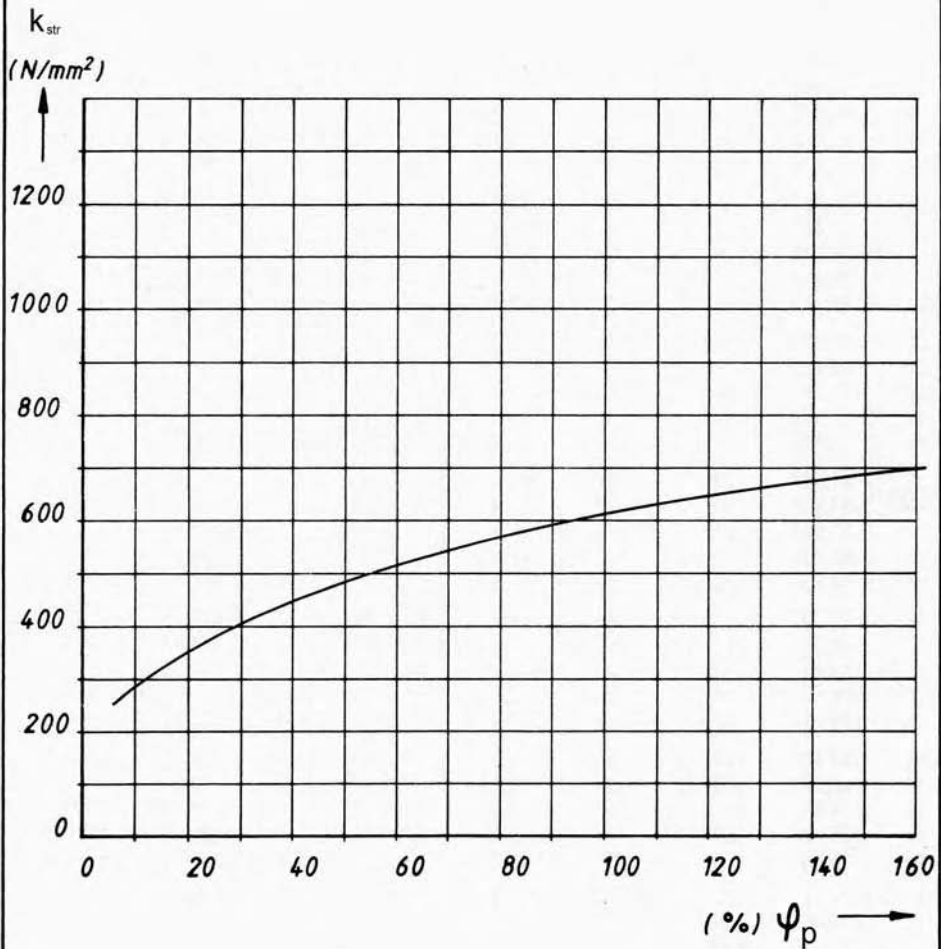


Flow stress curve

Material: CuZn 15 (Ms 85)

