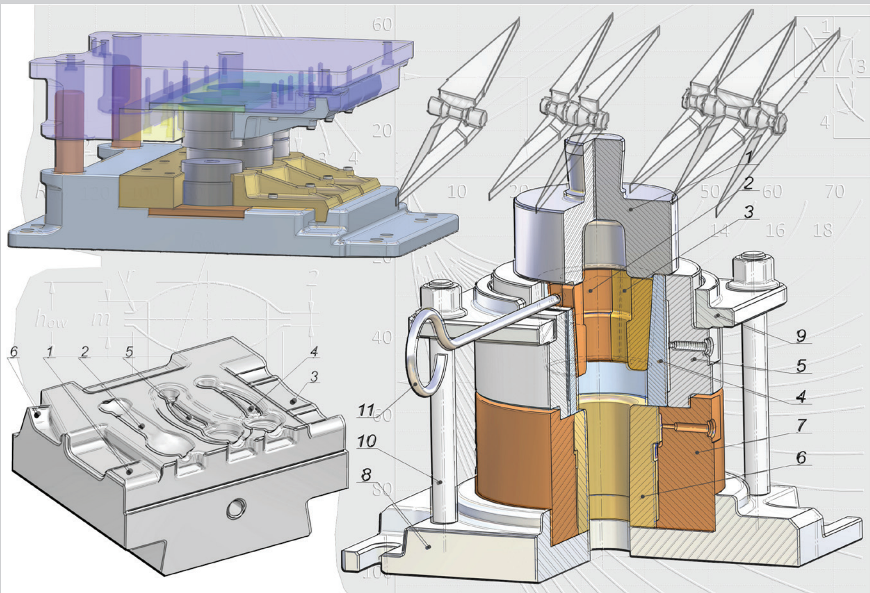
POLITECHNIKA LUBELSKA

Zbigniew Pater
Grzegorz Samołyk

Selected issues of metal forming



PODRĘCZNIKI

Lublin 2015

Selected issues of metal forming

Podręczniki – Politechnika Lubelska

HUMAN CAPITAL
NATIONAL COHESION STRATEGY

EUROPEAN UNION
EUROPEAN
SOCIAL FUND

Publication co-financed by the European Union
under the European Social Fund

Zbigniew Pater
Grzegorz Samołyk

Selected issues of metal forming

Politechnika Lubelska
Lublin 2015

Adviser by:
Dr. hab. inż. Paweł Droździel, prof. Politechniki Lubelskiej
Prof. Ing. Andrej Czán, PhD

Translation at the sole request of Lublin University of Technology

Free of charge publication.

The publication was prepared and published as a part of the project *Engineer with a warranty of quality – tailoring the course offer of the Lublin University of Technology to the requirements of the European labour market* (agreement number: UDA-POKL.04.01.01-00-041/13-00), co-financed by the European Social Fund, Human Capital Operational Programme, Submeasure 4.1.1.

Publication approved by the Rector of Lublin University of Technology

ISBN: 978-83-7947-126-3

Publisher: Lublin University of Technology
ul. Nadbystrzycka 38D, 20-618 Lublin, Poland

Realization: Lublin University of Technology Library
ul. Nadbystrzycka 36A, 20-618 Lublin, Poland
tel. (81) 538-46-59, email: wydawca@pollub.pl
www.biblioteka.pollub.pl

Printed by : TOP Agencja Reklamowa Agnieszka Łuczak
www.agencjatop.pl

The digital version is available at the Digital Library of Lublin University of Technology: www.bc.pollub.pl
Circulation: 200 copies

Contents

Preface

The metal forming is one of the production techniques where the reshaping and dimensions of a workpiece is achieved by using the appropriate tools on the billet. What is characteristic about this technique is that during shaping of the material, it experiences permanent deformations and in general, its mechanical properties are improved. Processes of shaping can be realised under cold conditions, warm or hot. They are counted as the basic methods of tools shaping.

The forging is one of the oldest manufacturing techniques. The first metal that was forged was cooper (ca. 4500 BC), which was shaped using hammers made from durable stones. Later on, those hammers were replaced by the ones made from bronze, and ultimately from iron (the oldest one, from excavations is dated around 3000 years). The first products forged serially were coins (VII c. BC – Lydia) made from electron (alloy made of gold and silver). During the Middle Ages there was a development of forging industry which involved spreading of waterwheel, used for example to drive forging bellows, hammers (from XIV century) and rolling mills (from XVII century). Further development of plastic working was caused by the use of steam as a drive for machinery (1783a – steam-driven rolling mill; 1839 – steam hammer; 1861 – hydraulic press). In the XX century many new processes of shaping were created, performed by machines with individual electric engines. Build for this purpose. More information about the history of plastic working can be found in the manual titled: "*Wybrane zagadnienia z historii techniki*".

This study is an updated issue based on the handbook titled: "*Podstawy technologii obróbki plastycznej metali*" [23] and adapted to the didactic process realised on the Lublin University of Technology in English. Taking into consideration the limited volume in the book, only selected process of bulk forming were included. Those realised in industrial establishments branching in metal processing and alloys (forging plants). Especially those covering the scientific profile of the Department of Computer Modeling and Metal Forming Technologies and didactics. Among excluded things were metallurgical processes of shaping (rolling, wire and tube drawing) the aims of which is to create semi-finished products (those processes are described in manual titled: "*Podstawy metalurgii i odlewnictwa*") and the processes of sheet metal forming that are described in the manual titled: "*Podstawy technologii obróbki plastycznej metali*". We are the authors of all of the above-mentioned manuals and they are published by the Publishing House of the Lublin University of Technology.

The handbook is intended for the students of Technical University studying on the faculties: "*Mechanical Engineering*", "*Materials Engineering*", "*Metallurgy*", and "*Production Engineering*". In order to extend the knowledge from discussed area, the readers are encouraged to read technical literature presented at the end of the handbook.

In conclusion, the authors express their acknowledgement to anyone whose remarks contributed to improving the quality of material included in the book. Special thanks are offered to the reviewer whose valuable remarks influenced creating the current form of the essay.

Authors

1. Open-die forging

Forging is the branch of plastic forming of metals that includes all issue related to manufacturing items forged with machines and forging tools. Forging means reshaping processed metal by means of the action of hammer tup or press ram while using the properties of deformated material. If those flat tools (anvils) exerts pressure only on the part of the material that can flow in few arbitrary directions, such forging process or upsetting is called open-die forging. Partial limitation of the metal flow while simultaneously pressing the part of the surface is able to realised in simple countoured forging tools called shaped dies.

Diagram illustrating the process of open-die forging is presented on the Fig. 1.1. The main operations included in this process are: metal reheating (most common in the form of ingot, billet or slug), forging on hammer or press, heat treatment and quality control. For the batch of forging, also laboratory tests (e.g. strength, hardiness, structure) are made. In order to do this, appropriate samples are taken from selected forgings.

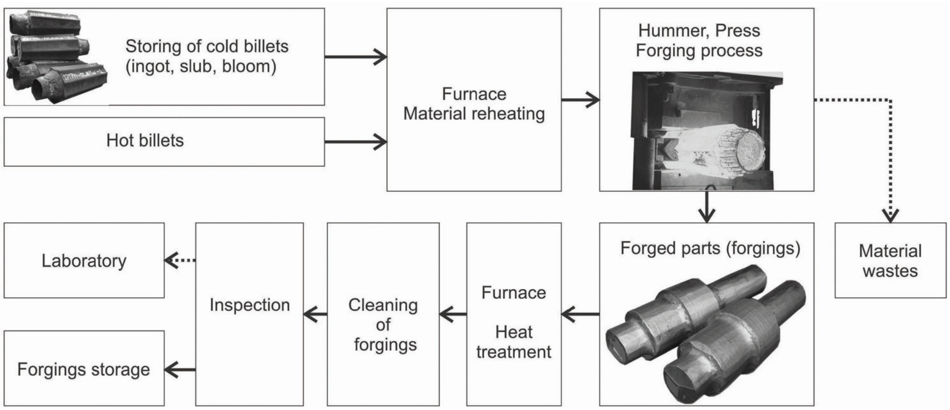


Figure 1.1. *Diagram of open-die forging processes*

During forging, the rate of material wrought in relation to the exit state is determined by coefficient of deformation (elongation). In general case when forging means only elongating and the coefficient of deformation λ is equal to the ratio of starting sectional area S_0 of billet to the ending cross-section S of forging:

$$\lambda = \frac{S_0}{S} \tag{1.1.}$$

The coefficient of deformation has a significant impact on the state of mechanical properties and the metal structure. The grain flow pattern is dependent on the selected method of forging. In the case of open-die forging under the hammer as an effect of the high velocity and uneven deformation, grain flow lines can slightly differ from the direction of metal flow. During open-die forging on the press, these deviations are much smaller.

According to the technical requirements, during open-die forging of forging the smallest values of deformation should be $\lambda = 3.5 \div 4$. Then, the mechanical properties in longitudinal and lengthwise directions are good and assure fulfilment of the structural-durability requirements.

1.1. Range of open-die forged products

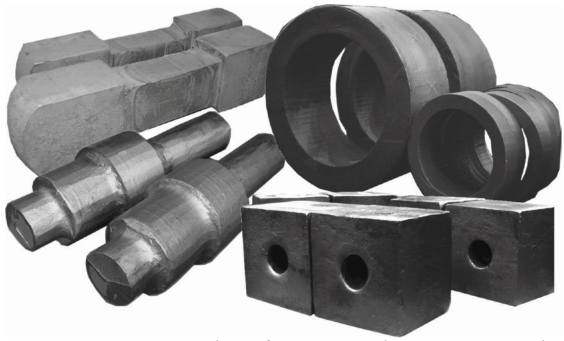


Figure 1.2. *Examples of parts made using open-die forging process in Polish industry*

Open-die forging is used for the production of very large forgings and for the production in small series (Fig. 1.2). Small forgings (weighing 0.5÷20 kg) are mostly manufactured on pneumatic forging hammer with the mass of falling elements from 50 to 1000 kg. Medium-sized forgings (weighing 8÷200 kg) are forged on steam-air hammers, falling parts mass of which is 500÷5000 kg. However, big forgings are manufactured in hydraulic presses with the pressure 6÷200 MN. Mass of those forgings is generally up to 160 tons and in some countries it can be even up to 250 tons.

Forgings made using open-die forging method are divided into semi-finished forging products and forged products. Semi-finished products are billets and slabs intended for further plastic working in forging plants, drawing plants and rolling mills. The forged products include significantly long forged bars (1.5÷6 m) with constant cross-sections (round, quadratic, rectangular, trapezoidal, triangular, hexagonal, octagonal and so on) and forged shapes, which can be divided into two groups:

- symmetrical forgings, including: plates, rollers, discs, cubes, regular profile prisms, die and unchain rings, sleeves, extended forgings, collar shafts, wearing shafts , rollers and drop weights of hammers;
- non-symmetrical forgings, irregular (Fig. 1.3). Most of all, the following should be included: crankshafts, eccentric shafts and extended forgings with over-the-top or bended axis (ship's rudderstock and anchoring, hooks, anchors, etc.).

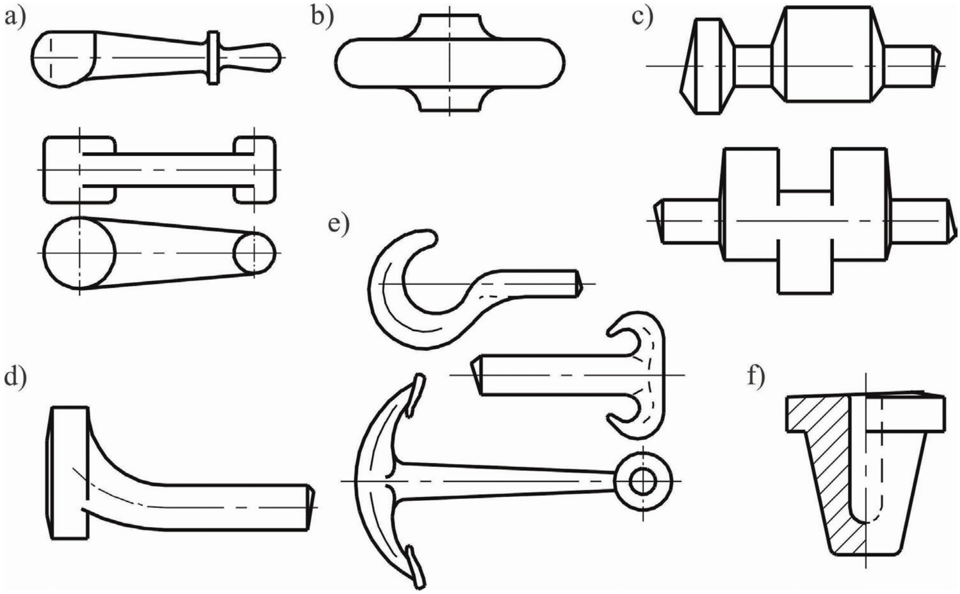


Figure 1.3. *Irregular forgings made using open-die forging process: a) lever and connecting rod, b) turbine's disc, d) zonal shaft, e) hooks and anchors, f) hobbed forging [32]*

1.2. Basic operations of open-die forging

During the technological process of open-die forging usually basic operations are combined in any order and any quantity. Those are: upsetting, progressive forging (also called as drawing-out or forging solid), punching (piercing or hobbing), bending, cutting, twisting and welding.

1.2.1. Upsetting

Upsetting means increasing of cross sectional area at the expense of the height or length of material, achieved by the effect of appropriate pressing of a press or hammer stroke. This operation is used for:

- manufacturing forgings that have cross-sections larger than charge section;
- quality improvement of forgings by malleable throughput of cast structure that causes fragmentation of micro-constituents and increasing the density of steel as a result of heating up voids and discontinuities existing in ingots;
- achieving comparable mechanical properties of forgings in longitudinal and lateral directions.
- During the upsetting process the following rules should be followed:
- ratio of billet height to the dimension that characterise cross-section (diameter, the length of shorter side) should not exceed the limit value of 2.5 for the round ingot and 3.5 for the square bloom;
- upset material should be reheated evenly (to the highest forging temperature) among the whole volume;
- before upsetting the ingot should be roundly reforged;
- upsetting should be made this way, so the deformations created after every strike of a hammer or as an effect of pressure of slider will exceed the values corresponding to critical drafts;
- the surface of billet intended for reheading should be free from external defects and its frontal area (adjoining anvils) should be perpendicular to the longitudinal axis;
- during upsetting largely dimensioned forgings, especially in the case of steel, demonstrating strengthening while constant deformation, it is advisable to apply full recrystallisation of metal.

In the axial section of the upset round billet (for example ingot), three deformation areas schematically shown on the Fig. 1.4. can be distinguished. The material from the I zone deform minimally as a result of friction (on the surface connecting anvils) suppressing metal flow. The biggest deformations are in the II zone while in the III zone deformation values are intermediary. It should be underlined that the transition between certain zones is continuous. It can be clearly seen on the Fig. 1.5, on which stain effective in cross section of deformed billet depending on the advancement of the process and the friction on the contact area material-anvil. The application of lube during the upsetting process is beneficial because the material deforms in a more uniform way and shaping forces decrease.

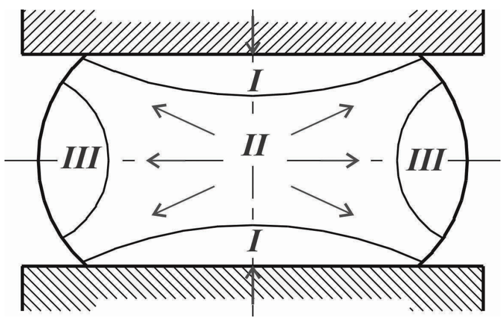


Figure 1.4. *Deformation areas in the axial section of upset round billet*

As an effect of friction forces on the contact area metal-anvil the billet becomes barrel-shaped after the upsetting process (Fig. 1.5). The shape of the ingot becomes more barrel-like with the increase of friction factor describing boundary conditions on the contact area. On the other hand cross-section changes of the rectangular billet that are result of upsetting process, are more complicated and in accordance with Fig. 1.6.

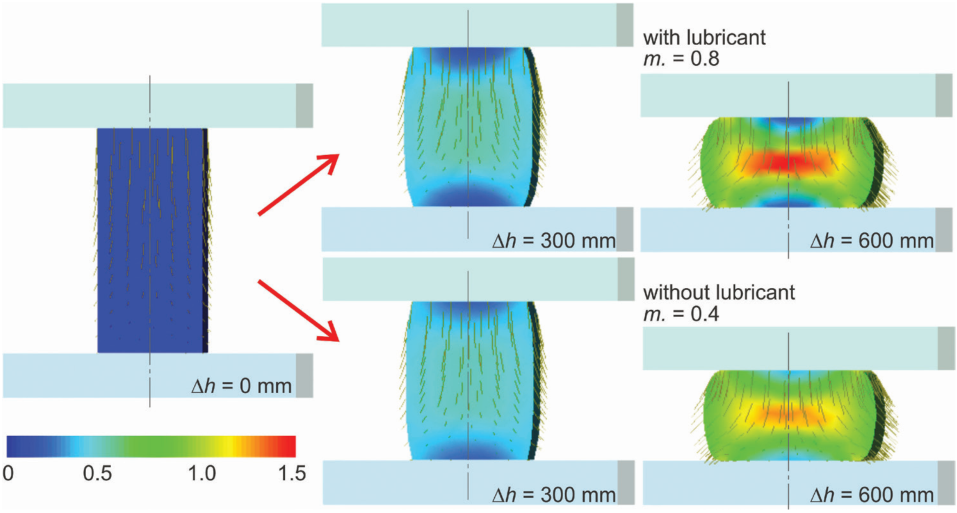


Figure 1.5. *Comparison of upsetting process of billet with starting dimensions Ø500x1000 mm, with presented the distribution of strain effective, realised with different friction and movement of upper anvil Δh (vectors show the velocity of metal flow)*

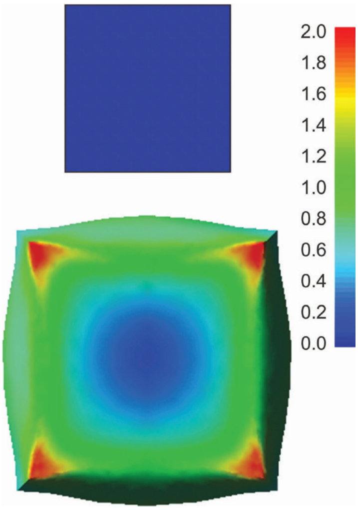


Figure 1.6. *Reshaping of square bloom (top view) with base of 500 x 500 mm and height 1000 mm (upper figure) subjected to the upsetting process to the height 400 mm (lower figure) with presented strain effective distribution*

Upsetting on hydraulic press is realised by flat anvils (Fig. 1.4) or special plates (holed dies) used for upsetting ingots. Those dies have holes drilled on a side in order to ease their transport. Sometimes, concave dies are used. Therefore, is it possible to centre the ingot while upsetting and creating of ingot's convex frontal area prevents creation of concaves in this part of forgings during drawing out process.

For forging of disks prepared for gears, shields and collars with jags upsetting with pad rings are used (see on Fig. 1.7). While using this method portion of material flow into conical holes in pads which makes blanks forged.

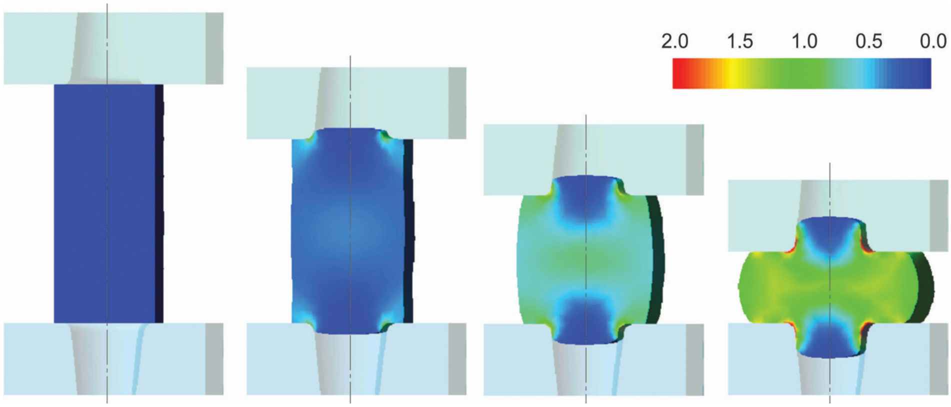


Figure 1.7. *Course of the open-die forging in shaped dies (two rings) with a marked distribution of strain effective*

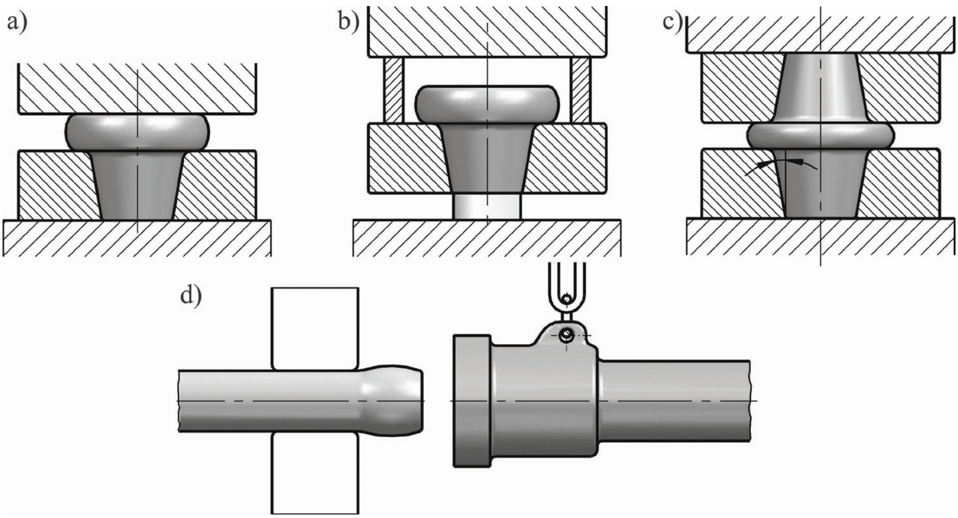


Figure 1.8. *Various methods of upsetting of the bar's end (a), the centre part of the bar in two rings (c), long bar using beater (d) and the way of knocking out forging from a ring (b) [31]*

Various ways of local upsetting are presented on the next Fig. 1.8. On the Fig. 1.8a upsetting of the end of the bar in a ring while on the Fig. 1.8c upsetting the middle of the bar in two rings. In both cases the material is upset only on the part not covered with rings. Removal of the rings from the forging requires additional knocking out realised in a way shown on the Fig. 1.8b. In the case of upsetting long bars not fitting in the forging machine's area (hammer, press), the way shown on the Fig. 1.8d., are used. In this way, the bar is clamped between anvils and the protruding part is upset using beater hanging on a crane in forging plant.

1.2.2. Progressive forging

Progressive forging (drawing out, cogging) means increasing the length of the billet in the direction of one of its axis at the expense of reducing cross section perpendicular to this axis. This operation is carried out by putting the material reheated to the forging temperature on the lower anvil and pressing or hammering with the upper anvil (Fig. 1.9a). Afterwards, the material is turned by 90° and pressed again (hammered) in the extended area. Two subsequent drafts with simultaneous rotation of 90° is called pass. After each pass shift of the material over the lower anvil occurs and the translation is repeated. The material reduces its height by $\Delta h = h_0 – h$, widen by $\Delta a = a – a_0$ and lengthens by $\Delta l = l – l_0$ at the same as an influence of anvils stroke. During the drawing out process, cross section is reduced from $S_0 = h_0 \cdot a_0$ to $S = a \cdot h$ value (Fig. 1.9b).

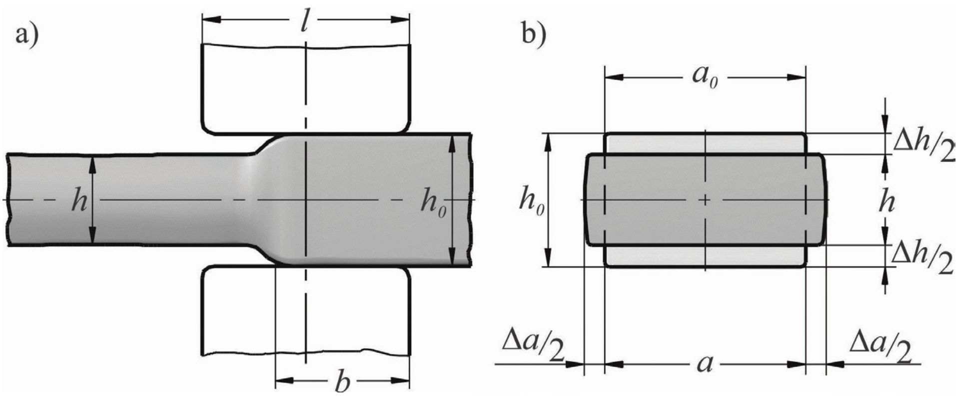


Figure 1.9. *Various methods of upsetting of the bar's end (a), the centre part of the bar in two rings (c), long bar using beater (d) and the way of knocking out forging from a ring (b) [31]*

During progressive forging process rotation of the billet can be made using alternating movement left and right (as you can see on Fig. 1.10a) or in one side (Fig. 1.10b). The second method (called helical) is used during forging of hard steel grades (e.g. tools) and metals that have low speed of recrystallization under the forging temperatures. In the case of drawing out of long and heavy forgings shaping is performed from the centre to one of the ends (Fig. 1.11a), and then after moving the handle to the opposite end, the second half of the forging is forged. However, drawing out short and lightweight forgings is performed from the end to the centre (Fig. 1.11b) When the first method is used, blacksmith moves away after each stroke and comes closer after the second one.

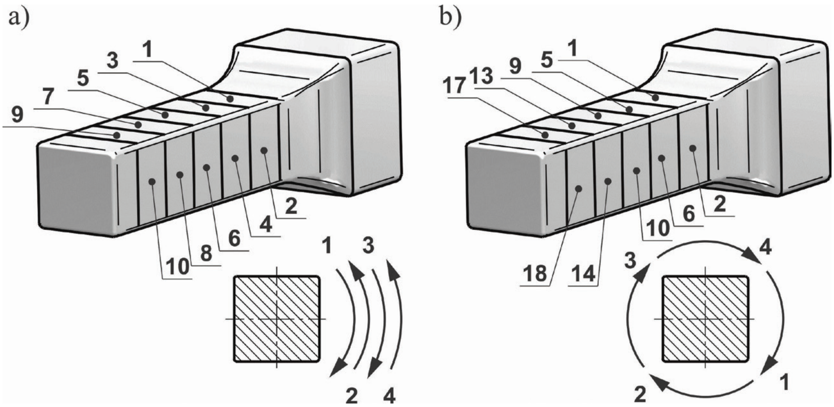


Figure 1.10. *Sequence of operations during progressive forging process while rotating the workpiece: a) oscillatory movement, b) one-way movement*

The other way of progressive forging, compared to the one presented on the Fig. 1.10, is shown on another Fig. 1.12. In this method a sequence of strokes are made only on one side of the lengthwise moving bar which is then rotated by 90°. Progressive forging processes can be realised by the usage of flat anvils (Fig. 1.12) or profiled dies (rhombic, semi-circular, asymmetrical [8]). The second way of above-mentioned ways of shaping is recommended for forging less malleable materials and round ingots. This way is illustrated in a graphic way on Fig. 1.13.