soft annealed

k_{str}	N/mm^2	$k_{str_{100\%}}$	N/mm^2
250		600	



$$k_{str} = k_{str_{100\%}} \cdot \varphi_p^n = 600 \cdot \varphi_p^{0.3310}$$

Table 2 Circumference and area of circles from 1 to 150 diameter

<i>d</i>	Circumf.	Area	<i>d</i>	Circumf.	Area	<i>d</i>	Circumf.	Area
1	3.1416	0.7854	51	160.22	2042.82	101	317.30	8 012
2	6.2832	3.1416	52	163.36	2123.72	102	320.44	8 171
3	9.4248	7.0686	53	166.50	2006.18	103	323.58	8 332
4	12.566	12.57	54	169.65	2290.22	104	326.73	8 495
5	15.708	19.63	55	172.79	2375.83	105	329.87	8 659
6	18.850	28.27	56	175.93	2463.01	106	333.01	8 825
7	21.991	38.48	57	179.07	2551.76	107	336.15	8 992
8	25.133	50.27	58	182.21	2642.08	108	339.29	9 161
9	28.274	63.62	59	185.35	2733.97	109	342.43	9 331
10	31.616	78.54	60	188.50	2827.43	110	345.58	9 503
11	34.588	95.03	61	191.64	2922.47	111	348.72	9 677
12	37.699	113.10	62	194.78	3019.07	112	351.86	9 852
13	40.841	132.73	63	197.92	3117.25	113	355.00	10 029
14	43.982	153.94	64	201.06	3216.99	114	358.14	10 207
15	47.124	176.71	65	204.20	3318.31	115	361.28	10 387
16	50.265	201.06	66	207.35	3421.19	116	364.42	10 568
17	53.407	226.98	67	210.49	3525.65	117	367.57	10 751
18	56.549	254.47	68	213.63	3631.68	118	370.71	10 936
19	59.690	283.53	69	216.77	3739.28	119	373.85	11 122
20	62.832	314.16	70	219.91	3848.45	120	376.99	11310
21	65.973	346.36	71	223.05	3959.19	121	380.13	11499
22	69.115	380.13	72	226.19	4071.50	122	383.27	11690
23	72.257	415.48	73	229.34	4185.39	123	386.42	11882
24	75.398	452.39	74	232.48	4300.84	124	389.56	12 076
25	78.540	490.87	75	235.62	4417.86	125	392.70	12 272
26	81.681	530.93	76	238.76	4536.46	126	394.84	12 469
27	84.823	572.56	77	241.90	4656.63	127	398.98	12 668
28	87.965	615.75	78	245.04	4778.36	128	402.12	12 868
29	91.106	660.52	79	248.19	4901.67	129	405.27	13 070
30	94.25	706.86	80	251.33	5026.55	130	408.41	13 273
31	97.39	754.77	81	254.47	5153.00	131	411.55	13 478
32	100.53	804.25	82	257.61	5281.02	132	414.69	13 685
33	103.67	855.30	83	260.75	5410.61	133	417.83	13 893
34	106.81	907.92	84	263.89	5541.77	134	420.97	14 103
35	109.96	962.11	85	267.04	5674.50	135	424.12	14314
36	113.10	1017.88	86	270.18	5808.80	136	427.26	14 527
37	116.24	1075.21	87	273.32	5944.68	137	430.40	14 741
38	119.38	1134.11	88	276.46	6082.12	138	433.54	14 957
39	122.52	1194.59	89	279.60	6221.14	139	436.68	15 175
40	125.66	1256.64	90	282.74	6361.73	140	439.82	15 394
41	128.81	1320.2	91	285.88	6504	141	442.96	15 615
42	131.95	1385.44	92	289.03	6648	142	446.11	15 837
43	135.09	1452.20	93	292.17	6793	143	449.25	16 061
44	138.23	1520.53	94	295.31	6940	144	452.39	16 286
45	141.37	1590.43	95	298.45	7088	145	455.53	16513
46	144.51	1661.90	96	301.59	7238	146	458.67	16 742
47	147.65	1734.94	97	304.73	7390	147	461.81	16 972
48	150.80	1809.56	98	307.88	7543	148	464.96	17 203
49	153.94	1885.74	99	311.02	7698	149	468.10	17 437
50	157.08	1963.50	100	314.16	7854	150	471.24	17 671