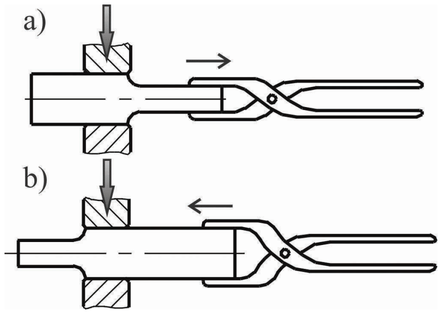


Figure 1.11. *The direction of material drawing out: a) long and heavy, b) short [31]*

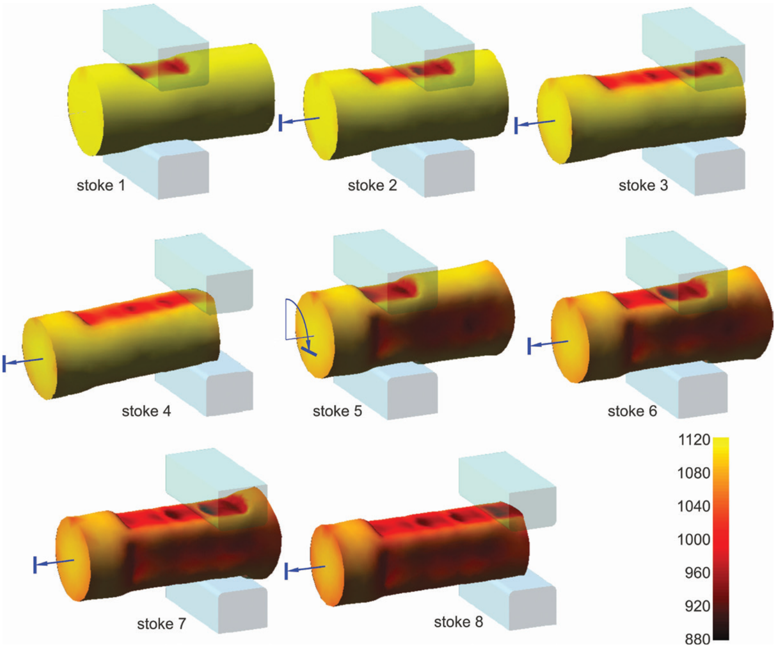


Figure 1.12. *The process of progressive forging steel-made ingot 2X18H9T with starting of dimensions Ø400x800 mm realised with 25% draft made in flat anvils (with temperature distribution shown is °C)*

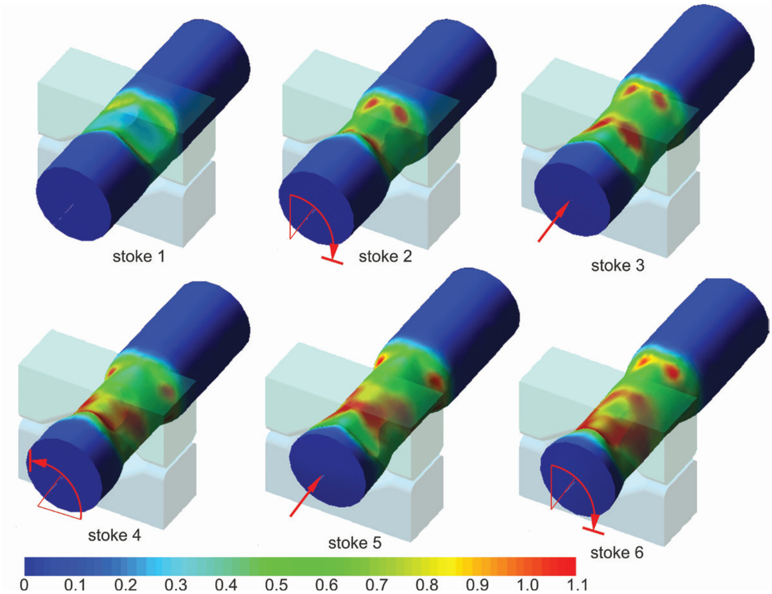


Figure 1.13. *The progressive forging process in rhombic anvils (of 90 angle) workpiece made of steel 20XGHM of starting dimensions Ø100x300 mm to square with side of 80 mm (with presented the distribution of strain effective)*

Progressive forging process should be conducted in the way that unitary draft given by the equation

$$\varepsilon = \frac{h_0 - h}{h_0} = \frac{\Delta h}{h} \tag{1.2}$$

where: h_0, h, Δh are dimensions according to Fig. 1.9 – were: for the presses $\varepsilon = 0.2 \div 0.3$ (beyond the critical degree of deformation); for hammers $\varepsilon = 0.03 \div 0.06$ (below the critical degree of deformation).

Anvils intended for progressive forging should have frontal areas mutually parallel, identical width and identical edge rounding. When width of anvils is uneven, forging's axis becomes twisted (Fig. 1.14), which causes unfavourable and unsafe working conditions of blacksmith.

The length of the workpiece l_n after n-th passage is calculated from the correlation

$$l_n = \lambda_n \cdot l_{n-1} \tag{1.3}$$

in which the coefficient of elongation λ_n (aspect ratio) is defined by Chile's equation

$$\lambda_n = \frac{1}{1 - \varepsilon_n \left(1 - f_n\right)} \tag{1.4}$$

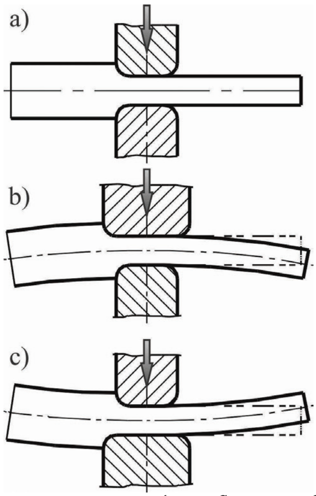


Figure 1.14. *The influence of the anvils on the progressive forging process: a) anvils of equal width, b) upper anvil wider than lower [16]*

where: ε_n – draft in n-th passage – relation (1.2), f_n – factor dependent on the ratio of workpiece's movement on the anvil (bite) l_p to the width of the surface squeezed before $a_{n\text{-}1}$ pass (Fig. 1.15). The f_n coefficient values are assumed from 0.2 to 0.7 according to the ratio $l_p/a_{n\text{-}1}$.

The strokes number of press ram (hammer tup) while taking into account specific draft ε_n are calculated by dividing the length of forging (billet) $l_{n\text{-}1}$ by bite l_p. Therefore

$$i_n = \frac{l_{n-1}}{l_p} \tag{1.5}$$

Apart from the normal methods of progressive forging on flat or profiled anvils, extensions can be made using special auxiliary tools. In such processes, we can include:

- progressive forging on draw bar (Fig. 1.16) used for stretching the length of hollow forging while simultaneously reducing its internal diameter. In this process V-shaped lower anvil, flat upper anvil and low tapered draw bar are used;
- progressive forging of rings on mandrel (Fig. 1.17) meaning extending the external and internal diameter of ring billet at the expense of thinning its wall;
- progressive forging on cone (Fig. 1.18) is performed by conical washer dies.

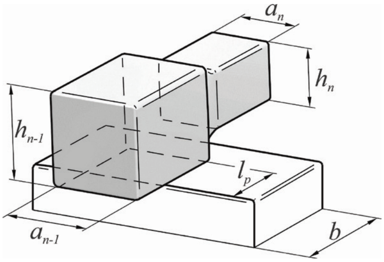


Figure 1.15. *Change of billet's dimensions during the progressive forging process*

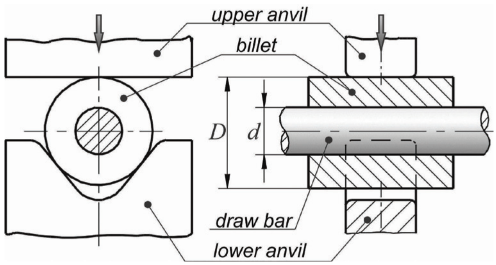


Figure 1.16. *Progressive forging of sleeve billet on tapered draw bar [31]*

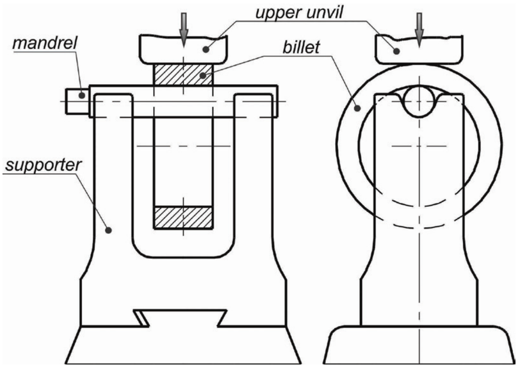


Figure 1.17. *Progressive forging of ring billet under the hammer of press [7]*

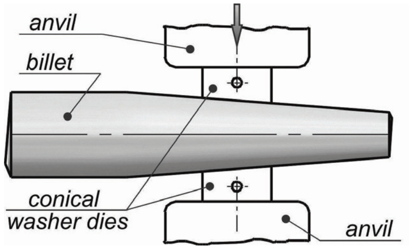


Figure 1.18. *Progressive forging on cone [31]*

During the progressive forging process many auxiliary operations are made. The most important are spreading, offsetting and joggling.

Spreading

Spreading means extending the width of billet, which increase faster length. This process is made by exerting pressure on the material using special fuller die, the rule that stretching starts from the centre is applied here. In the case of spreading only the part of the bar, first of all it is necessary to make a special notch using a notching tool.

Offsetting

Offsetting means reducing bar's cross section in one direction from the specified place. This process is diced into the following operations: marking, notching and drawing out. Marking is indicated by using notching tool of a small radius. Then, the marked place is deepen by using notching tool of appropriate shape (as you can see on Fig. 1.19).

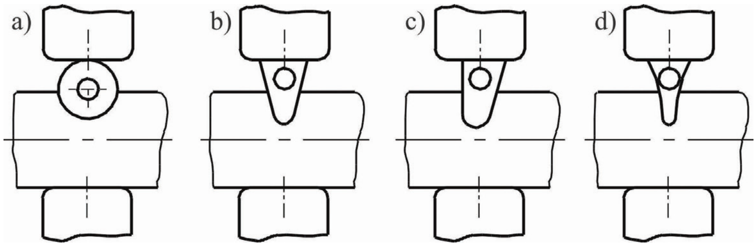


Figure 1.19. *Offsetting process: notching operation with using the notching tools: a) round, b) and c) triangular, d) shaped [31]*

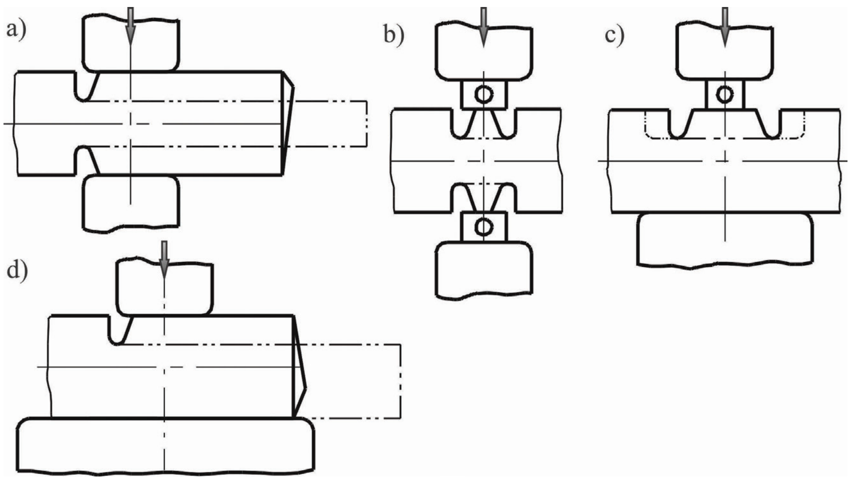


Figure 1.20. *Offsetting process: drawing out operation: a) directly in anvils, b) using flat or half-round washer dies, c) using one washer die or fuller tool, d) using criss-crossed small anvils [31, 32]*

Afterwards, reduction of intersection is performed. Marking and notching allows reduction of intersection at the end or in the centre of billet. When the reduction of intersection occurs on considerable length, offsetting is performed directly in anvils (Fig. 1.20a) However, when the offsetting length is small, this process is performed by flat or half-round washer dies (Fig. 1.20b). In the case of one-sided intersection decrease, form the exculpation side offsetting is performed by washer dies (Fig. 1.20c) or criss-crossed anvils (Fig. 1.20d) in order to assure sufficient surface finish.

Joggling

Joggling can be realised using two ways: with one-sided material notch (Fig. 1.21) or with two-sided notch (Fig. 1.22). During the first way of joggling, the material is notched from the top using triangular notching tool (Fig. 1.21a). Next, the material is rotated by 180° and put on the lower anvil, as presented on the Fig. 1.21b. As an effect of the pressure of upper anvil, metal moves along the left side of the lower anvil (Fig. 1.21c). After another rotation of billet by 180° replanting can be increased to the required value (Fig. 1.21d). Unevenness in the joggling are evened out on flat anvils.

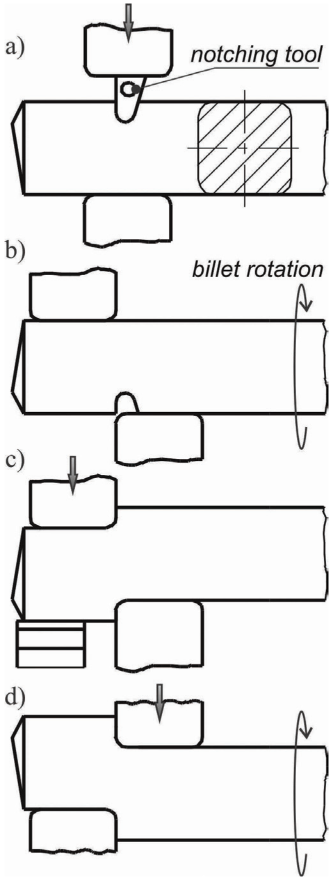


Figure 1.21. *Joggling process with one-side material notch (description in the text) [31]*

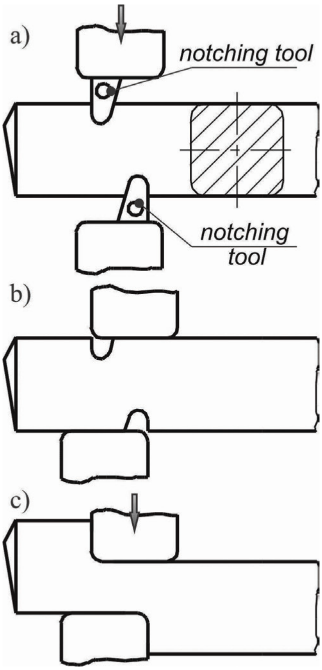


Figure 1.22. *Joggling process with two-sided material notch (description in the text) [31]*

When the second way is used, the material is notched on two sides using triangular notching tool (Fig. 1.22a). Afterwards, it is moved in the way that during stroke, the side walls were shifted from the perpendicular notches (Fig. 1.22b). Under the influence of tools' pressure the ultimate shift of one part of material towards the second one occurs (Fig. 1.22c).

1.2.3. Piercing

Piercing is forge operation during which holes or cavities in the billet are made. Practically, there are two essential methods of piercing, i.e. with underlying ring and without underlying ring.

Piercing with underlying ring (Fig. 1.23) also known as cutting out is used when the material thickness is small and smaller than the height of puncher. This process is performed in this way: reheated material is put on the ring laying on the lower anvil. Then, puncher is put on the material, aligned centrally to the hole in the ring – bigger diameter downwards and next, using the upper anvil the shear punch is pushed into the material until it reaches the ring. The process of piercing of forging using the aforementioned way is graphically described on the Fig. 1.24.

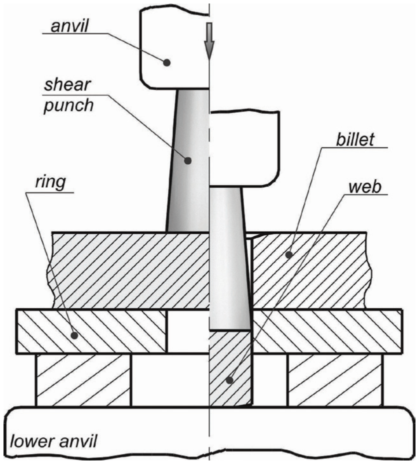


Figure 1.23. *Piercing with underlying rings: before start process (figure on the left) and after piercing (figure on the right) [31]*

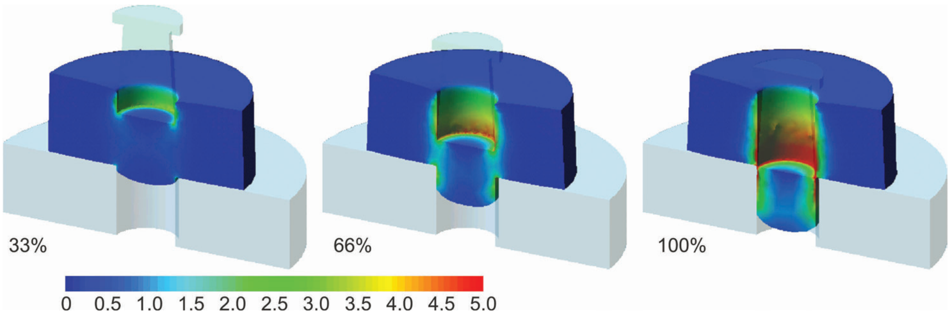


Figure 1.24. *Piercing of the forging made of C45 steel of Ø1000x400 mm dimensions reheated to temperature 1200°C while the tools are reheated to the temperature 250°C (with distribution of strain effective presented) on the underlying ring using the solid shear punch of the diameter Ø300 mm; the progress of process is shown in percentage*

Piercing without the underlying ring can be realised in two ways: solid shear punch and hollow shear punch. Piercing using solid shear punch is realised in the following way. After putting the material in the presses axis, shear punch is aligned centrally with the smaller diameter downwards (Fig. 1.25a). After making a slight cavity, shear punch is taken out and fine coal is poured into the cavity. Afterwards, the fine coal burns releasing gases (creating insulation layer between the tool and material preventing from jamming of shear punch) and then set shear punch. After pushing the tool to the full height, piercing is continued by putting swages on the shear punch (Fig. 1.25b) which amount depends on the hole's depth. When the thickness of bottom reaches the value corresponding to 10÷15% of forging's height, it is rotated and in the middle of the trail left by the deepening shear punch, the second shear punch is set and it is used for cutting out the web and pushing out deepening first shear punch. The second shear punch used for cutting out should have slightly smaller diameter than the deepening one in order to ease its passage through the hole.

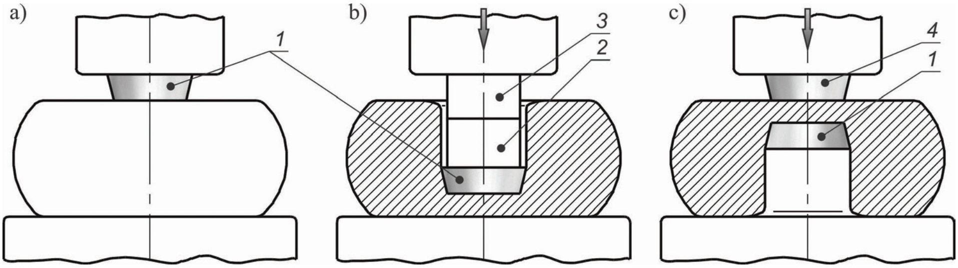


Figure 1.25. *Scheme of the piersing process of forging using the solid shear punch, where: 1 – first shear punch, 2 – first swage, 3 – second swage, 4 – second shear punch [31]*

The main disadvantage of this method is big deformation of forging. It can be seen on the subsequent Fig. 1.26 and 1.27 on which the changes in the shape of forgings while piercing with solid shear punch occur. It should be emphasized that increasing the diameter of the shear punch (while retaining the dimensions of billet) increases deformations of forging, reducing the manufacturing quality. The second disadvantage of piercing using solid shear punch is the necessity of using strong forces, which are also increasing along with the diameter of pierced hole.

Piercing using hollow shear punch is used for making holes of diameter larger than 450 mm in upset forgings. In this method, a hole ⅔ material thickness deep is made in the ingot using shear punch and swage. Next, billet is set on the ring and shaping is continued until it is penetrated throughout.

Piercing using hollow shear punch has many advantages such as:

- cutting out the core of ingots in which usually material defects are located and producing forgings of good quality;
- reducing deformations of forgings occurring while piercing (Fig. 1.30);
- reduction of shaping forces in relation to the method using solid shear punch (Fig. 1.28);
- shortening the time of making a wrought ingot.

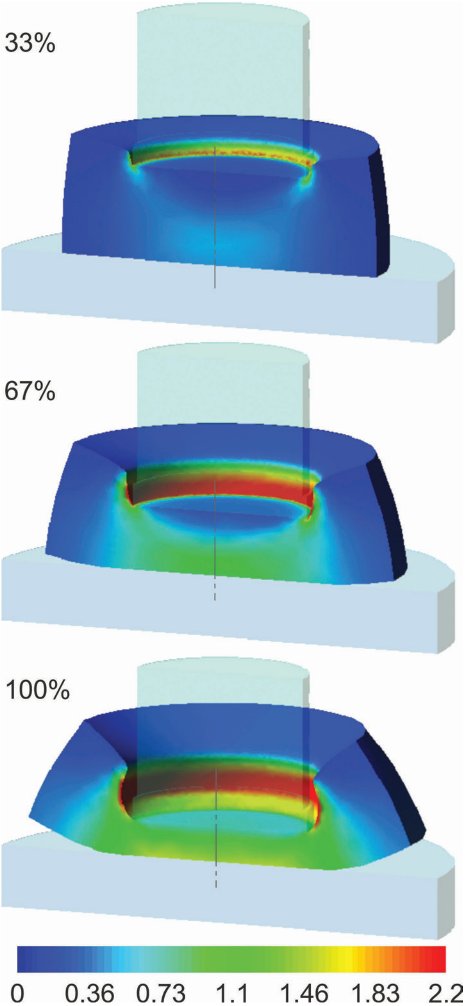


Figure 1.26. *Piercing of the forging made of C45 steel of Ø1000x400 mm dimensions reheated to temperature 1200°C while the tools are reheated to the temperature 250°C (with distribution of strain effective presented) using the solid shear punch of the diameter Ø600 mm; the progress of process is shown in percentage*

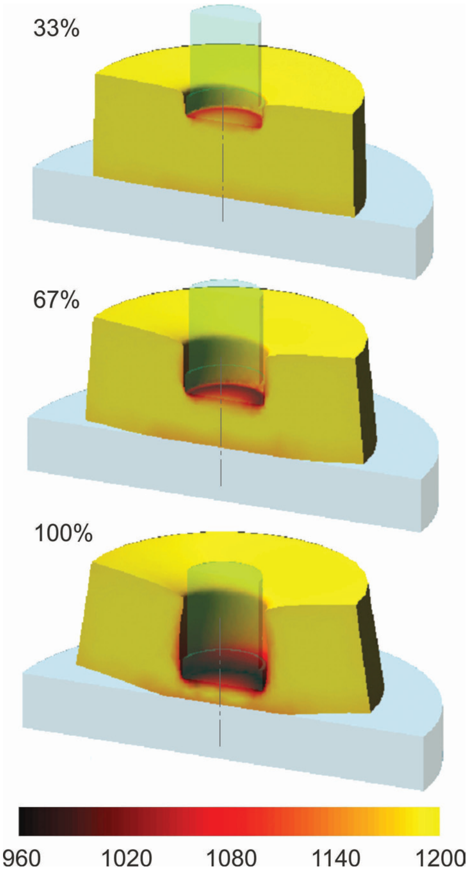


Figure 1.27. *Piercing of the forging made of C45 steel of Ø1000x400 mm dimensions reheated to temperature 1200°C while the tools are reheated to the temperature 250°C (with temperature distribution in °C presented) using the solid shear punch of the diameter Ø300 mm; the progress of process is shown in percentage*

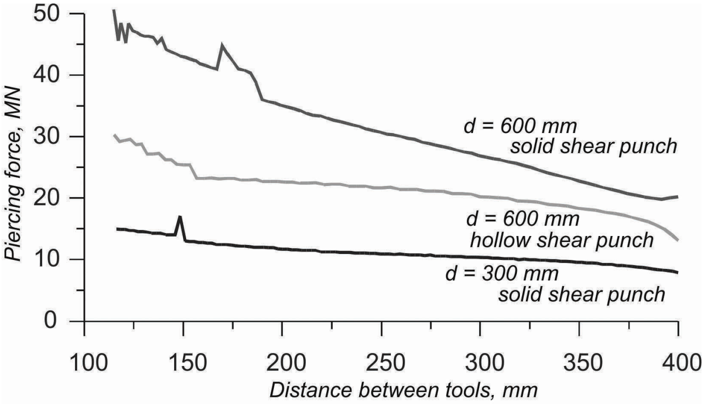


Figure 1.28. *Comparison of forces (computed using FEM) in the process of piercing hole of diameter d in the billet made of C45 steel of initial dimensions Ø1000x400 mm, reheated to the temperature 1200°C while the tools reheated to the temperature 250°C*

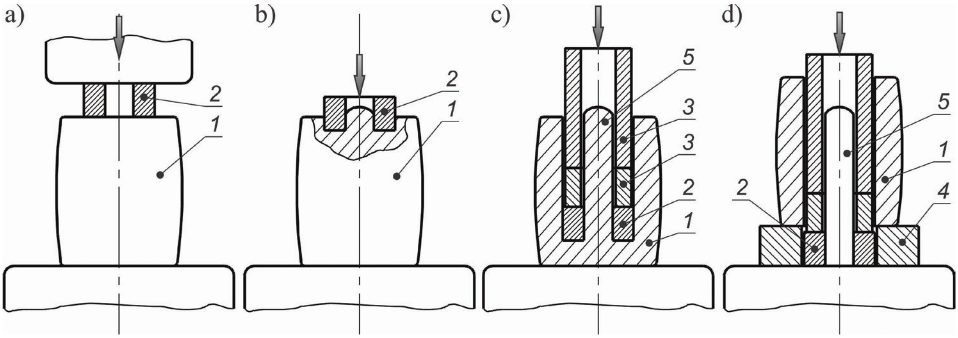


Figure 1.29. *Piercing of billet using hollow shear punch, where: 1 – billet (forging), 2 – hollow shear punch, 3 – hollow swage, 4 – ring, 5 – discard [31, 32]*

However, disadvantages of this method are difficulties occurring while taking off the shear punch taken out from cut-out core and lot of material defects.

After the piercing process, it is necessary to forge hollow forging on the mandrel or finish their external shape. In order to achieve accurate dimensions and regular shapes of forgings with holes piercing can be performed in additional right in the way shown on the Fig. 1.31. It should be emphasized that satisfactory process of piercing in the ring depends on proper choice of the clearance value between the billet and the ring (it can be chosen, for example on the base of numeral simulations results).

Discards resulting in the process of hollow shear punch can be reduced by piercing with a tool of smaller external diameter and additional stretch of pierced hole using barrelled bolt (Fig. 1.32). Using this method while batch production of rings results in big material savings.

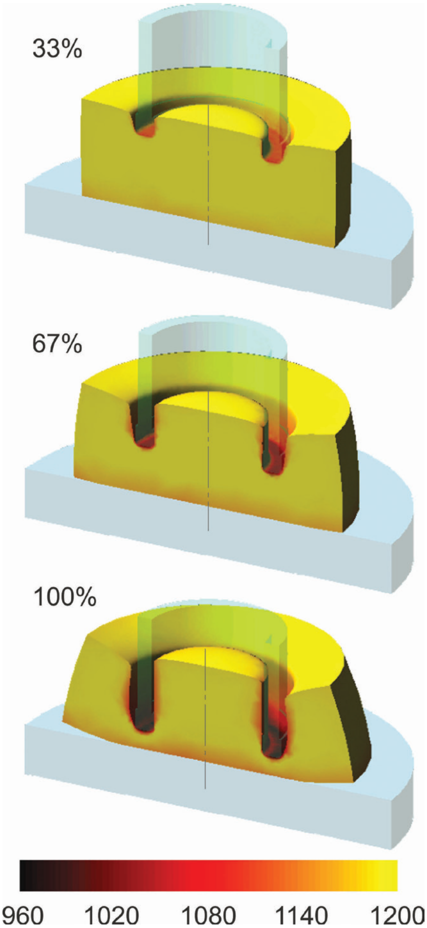


Figure 1.30. *Piercing of the forging made of C45 steel of Ø1000x400 mm dimension, reheating to temperature 1200°C while the tools are reheated to temperature 250°C (with temperature distribution in °C presented) on using hollowed shear punch of the external diameter Ø600 mm; the progress of process is shown in percentage*

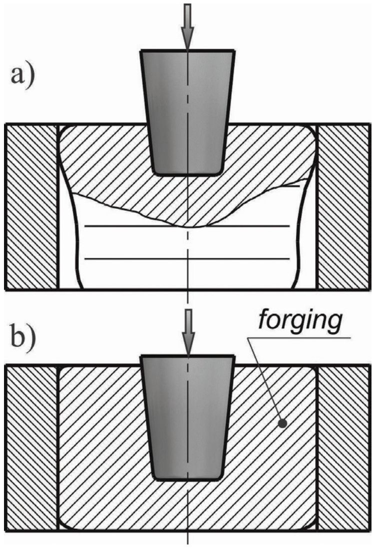


Figure 1.31. *Hobbing (piercing) process using the thrust ring: a) initial stage, b) end of process [16]*

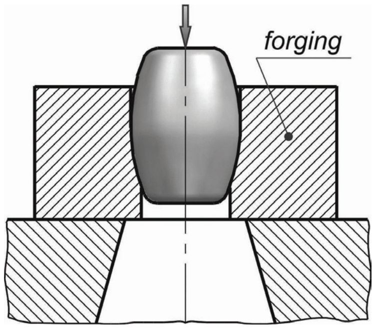


Figure 1.32. *Expanding and planishing of a hole using barrelled bolt [16]*

1.2.4. Bending

Bending is a forging process resulting in appropriate shaping of forgings without changing basic cross-sections. This operation is used for forging hooks, levers, various angle plates, crankshafts, etc.

In the place of bending, external layers of material are extended and internal are compressed which leads to deformation of cross section. As an effect, extended part is contracted and broadened [23]. Moreover, bended intersection is the weakest intersection of forging. In order to avoid this disadvantage, it is necessary to make preliminary thickening of intersection in the bending area and it should be large enough, so there is extra material for final finishing and smoothing of this part of the forging. Thickening is not performed when the bend radius is large and bend angle is small.

Bending is made on short segments. Wherein, the bars have to be bent down very close to bending place and in the case of thin flat bars and rods from mild steel bending process can be cold-applied.

On the Fig. 1.33 some of the ways of bending are shown. In the case of bending objects of light-gauge they can be clenched between anvils and bended by blacksmith's hammer strokes (Fig. 1.33a). Products of bigger intersections can be bent using forge plant crane (image 1.33b). However, during bending products of smaller dimensions sets of appropriately made top and bottom swages (Fig. 1.33c) or dies (Fig. 1.33d).

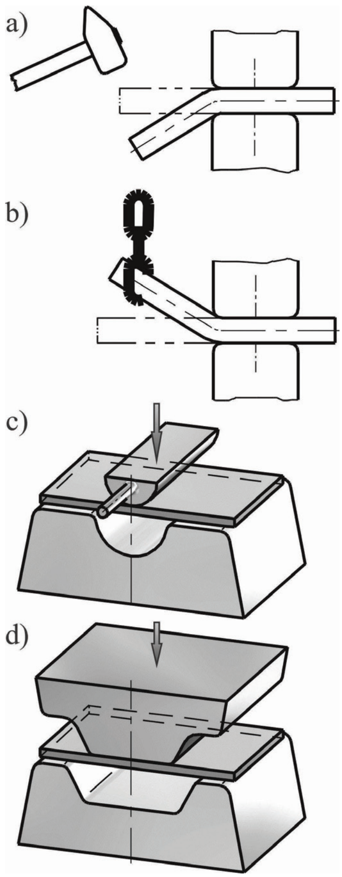


Figure 1.33. *The bending process: a) using a blacksmith's hammer, b) using a crane, c) using a swage, d) by dies [31, 32]*

1.2.5. Cutting

Cutting is a forge process, during which the following operations are made:

- parting workpiece into separate parts;
- cutting of the forged part out of the workpiece;
- complex shaped forgings, where is required for example cutting off the core, cutting off the edges, partition, etc.;
- removal of excessive material or technological discards (e.g. during forging of ingot, cutting off discard from the feet and head side).

Cutting process is realised using a special tool named sett (or sometimes a sate, chisel). Four main methods of cutting can be distinguished:

- One-sided cutting (Fig. 1.34a). The sett is put on the forging and gently pressed into the material. Next, powdered coal is poured into the pit, the sett is put on again and drive again to a required depth. Then, the sett is removed, forging is rotated by 180°, put a pad on top of incised place which as the effect of the press of upper anvil will ultimately split the forging into two parts. Using this way of cutting the result is a discard in the form of a short filler block of the same width as the sett but sheared edges are clean and without burrs.

- Two-sided cutting (Fig. 1.34b) where forging is parted on two opposite sides to the half of the thickness using sett not higher than ¾ cut material thickness. This way of cutting results in creating big burrs and is used only when the separated portion of material is a discard.
- Three-sided cutting (Fig. 1.34c) is performed in shaped anvils. In this method, the first two cuts are made using normal setts and the third using sett with a blade a bit shorter than the diameter of cut bar. This cut method is used in the case of cutting workpiece of circular cross-section.
- Four-sided cutting (Fig. 1.34d) in which forging is incised from four sides in depth approximate to the half of the material thickness. Next, sett is turned around and its greater width splits the forging into two parts. This method mainly used for cutting heavy forgings, (manufactured directly from ingots) allows to avoid creating burrs.

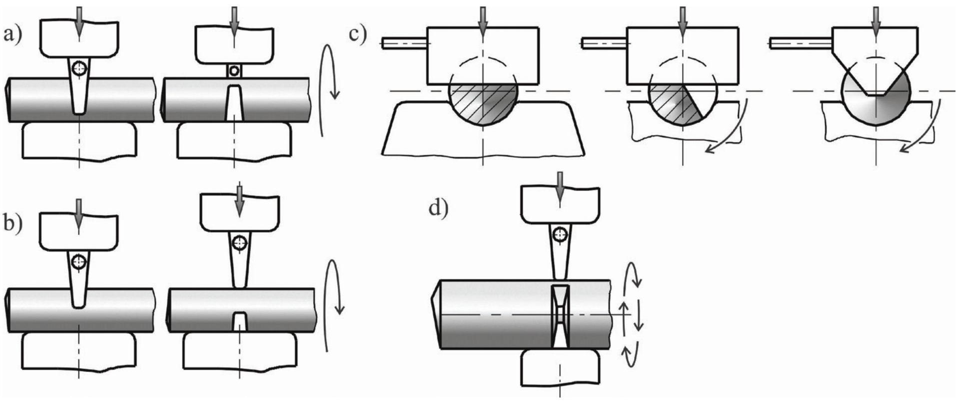


Figure 1.34. *Cutting process: a) one-sieded, b) two-sided, c) three-sided, d) four-sided [31]*

On the subsequent Fig. 1.35 several ways of cutting are shown, such as: shaped cropping (cutting off) of the end of levers (Fig. 1.35a), parting, and drawing aside with preceding the piercing of hole (Fig. 1.35b) and blanking allowance of material (Fig. 1.35c) while forging crankshaft. Cutting operation is also used for shearing local discards, especially while reforging forgings made of tool steel and high-speed steel.

1.2.6. Twisting

Twisting is a forging process, during which one part of forging is twisted in relation to the second one by a certain angle. It is used during manufacturing complex-shaped forgings e.g. crankshafts (with cranks lying in different planes), twist drills, etc.

Twisting is when one of the steps of forging is fixedly attached between anvils, while the second one is twisted using handwheel or lever (Fig. 1.36). During twisting in forging unfavourable stresses state occurs, close to pure shear stress. In the case of low ductility steel or improper reheating, it can result even in crack of the forging.

Process of forging can be performed up to a certain, maximal angle of twist, which for example for forgings made of carbon steel (carbon content 0.3÷0.4%) is 36°. When it is necessary to twist by a greater degree, it has to be performed step by step and preheating forging every next operation. Twisted surfaces should be smooth and free from cracks and laps. Cross-section of the twisted forging should be constant at the whole length.

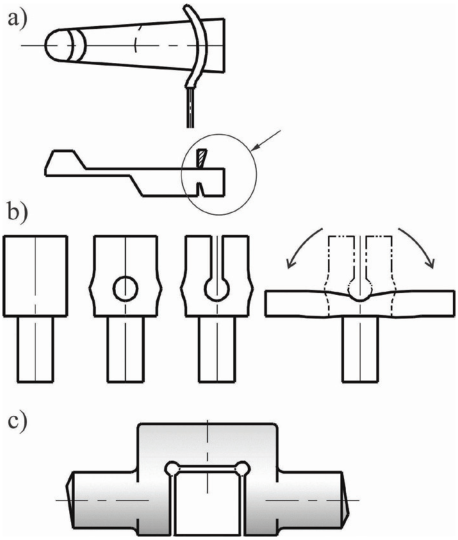


Figure 1.35. *Different ways of cutting process: a) cutting off, b) parting with piercing and drawing aside, c) blanking allowance [16]*

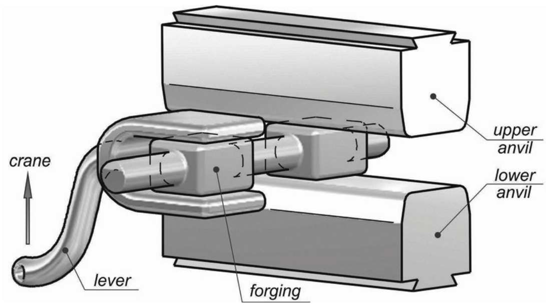


Figure 1.36. *Tipical example of the process of twisting a forging*

1.2.7. Welding

Welding (forge welding) is a forging process of connecting two pieces of metal preheated to suitable temperature (sometimes named weld temperature). Nowadays, this method is rarely used because of popularization of else processes, for example the welding, electrical recistance welding or the friction welding. The most common ways of forge welding are shown on the Fig. 1.37. Those are:

- Lap welding (Fig. 1.37a). Ends of the welded parts are upset and criss-crossed. Next, they are preheated to adequate temperature, cleaned from scale, put one on part on the top of the second and forge welded by quick stroks. In this way, bars of diameter up to 100 mm can be forge welded.
- Split welding (Fig. 1.37b). One of the ends of the bar after preheating and upsetting is notched along its axis and the ends are cut off. The end of the second bar is tagged. After cleaning both join sides from scales, they are placed together and the joining place is reforged using shaped dies. This method of forge welding gives better results than lap welding and is used for forge welding bars of big cross-sections or made of various steel grades.
- Butt welding (Fig. 1.37c). This method is worse that the two above mentioned and it is used only when because of the closely placed jag criss-crossing or cutting out and beveling the ends of bar is not possible. In this method, ends of the bars are preheated, cleaned from scale put together and welded by stroking in axial direction. Next, welded place (thickened) is reforged and smoothed to the bar dimension.

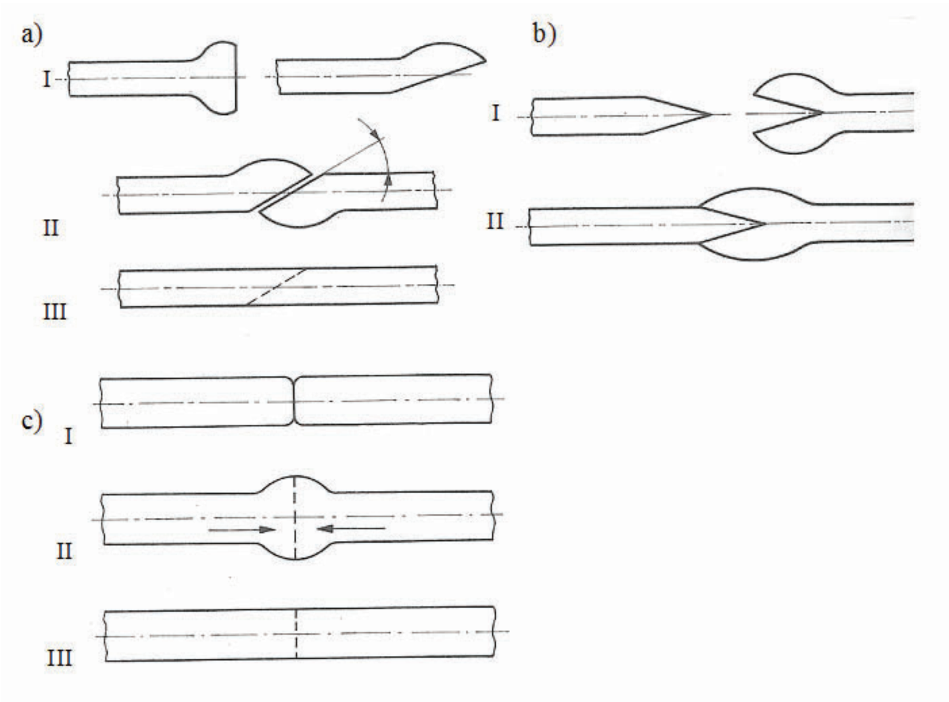


Figure 1.37. *Methods of forge welding: a) lap weld, b) split weld, c) butt weld; where: I – preparation of bar ends, II – setting bar ends towards each other, III – after wilding (finish part) [31, 32]*

1.3. Defects of open-die forgings

The defects of open-die forgings may be a result of material defects (occurring during metallurgical process or during reheating) or effects of forging process. The former ones may appear during forging process, heat treatment or finishing operations. Defects in the context of material workability means the properties of a forging that don't confirm to the design specifications, which make the forging unsuitable for the purpose for which it has been designed. The workability means the ability of a material to deform without the occurrence of any defect in a forging process. While the formability means the ability of a material to deform plastically without fracture in a forging process. The else notion is existed, which are related with defects. It is the ductility, which means the ability to deform plastically without fracture, however in standard test, and are expressed by some measure of limiting strain.

Below there is a list of the most significant open-die forging defects. Those are:

- Dents – single cavities of different sizes and shapes occurring on the surface of the forgings. The most common cause of such defects is a scale pressed into the material.

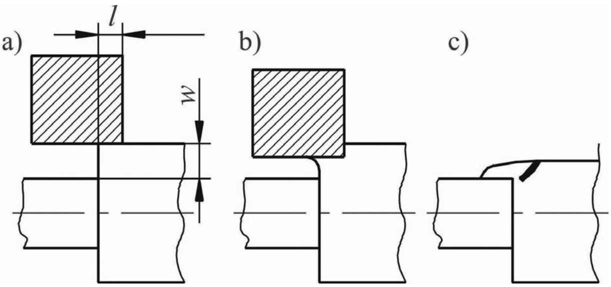


Figure 1.38. *Occuring of laps during progressive forging when l < w wherea), b) and c) are the following stages [16]*

- Laps (folds) being an effect of too high pressure used during elongating. One of the possible ways of appearing of this defect is shown on Fig. 1.38.
- Distort being mechanical damages of the forgings caused by a hammer or a press used when the forging was situated improperly.
- Wrong dimensions (discrepancy) being an effect of exceeding allowed deviations (i.e. because of the wear anvils).
- Poor grain flows pattern, which is a defect occurring when the technical conditions provide the continuity of grain

Figure 1.39. *Internal cracks called the forging cross in a bar from high-speed steel [16]*

flow and their parallelism to the forging's surface, but because of the forging process performed poorly the grain flows are cut or significantly deflected from the forging's surface.

- External surface or shear cracks and internal cracks, occurring in forgings during the process of forging and are often caused by: cracks in initial material, low temperature of forging from alloy steels or by too sudden chilling of the forgings.
- The forging cross are cracks inside the material forming a cross shape (Fig. 1.39). The cause may be wrong forging temperature, forging square bar into a round one or usage of wrong anvils. This defect occurs as a result of alternate tensile and negative stresses (being a consequence of turning the forging during progressive forging) leading to low cycle fatigue of plastic material.

2. Closed-die forging

Closed-die forging is a method of the bulk shaping of hot, warm or rarely cold material completely within the wall cavity of dies under pressure of press ram or by impact of hummer tup. The material of workpiece fills the die's cavity and adopts it. Cavity of die is developed to prevent the free flow of a material. The final product is called a die forging or sometimes a final part.

Closed-die forging is one of the most popular and common technologies of producing applied in the industry. The production of forge plants in member states of the European Union at the turn of 19th and 20th century was around 1.5÷2.0 mln tons of die forgings between the weight of 0.05 kg to ca. 60 kg. Only in Poland the production od die forgings comes from a dozen or so large forging plants that supply also the foreign market and from a several dozens of smaller plants where forging is not their only activity. It is so, because the mass production om metal objects where the die forging is a part of production process is the one to pay off the most (excluding the issue of final product's improvement). Above all it concerns the aircraft, automotive and agricultural industry as well as heavy, machine and arms industry. The Poland's biggest forging plants are affiliated with Polish Forging Association with its main headquarters in Cracow.

The basic classification of closed-die forging is a division on grounds of machine with which the process is carried out. Is distinguished closed-die forging processes with usage of [4, 10, 19, 23, 26-28, 31, 32]:

- drop forging hammers where metal is being squashed by stroking it (once or multiple times), deformation is made dynamically and the deformation energy comes from the transferred energy of the impact;
- forging presses (crank, screw and hydraulic ones) – metal is squashed under the pressure made by the tool and it deforms statically (that's why the main parameter of presses is the power of press ram);
- forge rolling machines;
- special machines, i.e.: screw press, three-slide forging press, orbital forging press or by using special devices (for example the Tadeusz Rut's upsetting device).

In further part of this chapter will be discussed the technique of die forging applied for hammers and forging presses.

2.1. Description of forging process

The closed-die forging process is a complex technology consisting of many operations and stages. The most important ones are: cutting of bar stock, reheating the initial material (when it's necessary; possibly also heat treatment in case of cold forging), operation of forging (shaping of preform and next forging with many machines or one operation of multi-stage forging on one machine), finishing operations (i.e. trimming of flash, cutting out the bottom, punching holes etc.), heat treatment of the forging (i.e. normalizing), operating of forging cleaning (by shot blasting or sand-blast cleaning in order to remove the scale) and finishing operations (calibration, straightening or burnishing). A part of the technological process are also quality tests (inspection) of initial materials, forging right after heat treatment as well as final product.

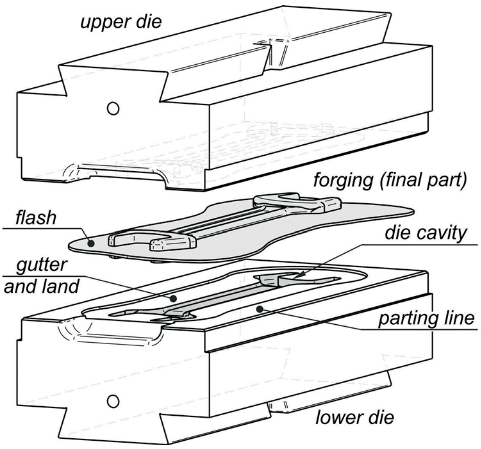


Figure 2.1. *Visualization of dies set (single-cavity type for drop forging process) together with final part (forging) and flash*

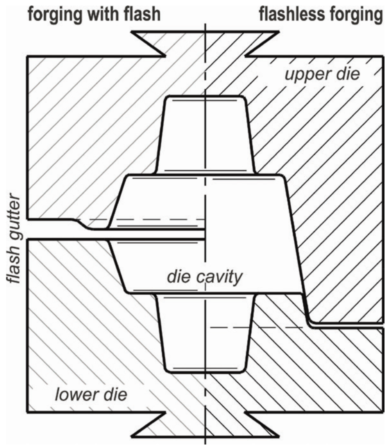


Figure 2.2. *Difference between opened-type dies (left side of figure) and closed-type dies (right side of figure) used in closed-die forging with flash and flashless forging process respectively*

Forging operation is performed on forging machine (with hammer or on press) using tools called dies. The dies contain cavity, in which the material is formed and they have a parting line (Fig. 2.1). Depending on the design of the die forging process is distinguished by the die structure (Fig. 2.2):

- closed-type dies for the flashless forging process – characteristic for that type of forging is that the volume of the forging equals the volume of the empty cavity;

- opened-type dies for the closed-die forging with flash – in the parting line of the dies here, there is a gap for the flash, that is for the excess of the material flowing out of the cavity in the final stage (finishing) of the forging process.

However, depending on the amount of cavities, is distinguished the following types of dies:

- single-cavity dies (i.e. shown in Fig. 2.1);
- multi-cavity dies (Fig. 2.3) – where the shaping of workpiece performed in each separate cavity is called a stage of forging process.

It can also be classified dies due to the methods of making their cavities therein. Up to this division, is distinguished the following dies:

- uniform – the whole die, including cavities, fixing and steering elements (e.g. dovetail, locks), is made from a single block (e.i. square bloom) of material (hot-work tool steel); this method is preferred in the case of hammer forging;
- assembled – cavities are made as inserts, which are installed in the block of the die (made of a cast steel) or in special die holders; this method of tools making is most frequently used for various forging press machines;
- divided – the die inserts are two congruent parts that connect during forging process (on press machine), however, at the end of the process they draw apart in order to make removal of the final part easier; such solution is used when the shape of forging is more complex which requires more than one parting line (plane) of the die.

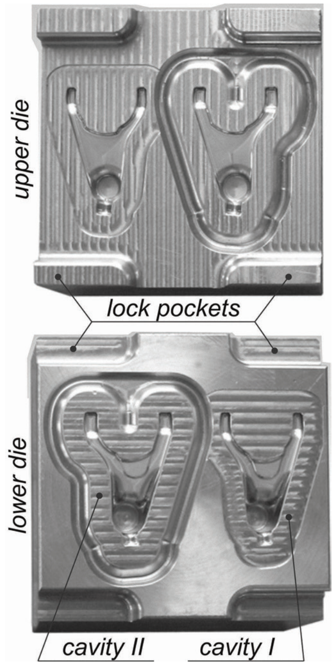


Figure 2.3. *Photography showing a set of multi-cavity dies for hot closed-die forging [13]*

Kinematics of metal flow

A way of material's flow during its deformation by die forging depends on both the shape and dimensions of the cavity as well as the shape and dimensions of the workpiece (initial billet). Assuming that the initial billet is a bar of a predetermined diameter and height, then depending on the ratio of those dimensions to the characteristic dimensions describing the die cavity, the flow of the workpiece material will vary. Therefore we can distinguish four ways of die cavity filling with material, namely the forging by:

- upsetting (Fig. 2.4a) – this is the simplest pattern of metal flow and it occurs when the diameter of the worpiece is smaller than the diameter of the pocket in the die cavity (when the final part has a boss); such that flow of the material is especially desirable when forging process is realised on a press; during the selection of the initial billet one should always strive to perform the process of forging according to this method;
- extrusion (Fig. 2.4b), when the diameter of the worpiece is bigger than the diameter of the pocket in the die cavity; forging process realised in opened-type dies according to this method, especially in presses always causes excessive outflow of the metal to a gap on a flash;
- upsetting and hobbing (Fig. 2.4c);
- upsetting, hobbing and extrusion (Fig. 2.4d) – the most complex material flow pattern, which usually occurs in real processes (that is when the forging has a very complex shape).

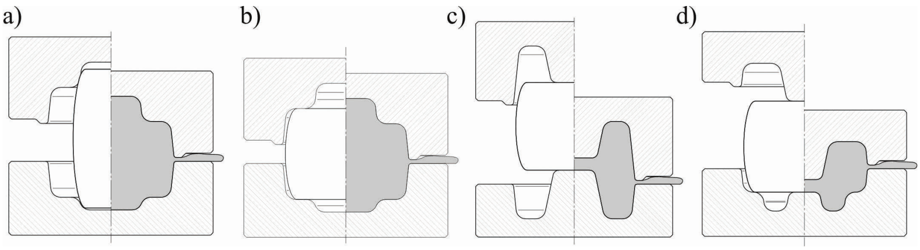


Figure 2.4. *Basic ways of filling the die cavity with material, where left side presents the shape of initial billet and the right one - the forging with flash*

The metal flow is also affected by the movement velocity of the tools. In the case of die forging process using forging hammers, the dynamic nature of die's impact causes the so-called phenomenon of inertia filling of the die cavity (Fig. 2.5). Additional inertial force occurring, which sense is oriented opposite to the velocity of the tool causes the difference between the height of h_1 and h_2 bosses in the final part (Fig. 2.5). During the forging process with forging hammers, the condition that $h_1 > h_2$ has to be fulfilled, whereas the boss of forging h_1 is in a moving die. However, when forging process with presses, due to the static nature of the movement of tools, these heights are equal. In summary, when hammer forging, high bosses of the forging has to always be placed in the upper die (the moving one). In order to achieve such character of forming, the Guang's empirical condition (2.1) has to be fulfilled, which in the case of forging by hammers is always fulfilled [25]:

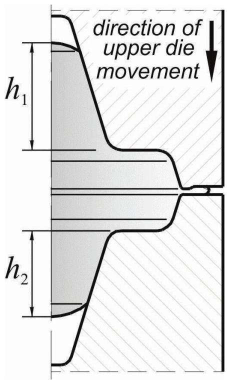


Figure 2.5. *Effect of the inertial filling of die cavity phenomenon during the hummer forging process*

$$v \geq 0.082 \cdot \sqrt{\sigma_p / \rho} \tag{2.1}$$

where: v – critical velocity (only when the forming velocity is greater than v is inertial filling evident), σ_p – material flow stress, ρ – density of the material.

Filling die cavity with material during closed-die forging process divides into steps. In the case of forging process in the opened-type dies (Fig. 2.6), this process can be divided into four main steps. The first step (Fig. 2.6a) begins when the upper die touches the metal – the process of (in most cases) free upsetting of initial material. Metal reduces its height under the influence of strokes of the upper die and increases its outer diameter, assuming a convex shape. The appearance of such a shape proves that metal deforms unevenly and the cause is the friction between the material and the walls of the cavity – typical distribution of effective strain in the cross-section of the workpiece is shown in Fig. 2.6. It clearly shows that there are several characteristic areas of different draught ratio and strain state in metal. Metal sticking to the wall of the die cavity hardly deforms permanently and it moves together with the tools (those are so called dead metal zones). However, the central area of the workpiece is thoroughly compressed, and its plastic strain is the greatest.

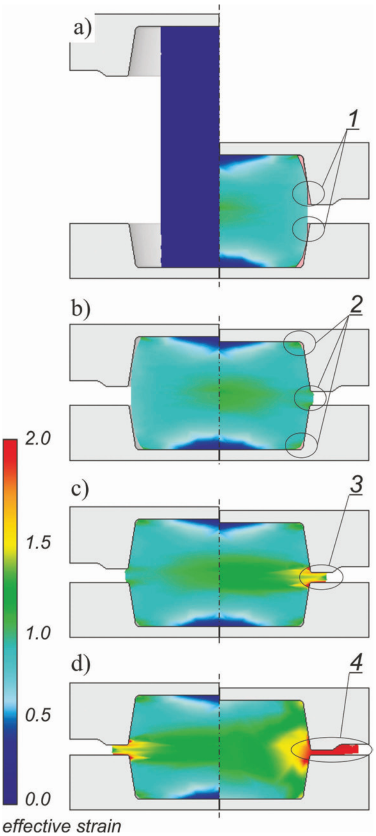


Figure 2.6. *Steps of filling a die cavity with material and distribution of effective strain in cross-section of the workpiece*

The second step of filling the die cavity starts when the material connects with the side walls of the cavities (detail 1 on Fig. 2.6a). In this phase, the metal continues to be upset and under the pressure of the tools it flows on sides causing the filling of the cavity profile. This step ends with the moment when the excess metal starts to flow between the dies. At the end of this step, the cavity is almost filled by the metal, with the exception of corners and edges (detail 2 on Fig. 2.6b). In this phase, a slight increase in forming force occurs, which is caused by the increase of the friction forces occurring on the side walls of the die cavity.