<i>d</i>	Circumf.	Area	<i>d</i>	Circumf.	Area	<i>d</i>	Circumf.	Area
151	474.38	17 908	201	631.46	31 731	251	788.54	49 481
152	477.52	18 146	202	634.60	32 047	252	791.68	49 876
153	480.66	18 385	203	637.74	32 365	253	794.82	50 273
154	483.81	18 627	204	640.88	32 685	254	797.96	50 671
155	486.95	18 869	205	644.03	33 006	255	801.11	51 071
156	490.09	19 113	206	647.17	33 329	256	804.25	51 472
157	493.23	19 359	207	650.31	33 654	257	807.39	51 875
158	496.37	19 607	208	653.45	33 979	258	810.53	52 279
159	499.51	19 856	209	656.59	34 307	259	813.67	52 685
160	502.65	20 106	210	659.73	34 636	260	816.81	53 093
161	505.80	20 358	211	662.88	34 967	261	819.96	53 502
162	508.94	20 612	212	666.02	35 299	262	823.10	53 913
163	512.08	20 867	213	669.16	35 633	263	826.24	54 325
164	515.22	21 124	214	672.30	35 968	264	829.38	54 739
165	518.36	21 382	215	675.44	36 305	265	832.52	55 155
166	521.50	21 642	216	678.58	36 644	266	835.66	55 572
167	524.65	21 904	217	681.73	36 984	267	838.81	55 990
168	527.79	22 167	218	684.87	37 325	268	841.95	56 410
169	530.93	22 432	219	688.01	37 668	269	845.09	56 832
170	534.07	22 698	220	691.15	38 013	270	848.23	57 256
171	537.21	22 966	221	694.29	38 360	271	851.37	57 680
172	540.35	23 235	222	697.43	38 708	272	854.51	58 107
173	543.50	23 506	223	700.58	39 057	273	857.65	58 535
174	546.64	23 779	224	703.72	39 408	274	860.80	58 965
175	549.78	24 053	225	706.86	39 761	275	863.94	59 396
176	552.92	24 328	226	710.00	40 115	276	867.08	59 828
177	556.06	24 606	227	713.14	40 471	277	870.22	60 263
178	559.20	24 885	228	716.28	40 828	278	873.36	60 699
179	562.35	25 165	229	719.42	41 187	279	876.50	61 136
180	565.49	25 447	230	722.57	41 548	280	879.65	61 575
181	568.63	25 730	231	725.71	41 910	281	882.79	62 016
182	571.77	26 016	232	728.85	42 273	282	885.93	62 458
183	574.91	26 302	233	731.99	42 638	283	889.07	62 902
184	578.05	26 590	234	735.13	43 005	284	892.21	63 347
185	581.19	26 880	235	738.27	43 374	285	895.35	63 794
186	584.34	27 172	236	741.42	43 744	286	898.50	64 242
187	587.48	27 465	237	744.56	44 115	287	901.64	64 692
188	590.62	27 759	238	747.70	44 488	288	904.78	65 144
189	593.76	28 055	239	750.84	44 863	289	907.92	65 597
190	596.90	28 353	240	753.98	45 239	290	911.06	66 052
191	600.04	28 652	241	757.12	45 617	291	914.20	66 508
192	603.19	28 953	242	760.27	45 996	292	917.35	66 966
193	606.33	29 255	243	763.41	46 377	293	920.49	67 426
194	609.47	29 559	244	766.55	46 759	294	923.63	67 887
195	612.61	29 865	245	769.69	47 144	295	926.77	68 349
196	615.75	30 172	246	772.83	47 529	296	929.91	68 813
197	618.89	30 481	247	775.97	47 916	297	933.05	69 279
198	622.04	30 791	248	779.11	48 305	298	936.19	69 746
199	625.18	31 103	249	782.26	48 695	299	939.34	70 215
200	628.32	31 416	250	785.40	49 087	300	942.48	70 686

Table 3 Masses of round, square, hexagonal bar steel

Mass of 1 running metre in kg; density 7.85 kg/dm ³							
Thickness mm	○	□	Hex	Thickness mm	○	□	Hex
5	0.154	0.196	0.170	46	13.046	16.611	14.385
6	0.222	0.283	0.245	47	13.619	17.341	15.017
7	0.302	0.385	0.333	48	14.205	18.086	15.663
8	0.395	0.502	0.435	49	14.803	18.848	16.323
9	0.499	0.636	0.551	50	15.414	19.625	16.996
10	0.617	0.785	0.680	51	16.036	20.418	17.682
11	0.756	0.950	0.823	52	16.671	21.226	18.383
12	0.888	1.130	0.979	53	17.319	22.051	19.096
13	1.042	1.327	1.149	54	17.978	22.891	19.824
14	1.208	1.539	1.332	55	18.650	23.746	20.565
15	1.387	1.766	1.530	56	19.335	24.618	21.319
16	1.578	2.010	1.740	57	20.031	25.505	22.088
17	1.782	2.269	1.965	58	20.740	26.407	22.869
18	1.998	2.543	2.203	59	21.462	27.326	23.665
19	2.226	2.834	2.454	60	22.195	28.260	24.474
20	2.466	3.140	2.719	61	22.941	29.210	25.296
21	2.719	3.462	2.998	62	23.700	30.175	26.133
22	2.984	3.799	3.290	63	24.470	31.157	26.982
23	3.261	4.153	3.596	64	25.253	32.154	27.846
24	3.551	4.522	3.916	65	26.05	33.17	28.72
25	3.853	4.906	4.249	66	26.86	34.20	29.61
26	4.168	5.307	4.596	67	27.68	35.24	30.52
27	4.495	5.723	4.956	68	28.51	36.30	31.44
28	4.834	6.154	5.330	69	29.35	37.37	32.37
29	5.185	6.602	5.717	70	30.21	38.46	33.31
30	5.549	7.065	6.118	71	31.08	39.57	34.27
31	5.925	7.544	6.533	72	31.96	40.69	35.24
32	6.313	8.038	6.961	73	32.86	41.83	36.23
33	6.714	8.549	7.403	74	33.76	42.99	37.23
34	7.127	9.075	7.859	75	34.68	44.16	38.24
35	7.553	9.616	8.328	76	35.61	45.34	39.27
36	7.990	10.714	8.811	77	36.56	46.54	40.31
37	8.440	10.747	9.307	78	37.51	47.76	41.36
38	8.903	11.335	9.817	79	38.48	48.99	42.43
39	9.378	11.940	10.340	80	39.46	50.24	43.51
40	9.865	12.560	10.877	81	40.45	51.50	44.60
41	10.364	13.196	11.428	82	41.46	52.78	45.71
42	10.876	13.847	11.992	83	42.47	54.08	46.83
43	11.400	14.515	12.570	84	43.50	55.39	47.97
44	11.936	15.198	13.162				
45	12.485	15.896	13.797				