In the next step, the excess of the material flows out of the cavity forming a ring in the form of the flash (detail 3 on Fig. 2.6c). This excess causes the increase of resistance in the flow outside the cavity (by reducing the workability of the flash and appearance of friction forces on the contact surface between the material and the land), and as a result – makes the material to fill the empty space in the corners of the die cavity. This is an important role of the land in die forging.

Last, the fourth step of closed-die forging process (Fig. 2.6d) is particularly important during the implementation of hammering process. To receive a final product with desired dimensions (and precision), one should perform a few additional impacts of the upper die. This causes the excess of the material is pushed into the gutter (through the land), unfortunately, at the expense of rapid growth of forming force. A feature of this step is highly heterogeneous ratio of material's deformations, where the largest over forging is in the area of the land.

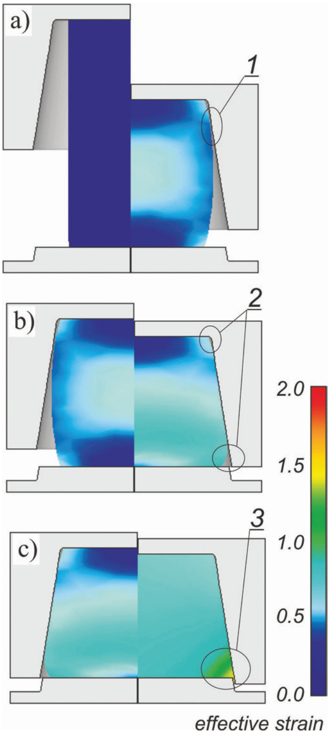


Figure 2.7. *Steps of filling a die cavity with material during flashless forging process and distribution of effective strain in cross-section of the workpiece, which should be compared with distribution presented on Fig. 2.6.*

During flashless forging process (Fig. 2.7), the filling the die cavity consists of three steps. The first two are very similar to the steps observed in the forging in opened-type dies (Fig. 2.6). The second step begins from the connection of material with the side walls of cavity (detail 1 on Fig. 2.7a), and ends when the cavity profile is almost full – only corners are left unfilled labeled as detail 2 on Fig. 2.7b.

In the last third step of the material fills all the free corners (in particular the area marked on Fig. 2.7c as detail 3), and the worpiece becomes its final height. At the same time, the resulting ratio of metal draught is almost identical in the whole volume of the forging. It is crucial to choose the correct volume of the initial billet, as its deficiency can cause not full filling of the cavity, while its excess can lead to tool stick (metal tries to flow into the gap between the dies – a detail 3 on Fig. 2.7c).

Comparing the forging process' steps in both opened-type and closed-type die forging shown in Fig. 2.6 and Fig. 2.7, it can point out the fundamental difference between these two methods of shaping a forging. Namely, the close-die forging process includes an excess material on both the flash has and on scale (when the process is hot shaping). Whereas in closed-type dies (i.e. flashless forging processd) there is no excess on flash, what increases the material yield of about 10 to 30% and reduces forging's weight of 2 to 5%. Eliminating the need of trimming the flash cause the advantage of flashless forging process, namely, shorter production cycle.

In conclusion, the advantages of the flashless forging process in comparison to closed-die forging process with flash are:

- no loss of material on the flash;
- preferred grain flaw pattern and thus better mechanical properties of the final product;
- useful machine energy is converted only into plastic deformation of a while in opened-type dies it's also converted into flash forming

Unfortunately, flashless forging process also has disadvantages (of course in relation to the process carried out in the open-type dies), i.e.:

- low safe live of the dies;
- less universal method – it can only shape forgings having simple shapes which have not any ribs and high bosses;
- the need for accurate cutting of initial billet;
- the need for alignment of initial billet (so called proper setting) in die cavity;
- generally greater forming forces resulting from the triaxle compresion stress state of material.

2.2. Comparison of hammer forging and press forging

During closed-die forging with forging hammers material forming takes place dynamically, which causes, amongst others, previously described phenomenon of inertial filling of die cavity. The material flows more surfactants, and kinematic energy of moving parts of the hammer is only partially converted into a work of deformation – hammers efficiency does not exceed 5%. However, the advantage of these forging machines is their versatility. Taking also the features of forging with flash into account, technological capability of forging hammers are really broad. Unfortunately, the dynamic nature of those machines' work has a negative influence on human health and the environment. An example could be one of the Polish forging plants located in Cieszyn Silesia that, due to the vibration and noise during hammers' work, had to replace the stock of machines with forging presses.

However, in the case of forging process on crank presses, the workpiece deforming is realized by implementing the continuous and (relatively) slow pressure of the press ram. The occurring pressure causes deformation of the material in the whole volume of the workpiece and, at the same time, more intensive flow of metal to the sides. The advantages of crank presses are:

- quiet, vibration-free work of the machine;
- high accuracy of press ram course;
- the rigidity of the press frame and guidance parts;

- the fact that machine has a lower and upper press knock-out (the dies may have the ejectors).

These advantages allow to make forgings of high dimensional accuracy with small draft angles and small machining allowances. Nevertheless, compared with drop forging hammers, the crank presses have the following disadvantages:

- smaller versatility;
- increased cost of forging process, especially of small series;
- a high difficulty level of tools settings and time-consuming preparation of the machine for running;
- inaccurate dies setting can cause overload, jamming or damage of the tools or a machine;
- forging of worpieces requiring high pressures reduces the press life, finally lead to the regeneration of press;
- before forging in the finishing die cavity the workpiece must be free of scale.

During closed-die forging in screw presses the energy of the transmision system (i.e. friction wheel, flywheel, male screw and slide) is converted into effective work by means of a not to be self-made locking screw mechanism (i.e. male and female screws). Such construction of the screw press ensures that the machine is capable of storing large amounts of rotational kinetic energy of the flywheel, and during the forging process, this energy is converted into deformation work (like in a hammer during a impact) and pressure (like in a crank press). This enables the shaping of workpieces that require:

- application of energy-consuming forging operations, in which the plastic deformation of workpiece is large, but the pressure of one is low;
- or the application of very high pressure at low energy-consuming process, because the plastic deformation of workpiece is small (e.g. a forging of turbine blade).

For screw presses distinguishes three values of the pressure that can be exerted on the workpiece during the movement of the press slide. It is the:

- nominal pressure – value characteristic for screw presses (determines their capacity) that is taken under consideration during designing of the forging process; with that pressure 80 to 85% of the energy is converted into effective plastic deformation of the workpiece;
- allowable pressure – is 1.6 of nominal capacity, but at which only 45÷50% of effective energy is used for plastic deformation of the workpiece;
- maximum pressure – the highest pressure value that can be obtained by press when there is a hard impact (i.e. upper die touches lower die), during which plastic deformation of workpiece equals zero; for screw presses equipped with a slipping device (or any electronic torque limiter, which is used to discharge excess energy from overload) the maximum pressure value is two times higher than nominal, and without a slipping device – 2.8 times greater.

An important feature of screw forging presses is the lack of kinematic limits for the slide. This means that the forging process can be carried out until dies touch each other. As a result, the dimensions accuracy of final parts at height is the largest among all the methods of forging. When the impact energy of the die is too small for the dies to connect, an slide impact is being repeated. This possibility eliminates the defect of an incomplete forging (i.e. is not any unfilled section of die cavity, where would be not completely filled by the flowing material).

Screw presses are suitable for forging in both opened-type and closed-type dies. The setting of the dies is very simple and easy operation, for there is no need to adjust the height of the closed dies. This is due to lack of a precise alignment of the slide at its bottom position.

The biggest advantage of screw presses is the linear velocity of the slide, where the highest value of 0.6÷1.5 m/s is reached in the moment of two dies connection (that is in the final forging step). This is the optimal value when forge different types of steel and non-ferrous alloys under hot condition. The impact of such a speed causes 5÷10 times smaller stress in the dies than during the forge with hammers. The main disadvantages of screw presses are:

- inability to perform preliminary operations (i.e. preshaped a preform), which have to be realised on other machines (hydraulic presses etc.);
- hammer effect (vertical and torsional) to the machine foundation;
- the need for resetting in the control system during continuous running of machine;
- substantial angular (torsion) strain of the press frame during the main stroke of slide.

2.3. Forgings

The overall classification of forgings

The idea of forgings (final parts) classification into groups is based on the need for both the operating procedure during the designing of the technological process, as well as the implementation of forgings by method that will guarantee the most optimal conditions (e.g. economic ones). Forgings shown in Fig. 2.8 can be grouped into three basic groups in respect to their shape and orientation of impact direction. Therefore, we distinguish the following forgings:

- frontal forgings, which have the shape of a solid of revolution with a circular, polygonal or cross projection – this group include forgings having pins or full flange, forging full blade type, forging with a through hole, ring-shaped forgings, the sleeve-type hollow forgings and shank forgings; forging of this type are made by upsetting in the direction of the vertical (main) axis of the workpiece, which is usually in the form of a slug of the bar;

- longitudinal forgings, which have length greater than the cross dimensions – this group of products includes straight, bent and branched forgings; forging of this group are forged in the direction of the perpendicularly to the axis of the workpiece, often being the same as the main axis of the product. The billet is either a bar (rarely) or a preform (more often), which is made is multi--cavity dies during one operation (hammer forging) or on a separate machine during a separate operation (e.g. by press forging);
- combined forgings – typically with a complex shape that requires forging in at least two orientations, mainly in the direction of the main axis and in a direction crosswise to the axis; such forging process is usually multi-operational, where each operation is realised on a separate forging machine.

Figure 2.8. *Typical die forgings, made in Polish forging plant*

In general, each forging can be manufactured by at least two alternative methods, whilst there is always a favored method associated with characteristics of forging equipment. The choice of the method of usually depends on the base of a forge plant (i.e. owned machines). For example, a frontal forging with a boss, flange or hub may be forged by process of:

- a closed-die forging with crank presses or with hammers;
- an upset forging from the bar directly on the horizontal forging press;
- an upset forging on the orbital forging presses (at low heights the parts have thin discs).

Next, the frontal forging with a shank can be forged by:

- upsetting and shaping in crank, screw or horizontal presses;
- extruding a shank on crank or hydraulic presses;
- swaging a shank on swaging machine;
- upsetting with the electric upsetters.

Whereas, the frontal hollow forgings like sleeves or gears can be shaped way:

- forging on crank or hydraulic presses with hollow (bottom) which is cut-out during flash trimming;
- upsetting and shaping from the bar on the horizontal forging presses (when small holes) with a through hole;

- deforming with a preform or hollow preform on orbital forging presses (when height of final product is relatively small).

The longitudinal forgings, both straight and curved having forks or different extension elements, are usually forged with a preform with the following methods:

- one-operational hammer forging in multi-cavity die, where both preform and forging are shaped by the same die;
- making a forging on crank presses with a preform, which made priorly in a separate operation, using a different forging machine (e.g. as shown on Fig. 2.9).

Figure 2.9. *Example of made of two forgings (dual system) by the method of multi-cavity die forging with hammer from preform made by the cross-wedge rolling method*

Forgings classification into classes in depended on the forging machine

Typical classification of die forgings is closely related to their destiny to be made in a specific forging machine. This division is also based on the stroke direction of movable die and on the shape of the forgings, but often also other things important for certain forging method are taken into consideration. This causes that the parent form class of forgings are divided into form groups, or even subgroups (as it is done for example in the case of hammer forging). The aim of expanding the division system was to introduce maximum simplification of the process of technological development and construction of the equipment. In summary, any kind of forging is assigned a specific procedure, which consists essentially of well-known elementary schemes.

The forgings made with hammers are divided into three main form classes from which further division into three form groups proceeds, namely:

- form class I – they are longitudinal forgings, which are subdivided into four form groups, namely: forgings with a straight long axis (e.g. shafts, connecting-rods, ribbed or flat with complex cross-sections), with long axis curved in one plane or more then one plane (the parting line of dies being planer or curved), forgings having extending elements (straight axis or curved) or forks (open or closed ones of varying shape and size) – a total of the form class is distinguished by 12 different variants of forgings;
- form class II – are frontal forgings solid-type with a boss, flange or hub, which have a round (form group A), square or similar contour in their par-

ting line (form group B) or the forgings are a type of ring-and-trunnion cross (form group C); the latter group forging must have the highest volume of concentrated small material in conjunction central portion of the round or square shape;
- form class III – this class include forgings, whose shapes and dimensions occupy intermediate position between class I and class II (so called form group A), which consist of elements belonging to one of the two preceding classes (form group B) or are combined forgings (form group C).

The drop forgings forged on crank presses are divided into four classes:
- form class I – frontal forgings with round or similar to the round contour in a parting line;
- form class II – forgings are longitudinal, having a straight major axis; depending on the differences in cross-sections, forgings are made in directly from the stuck of bar or from a preform made of prior on another forging machine;
- form class III – forgings are longitudinal, having a major axis curved;
- form class IV – frontal forgings, usually with shank, forged by the forward or backward extrusion, which have a barrel on the end – those are i.e. engine valves, forgings of steering knuckle type, forgings with through holes or with unilateral cavities; forgings of this class is made in a opened-type die with one or two parting lines.

The forgings forged on screw presses are divided into three classes:
- form class I – small longitudinal forgings, with the main axis straight or curved, which may include extending elements and forks;
- form class II – are small, having an average size frontal forgings being: engine valves, bolts, screws, cups and bowls;
- form class III – are small forgings with common features or an intermediate shape between the previous classes and forgings of complex shapes, thus determining the use of two or more parting lines, for example forgings being globe valve bodies.

The forgings forged on hydraulic presses are divided into four classes:
- form class I – sleeve-type forgings, cylinders, caps and shells that require shaping by piercing and drawing;
- form class II – forgings of an longitudinal shape, constant or variable cross--section, which are shaped by extrusion – for example: tubes, rods and profiles; within this classes, two subgroups can be distinguished, i.e.: forgings forged of metal with a low melting point (e.g. copper, aluminum, zinc and alloys of these metals) and a high melting point (e.g. steel, titanium and its alloys, nickel and its alloys);
- form class III – forging having complex shapes, compact structure and relatively large wall thickness, for example: hubs, the wheels of railway vehicles, shafts;

- form class IV – forgings of any shape and size (mainly for aviation industry) made of light non-ferrous alloys, for which slow shaping is recommended and that their hot forging temperature does not exceed 450°C – e.g. aluminum alloys and magnesium alloys.

Defects of the forgings

Forgings defects arise because of poor quality billet but also they are the result of mistakes made during the implementation of the production process (technological errors). The most common defects of the billet are: cracks, flakes, lapping, delamination, non-metallic inclusions and clusters of small cracks (so called snowflakes). However, forging defects, which source is associated with its implementation technology (in addition to forging), are occurring during:

- cutting operations – these are the disadvantages of directly affecting the forging process (like the quality of the material), causing its limits or are the source of new defects that arise during forging – when cutting non-planar surfaces can develop cuts, bevels, burrs, curves rupture of the bar and the rod front cracks;
- reheating the billet – excessive scale, decarbonizing, overheating and burnout at the grain boundaries; this group of defects also has a direct impact on the process of forging;
- finishing – a deformation of the edge, the residual flash after trimming operation;
- heat treatment – a considerable scatter and different hardness at different points in the same forging, hardening cracks, pickling embrittlement.

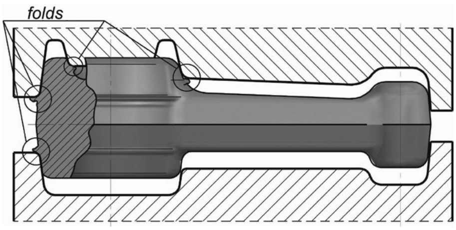


Figure 2.10. *Folds occurring because the previous preforming cavity had an improper shape*

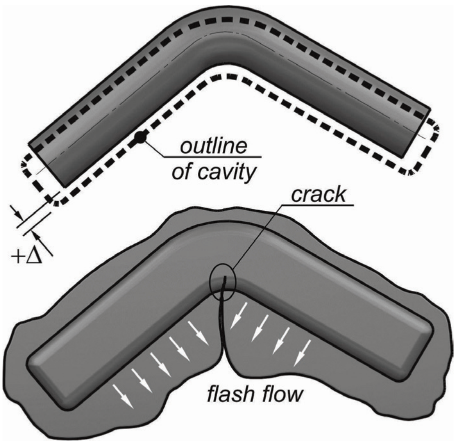


Figure 2.11. *Bad preform setting (a shift of +Δ value relative to an outline of cavity) causes a crack in a forging between two flashes*

The most common important forgings defects that arise during forging, are:

- pits, occurring because of the scale or other foreign matter pressed into the surface of forging;

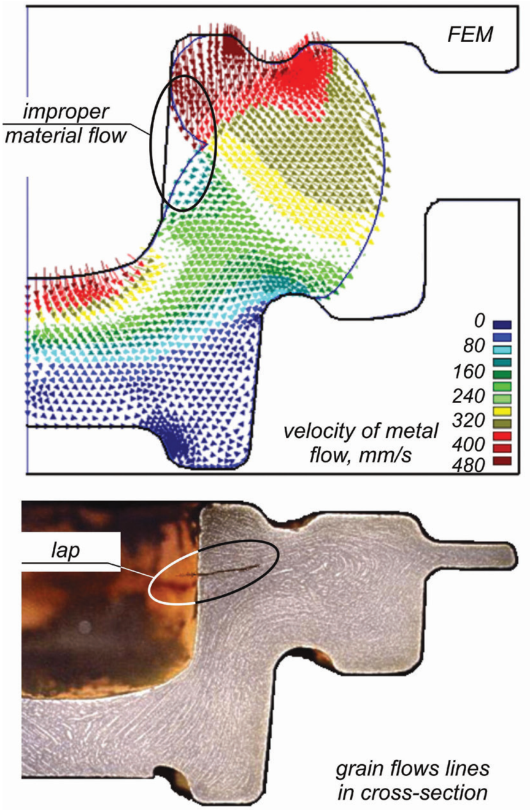


Figure 2.12. *Lap and the scheme of its creation as an effect of improper material flow (incorrectt design of forging process)*

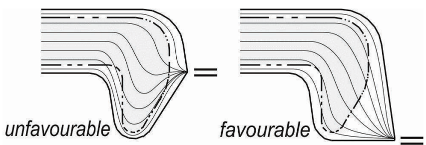


Figure 2.13. *Grain flow lines in the cross-section of forging depending of parting line localisation*

- folds (Fig. 2.10), which are formed when the deformed material flows in the wrong direction, creating a bulge, which in turn is indented in the forging; the cause of this defect is the most common design errors of the previous die cavity (i.e. before finishing stage);
- cracks between two flashes (Fig. 2.11), which are features on folded material at the interface of two flashes flowing in different directions; on the line of contact flashes formed crack, always proceeding in the direction of the surface of forging;
- laps (Fig. 2.12), arising from the improper flow of the material;
- distortion, which are mechanical damages arise forgings and if during the shaping workpiece was outside the die cavity;
- unfilled sections – some section of die cavity is not completely filled by the flowing material; this defect arises due to the low temperature of the workpiece, small volume of initial billet, construction errors of cavity or low energy of hammer blow;
- underfilling (incomplete forging deformation) – all height dimensions of a forging are larger than they should; causes of this defect are: low temperature of workpiece, too few hammer blows or low energy machines; when this defect was appeared it should be re-forge again a forging;
- mismatch, arising from the shift of the die cavities relative to each other in the parting line;
- improper grain flow, which usually is the result of improper shape of the preform and improper installation of the billet in the die cavity; unfavorable

lines of grain flow in the forging; for example in terms of the final part using this defect may also be the result of incorrect forging design (Fig. 2.13);

- forging cross, or cracks inside the material; reason of this defect occurrence is incorrect temperature of forging, improperly method of forging a round bar to a square bar and use the tools with incorrect shape of cavity surface;
- residual flash or trimmed flat – cause of these defects are inaccurate production of the trimming die; the positive (residual flash) and negative (trimmed flat) values permitted are given is standards;
- warping or twisting caused by uneven cooling of forgings; the straightness and flatness tolerances are also given in standards;
- improper dimensions of forging – exceeding the permissible tolerances as a result of wear of die cavity or improper workpiece temperature;
- residual stresses in forging caused by inhomogeneous deformation and improper cooling of forging.

2.4. Initial material for die forging

Die forgings are made of initial material which is usually classified according to its grade and geometrical form. The most popular materials include constructional carbon or alloy steel. A separate group is formed by non-ferrous metals, the most common of which are used for die forgings production are aluminum alloys (mainly in automotive and aviation industry). The group also includes copper alloys (mechanical engineering, construction and food industry), magnesium alloys (aviation industry) as well as titanium alloys (aviation and space industry), the plastic working technique of which differs considerably from the rest of the abovementioned non-ferrous metals.

Depending on the geometric qualities of a particular forging and the shaping method, the initial material might take the form of a basic solid (e.g. a stock of bar, tube, round or square billet or another metallurgical product) or of a complex solid – preform (i.e. semi-finished product). Metallurgical products are very often used in charge material production, especially when the frontal or longitudinal forgings of simple shapes are forged. These can take the form of:

- billets, of cross-section similar to square or flat – produced with normal (ranging between $^{+1.0}/_{-2.0}$ and $^{+3.0}/_{-4.0}$ mm) or increased (between ±1.1 and ±2.8 mm) tolerance and with the dimensions (side of a square dimension) ranging from 42 mm to 140 mm;
- round and square bars (hot-rolled) – produced by a hot-rolling method with the tolerance ranging between $^{+0.2}/_{-0.5}$ and $^{+0.9}/_{-2.5}$ mm and the scope of dimensions amounting to Ø8÷200 mm in the case of round bars and 12÷160 mm in the case of square bars;

- shape bars (hot-rolled section), mainly of flat cross-section (ranging between 15x4 and 400x100mm) or hexagon cross-section (amounting to 19÷100 mm);
- drawn round bars (within the scope of 3÷100 mm and with tolerance ranging from $^{+0.00}/_{-0.08}$ to $^{+0.00}/_{-0.25}$ mm) or peeled bars (mainly steel) – this type of initial material is recommended in the case of precision forging process, where the reheating of the material is local, or in the case of cold forging process;
- seamless tubes – hot-rolled or cold drawn.

In the case of longitudinal or combined forgings which are characteristic of complex shapes, the initial material used during the forging process has the form of an preform. A preform is a solid similar in shape to a forging, especially when it comes to its outline in the die parting line. Particular preform cross-sections correspond to the respective forging cross-sections taking into account the potential flash. There are two types of preforms:

- ideal preform – analytical solid of revolution which is designed to determine the optimal shape of an real preform (i.e. material distribution) and to ensure the proper technological process of die forging – i.e. determine and optimise the number of process stages;
- real (true) preform – true form of the initial material for preshaping steps in the forging process; in the case of hammer forging, it is manufactured in the same die but using the separate cavities called the preshaping dies, whereas in the case of press forging, the preform is manufactured in a separate process with a different forging machine. A preform is always made out of initial material in the form of a basic solid.

Regardless of the form of the initial material, its volume is always determined on the basis of the following relation:

$$V_w = (V_{od} + V_r) \times {}^{100}\!/_{100\text{-}z} \tag{2.2}$$

where: V_{od} – volume of the forging; V_r – volume of the flash. The sum of both these volumes (V_{od} + V_r) can be replaced with the volume of an ideal preform Vip provided that it was designed. The coefficient z in the formula takes into account the loss of material resulting from the forming of oxide scale when the initial material is being reheated. If the reheating process takes place in the forging furnace, the coefficient z is 2.5÷4.0. In the case of electric reheating, it is assumed that z is 0.5÷1.5. If the initial material is expected to be reheated multiple times, each subsequent time requires the value of the coefficient to be increased by 50%. In the case of hammer forging, it is also necessary to provide a tonghold material which allows for the forging to be taken hold of using tongs.

2.5. Methods of shaping preforms

The preform can be made using various methods of plastic working. In the case of hammer forging, both the preform and the forging are forged in a single operation divided into a number of steps, i.e. using a single multi-cavity die which primarily includes preformed cavities (for fullering and edging the preform), blocked and finished cavities (giving the forging its rough and subsequent final shape respectively). An example of shaping the preform in a way presented above, along with the forming of the forging, is presented schematically on Fig. 2.14. The steps 1 and 2 deal with shaping the preform, step 3 allows for the preform main axle to be bent, whereas steps 4 and 5 deal with giving the forging its final shape (die forging product). The last step involves cutting the forging off the bar – on Fig. 2.14 there is presented solely the location of the knife in the block of die.

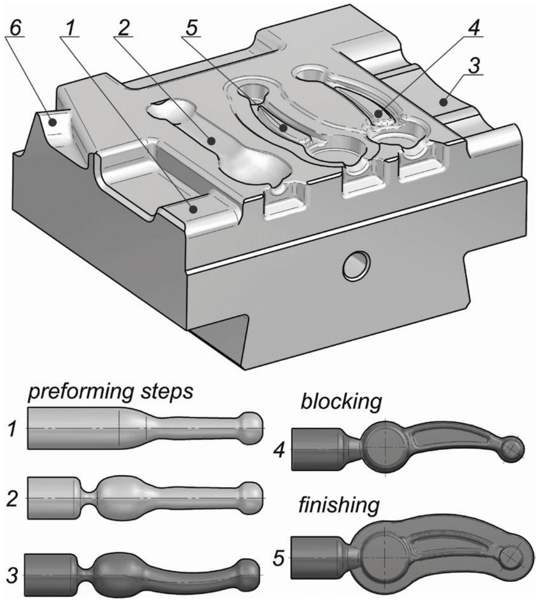


Figure 2.14. *Multi-cavity die for a hammer forging process, where: 1 – fullering, 2 – edging, 3 – bending, 4 – blocking (rough shaping of the forging), 4 – finishing (giving the forging its final shape), 6 – cutting-off (separating the forging of the bar or the tonghold material)*

This method of preforming the preform is possible only on die forging hammers because the shaping process often requires multiply hammer blows, the energy of which has to be matched respectively. This is why some steps are not possible on forging press – in such a situation, only the forging is made on the press, whereas the preform is manufactured in a separate operation using a different machine.

In industrial practice, one can distinguish the following methods of shaping preforms:

- open die forging – used in the case of small lot production of any type of longitudinal preforms as well as flat and compact preforms which require initial upsetting; this method is labor-intensive and produces preforms which are low in quality and accuracy as well as lead to substantial losses in material, the advantages include flexibility as well as simple and cheap tools;

- swaging, mainly on rotary swaging machines – productive method of shaping longitudinal preforms of variable section with high accuracy;
- shaping on electric upsetters – method used for shaping preforms which have large cross-section variations at their ends or in the middle, i.e. when the ratio between the length of upset part of forging and the initial diameter is significant; usually this method used to upsetting the bars up to 100 mm in diameter;
- shaping on the horizontal upsetting machine – method commonly used to forge longitudinal preforms having large cross-section variations at their ends; it is carried out by means of heading in a single or multiple steps; it is also possible to manufacture hollow frontal preforms, e.g. for finish orbital forging of products such as discs, bevel gear wheels, etc.; horizontal forging machine is used in forging plants which have machines used to manufacture final forging products;
- forging process on three-slide forging press (TSFP) and special upsetting devices (e.g. using Tadeusz Rut's method) which are installed on universal presses – the method is used to shape preforms with large cross-section variations anywhere on a bar of any length; it is cost-effective when the production lot reaches a couple of hundred products a year;
- longitudinal or periodical rolling on forge rolling mills – this method is used to manufacture a wide range of longitudinal preforms, e.g. connecting-rod preforms, bike cranks, spanners, various types of leverages and driving axle; the shaping process takes place on special frame or bracket rolling mills; very commonly used;
- cross rolling, including triple roll mill using screw rollers (producing smaller preforms) or the method of cross-wedge rolling (as exhibited on Fig. 2.9) – shapes longitudinal preforms of variable cross-section in the shape of a solid of revolution.

2.6. Forging dies

2.6.1. Dies for hammer forging process

Because the hammer work is dynamic, the dies are made of relatively massive blocks of tool steel. High versatility of hammer forging technique is the reason why the parts subjected to it usually require numerous steps – thus, multi-cavity dies are most commonly used in this industry practice. Depending on their purpose, cavities can be divided into three types:

- forging die cavities, designed to deform a forging – can be distinguished two type of cavities; the finishing (impression) die cavity is used to shaping final forging; the blocking die cavity is used to rough shaping of the forging and is meant to relieve the finishing cavity, thereby prolonging the tool's life;

- preforming die cavities, used to produce a preform; these cavities can be divided into four groups, i.e. first group – fullering and edging cavity; second group – bending and preshaping die cavity; third group – upsetting or flattening plane; fourth group – cavity which emerged as a result of joining two cavities from the first and the second groups, e.g. preshaping and edging;
- supportive die cavity, designed to carry out ancillary activities during multi--cavity forging process, e.g. cutting the forging off the bar.
- In the case of hammer die forging, the forging tools can take the structure of:
- uniform die block – most commonly used; an example of which is presented on Fig. 2.14;
- assembled die (with exchangeable die inserts) – used only in justified cases where the basic reason for producing die inserts is the irregular wear of various working impressions (especially the die cavity).

Die inserts are most frequently used for:

- fragments of finishing cavity which are prone to intensive wear from mechanical and thermal fatigue;
- blocking or bending cavity, in there the high boss jutes the parting line out;
- any cavities which are more efficient to make as milled (or turned) inserts and when produced by means of powder hot pressing and sintering technology.

Using die inserts allows for the production of cases to be carried out using considerably cheaper material (e.g. carbon tool steel or cast steel) while the inserts themselves are made from materials of better quality and are being constantly improved for higher hardness (alloyed steels with Cr, Mo, W, V or hot-work tool steels). Such technological solution is also beneficial in terms of die repair and recovery which is both easier and less expensive. The shape and the dimensions of inserts are chosen accordingly to the shape and the dimensions of forgings. The inserts which are predominantly used are round, rectangular or square. An example of die inserts is shown on Fig. 2.15.

Closed-type dies

Closed-type dies, used in flashless hammer forging process, might take the form of uniform or (more frequently) assembled dies (Fig. 2.15). These have to be equipped with special locks. Depending on the lock design, we can distinguish three types of closed-type dies with:

- a single lock (Fig. 2.15a), which are used during hammer forging process with a very precise guidance; dies designed in such a way are used to manufacture forgings such as gear wheels, rings and flanged pins;

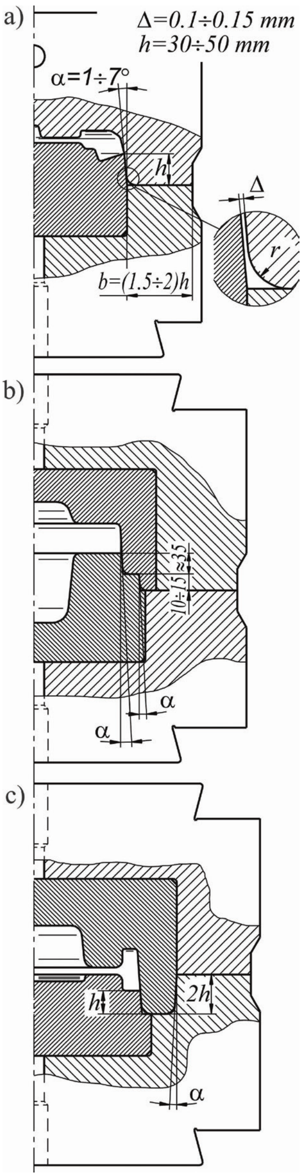


Figure 2.15. *The assembled closed-type dies for hammer forging process*

- a double lock (Fig. 2.15b), where the upper lock prevents metal from flowing outside the cavity, whereas the bottom lock protects the dies from shifting (mismatching of a forging); the lock design allows for the height of the upper lock to be reduced which improves its strength and durability; dies with a double lock are used to forge products such as flanged pins with a shank of considerable length;
- a lock and a counter lock (Fig. 2.15c) – the inside lock has a normal location and is responsible for preventing the metal from flowing outside the die cavity, whereas the outside lock has a reversed location and its task is to ensures proper die guidance and to protect the inside lock.

The finishing cavity in a closed-type die is usually made by means of a special compensator which is responsible for fitting a minor excess of the initial material inside the cavity. Volume variations of the material occur mainly due to the precision with which billet is cut. In the industry conditions, two types of compensators are used:

- external, cylindrical, ringed or conical in shape, which is made on the front surface of the forging, e.g. on the shank extension or another element which stands mayor solid of forging out;
- internal, which is placed on the bottom of the forging, e.g. as an additional gutter above the bottom (Fig. 2.15a).

Flash gap in opened-type dies

A characteristic feature of forging process with opened-type dies is the production of technological discard in the form of a flash (Fig. 2.1, Fig. 2.16). It is the material excess which stored in a specifically designed space located in the parting line outside the die cavity – i.e. in the flash gap which is made only for the finishing cavity. As exhibited on Fig. 2.16, the flash gap consists of:

- land – a space between two die halves which is responsible for resisting the free outflow of metal outside the die cavity, thereby ensuring the proper degree to which the cavity ought to be filled with the flowing material (i.e. preventing the unfilled sections defect); cavity filling increases as the ratio of land width to thickness increases up to about 5, but larger ratios do not increase filling substantially and are undesirable due to increased forming forces and excessive die wear;

- gutter – a container storing the excess material, the volume of this space has to be bigger than the amount of stored metal to prevent the flash from being additionally deformed by upper die (flattened).

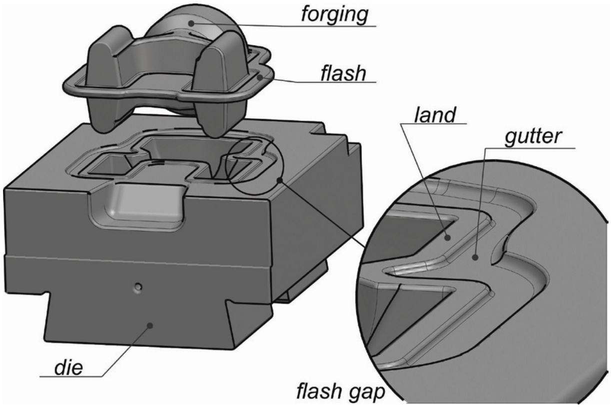


Figure 2.16. *Example of a hammer forging die, forging with flash and a flash gap*

The third purpose of a flash gap is to create a metal ring which surrounds the forging and separates the two dies. It is particularly important in the case of hammer forging as the potential crush of the two dies might lead to them being damaged. All three purposes of a flash gap are fulfilled to a different extent depending on the type of the forging machine and the forging process.

As presented on Fig. 2.17, the flash gap might take the form of an external gap (designed for the flash) or an internal gap (designed for the bottom). The use of the internal gap is very beneficial provided that the rule according to which the material located inside the gutter should not be deformed by upper die is fulfilled. This technological solution leads to a considerable decrease in the forming force, e.g. in comparison to the traditional one shown on Fig. 2.17a. The reason why the forming force is reduced is because the contact surface between the metal and the die is significantly smaller and the value of the maximum pressure, located on Fig. 2.17b in the central part of the bottom, is reduced. Furthermore, provided that the solution corresponds to the one presented on Fig. 2.17b, the inside gutter might also act as a compensator, especially during the forging of closed-type dies (the flashless forging process).

2.6.2. Dies for crank press forging process

During closed-die forging process on crank press, the only executable steps are the ones which can be carried out by applying the slide pressure only once. Apart from the basic steps, i.e. finishing and blocking, also the preforming steps are used. These include:

- upsetting or flattening – by means of the cavity or plane to upset or flatten an initial material (usually in the form of a bar stock);
- edging preforms of elongated axle – by means of closed cavity where a initial material is gathered into a local region;
- bending or preshaping – by means of bending or preshaping cavity.

Particular cavities are made in separate die inserts which are mounted in special holders. To make the removal of the forging from the cavity easier, an ejector is used powered by an appropriate mechanism coupled with a press knock-out. The whole set consisting of the abovementioned parts is called a die-set for crank press forging. A typical structure of such the die-set is presented in Fig. 2.18. Die inserts 5 and 6 are fixed to the die-holder plates with clamp-buttons 7 and support plates 8, accordingly – to the lower 1 and to the upper 2 plate. The die-holder plates 1 and 2 are made as steel casting. It is recommended to use backing plates 3 and 4 between the die-holder plates and the die inserts. The backing plates are responsible for transmitting the pressures exerted by the die inserts during the forging process. In the front part of the die-holder plates (from the side of the blacksmith), special resistance key-slots are made to provide a base for locking the clamps. In the back part of the die-holder plates, guide systems are made 9 consist of the guide posts and bushings. It is important to note that, in comparison to hammer, the press slide guidance is a lot more precise and does not require more accurate die lock system. If the rectangular die inserts are used, additional

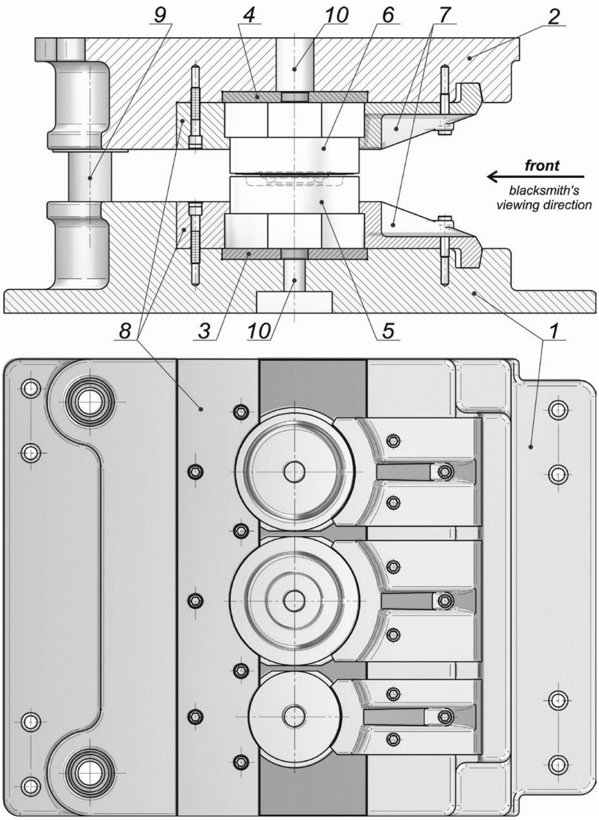


Figure 2.18. *The die-set for crank press forging process where type I holders were used; description in the text*

elements protecting the inserts from transverse shifting ought to be used as well. There is a rectangular chambers for inserts in the die-holder plates and the support plates are in the shape of a wedge.

The closed-die forging process on a crank press is usually carried out in three steps at the most (as shown on Fig. 2.18). As a general rule, only one preforming die cavity is used along with one or two finishing die cavities. The frontal forgings are made in the course of:

- one step (finishing cavity) when the compact forgings are no bosses, hubs, holes or big rim;
- two steps (preforming cavity, finishing cavity) when the disc-type structural forgings are boss and holes and the differences in their heights are minor, whereas the corner radius are sufficiently big;
- three steps (preforming cavity, blocking and finishing cavities) when rib--web-type structural forging are bosses, rims and hubs of considerable height differences and the corner radius is small.

In crank press dies, a mechanism of ejecting the forging out of its cavity is used. A typical mechanism consists of two basic parts:

- ejector, which is a part of the cavity and is in direct contact with the workpiece;
- knock pin, which is located outside the die (die insert) and is responsible for transmitting the ejecting load (force) from the press knock-out to the ejector.

The ejector is placed in the die in such a way so as not to cause any damage to the surface of the forging. It can be distinguished three types of a knock-out system:

- type I, where the pressure is transmitted directly to the forging and the working surface of the ejector is a part of the cavity surface;
- type II, where the pressure is exerted on the forging bottom;
- type III, where the pressure is transmitted to the flash, in the land area; due to the risk of cutting the flash, a number of ejectors of a sufficiently big diameter are used.

An example of the ejecting mechanism for the frontal forgings is presented on Fig. 2.19. It consists of two type I ejectors in the shape of a pin – the upper 3 and the lower 4, which are places centrally in the die inserts 1 and 2. Leaning against the die holder – the upper 6 and the lower 7 – there are collars which are made on the ejector's circumference. The knock pins are presented schematically by

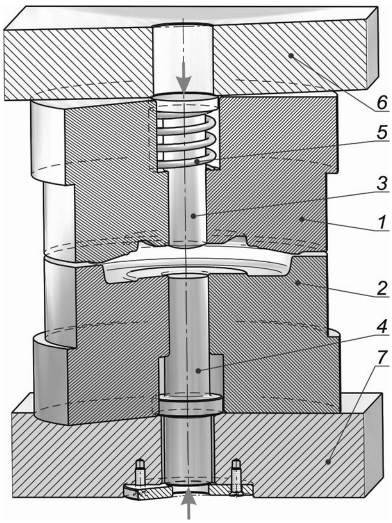


Figure 2.19. *Ejecting mechanism used for frontal forgings*

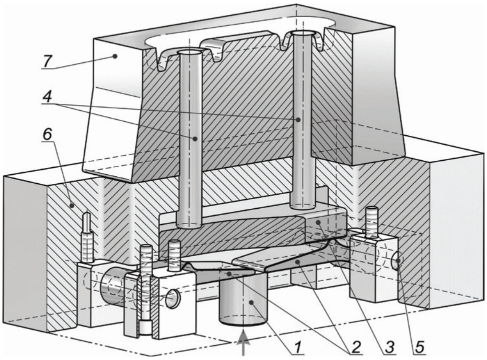


Figure 2.20. *Ejecting mechanism used for longitudinal forgings and multi-cavity dies*

means of arrows. The upper ejector has a spring 5 which makes it automatically return to its starting position. The mechanism presented is characteristic of a compact design. It does not influence the precision with which the forgings are made and does put the ejectors at risk of being overloaded.

The next Fig. 2.20 presents the ejecting mechanism for longitudinal forgings. The press knock-out applies pressure by means of knock pin on two leverages 2 rotating on the pin 5 and pressing on the plate 5. Leaning against the plate, there are two type II ejectors 4 which move inside the die holder 6. The mechanism constructed in such a way is also used during multi-cavity forging where every die insert has a separate ejector.

The clamps are used for mounting the die inserts. Depending on their shape, the mounting process and the location of chamber in die holder plate for installing a die insert, it can be distinguished four basic types of clamps:

- type I – clamps for mounting round (or rectangular) inserts by means of clamp-buttons 2 and support plate 3 (Fig. 2.21a);
- type II – clamps for mounting round inserts by means of clamping plates 4 (Fig. 2.21b);
- type III – clamps for mounting rectangular inserts by means of wedges;
- type IV – clamps for mounting rectangular inserts by means of part in the shape of a wedge; the die insert is placed in a special cassette which makes it impossible to regulate its location. One insert is mounted by means of four wedges.

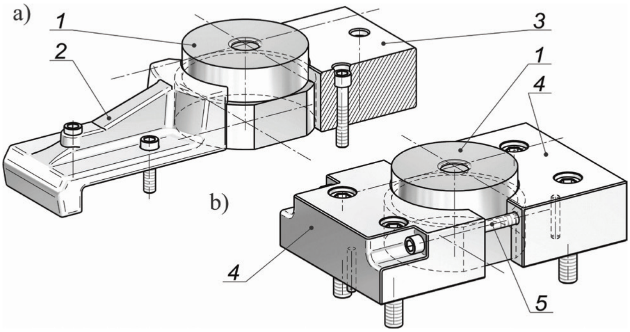


Figure 2.21. *Clamps for mounting round type I (a) and type II (b) die inserts, where: 1 - die insert, 2 – clamp-button, 3 – supporting plate, 4 – clamping plate, 5 – clamping bolt*

2.6.3. Dies for screw press forging process

Tools for closed-die forging process on screw presses are designed under similar principles and other forging machines (i.e. hammers, crank presses or horizontal forging machines). As a result, the same standards and project recommendations are used. The differences include only:

method of mounting the dies for the table and press slide;

- the use of ejector – it is used only for the cavity in a lower die;
- mutual placement of dies – during designing the dies, cracks between them are not included in the plane of parting line, as on the screw presses it is permitted to touch them, as the screw mechanism applied in the press eliminates the danger of jamming the tools or overloading the machine.

In industrial practice, the forging processes on the screw presses are realized in accordance with the shaping method in dies:

- opened-type, which have a flash gap with a closed-type gutter (as in the case of forging process on hammer);
- closed-type undivided – in accordance with technology used in forging process on hammer;
- closed-type divided, where a lower die is performed from two inserts (e.g. Fig. 2.22) assembled during stroke, and disassembled upon removing the forging from the die; such a technology is used to make forgings with a complex shape, e.g. type of engine valves, pins or stepped and toothed shafts.

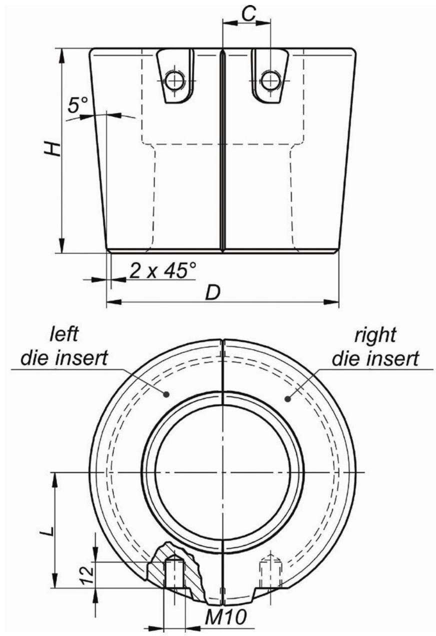


Figure 2.22. *Example of divided die for screw press forging process, where the recommended values of dimensions are D = 80÷140 mm, H = 115÷215 mm, L = 35÷65 mm, C = 22÷40 mm*

Due to the inaccurate guidance of the screw press slide, it is recommended to perform a special die lock. In case of the longitudinal forgings, cross locks or guide pins are used. On deforming the frontal axial-symmetrical forgings, the alignment of the upper die is performed in the lower die. Whereas, for the construction reasons, more often the solution is encountered where the guide recess is made in the upper die called also a punch.

Dies fixed on the screw presses are performed most often as the tool-set (attachment) consisting of die inserts and die holders. The upper die (or die holder plate) is fixed in the press slide by means of:

- shank (with a standardized, proper shape) placed in a special shank holder – such a solution issued only for the tools with small weight (on shaping frontal axial-symmetrical forgings) or in case of applying guide posts;
- holding bolts, which are placed directly in T-slots of the press slide, whereas in the die the central dowel pin is performed (instead of shank) and recess for holding bolts;
- bolts with hook clamp assemblies.

Whereas, the lower die (or die holder plate) is fixed on the press table (bolster plate), using T-slots by means of:

- holding bolts;
- bolts and hook clamp assemblies or shaped strap clamps;
- clamping plate, which is screwed to the lower die holder plate by means of clamping screws, whereas between the clamping plate and die the divided sleeve (or die container) is placed.

a) b)

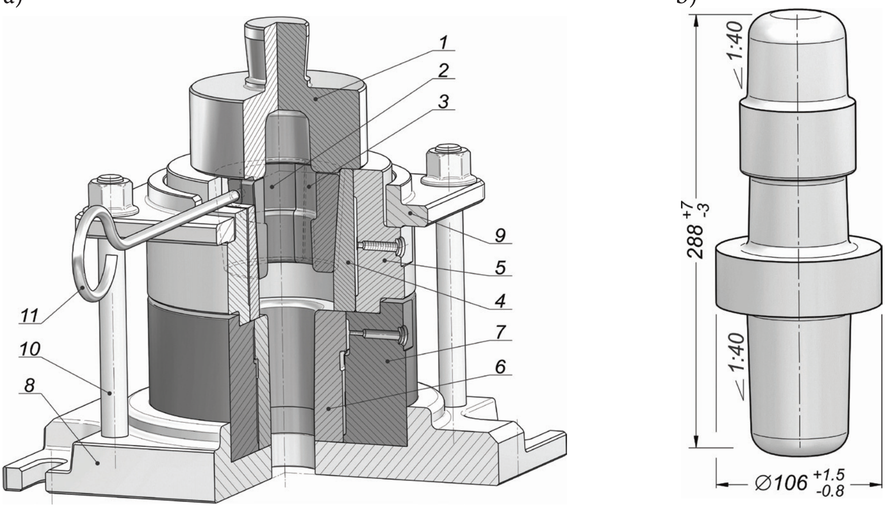


Figure 2.23. *Example of the die-set (a) for forging a stepped shaft (b) on screw press [23]; description in the text*

The example of the die-set to forge the forging of stepped shafts type (e.g. toothed) on the screw press was shown on the Fig. 2.23. The upper die 1 (called a punch) has a shank and a round lock. Between the upper die and the divided die inserts 2 and 3 (which were shown in the previous Fig. 2.22) the space was used for the radiant flash, whereas between the upper die and sleeve 4 and the die container

5 and no gap is allowed. Sleeves 4 and 6 are placed in the containers 5 and 7, in which special channels were performer for the cooling liquid for the tools being in contact with the material shaped. The lower die as the tool-set consisting of the inserts, sleeves and die containers, is clipped with a die holder plate 8 by means of a clamping plate 9 and four clamping screws 10. Whereas the die holder plate is fixed on the table (bolster plate) of the press by means of holding screws (not showed on the figure). In the die holder plate, additionally the central hole was performed for ejector. In order to assemble and put out divided inserts 2 and 3 from sleeve 4 removing handles 11 are used. They are performed usually from the wire with a diameter Ø12 mm, and their length is within the range of 350÷450 mm.

3. Extrusion

3.1. Introduction

The extrusion is defined as process of plastic deformation of billet, generally cylindrical and cold or reheated, which is placed in a container and next forced to flow by compression through a hole of die and obtains the shape of cross-section, corresponding to this die hole. A cross-section area of extruded product is smaller then the original billet.

The process of extrusion is applied in generating products (forgings) with different shapes: conical, cylindrical, smooth, with subsidiary elements, solid, hollowed. With this method one may also deform forgings with a complex shape – Fig. 3.1. The analysis of the products generated in forging plants shows that a significant amount of them can be obtained with extrusion process. For the example, in car industry 10÷12% of forgings can be obtained with this method.

The largest advantages of the extrusion process includes:

- occurrence of favorable triaxial stress state (a compressive generally), which allows for forming of products made also from hardly deformable metal alloys;
- relatively high material yield – in relations to the closed-die forging technology in the extrusion process there is no flash and the allowances are greatly reduced for the machining process;
- increase the accuracy of forging process, with simultaneous increased a productivity and reduced a labour consumption of process;
- easiness in mechanization and automation of process.

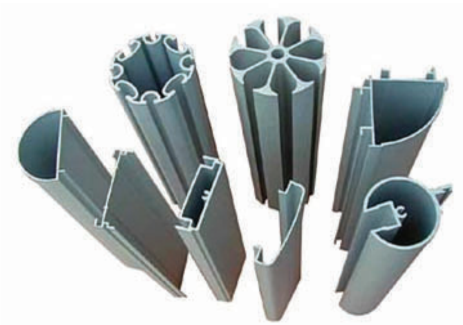


Figure 3.1. *Examples of typical products (from aluminum alloy) of complex shape, produced by extrusion [23]*

The negative features of the extrusion process may include relatively large pressures on the surface of tools, higher consumption of energy and small life of the tools (especially dies and dummy blocks).

3.2. Classification of extrusion processes

3.2.1. Division due to material flow in relative to ram movement

Due to the direction of the material flow in relation to the ram movement, the following are distinguished:

- Forward (direct) extrusion (Fig. 3.2), in which the material is extruded with a ram from the container through the hole of the die located opposite the ram. The direction and sense of the material flowing is consistent with the direction and sense of the ram movement. In the case, the material is moved towards the walls of the immovable container, which caused the occurrence of friction forces on the surface of the contact material-container which while counteracting the movement of the material, increase the total force of extrusion process.

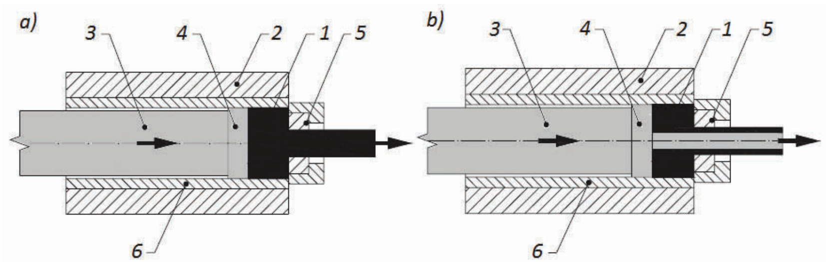


Figure 3.2. *Scheme of the forward extrusion of rod (a) and hollow part (b), where: 1 – billet, 2 – container, 3 – ram, 4 – dummy block, 5 – die, 6 – liner [33]*

- Backward (indirect) extrusion (Fig. 3.3), used for creation of solid and hollowed products. In case of solid forgings, the material is extruded from the container through the hole in a hollowed ram, and during shaping the hollowed forgings through the hole created by the container and ram. It is characteristic that in both these processes the material flows in the direction consistent with the movement direction of a ram, but the sense of the movements is opposite.

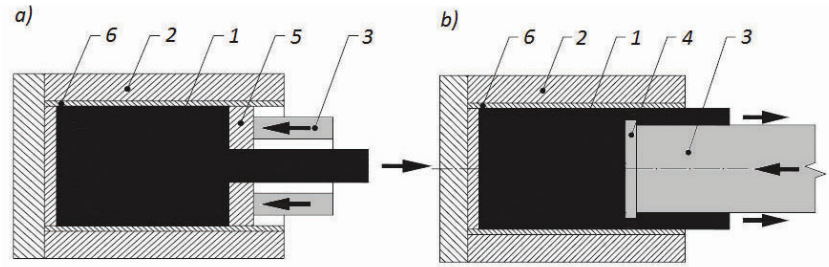


Figure 3.3. *Scheme of the backward extrusion of rod (a) and tube (b), where: 1 – billet, 2 – container, 3 – rode, 4 – dummy block, 5 – die, 6 – liner [33]*

- Combination extrusion (Fig. 3.4), which constitutes the connection of the extrusion processes occurring at the same time, discussed above, direct and indirect.
- Lateral extrusion (Fig. 3.5), in which the direction of the material flow is different than the direction of ram movement. Most often the directions defining the outflow of the material and movement of the ram are perpendicular to each other. Then we speak about radial or crosswise extrusion. This type of extrusion, with reference to stress and strain state is similar to forward extrusion. However in comparison with it in the analyzed type of extrusion there is non-uniform of material deformations, due to the lack of axial symmetry of the process [11, 33].

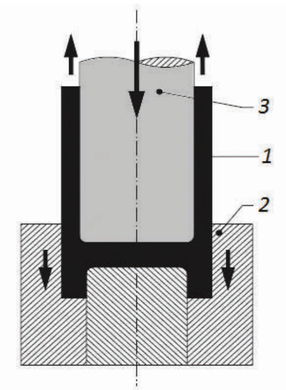


Figure 3.4. *Scheme of the combination extrusion, where: 1 – billet, 2 – die, 3 – ram [33]*

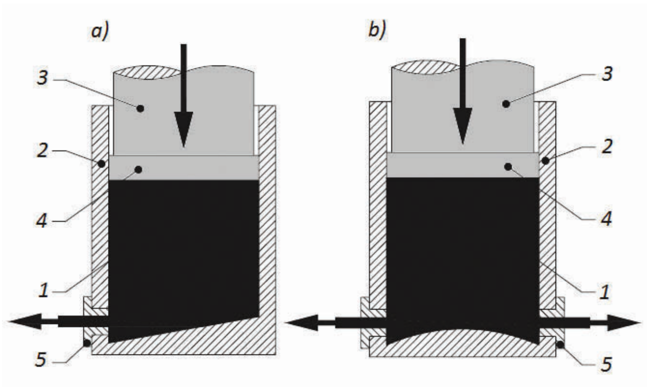


Figure 3.5. *Scheme of the lateral extrusion with one-direction (a) and multi-direction (b) outflow of material, where: 1 – billet, 2 – container, 3 – ram, 4 – dummy block, 5 – die [33]*

3.2.2. Division due to temperature of billet

Due to the temperature of the initial material, the methods of cold extrusion, hot extrusion and warm extrusion are distinguished. In tables 3.1 and 3.2 general comparison was presented of the listed methods of extrusion (against the background of the machining technology) with reference to material yield and energy consumption, as well as accuracy of final products. Whereas, in a further part of sub-chapter particular methods were characterized.