Table 4 Masses of plate

		Material: steel, density 7.85 kg/dm ³							Mass per m ² in kg
Thicknesses s in min nominal size		Plate dimensions							
		Measurements in mm and mass in kg							
		530 × 760	500 × 1000	600 × 1200	700 × 1400	800 × 1600	1000 × 2000	1250 × 2500	
0.40 m ²	0.5 m ²	0.72 m ²	0.98 m ²	1.28 m ²	2 m ²	3.11m ²			
0.2	Thin sheet	0.632	0.785						1.57
0.24		0.759	0.942						1.884
0.28		0.885	1.099	1.583					2.198
0.32		1.012	1.256	1.809	2.462				2.512
0.38		1.202	1.491	2.148	3.077	3.818	5.966		2.983
0.44		1.391	1.727	2.487	3.385	4.421	6.908		3.454
0.50		1.581	1.962	2.826	3.846	5.024	7.85		3.925
0.75		2.371	2.944	4.239	5.770	7.536	11.775		5.887
1		3.162	3.925	5.652	7.693	10.048	15.7		7.85
1.25					12.56	19.625		9.812	
1.5	Thin sheet					15.072	23.55		11.775
1.75						17.584	27.475		13.737
2						20.096	31.4	49.062	15.7
2.25						22.608	35.325	55.195	17.662
2.5						25.12	39.25	61.328	19.625
2.75						27.632	43.175	67.461	21.587
3	Medium sheet					30.144	47.1	73.594	23.55
3.5						35.168	54.95	85.859	27.475
4						40.192	62.8	98.125	31.4
4.5						45.216	70.65	110.391	35.325
4.75						47.728	74.575	116.523	37.287
5	Heavy sheet					50.24	78.5	122.655	39.25
6						60.288	94.2	147.188	47.1
7						70.336	109.9	171.719	54.95
8						80.384	125.6	196.25	62.8
9						90.432	141.3	220.781	70.65
10						100.48	157	245.312	78.5

Table 5

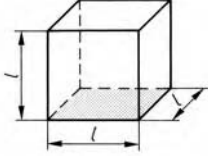
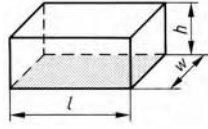
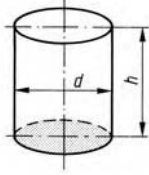
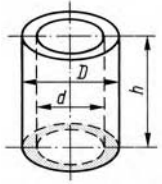
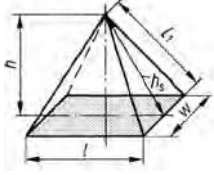
Volume			
Cube 	V volume A_0 area	l side length	$A_0 = 6 \cdot l^2$ $V = l^3$
Square prism 	V volume A_0 surface area l side length	h height w width	$A_0 = 2 \cdot (l \cdot w + l \cdot h + w \cdot h)$ $V = l \cdot w \cdot h$
Cylinder 	V volume A_0 surface area A_s lateral surface area	d diameter h height	$A_0 = n \cdot d \cdot h + 2 \cdot \frac{\pi \cdot d^2}{4}$ $A_s = n \cdot d \cdot h$ $V = \frac{\pi \cdot d^2}{4} \cdot h$
Hollow cylinder 	V volume A_0 surface area D outside diameter	d inside diameter h height	$A_0 = n \cdot d \cdot h + \pi/2 \cdot (D^2 - d^2)$ $V = \frac{\pi \cdot d}{4} \cdot (D^2 - d^2)$
Pyramid 	V Volume h height h_s slant height	l side length l_1 slant edge length w width	$l_1 = \sqrt{h_s^2 + \frac{l^2}{4}}$ $h_s = \sqrt{h^2 + \frac{l^2}{4}}$ $V = \frac{l \cdot w \cdot h}{3}$

Table 5 (continued)

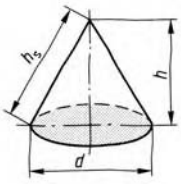
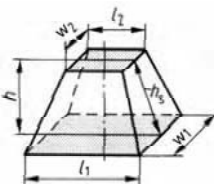
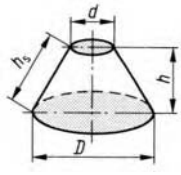
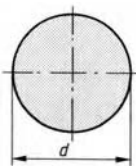
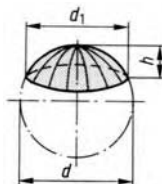
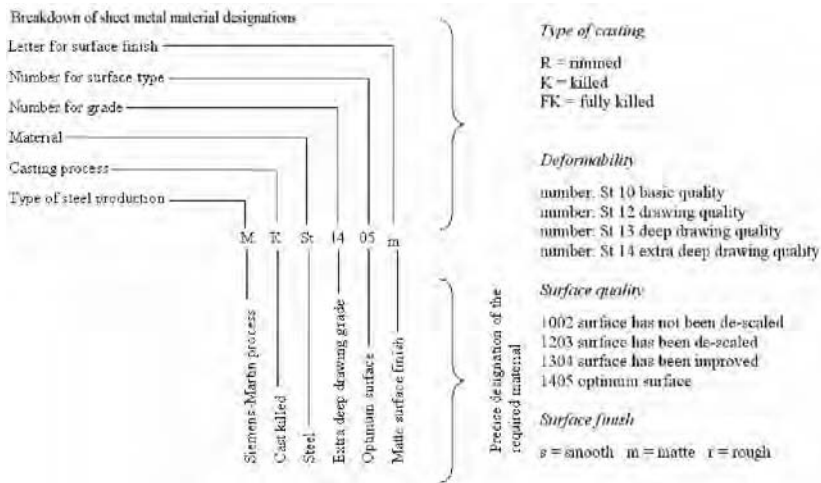
<p>Cone</p> 	<p>V volume A_M lateral surface area d diameter</p>	<p>h height h_s slant height</p> $V = \frac{\pi \cdot d^2}{4} \cdot \frac{h}{3}$	$A_M = \frac{\pi \cdot d \cdot h_s}{2}$ $h_s = \sqrt{\frac{d^2}{4} + h^2}$
<p>Pyramidal frustum</p> 	<p>V volume A_1 lower base area A_2 upper base area</p>	<p>h height h_s slant height l_1, l_2 side length w_1, w_2 width</p> $V = \frac{h}{3} \cdot (A_1 + A_2 + \sqrt{A_1 \cdot A_2})$	<p>$A_1 = l_1 \cdot w_1$ $A_2 = l_2 \cdot w_2$</p> $h_s = \sqrt{h^2 + \left(\frac{l_1 - l_2}{2}\right)^2}$
<p>Cone frustum</p> 	<p>V volume A_s lateral surface area D bottom diameter</p>	<p>d top diameter h height h_s slant height</p> $V = \frac{\pi \cdot h}{12} \cdot (D^2 + d^2 + D \cdot d)$	$A_s = \frac{\pi \cdot h_s}{2} \cdot (D + d)$ $h_s = \sqrt{h^2 + \left(\frac{D - d}{2}\right)^2}$
<p>Sphere</p> 	<p>V volume A_0 surface area</p>	<p>d sphere diameter</p> $V = \frac{\pi \cdot d^3}{6}$	$A_0 = \pi \cdot d^2$
<p>Spherical segment</p> 	<p>V volume A_s lateral surface area A_0 surface area</p>	<p>d sphere diameter d_1 small diameter h height</p> $V = \pi \cdot h^2 \cdot \left(\frac{d}{2} - \frac{h}{3}\right)$	<p>$A_s = \pi \cdot d \cdot h$ $A_0 = \pi \cdot h \cdot (2 \cdot d - h)$</p>