Table 3.1. *Material yield and energy consumption in selected processes of metal working [6]*

Type of process	Material yield, %	Energy consumption, MJ/kg
Machining	40÷50	80÷100
Hot extrusion	75÷80	53÷56
Warm extrusion	85	48
Cold extrusion	85	48

Table 3.2. *Accuracy of producing parts in selected processes of metal working [6]*

Type of process	Achieved accuracy class of diameter											
	5	6	7	8	9	10	11	12	13	14	15	16
Grinding	X	X	X	X	X							
Turning		X	X	X	X	X						
Cold extrusion			X	X	X	X	X	X				
Warm extrusion				X	X	X	X	X	X			
Hot extrusion							X	X	X	X	X	X

Cold extrusion

Cold extrusion process is used, first of all, to making parts of machines for ready, characterized with increased mechanical properties, high dimension-shape accuracies, good quality and smoothness of surface and beneficial structure. For cold extrusion the following material are used:

- Carbon and low-alloy steels containing: C < 0.35% for backward extrusion and C < 0.6% for forward extrusion; Si in scope 0.15÷0.35%; Mn < 1%; S, P < 0.035÷0.040%; Ni < 1%; Cr < 0.9%; Mo < 0.4% [15].
- Non-ferrous metals. Aluminum, copper or alloys of these metals were the first metals shaped with the cold extrusion method. The best workability in the group was presented by pure aluminum. It decreases however after making an alloy of this metal with magnesium (up to 2%), copper (up to 1%) and, first of all, with silicone (up to 1%). Pure copper has also good workability, which in case of brasses decreases with an increase of zinc contents (37% Zn is the limit value for cold extrusion).

The variety of cold extrusion is the impact extrusion process, which is used to produce hollowed products, as cans for drinks, toothpaste tubes, etc. The process requires soft materials, such as: aluminium, copper, lead. In the process, small amount of initial material is placed in the die and is subject to be shaped by punch, mounted to the ram of a high-speed mechanical press, in the manner presented on the Fig. 3.6.

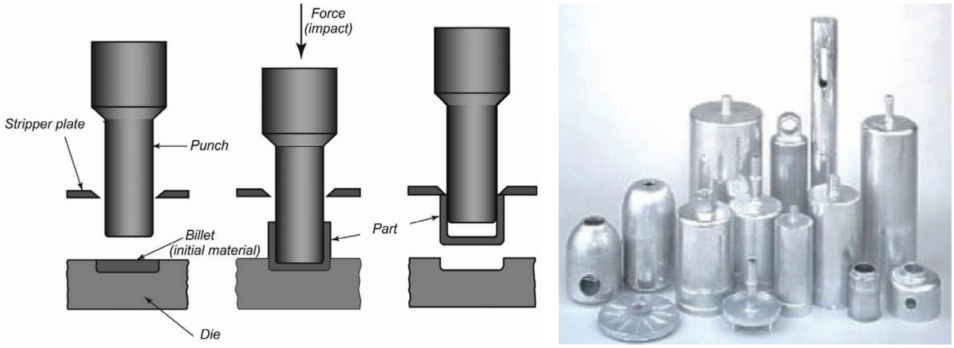


Figure 3.6. *Scheme of the impact extrusion process with exemplary products [23]*

Warm extrusion

Warm extrusion process is realized in increased temperature of the initial material but smaller then its recristalization temperature. It allows to obtain parts with slightly worse surface and accuracies as in case of cold extrusion. Simultaneously, due to an increase of plasticity of the material, the extrusion force is reduced, which allows for shaping with an increased deformation of the material.

Hot extrusion

Hot extrusion process is usually used for metallurgical extrusion of rods, pipes and extruded sections, being subject to other forming processes or finishing on a later step of production. Semi-products obtained with the hot extrusion method are characterized by worse mechanical properties and quality of the surface as well as more numerous defects (straightness, internal and surface cracks, tearing etc.) than in case of the cold extrusion processes. The scope of temperatures used in hot extrusion is as follows:

- lead 20÷250 °C,
- aluminum and its alloys 375÷475 °C,
- copper and its alloys 650÷975 °C,
- steel 875÷1300 °C,
- heat-resisting and high-temperature alloys 975÷2200 °C.

3.2.3. Division due to applied equipment

Due to the type of the equipment applied (tools, press), vertical and horizontal extrusion processes are distinguished. Both these processes are realized generally with the use of hydraulic presses, the examples of which are presented on the Fig. 3.7. In case of using the horizontal press during extrusion, practically there is no limitation due to the length of the part extruded, also its cutting to suitable length is easier. The machines of the type occupy however much larger area in the forging plant.

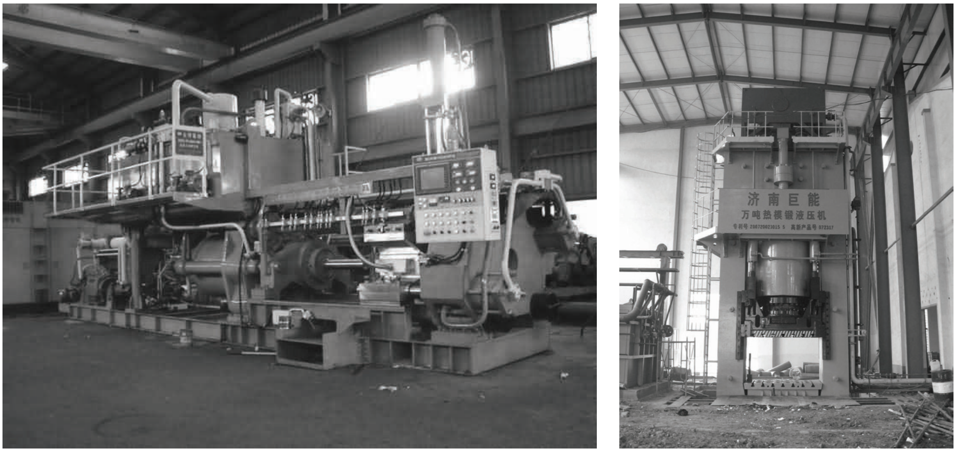


Figure 3.6. *Hydraulic presses used for horizontal (on the left side) and vertical (on the right) extrusion process*

3.2.4. Special methods of extrusion

Continuous rotary extrusion

The continuous rotary extrusion process, called also Conform™ method (Fig. 3.8), which main feature is that the pressure on the material is applied not by a ram but by a friction wheel 2, with a groove 6. In the groove the feedstock material (a billet in form of rod) 1 is put tangentially against the turning wheel. Thanks to the off-centre mounted extrusion shoe 3 the material is pressed against the friction wheels, that transfers the material to extrusion zone and extracts it through the die 4. The final extruded product 5 goes through the opening in the extrusion shoe. The friction that is generated between the wheel and the feedstock causes metal heating and a pressure increase to a level that allows

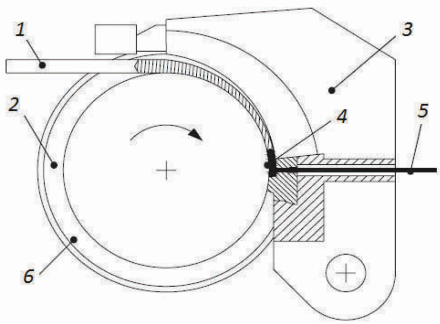


Figure 3.8. *Scheme of Conform™ method, where: 1 – feedstock, 2 – friction wheel, 3 – shoe, 4 – die, 5 – extruded part, 6 – groove*

the feedstock to go through the die. The single groove system is normally used for the production of solid and hollow sections. As the product leaves the wheel in a radial direction the process is commonly referred to as radial extrusion. The capacity and flexibility of the process is substantially increased by the use of two grooves in the wheel (i.e. the twin groove system). This system enables extrusions of larger cross-sectional area to be produced with standard size feedstocks and at acceptable output rates. The twin groove system also allows the use of more robust tooling in the extrusion zone and creates more space to permit extrusions of high width to thickness ratio to be produced.

The next Fig. 3.9 shows a continuous rotary extrusion machine, that is used in production of copper and aluminum parts (the feedstock can not only be semi-metallurgy products but also granules and powders). The efficiency of the presented machine (with single groove system) is between 350 kg/h, with the diameter of the extrusion being 12.5mm, and 2040 kg/h, with the diameter of the extrusion being 25 mm. The advantages of this machine is easy and quick exchange of the die and efficiency of the extrusion, even with a small number of the extruded parts.

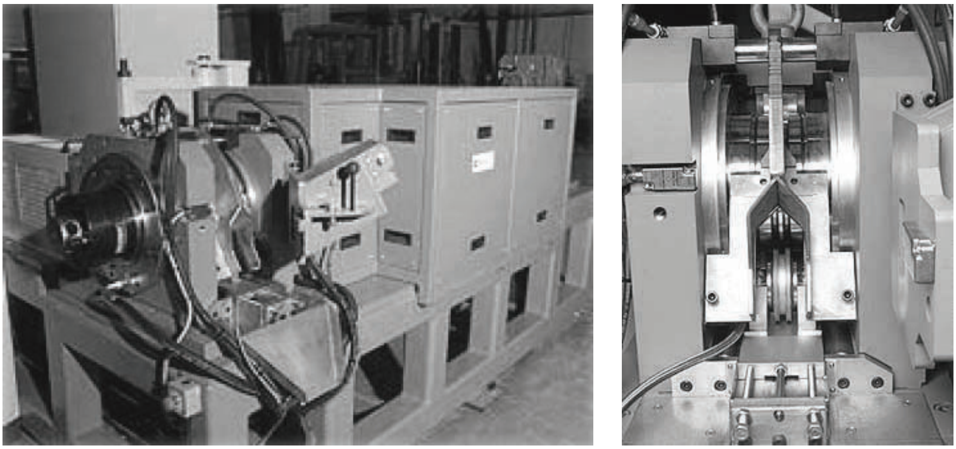


Figure 3.9. *The continuous rotary extrusion machine MC260, produced by Meltech-Confex company (Great Britain)*

Extrusion with reversely rotating die

The extrusion process with reversely rotating die (KOBO method), the name of which comes from the surnames of the inventors, i.e. Korbiel and Bochniak, is based on a cyclic transformation of the extruded materials, that is achieved by a cyclic change of deformation path conditions. In practice the effect is achieves by giving a reverse rotation to the die during the extrusion process (Fig. 3.10). Advantages of the KOBO method are the following: the possibility to diffract the grain structure even to nanostructural sizes; possibility to produce elements with complex shapes, from hardly deformable metals and its alloys (Fig. 3.11); reduction of the deformation work; less wear of the tools [2, 3].

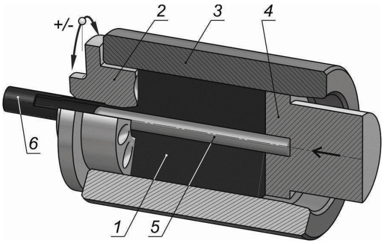


Figure 3.10. *Scheme of extrusion process with KOBO method: 1 – billet, 2 – reversely and cyclically rotating die, 3 – container, 4 – ram, 5 – mandrel, 6 – hollow part*

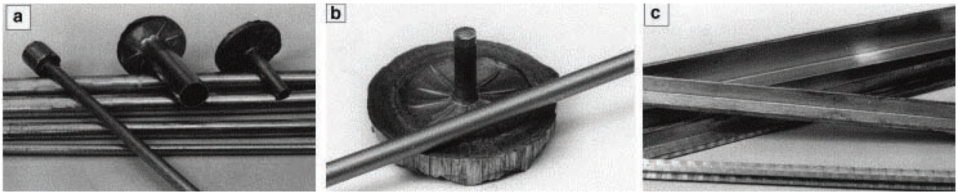


Figure 3.11. *Extruded parts made from copper (a), CuP6 alloy (b) aluminum alloys (c) with the KOBO extrusion method carried at room temperature [3]*

Hydrostatic extrusion

In hydrostatic extrusion process the material is extruded from the container through a hole in the die not by a ram but by an incompressible fluid medium under high pressure surrounding the billet (Fig. 3.12). It separates the billet from the container causing the decrease of friction on the contact surface, that leads to a forming force reduction. The pressure of the fluid medium is increase by both static and dynamic methods. What is interesting, the working medium (exerting pressure on the billet) is not necessarily a fluid. A gaseous medium or a metal with low compressive strength can be used.

The hydrostatic extrusion process can be carried out using standard vertical and horizontal presses with hydraulic or mechanical drive. Extrusions in both simple and complex shapes can be made with this method. Generally, the brittle metals and its alloys are extruded by this method because increases ductility of the extruded material.

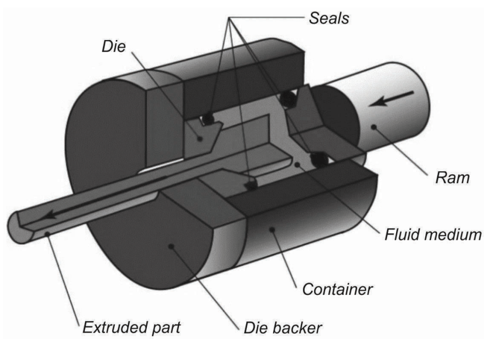


Figure 3.12. *Scheme of the hydrostatic extrusion process [23]*

The process of hydrostatic extrusion can be classified according to various criteria: the physical state of the working medium, the deformation rate, the ratio of the frontal and side pressure. The most popular classification concerns the physical state of the medium, according to which we can distinguish the following methods of hydrostatic extrusion (under hot condition):

- gaseous static, in which the medium is a gas under high pressure;
- true, where a medium with increased viscosity in a liquid or semiliquid state is used;
- pseudo fluid media, such as powders and materials with low compressive strength;
- in solid metal and non-metal sheathing.

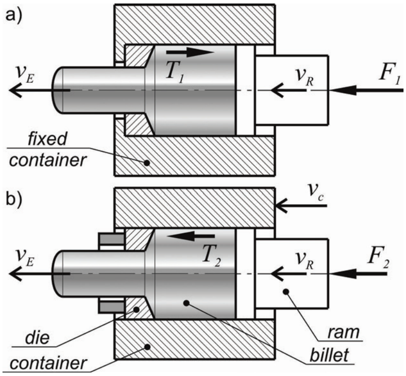


Figure 3.13. *Scheme of the common forward extrusion (a) and the extrusion with active contact friction force (b), where: T_1, T_2 – friction forces; F_1, F_2 – extrusion loads (where $F_2 < F_1$); v_R – ram velocity; v_c – container velocity, v_E – velocity of material flow out*

Extrusion with active friction

In the extrusion process with active contact friction force the ram and the container are moving simultaneously, but with specific and different velocities. In this process (Fig. 3.13b) so called active friction is created on the walls of the container, that supports the material flow, because the direction of the friction force T_2 is consistent with the direction of the material extrusion (v_E). As a result of the friction force, the total extrusion force F_2 is decreased (in comparison with the force F_1 obtains in common forward extrusion process).

3.3. Characteristics of extrusion process

Stress and strain state

Numerical modelling offers a possibility to describe the extrusion process concerning the stress and strain state. By use of the a FEM simulation of three extrusion methods have been carried out: forward extrusion, backward extrusion, and extrusion with active friction. The data for calculations are the following:

- material – pure aluminum in grate AW-Al99,0Cu, where the ultimate tensile strength R_m is about 140 MPa;

- the billet and tools temperature is 20 °C;
- the velocity of the ram is 10 mm/s;
- the friction coefficient is 0.1 (according to the Coulomb model of friction);
- heat transfer coefficient is 20 kW/m^{2}K;
- geometrical model of the backward extrusion process according to Fig. 3.14 (in other considered cases same dimensions of the billet, container and same diameter of extruded part had been used).

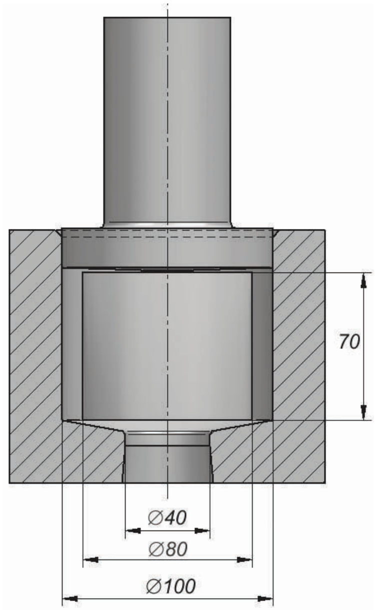


Figure 3.14. *Geometrical model of forward extrusion process used in the numerical analysis*

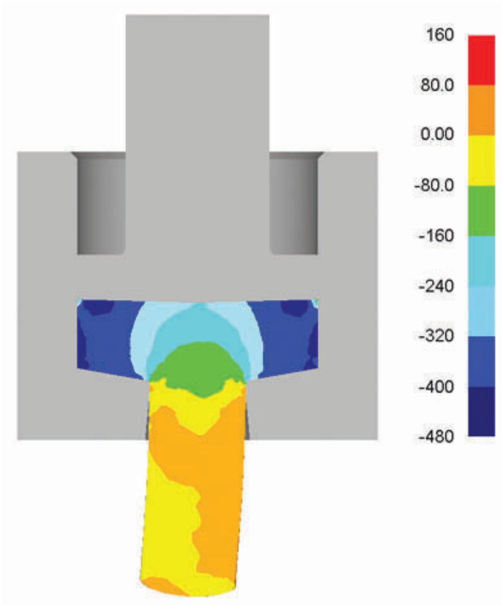


Figure 3.15. *Distribution of mean stress (in MPa) in axial-section of the extruded part made using a forward extrusion method*

According to the results of carried out FEM simulations it was found that during the extrusion process a triaxial stress state in the material occurs. Though, range of the material in the container is usually under tiaxial compression. Distribution of the mean stress presented on Fig. 3.15 may be the proof. Under the influence of the ram the material flows towards the hole in the die. The maximal value of the stresses occur in the corners of the container, where the accumulated material forms so called dead zones. Extruding material from these zones is difficult and requires an increase of extrusion force. In the extruded part there are tensile stresses formed because the flow of the material is free in the axial zone, and in the surface zone the flow is slowed by the friction forces at the area contact between material and tool.

The next Fig. 3.16 shows the distribution of effective strain in the extruded parts made using different extrusion methods. From the result it appears that the deformations are layered. They are smaller in the first section of the part and the gradually increase towards the final section. Such distribution of the strain is a reflection of the load scheme (the effect of the applied friction forces) and the geometry of the process (at first the initial material is pre-upset, then the part is extruded). Regarding the influence of the extrusion method on the distribution of strain it needs to be stated that they are most versatile in case of backward extrusion and least versatile in case of extrusion with active friction.

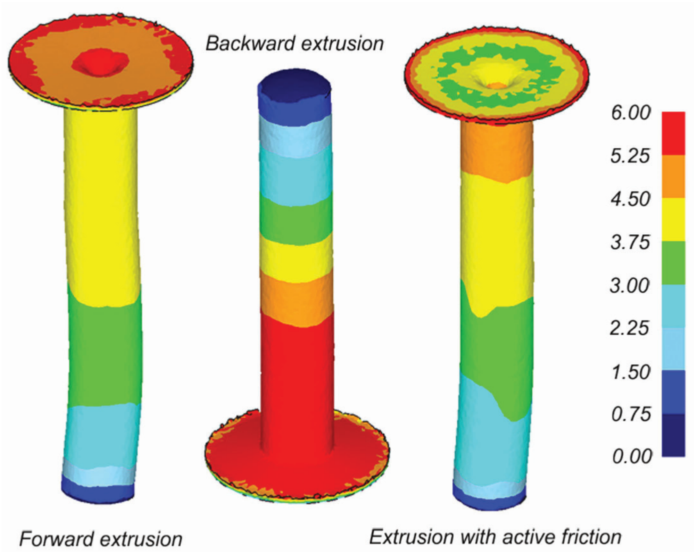


Figure 3.16. *Distribution of effective strain in extruded parts made using various extrusion methods*

Influence of selected factors of the extrusion process on its course

The are many factors influencing the course of extrusion process, which are the following: properties of the shaped material, the coefficient of cross-section reduction, the length of the initial material, the strain rate, temperature, lubrication (discussed in chapter 3.5), geometry of used tool equipment and others.

Properties of extruded material are a result of its chemical composition and structure. The most commonly extruded parts are from iron, copper, aluminum and alloys of these metals. To be able to determine the exact properties of the material, conducting plastometric tests are needed, during which the flow stress is determined (usually, expressing as a function of strain, strain ratio and temperature).

The ratio of plastic deformation determines the changes in dimensions of the material that occurred during extrusion process. The basic measurement here in the true strain ε, that is calculated from the following relation:

$$\varepsilon = \ln\frac{S_0}{S_1} \tag{3.1}$$

where: S_0 – the cross-sectional area of billet, S_1 – the cross-sectional area of the extruded product.

Another parameter used to determine the ratio of material plastic deformation in extrusion process is the coefficient of elongation λ, defines as:

$$\lambda = \frac{l_1}{l_0} \tag{3.2}$$

where: l_0 – length of the billet, l_1 – length of the extruded part. Wherein, the expression (3.2) can be used when the cross-sectional shape of extruded parts is the same as the billet. The extrusion process is usually made with the coefficient of elongation at about 50. It is, however, possible to carry out the extrusion process even with a six-times larger value of this parameter.

The length of the billet (usually cylindrical) is determined by the ratio of its length to the dimensions of its cross-section (diameter). Because of the fact that in the first section of the extruded part the material is less deformed, and its strain increases with the length (Fig. 3.16). The billet used in the extrusion process has the above mentioned ratio value between 1.5÷3. Such solution enables to minimalize the versatility of strain on the length of the produced part. It should not be forgotten that in case of forward extrusion increase of the billet length causes the increase of the friction forces on the side surfaces of the extruded material, that leads to an increase of total extrusion force.

The velocity of material forming: in the extrusion process we can distinguish the velocity of the material flow, the velocity of the material forming (the velocity of the ram), and the strain rate (velocity of the strain changing). In order to achieve the most uniform structure and same mechanical properties the extrusion process should be carried out in such a way so that the material is shaped with the closest possible values. It necessary to control the ram velocity, that should be the highest in the initial phase of the extrusion, and it should decrease with the advancement of the process.

The temperature of material forming: the optimal extrusion temperature can be defined on the basis of the thermal balance of the process that takes into account the heat:

- delivered by the billet material,
- delivered as a result of friction work change and plastic deformation work,
- transferred to the equipment (container, ram, die) and outside.

The calculated range of temperatures of hot extrusion of various materials is presented in the chapter 3.2.2.

Geometry of equipment: it is important for the extrusion process to choose a suitable shape of the die and the ram (dummy block). In a typical die used in this process we can distinguish three zones (Fig. 3.17):

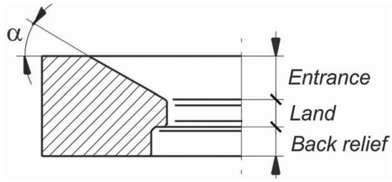


Figure 3.17. *Typical structure of the extrusion-die used in the forward extrusion process*

- entering, where the reduction of the material cross-section takes place;
- calibrating (land), where the final forming of the extrusion cross-section takes place;
- back relief.

The extrusion dies can have one or several holes, when a few parts are extruded simultaneously. Dies with multiple holes are used to extrude products with a small cross-section. Depending on the used shape of the inlet section we can distinguish the following types of dies (Fig. 3.18), flat, conical, flat-conical, double-conical, bow.

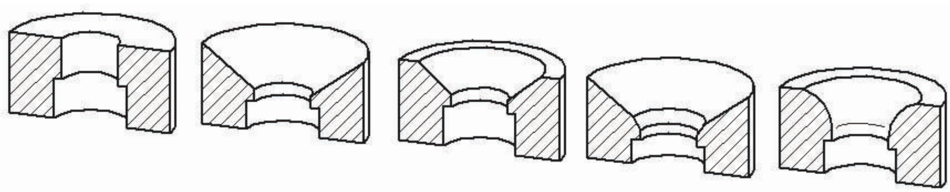


Figure 3.18. *Types of extrusion-dies for forward extrusion process (from the left): flat, conical, flat-conical, double-conical, bow*

In the process of forward extrusion the dummy blocks (Fig. 3.2) are used, that separate the material from the ram. Its diameter is smaller by 1÷2 mm than the diameter of the container and its working surface can be flat, convex or concave (offers the best evenness of the material flow).

On the next Fig. 3.19 there is shown the typical shape of punch used in the backward extrusion process (i.e. instead of dummy block). Particularly significance in this case, is a proper design of the length of the cylindrical zone *a*. It should ensure obtaining a shape of the hole in the extruded part of a quality predetermined to achieve with the least possible forming force.

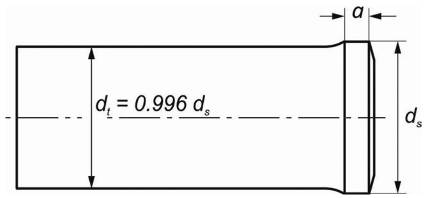


Figure 3.19. *Shape of the punch used in the cold backward extrusion process*

In the hot production of intricate hollow and semi-hollow shapes the bridge-chamber type extrusion-dies are used (Fig. 3.20). During extrusion in this tooling equipment (called extrusion with welding) the material is slit on the extrusion bridge die and formed metal flows are passing through the inlet ports to the welding chamber where they are combined. The hollow shapes produced this method have a characteristic longitudinal welds, the number of which depends on the construction of the used die [17, 18].

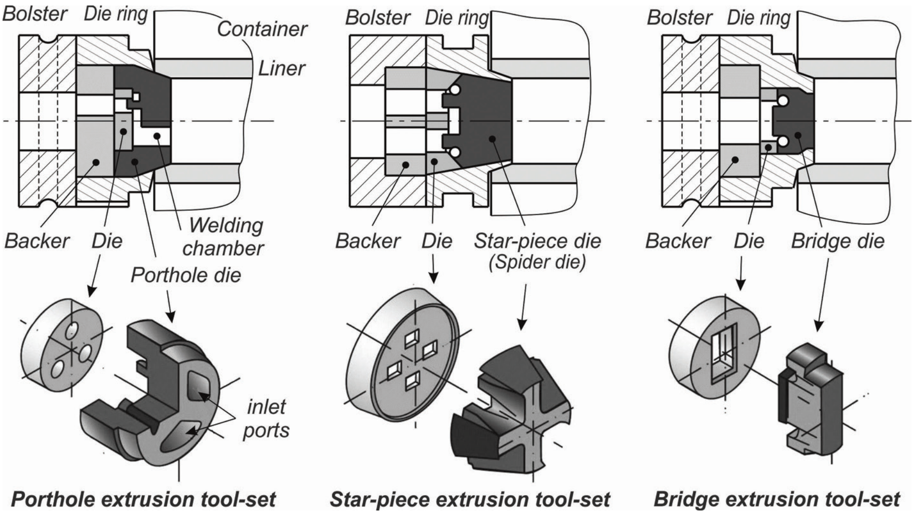


Figure 3.20. *The bridge-chamber type tool-sets used in hot extrusion process of hollow and semi-hollow shapes; according to [17]*

3.4. Extrusion force

The extrusion force is a deciding parameter in regards of the tooling equipment construction and the selection of materials for particular tools. It is also crucial for the selection of the adequate machine (press) ensuring the appropriate realisation of the extrusion process. Fig. 3.21 shows the dependence of the extrusion force *F* from the path of the ram in the processes of forward extrusion, backward and hydrostatic extrusion.