Table 6 Types and strengths of sheets less than 3 mm thick

Short designation	Steelmaking process	Casting process	C %	N/mm ²	Re N/mm ²	N/mm ²	Failure strain A %	Properties	Old designation
T St 1001 to 03	T		0.15	280 to 500	—	300 to 350	—	Basic quality, easy to form	—
St 1001 to 03	M or Y		0.15	280 to 500	—	300 to 350	—	Basic quality, easy to form	St II 23 to St IV 23
WU St 1203 to 05	W	R	0.10	270 to 410	—	240 to 300	24	Drawing quality	—
U St 1203 to 05	M or Y	R	0.10	270 to 410	—	240 to 300	24	Drawing quality	St V 23 to St VI 23
U St 1303 to 05	U	R	0.10	270 to 370	270	240 to 300	27	Deep drawing quality	—
R St 1303 to 05	M or Y	K	0.10	270 to 370	270	240 to 300	27	Deep drawing quality	St VII 23
U St 1404 to 05	M or Y	R	0.10	280 to 350	240	250 to 320	30	Extra deep drawing quality	St VII 23
RR St 1404 to	M or Y	FK	0.10	270 to 350	240	250 to 320	30	Extra deep drawing quality	St VIII 23

Table 7 Low-carbon unalloyed steels for screws and bolts, nuts and rivets. Guaranteed chemical composition

Steel grade		Deoxidation type ¹⁾	Chemical composition in wt %				
Short name	Material number		C ²⁾	Si	Mn	P	S
USt 36	1.0203	R	≤ 0.14 ³⁾	traces	0.25 to 0.50	≤ 0.050	≤ 0.050
UQSt 36	1.0204	R	≤ 0.14 ³⁾	traces	0.25 to 0.50	≤ 0.040	≤ 0.040
RSt 36	1.0205	K	≤ 0.14 ³⁾	≤ 0.30	0.25 to 0.50	≤ 0.050	≤ 0.050
USt 38 ⁴⁾	1.0217 ⁴⁾	R	≤ 0.19 ⁵⁾	traces	0.25 to 0.50	≤ 0.050	≤ 0.050
UQSt 38 ⁴⁾	1.0224 ⁴⁾	R	≤ 0.19 ⁵⁾	traces	0.25 to 0.50	≤ 0.040	≤ 0.040
RSt 38	1.0223	K	≤ 0.19 ⁵⁾	≤ 0.30	0.25 to 0.50	≤ 0.050	≤ 0.050
U 7 S 6 ⁶⁾	1.0708 ⁶⁾	U ⁶⁾	≤ 0.10	traces	0.30 to 0.60	≤ 0.050	0.04 to 0.08
U 10 S 10 ⁷⁾	1.0702 ⁷⁾	U ⁷⁾	≤ 0.15	traces	0.30 to 0.60	≤ 0.050	0.08 to 0.12

¹⁾ R rimmed, K killed (including semikilled).
²⁾ • On ordering a lower maximum carbon content can be agreed on; in this case, however, the minimum tensile strength value according to Table 2 no longer applies.
³⁾ For dimensions above 22 mm the maximum content is 0.18% C.
⁴⁾ In the next version of this norm, this steel may be deleted subject to verification (see annotations).
⁵⁾ For dimensions above 22 mm the maximum content is 0.22% C.
⁶⁾ • When ordering, the killed steel R 7 S 6 (material number 1.0709) with max. 0.40% Si and an upper manganese level of 0.80% may be delivered on agreement.
⁷⁾ • When ordering, the killed steel R 10 S 10 (material number 1.0709) with max. 0.40% Si and an upper manganese level of 0.80% may be delivered on agreement.

Table 8 Selection of steels suitable for cold extrusion

Short designation of material		Material no.	Notes	
Steels with no further heat treatment	UQSt 36-2 (Muk 7) Ma 8 (Mbk 6)	1.0204 1.0303	Later treatment possible if necessary.	
	Steels with particularly low C content = 0.05%		Only relevant magnetic properties affect selection.	
Steels for later heat treatment				
Case hardened steels	unalloyed	Ck 10 Cq 15	1.1121 1.1132	Also C10, C15 and Ck 15 if required
	alloyed	15 Cr 3 16 MnCr 5 20 MnCr 5 15 CrNi 6 17 CrNiMo 6 20 MoCr 4	1.7015 1.7131 1.7147 1.5919 1.6587 1.7321	C contents generally below 0.25%; the core strength is heavily influenced by the alloy elements.
Quenched and tempered steels	unalloyed	Cq 22	1.1152	Also C 35 and C 45 if necessary Quenching and tempering can be used to reach the tensile strength required for a certain application, with sufficient toughness. The hardenability depends upon the composition; with unalloyed materials the C and Mn contents determine the material properties which can be achieved when quenching and tempering (oil or water hardening must be agreed on when ordering). With high degrees of deformation, high strengths can also be achieved with no subsequent heat treatment. Steels with a guaranteed Cr content, e.g. 38 Cr1, 46 Cr1, 38 Cr2, 46 Cr2, are easier to quench and temper but do not necessarily have a better deformability than steels with no guaranteed Cr content; for this reason they are not listed in this table. A special check should always be made to see whether they need to be used.
		Cq 35 Cq 45	1.1172 1.1197	
Corrosion-resistant steels	ferritic	X 7 Cr 13	1.4000	heat treatable
		X 10 Cr 13	1.4006	heat treatable
X 22 CrNi 17		1.4057	heat treatable	
X 12 CrMoS 17		1.4104	heat treatable	
austenitic	X 5 CrNi 18 9	1.4301	with higher degrees of deformation in special cases	
	X 2 CrNi 18 9	1.4306		
	X 2 NiCr 18 16	1.4321		
	X 5 CrNiMo 18 10	1.4401		
	X 10 CrNiTi 18 9	1.4541		
	X 10 CrNiMoTi 18 10	1.4571		
	X 2 CrNiMo 18 12	1.4435		

Table 9 Nominal diameters and permissible variations for round steel wire rod for screws and bolts (measurements in mm), Euronorm 108

Nominal diameter d	Diameter Permissible variation when dimensions accurate		Nominal diameter d	Diameter Permissible variation when dimensions accurate	
	A	B		A	B
5.0			16.0		
5.5			16.5		
6.0			17.0		
6.5			17.4		
7.0			17.5	± 0.30	± 0.25
7.5			18.0		
7.8			19.0		
8.0	± 0.20	± 0.15 ¹⁾	19.5		
8.25			20.0		
8.5			20.5		
8.75			21.0		
9.0			21.3		
9.5			21.5		
9.75					
10.0					
10.5			22.0		
11.0			22.5		
11.5			23.0		
11.75			24.0		
12.0			24.5		
12.5	± 0.25	± 0.20	25.0	± 0.35	± 0.30
12.7			26.0		
13.0			26.5		
13.5			27.0		
13.75			28.0		
14.0			29.0		
14.5			30.0		
15.0					

¹⁾ This value applies only to coil weights of up to 200 kg. For larger coil weights a variation of ± 0.20 mm is permissible.

Table 10 Tooling materials

Material		Max. HRC hardness	Tooling type and HRC assembly hardness (mean values)												Impression die					
Material number	Designation		Shearing		Drawing		Stamping		Bending		Cold sinking		Extrusion			Shrinking		Upsetting		
			Pch	Die	Pch	Die	Pch	Die	Pch	Die	Pch	Die	Pch	Die	1 st ring	2 nd ring	Pch	Die	Upp.	Low.
1530	C 85 W 1	63	61	61	61	61	61	61	61	61	61	61	61	61			61	61		
1540	C 100 W 1	64	62	62	62	62	62	62	62	62	62	62	62	62			62	62		
1550	C 110 W 1	65	62	62	62	62	62	62	62	62	62	62	62	62			62	62		
1620	C 70 W 2	63	60	60																
1640	C 100 W 2	65	62	62	62	62	62	62	62	62	62	62	62	62						
1650	C 115 W 2	65	62	62					62	62	62	62	62	62						
1660	C 130 W 2	65		62	62															
2025	110 Cr 2	65												59	59					
2056	90 Cr	65		62	62	62	62	62	62	62	62	62	62	62						
2057	105 Cr 4	65												61	61					
2060	105 Cr 5	65	61	61										61	61					
2063	145 Cr 6	65	61	61	61	61	61	61	61	61	61	61	61	61						
2067	100 Cr 6	64	63	63	63	63	63	63	63	63	63	63	63	63						
2080	X 210 Cr 12	65	62	62	62	62	62	62	62	62	62	62	62	62			62	62	62	62
2127	105 MnCr 4	65	60	60	60	60	60	60	60	60	60	60	60	60			60	60		

Table 28.3 Basic values of k_{f_1} for $\dot{\varphi}_1 = 1 \text{ s}^{-1}$ with the deformation temperatures provided and material exponent m to calculate $k_f = f(\dot{\varphi})$