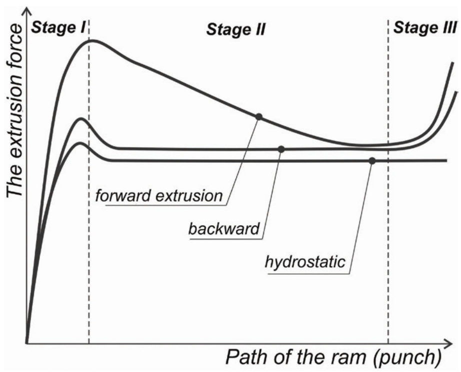


Figure 3.21. *The extrusion force course chart in the process of forward, backward and hydrostatic extrusion; description in the text*

At the beginning of the process (stage I) the force *F* is increasing to reach the maximum value, which is the highest in the forward extrusion, and the lowest in the hydrostatic extrusion. At this stage the upsetting of the billet takes place (its diameter is smaller than the diameter of the container), from the moment the material fills the container completely.

At the next phase of the process (stage II) the steady outflow of the material from the die takes place. The value of extrusion force is constant at this stage in the case of backward extrusion and hydrostatic extrusion, or it decreases (as a result of the decrease of the billet length leading to the reduction of the friction forces) in the forward extrusion process. This stage of the process is also called laminar extrusion.

At the last phase of the process (stage III) a sudden increase of the force *F* takes place, being a result of a low height of the material remained in the container. The material located in the dead zones starts to flow, what requires a forming force increase. In this phase of the process a characteristic sink hole can be formed at the end of billet, visible on Fig. 3.16.

The extrusion force depends on many parameters such as: type of the shaped material, extrusion temperature, velocity of the ram movement, type of the lubricant, geometry of the tools. For example, in the forward extrusion process the angle of the cone of die α has a great influence on the force *F*. Results of research on this matter showed that the decrease of the die angle α initially leads to a decrease of force *F* and subsequently to its increase – Fig. 3.22. The optimal angle of the die cone (depending on the other parameters of the process) is usually between 45÷30°.

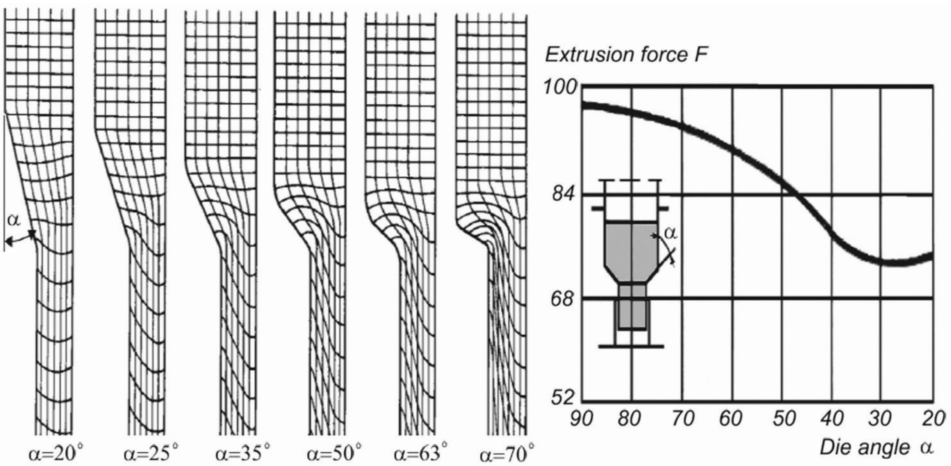


Figure 3.22. *The influence of the die angle on the material flow (shows by deformation of a flow net) and on the maximal force in the forward extrusion process [23, 33]*

An estimation of the value of the extruding force F can be calculated with the following relation:

$$F = S_0 \; k \; \ln\frac{S_0}{S_1} \tag{3.3}$$

where S_0 and S_1 are the areas of the cross-section of the billet and the extruded part, and k is the extrusion constant, that can be selected using the diagram shown on Fig. 3.23.

3.5. Friction and lubrication in extrusion process

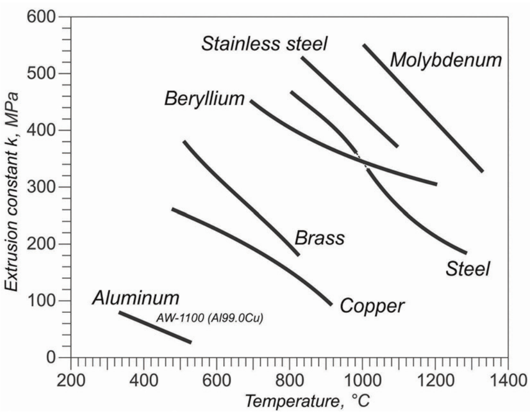


Figure 3.23. *Extrusion constant k for various metals at different temperatures [9]*

Friction has a great influence on the course of the extrusion process. It causes an occurrence of shear stresses on the contact surface that alter the scheme of stress state, cause inequality of deformation and an increase of the extrusion force. Friction acts as a brake on the flow of material in the subsurface layers and, therefore, in the extrusions produced in the process without lubrication folds of transverse lines of the flow net can be found (Fig. 3.24). What is more, the friction significantly increases the wear of the tools. Please note that the size of the dead zone changes, too.

In order to reduce friction, lubrication of the tools or the billet is used. It is important that the lubricant has sufficient viscosity in the processing temperature and creates a thin, continuous film resistant to high pressure in the container. The lubricant should not contain ingredients which could negatively affect the shaped material and should have the friction coefficient as little as possible. In addition, it should have good insulating properties, in order to prevent the billet material from cooling, and at the same time protect the working surfaces of tools against overheating.

Usually, during hot extrusion of steel a lubricating medium made of flake graphite and vegetable oil mixture is used. Such media have low friction coefficient but also high thermal conductivity. That is why they cannot be used in extrusion of products with great length. Additional drawback of these lubricants it that the scale sticks to them, and it is very hard to remove with compressed air that is used to blow through the dies. In the case when the oil burns, it produces a smell unpleasant for the service workers. Because of the mentioned reasons other lubricants are gaining popularity, for example glass (in the form of canvas, wool or powder) or a mixture of water-glass (i.e. the sodium silicate) and the graphite that are free of aforementioned disadvantages.

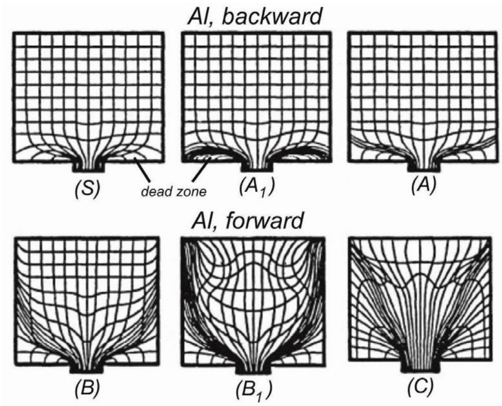


Figure 3.24. *Deformations of the flow nets put on the cross-section of the extrusions, while there is: A – no friction between material and container, B – friction between material and container, S – lubrication with water-glass, C – container temperature lower than the billet temperature, A1, B1 – data for aluminum [20]*

Glass has low thermal conductivity and when applied on the surface of the heated material it sticks to it and works as a protective layer that separates the material from the tool. With appropriate viscosity and lubricating properties in defined extrusion conditions pure glass (or water-glass mixed with graphite) acts as a very good lubricant.

In the process of cold steel extrusion very good results are achieved with phosphatizing the billet surface and subsequently submerging it in soap emulsion. This solution causes the decrease of extrusion force by 20% compared to the material coated with a layer of copper, by 50% compared to the material lubricated with machine oil, and by 65% compared to the extrusion process without the use of any lubricant. In the processed of cold extrusion of parts from copper and aluminum alloys, good results are achieved with the use of a paste containing machine oil and powdered graphite mixed in the ratio 1:3.

3.6. Extrusion of forgings

Basic use of extrusion technology is the production of various types of solid and hollow or semi-hollow shapes in the steelworks or the non-ferrous metal extrusion plants. Examples of typical extruded shapes is shown on Fig. 3.25. The additional application of extrusion method has been produced the die forgings in forging plants.

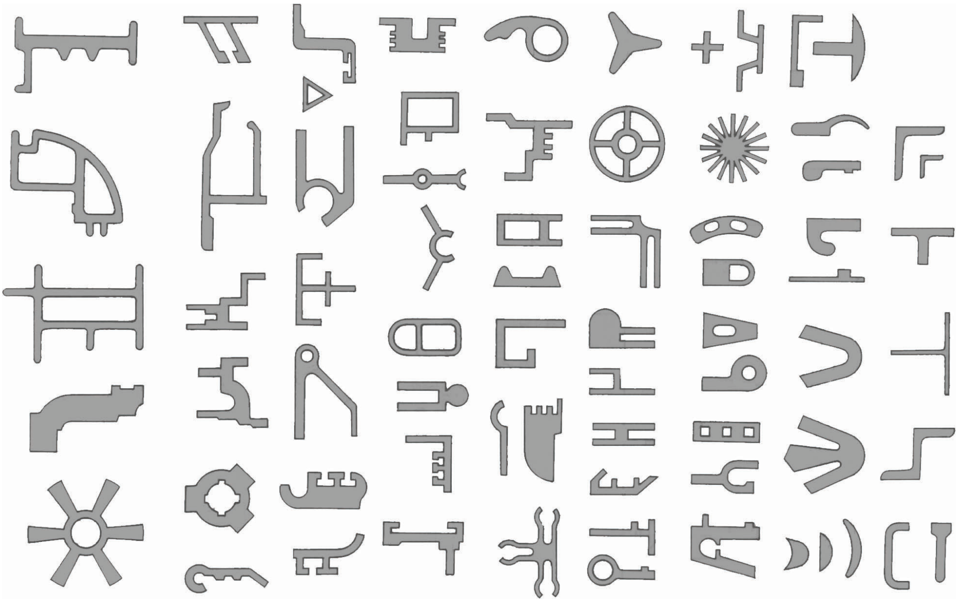


Figure 3.25. *Production range of solid, hollow and semi-hollow shapes produced in the extrusion process [31]*

3.6.1. Classification of forgings

Range of the forgings produced in a hot extrusion process, depending on their shape can divided into the following groups (Fig. 3.26):

- Group I includes shaft forgings having a single subsidiary element at the end or in the middle. Forgings in this group have two main parts, i.e. the shaft and the element which may have a completely different shape. For example, the shaft can be cylindrical, conical or can even have offsets. In contrast, the subsidiary element is usually cylindrical, conical or spherical, it may be smooth or have recesses. Forgings from this group are usually made using forward extrusion (sometimes, to shape the subsidiary element with a more complex geometry additional die forging process is used).
- Group II includes forgings with a more complex shape, that have a fork at the end or an asymmetric subsidiary element and a one-sided shaft of any desired shape. In the forward extrusion process the shaft of the forging is shaped, the element is formed by forging process in divided dies.
- Group III includes forgings with through holes or blind, usually with flanges. In addition, it also includes forgings that are forked with through holes. The sleeve part of the forgings is produced by extrusion. The flanges or forks are made by extrusion process with using opened-type dies or by additional die forging process.

- Group IV includes forgings of a very complex shape having: two or more subsidiary elements, side elements, one-sided recesses, forks etc. Production of this kind of forgings requires the use of special divided dies.

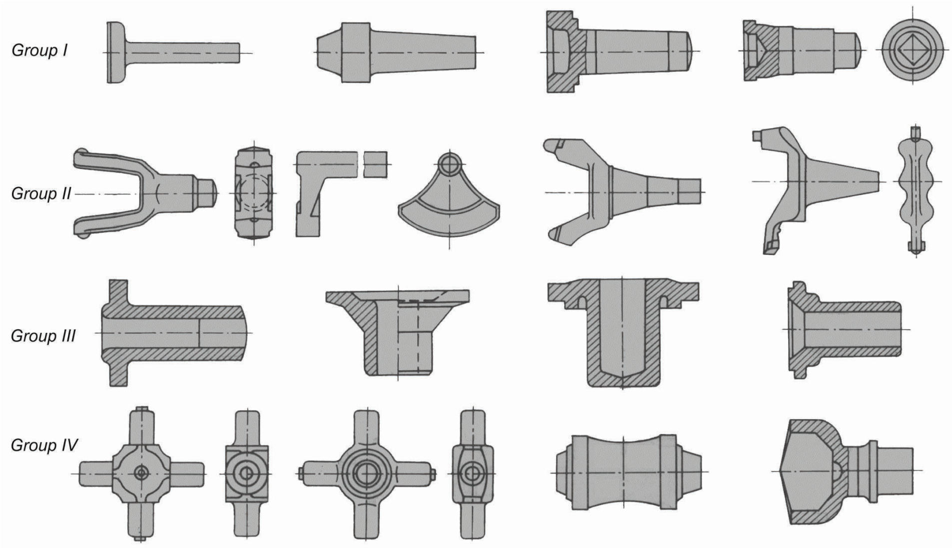


Figure 3.26. *Classification of forgings made with the hot extrusion process [31]*

3.6.2. Defects of extruded products

During the extrusion process interference of the forming stability may occur, as a result of which the produced forging is defective and often not suitable for use. The most common defects of extruded products include:

Delaminations, which are caused by high temperature of material shaping causes incipient melting of the material that subsequently leads to cracking of the product (so called a hot shortness).

External cracks caused by excessive roughness of the surface of the tools used in the extrusion process.

Heterogeneity of material deformation as consequence of the dead zone in which the material is not being deformed.

Properties and structure change (e.g. grain growth) due to heterogeneous material flow.

Central bursts (so called Chevron cracks), resulting from excessive flow velocity variation of the material that flows from the die, respectively in its centre and in the top layer. The inclination to forming of cracks increases when the zones of plastic deformation created by the influence of the die do not overlap of meet each other (Fig. 3.27). The increase of the size of the plastic zone can be achieve by a decrease of the convergence angle of the die and/or increase of cross-section reduction.

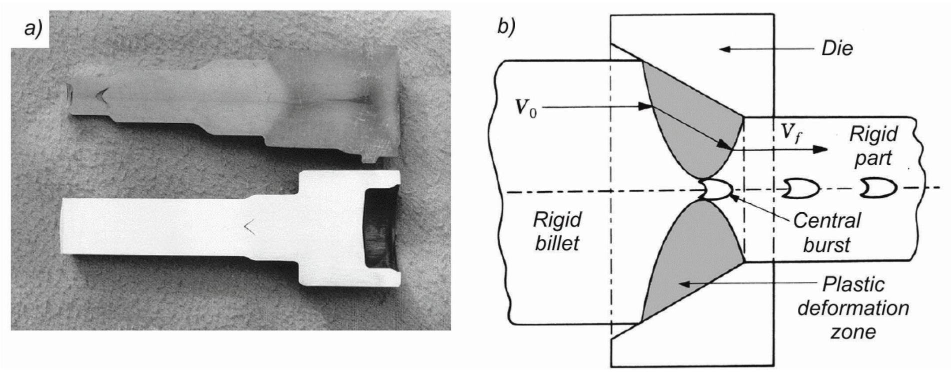


Figure 3.27. *Chavron cracks in the extruded steel bars (a) and a schematic illustration of distribution of rigid and plastic deformation zones in a extruded product (b) [1]*

4. Forge rolling

The rolling technology, widely used in metallurgy, is also more often used in the forging industry to shape preforms and forgings like stepped axles and shafts. The forge rolling technology is situated between the metallurgic rolling (i.e. flat, shape, ring and tube rolling) and forging (i.e. roll-forging, cross and skew rolling), is broadly described in the handbook [19].

The process of forge rolling are usually carried out in the conditions of hot plastic working. Depending on the type of movement, shape and position of the rollers (tools), it can be distinguished the three methods of forge rolling (Fig. 4.1):

- roll-forging (Fig. 4.1a) in which: the material is drawn to the rollers with parallel axes, rotating in opposite directions, the tangency points of the roller with the shaped material are moving along the length of the rolled billet; the roll-forging is a type of a flat rolling method, which is usually used to hot rolling preforms;
- cross-rolling (Fig. 4.1b), in which: the material is rotating, rollers with parallel axes rotate in the same direction, and the tangency points move along the circumference of the material, in the plane perpendicular to its axis;
- skew-rolling (Fig. 4.1c), in which the material makes a progressively-rotating movement, the rollers are inclined relative to each other, rotating in the same direction, the tangency points of the rollers with the material move along the material.
-

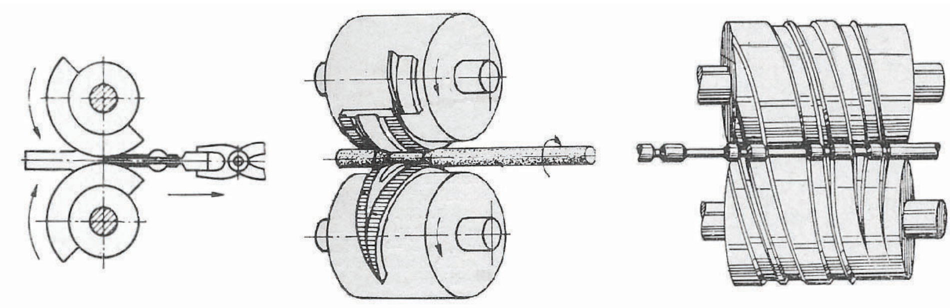


Figure 4.1. *The forge rolling methods [23]: a) roll-forging (flat-rolling), b) cross-rolling, c) skew-rolling (note: in all cases is shaped the same preform*

4.1. Roll-forging

4.1.1. Parameters characteristic for flat rolling

The simplest case of flat-rolling is the forming a strip with rectangular cross-section on smooth rollers (barrel) – Fig. 4.2. As a result of the friction forces that act between the workpiece and the rolls, the strip is drawn between the rollers and deformed. As a result of the impact of the roller on the strip (within the area delimited by cross-sections AA and BB, so called roll gap – Fig. 4.2) its height decreases from h_0 to h_1. At the same time the length and width of the strip increases, respectively from l_0 and b_0 to l_1 and b_1. Measurements of plastic deformation used in the process of flat-rolling are the following:

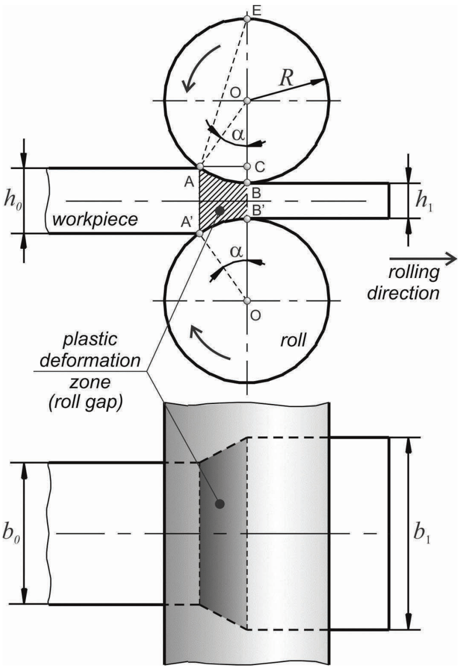


Figure 4.2. *The plastic deformation zone in the flat-rolling process [23]*

- absolute draught (reduction)

$$\Delta h = h_0 - h_1 \qquad (4.1)$$

- absolute spread

$$\Delta b = b_0 - b_1 \qquad (4.2)$$

- absolute elongation

$$\Delta l = l_0 - l_1 \qquad (4.3)$$

- relative reduction

$$\varepsilon_h = \frac{\Delta h}{h_0} = \frac{h_0 - h_1}{h_0} \qquad (4.4)$$

- relative spread

$$\varepsilon_b = \frac{\Delta b}{b_0} = \frac{b_0 - b_1}{b_0} \qquad (4.5)$$

- relative elongation

$$\varepsilon_l = \frac{\Delta l}{l_0} = \frac{l_0 - l_1}{l_0} \qquad (4.6)$$

- coefficient of reduction

$$\gamma = \frac{h_1}{h_0} \qquad (4.7)$$

- coefficient of spread

$$\beta = \frac{b_1}{b_0} \qquad (4.8)$$

- coefficient of elongation

$$\lambda = \frac{l_1}{l_0} = \frac{S_0}{S_1} \tag{4.9}$$

where: S_0 – cross-sectional area of workpiece, S_1 – cross-sectional area of strip after rolling.

In the case when the rolling process is carried out in several roll passes, the total coefficient of elongation λ_c equal to the product of the elongation coefficients λ_1, λ_2, λ_3, … λ_n in particular roll passes.

$$\lambda_c = \lambda_1\ \lambda_2\ \lambda_3 \ldots \lambda_n \tag{4.10}$$

where: n – number of passes.

The roll bite condition

Biting the strip by the rollers is achieved thanks to the tangential frictional forces acting at the contact surface between the rolled material and the tool. Distribution of forces acting during the rolling process at the moment when the material is bite is shown on Fig. 4.3. The condition for biting is that the horizontal component T_x of the tangential friction force T is greater than the horizontal component N_x of the radial force N. After considering the trigonometric dependence of this condition can be written as

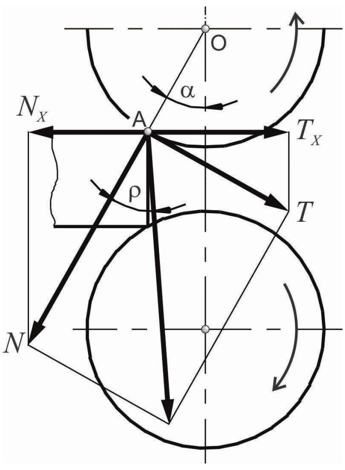


Figure 4.3. *Roll forces acted on the strip at the moment of biting*

$$T \cos\alpha > N \sin\alpha \tag{4.11}$$

where: α – angle of bite, formed by the radius of the roller passing through the point of the first contact of the strip with the roll and the vertical line connecting both roller centers – Fig. 4.3. Frictional force T on the basis of the Amontons-Coulomb friction law can be described as:

$$T = N\ \mu = N\ tg\rho \tag{4.12}$$

where: μ – friction coefficient, ρ – friction angle (μ = tgρ). Substituting the relation (4.12) to the inequality (4.11) after transformation we finally get:

$$tg\rho > tg\alpha \quad \text{or} \quad \rho > \alpha \tag{4.13}$$

From the above relation it seems, that the biting and drawing the strip between the rollers occurs when the bite angle is smaller than the friction angle.

4.1.2. Phenomena occurring in roll gap

The rolling process depends on several parameters, but the most important of them is the elongation, which greatly influences the intensity of metal forming. With a defined draught the elongation is the greater, the smaller spread is and vice versa. For this reason, flat-rolling process aims at minimizing the spreading value.

The spreading value (i.e. increase in strip width) can be reduced by:

- decrease of: rollers diameter, friction coefficient;
- increase of: velocity of rolling, forming temperature, the ratio of the strip width to the its height, number of passes.

The value of spread in the flat-rolling process can be estimated using e.g. the Siebel's equation [30]:

$$\Delta b = b_1 - b_0 = a\frac{\Delta h}{h_0\sqrt{R_{cz}\Delta h}} \tag{4.14}$$

where: a = 0.35÷0.45 (smaller value a should be assumed for the rolling temperature over 1000°C), R_{cz} – roller working radius, Δh – absolute reduction. However, better results can be achieved by using numerical modelling methods, where can be taken into account all parameters of a particular case of rolling process. Examples of the strip width increases during flat-rolling, calculated using FEM are shown on Fig. 4.4.

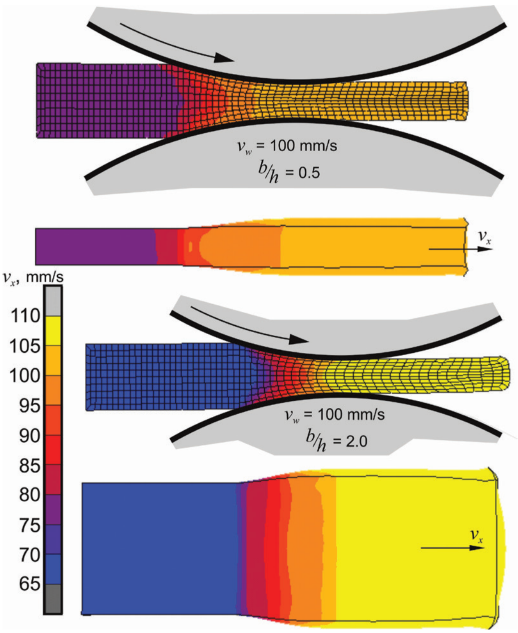


Figure 4.4. *The width of the strip increases (spreading) during flat-rolling process and the distribution of metal flow velocity in the x direction, depending on the dimension ratio b/h*

In the flat-rolling process the strip that enters the roll gap zone has a velocity smaller than the tangential velocity of the rollers. In contrast, the velocity of the workpiece exiting the zone is greater than the tangential velocity of the rollers. Therefore, there is a place on the surface of contact between tools and the shaped material, called no-slip point (or neutral point), where the rollers velocity is equal to the material flow velocity.

The increase in the exit velocity of workpiece relative to the tangential roller velocity v_w is called

forward slip. However, the occurrence a lower velocities of the workpiece at the entry zone is called **backward slip**. For numerical description of these phenomena the following relations are used:

relative forward slip s_w:

$$s_w = \frac{v_1 - v_w}{v_w} \tag{4.15}$$

relative backward slip s_o:

$$s_o = \frac{v_0 - v_w}{v_w} \tag{4.16}$$

where: v_1 – velocity of the material drawn between the rollers, v_w – tangential velocity of rolls, v_0 – velocity of the material exiting the rollers (i.e. roll gap zone).

Many factors influence the value of forward slip in the flat-rolling process. Intensification of this phenomenon is caused by an increase of: roller diameter, friction coefficient, relative reduction ,and the forming temperature.

4.1.3. Rolling of preforms

Designing of the flat-rolling (i.e. roll-forging) processes for preforms (in the sense of a final product of the rolling process) includes:

- construction of the final product and defining the dimensions of the initial material (billet);
- determining the arrangement of the roll grooves on the roll barrels;
- calculation of the dimensions of the roll grooves for the assumed roll passes system (wherein the space between surfaces of two roll grooves is named the roll pass);
- determining basic force parameters of the flat-rolling process.

Designing of the preform (of course as a final product of the rolling process) is conducted in a way similar to the die forgings shaped on the hammers, shown in chapter 2. Knowing the shape and dimensions of the rolled preform, an initial material cross-section S_0 is determined:

$$S_0 = (1.05 \div 1.2) S_{p\max} \tag{4.17}$$

and an initial material length l_0 is:

$$l_0 = \frac{V_{ip}}{S_0} z \tag{4.18}$$

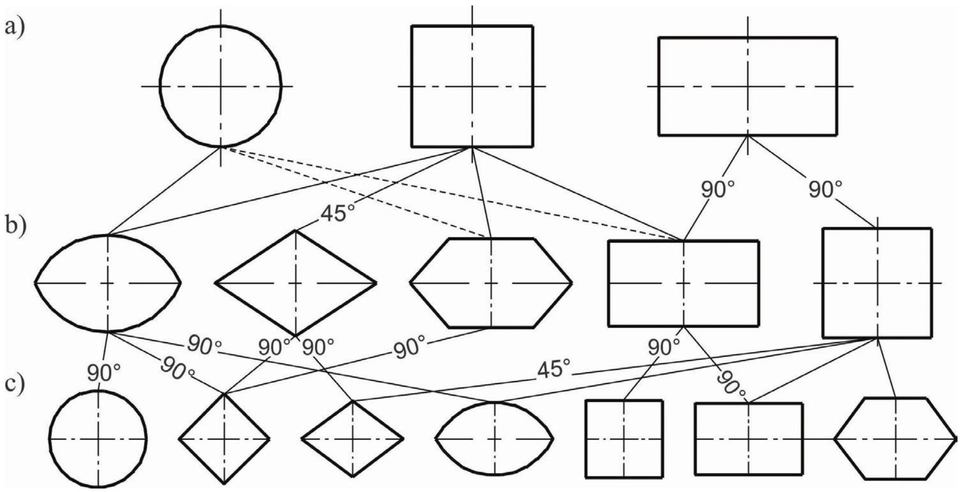


Figure 4.5. *The roll passes systems for design a elongating roll groove, where: a) cross-sectional shape of initial material, b) the first pass, c) the second pass [19]*

In the formulas (4.17) and (4.18) the following assumptions are made: S_{pmax} – largest cross-sectional area of the preform, V_{ip} – volume of the ideal preform, z – loss coefficient for scale.