Material		m	k_{f_1} where $\dot{\varphi}_1 = 1 \text{ s}^{-1}$ (N/mm ²)	T (°C)
St	C 15	0.154	99/ 84	1100/1200
	C 35	0.144	89/ 72	
	C 45	0.163	90/ 70	
	C 60	0.167	85/ 68	
	X 10 Cr 13	0.091	105/ 88	1100/1250
	X 5 CrNi 18 9	0.094	137/116	
	X 10 CrNiTi 18 9	0.176	100/ 74	
Cu	E-Cu	0.127	56	800
	CuZn 28	0.212	51	800
	CuZn 37	0.201	44	750
	CuZn 40 Pb 2	0.218	35	650
	CuZn 20 Al	0.180	70	800
	CuZn 28 Sn	0.162	68	800
	CuAl 5	0.163	102	800
Al	Al 99.5	0.159	24	450
	AlMn	0.135	36	480
	AlCuMg 1	0.122	72	450
	AlCuMg 2	0.131	77	450
	AlMgSi 1	0.108	48	450
	AlMgMn	0.194	70	480
	AlMg 3	0.091	80	450
	AlMg 5	0.110	102	450
	AlZnMgCu 1.5	0.134	81	450

$$k_f = k_{f_1} \left(\frac{\dot{\varphi}}{\dot{\varphi}_1} \right)^m \quad \text{For } \dot{\varphi}_1 = 1 \text{ s}^{-1} \text{ then } \boxed{k_f = k_{f_1} \cdot \dot{\varphi}^m}$$

Table 28.4 Flow stress depending on the forming speed for the forging temperature $T = \text{constant}$

Material	T (°C)	$k_f = f(\dot{\phi})$ for $T = \text{const.}$ k_f in N/mm ²								
		$\dot{\phi} = 1$ (s ⁻¹)	$\dot{\phi} = 2$ (s ⁻¹)	$\dot{\phi} = 4$ (s ⁻¹)	$\dot{\phi} = 6$ (s ⁻¹)	$\dot{\phi} = 10$ (s ⁻¹)	$\dot{\phi} = 20$ (s ⁻¹)	$\dot{\phi} = 30$ (s ⁻¹)	$\dot{\phi} = 40$ (s ⁻¹)	$\dot{\phi} = 50$ (s ⁻¹)
C 15	1200	84	93	104	110	120	133	141	145	153
C 35	1200	72	80	88	93	100	111	118	122	126
C 45	1200	70	78	88	94	102	114	122	128	132
C 60	1200	68	76	86	92	100	112	120	126	131
X 10Cr 13	1250	88	94	100	104	109	116	120	123	126
X 5CrNi 18 9	1250	116	124	132	137	144	154	160	164	168
X10CrNiTi 189	1250	74	84	94	101	111	125	135	142	147
E-Cu	800	56	61	67	70	75	82	86	89	92
CuZn 28	800	51	59	68	75	83	96	105	111	117
CuZn 37	750	44	51	58	63	70	80	87	92	97
CuZn 40 Pb 2	650	35	41	47	51	58	67	73	78	82
CuZn 20 Al	800	70	79	90	97	106	120	129	136	142
CuZn 28 Sn	800	68	76	85	91	99	110	118	124	128
CuAl 5	800	102	114	128	137	148	166	178	186	193
Al 99.5	450	24	27	30	32	35	39	41	43	45
AlMn	480	36	40	44	46	49	54	57	59	61
AlCuMg 1	450	72	78	85	90	95	104	109	113	116
AlCuMg 2	450	77	84	92	97	104	114	120	125	129
AlMgSi 1	450	48	52	56	58	62	66	69	71	73
AlMgMn	480	70	80	92	99	109	125	135	143	150
AlMg 3	450	80	85	91	94	99	105	109	112	114
AlMg 5	450	102	110	119	124	131	142	148	153	157
AlZnMgCu 1.5	450	81	89	98	103	110	121	128	133	137

$\dot{\phi} = 70$ (s^{-1})	$\dot{\phi} = 100$ (s^{-1})	$\dot{\phi} = 150$ (s^{-1})	$\dot{\phi} = 200$ (s^{-1})	$\dot{\phi} = 250$ (s^{-1})	$\dot{\phi} = 300$ (s^{-1})
161	170	181	189	196	201
133	140	148	154	159	164
140	148	158	166	172	177
138	147	157	164	171	176
130	134	139	143	145	148
173	179	186	191	195	198
156	166	179	188	196	202
96	101	106	110	113	116
126	135	148	157	164	171
103	111	120	128	133	138
88	96	104	111	117	121
150	160	172	182	189	195
135	143	153	160	166	171
204	216	231	242	251	258
47	50	53	56	58	59
64	67	71	74	76	78
121	126	133	137	141	144
134	141	148	154	159	163
76	79	82	85	87	89
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