Depending on the shape and dimensions of the preform the rolling process is carried out with one or several roll passes. Several basic roll passes systems are distinguished, of which a schematic illustration is shown on Fig. 4.5. Combination shown on this figure can be repeated the desired number of times. More complex roll pass shapes can be assumed, which, however, causes considerable difficulties in calibration of the tool segments and their subsequent machine-making.

In order to determine the dimensions of the roll pass (in the selected roll passes system), several different methods of roller calibration can be used. These methods are developed by: Spiess, Haller, Bachtinov-Shtiernov, Smirnov, Atroshenko, Kaufman, Martynov and Chamouard-Bielin. A detailed description of proceeding when rolls calibrating using the mentioned methods, specified in the resources [5, 19], is far beyond the scope of this study. Below only rollers calibration according to Martynov's method is described, which was used in the example illustrating the use of the flat-rolling a preform in the closed-die forging process a connecting rod part.

Martynov recommends the use of special nomograms in the determinations of the shape for the roll passes system: round – oval – round (Fig. 4.6) and round – oval – square. The dimensions of the roll passes can be read from the nomograms, depending on the desired total elongation coefficient and the starting rod diameter d_0. Knowing the diameter d_0 a horizontal line is drawn through the corresponding point (in the upper part of the nomogram) to the intersection of the curves corresponding to the desired value of total elongation coefficient λ_c.

Then the values of the radius of the oval R_{ow} are read (left part – the top of the nomogram) and the height of the oval h_{ow} (right part – the top of the nomogram). The calibration ends with the reading of the width of the oval b_{ow} on the vertical scale in the lower part of the nomogram, corresponding to the assumed value R_{ow}.

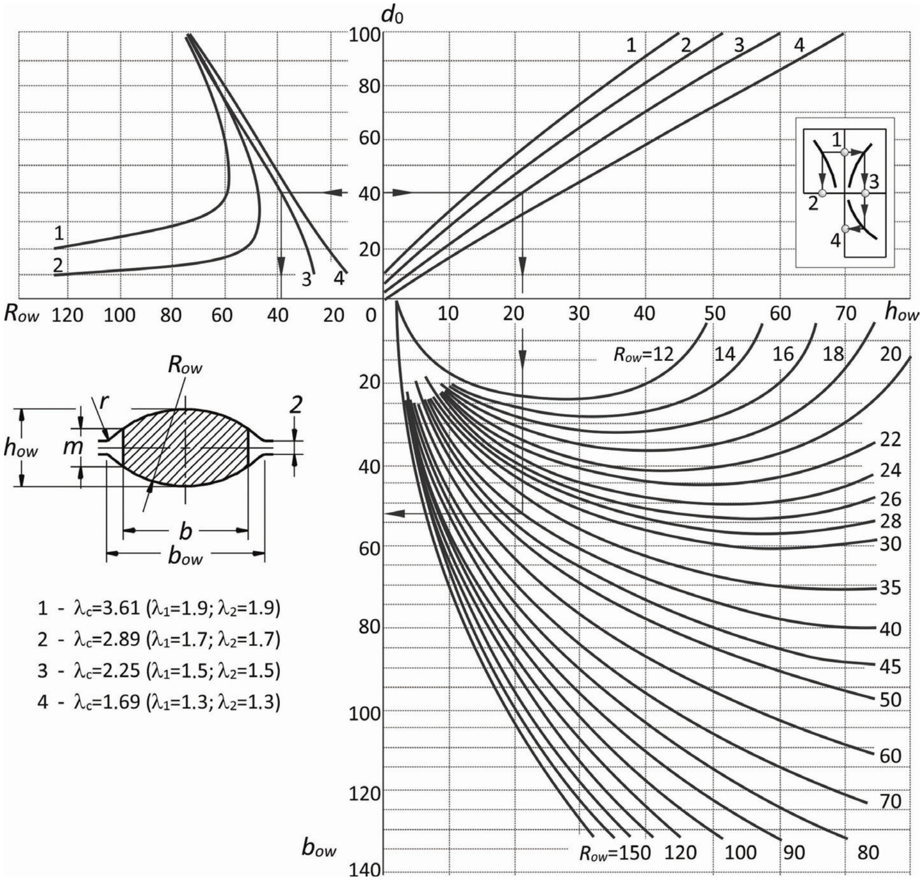


Figure 4.6. *Nomogram for determining the dimensions of roll grooves (oval pass) in the rolls passes system: round – oval – round [19]*

The length of the roll pass is calculated as follows:

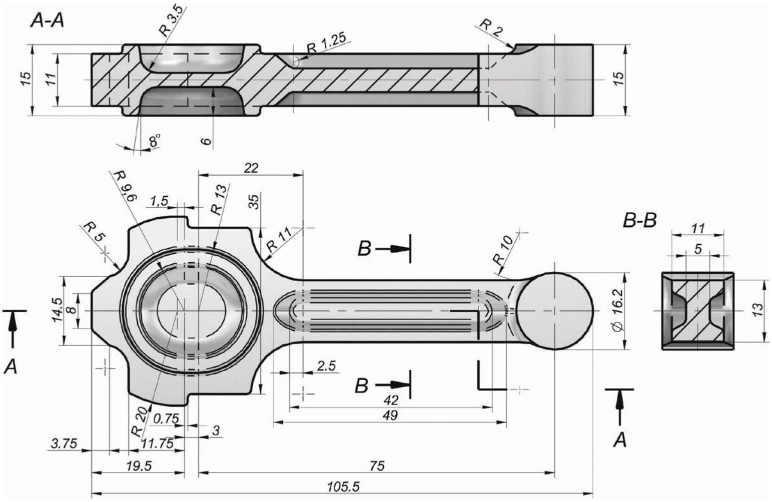
$$l_w = \frac{l_n}{s_w + 100} \tag{4.19}$$

where: l_w – the length of the roll pass or its parts measured along the arc with the radius R_{cz}, l_n – length of the roll pass or its part in the hot state, s_w – forward slip on the given distance (usually $s_w = 4 \div 6\%$).

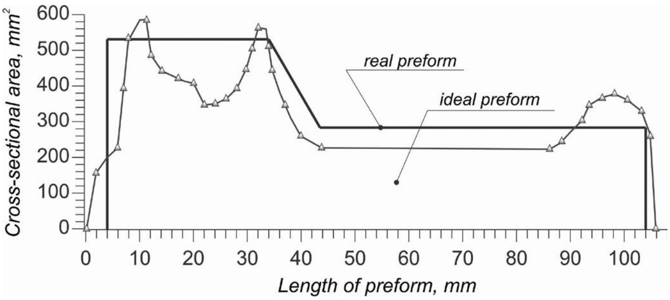
The example of using a roll-forging technology

The example of the closed-die forging process a connecting rod (Fig. 4.7), in which a flat-rolling process was used to shape preform is presented in this section of the chapter. It was assumed that this forging would be forged on the crank press with using the flash gap, where the land height *h* is equal 1 mm.

a)



b)



c)

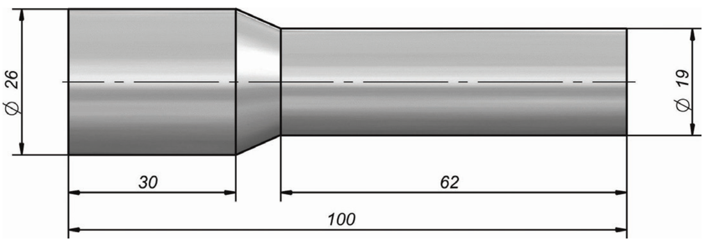


Figure 4.7. *Construct a rolled preform, where: a) forging, b) preform volume distribution, c) final shape of real preform [23]*

The volume distribution of real preform (i.e. a diagram of cross-sectional area vs. length of rolled preform) was determined on the basis of the volume distribution of ideal preform (shown on Fig. 4.7.b). Both diagrams were made in an analogous way as for typical die forging shaped on hammers. Next, on the basis of the real preform volume distribution dimensions of the rolled preform were calculated and its drawing was made (Fig. 4.7c). The diameter of the initial material was assumed to be equal with the largest forging diameter, i.e. diameter d_0 is 26 mm.

In the next step, using the relation (4.9), the total elongation coefficient λ_c was calculated:

$$\lambda_c = \frac{S_0}{S_1} = \frac{26^2\ \pi/4}{19^2\ \pi/4} = 1.87 \tag{4.20}$$

For the obtained total elongation coefficient, rolling process can be performed in two passes: oval and round.

For determining the dimensions of the oval roll pass (i.e. the first pass), the Mantynov's nomogram was used (Fig. 4.6), from which following data was read: the oval radius R_{ow} = 30 mm, height of the oval h_{ow} = 15 mm, width of the oval b_{ow} = 38 mm. In the next step, the cross-sectional area of the oval roll pass S_{ow} was calculated, using the approximate relation:

$$S_{ow} = \frac{\pi}{4} h_{ow} b_{ow} \tag{4.21}$$

which result was S_{ow} = 447.7 mm^2.

Then, using the law of constant volume, the length of the piece of a forging shaped in the oval pass was calculated, which is l_{ow} = 40 mm. Whereas the length of the first roll pass calculated from the relation (4.10), after accepting the forward slip s_w = 4%, was l_{w1} = 38.46 mm. The dimensions of the second (round) roll pass were imposed by the final preform drawing. The length of the round roll pass, calculated similarly as the first roll pass, was l_{w2} = 67.3 mm.

Taking into consideration the calculated rolls passes dimensions (corrected of reheating shrinkage of 1.5%), a roll segment for the rolling mill with the roll barrels diameter of Ø110 mm was designed, and it is shown on Fig. 4.8. The rolling process a preform of

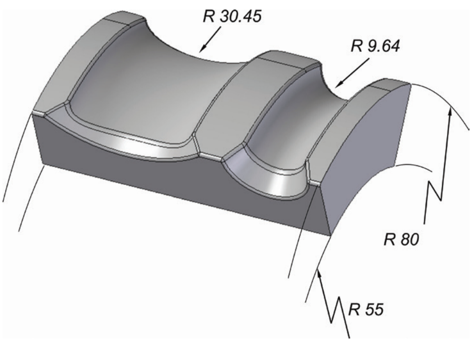


Figure 4.8. *The roll segment for rolling process a preform for closed-die forging a connecting rod*

the connecting rod forging was modeled numerically, using the finite element method (FEM). Thus designated successive steps of preform rolling process shown on Fig. 4.9. The closed-die forging process a forging from rolled preform shown on the next Fig. 4.10, which proves the correctness of the designed solution. Moreover, the analysis of obtained shapes of the forging with flash shows, that the further improvement of closed-die forging process by reducing the volume of flash is possible.

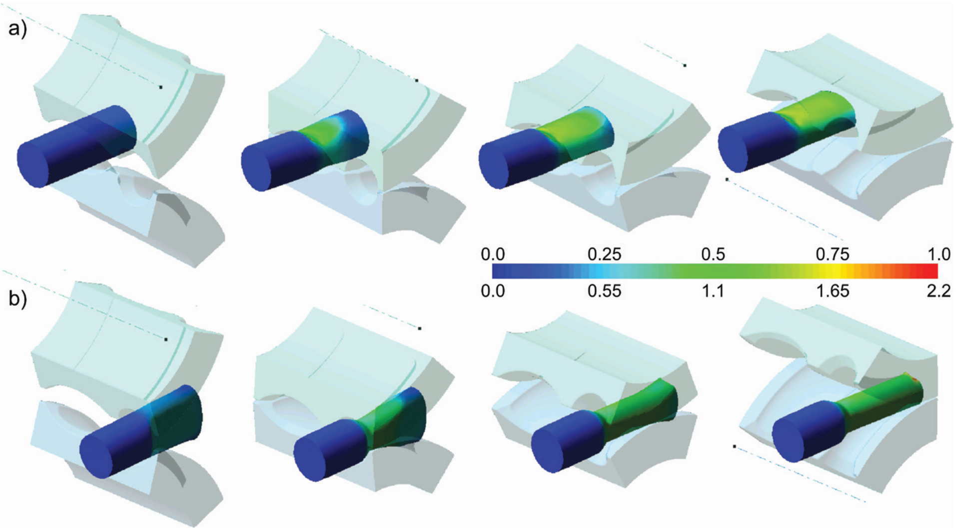


Figure 4.9. *The rolling a preform in the oval (a) and round (b) roll pass; the distribution of effective strain is shown*

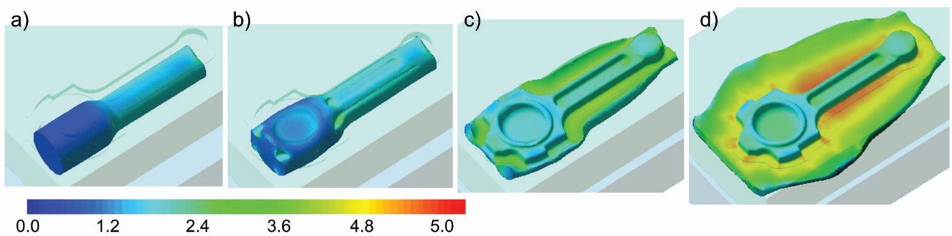


Figure 4.10. *The course of closed-die forging process a connecting rod from a rolled preform; the distribution of effective strain is shown*

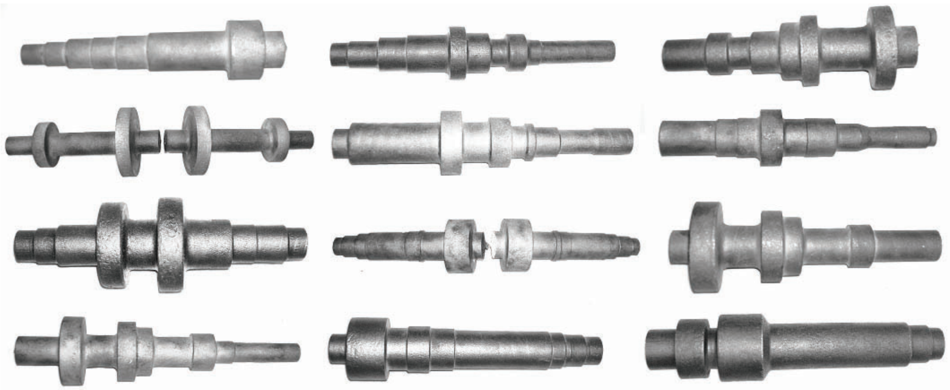
4.2. Cross-wedge rolling

The cross-wedge rolling (CWR) is a process in which axially symmetric parts with the help of wedge tools are formed. These tools are attached to the rollers or the plates of rolling mills. This process of rolling is usually performed under hot conditions [21, 22]. The CWR method is mostly used in large-lot and mass production of following parts:

- final products used mainly in automotive industry such as the shafts, multi-stepped shafts, camshafts and solid or hollow axle;
- semi-final products (the rolled forgings) used in automotive, engineering and aircraft industries such as the suspension system pins, steering mechanism pins, pinions, worms etc.;
- preforms used in the closed-die forging process such as spanners, connecting rods, levers, forks etc.;
- high-voltage insulator cores, rolled as a final-product;
- screw spikes, where the thread is rolled as a finished shape;
- steel balls for the ball mills.

The examples of products formed by the means of the CWR method are shown on a Fig. 4.11.

a)



b)

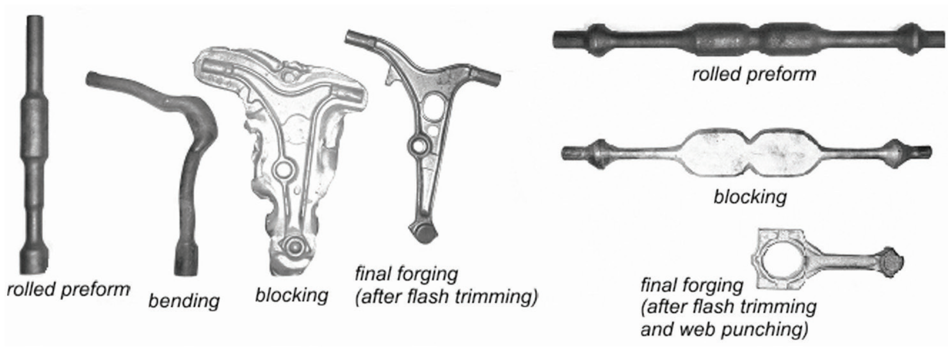


Figure 4.11. *Examples of products formed by means of cross-wedge rolling technology, where: a) forgings of stepped shafts and axle, b) preforms rolled and the forgings obtained using these preforms*

4.2.1. Parameters characteristic for CWR process

The main parameters of the cross-wedge rolling process include (according to a Fig. 4.12): the forming angle α, the spreading angle β, the billet diameter d_0, the forging diameter d and the rolling length l.

A typical wedge segment used during the CWR process consists of the following zones: knifing, forming (stretching) and sizing. In the knifing zone, the tool cuts into the material to a depth Δr, gradually reducing its diameter to the desired value d. In the forming zone, due to the reaction of side walls of the wedge, the diameter is reduced to the desired length $2l$. In the sizing zone, the material is subjected to rotational compression and it ensures removal curvatures and other shape irregularities of the rolled product generated in previous phases of the process. Behind the sizing zone, there are often cutting zone with side cutters which separate the deformed ends (discards) of the forged product. In the case of simultaneous rolling two or more parts, there are separating cutters at the end of the wedge segment. To make rotating the billet during the process easier, on the wedges side surfaces there are special technological serrations. Similarly, the guiding devices placed in the first zone of the wedge segment are serrations. Their aim is to stabilize the billet location during starting the rolling process.

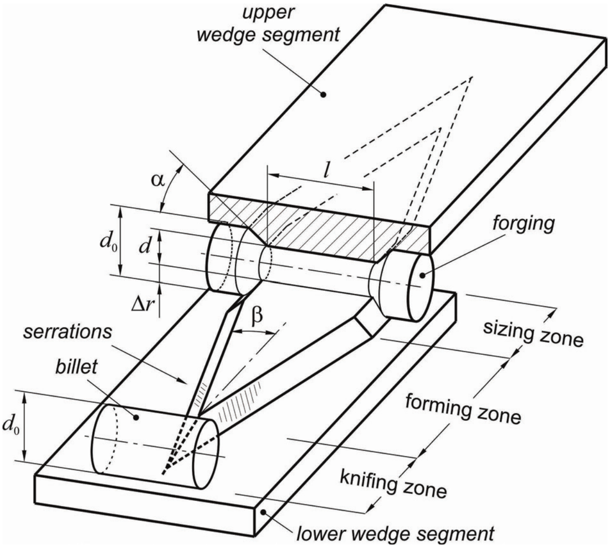


Figure 4.12. *Scheme of the cross-wedge rolling process using flat wedge segments*

To define the plastic deformation in the products formed with the CWR method, following expressions are used:

relative reduction (also called reduction ratio):

$$\delta = \frac{d_0}{d} \tag{4.22}$$

cross-sectional area reduction:

$$R_p = \left(1 - \frac{d^2}{d_0}\right) \cdot 100\% \tag{4.23}$$

4.2.2. Methods of CWR process

Depending on a course of the cross-wedge rolling process, following methods can be distinguished (Fig. 4.13):

- The conventional cross-wedge rolling method based on the diameter reduction – Fig. 4.13a. In this process, the diameter of the billet is reduced beginning from the middle to its ends. The cross-sectional area reduction is accompanied by free elongating of the forging in the axis direction.
- The inverted cross-wedge rolling method with upsetting – Fig. 4.13b. In this case, the diameter of the billet is reduced from both ends, beginning from the ends to the middle. As a result, the middle of the workpiece is affected by axial compression forces. When the stress value (caused by these forces) reaches the yield point, the middle part of the workpiece upsets. With this kind of the CWR method, forgings with diameters bigger (even of 25%) than the diameter of the used billet can be formed.
- The multi-wedge cross rolling method – Fig. 4.13c. In this method the workpiece is formed simultaneously by several pairs of wedges, however, its particular steps may be rolled using the conventional or inverted rolling method. Using the multi-wedge cross rolling process allows shortening the length of the wedge segments, even 3 times, but it is accompanied by increasing the forming load.

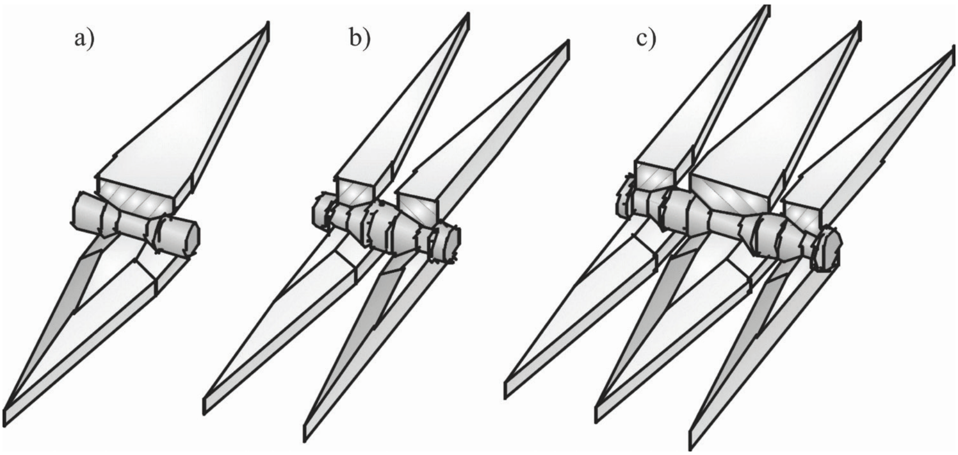


Figure 4.13. *The classification of cross-wedge rolling process: a) conventional CWR method; b) inversed CWR method with upsetting; c) multi-wedge cross rolling method*

Another classification of cross-wedge rolling methods may be performed taking into account the shape of wedges and the method of fixing them in the rolling mills. Using this criterion, there are following five variants (Fig. 4.14):

- The CWR in the configuration wedge roller – concave wedge segment (Fig. 4.14a). The forging is rolled between the powered roller with the convex wedge and the motionless segment, to which the concave wedge is attached. During rolling the forging, making the rotary motion around its own axis, it is rolled over the motionless segment. This CWR variant is characterized by the simplicity of construction, compactness of shape and high efficiency. However, making and preparing to work the motionless concave wedge is difficult.
- The CWR in the configuration two or three wedge rollers (Fig. 4.14b, c). The billet is placed parallel to the axes of rollers, rotating in the same direction. In the two-wedge cross rolling method, additional work guiders must be used, protecting the workpiece from its falling out from the rollers working area. In the case of using three rollers, besides the elimination of guiding the workpiece, the probability of metal cracks in the axial zone decreases. At the same time, because of the geometric restrictions, the length of the wedges is smaller. The advantage of such CWR schemes is the possibility of continuous rolling from a rod which makes these methods suitable for producing short forgings.
- The CWR in the configuration flat wedge segments (Fig. 4.14d). The tool segments of flat wedge rolling mills are easy to produce which makes rolling process in this scheme cost-effectively, even in the conditions of mean--lot production. The disadvantage of this method is the occurrence of dead movement of tools, which takes about 40% of one working cycle time and decreases the process efficiency.
- The CWR in the configuration two concave wedge segments (Fig. 4.14e). In this method, the workpiece is shaped between two moving concave wedge segments. Because of the complexity of the tools, this method has not been widely used in practice so far.

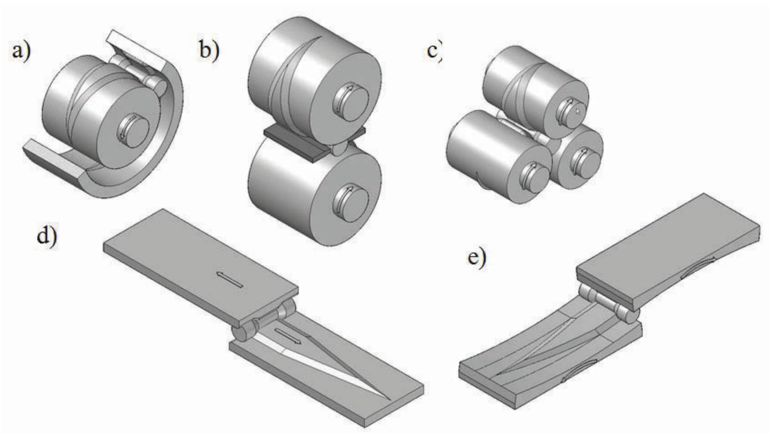


Figure 4.14. *Methods of cross – wedge rolling in configurations: a) wedge – concave segment, b) two wedges, c) three wedges, d) two flat wedges, e) two concave wedges*

4.2.3. CWR process limitations

The cross-wedge rolling process stability can be affected by the phenomena, for example the uncontrolled slipping between workpiece and tools. Moreover, during the CWR process the workpiece core necking or the axial cracks can be occurred.

Uncontrolled slipping phenomenon

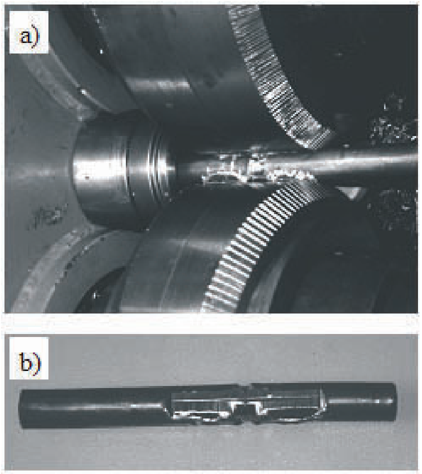


Figure 4.15. *Uncontrolled slipping phenomenon: a) the CWR process view, b) forging with defect*

Uncontrolled slipping occurs when a sum of force moments causing the workpiece rotation is lower than a sum of force moments opposing this rotation. In such case, the tool segments moving in opposite directions and tear surface layers of workpiece off (Fig. 4.15). A commonly used method preventing uncontrolled slipping is making on the side surfaces of the wedges technological serrations with a depth of 0.5÷1.5 mm, in a distance of 3÷5 mm from one another. In order to perform the stable CWR process without slipping, the following inequality must be met:

$$(0.25 + 0.0038\alpha)\beta^{0.925} \le 1.93 \qquad (4.24)$$

in which the forming angle α and the spreading angle β are expressed in degrees.

Core necking phenomenon

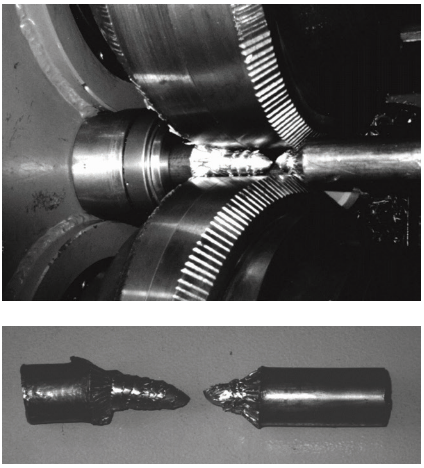


Figure 4.16. *Core necking of workpiece phenomenon: a) the CWR process view, b) forging with defect*

The core necking of the workpiece formed with the CWR method occurs when tensile stresses (caused by the action of axial component of the rolling force) reach the value of the yield point. Then the material suddenly starts flowing in the axial direction and it is accompanied by the workpiece necking (a neck characteristic for the tensile test is formed) until it cracks – Fig. 4.16. The core necking most usually occurs while using wedges with big α and β angles. According to Tsukamoto [28], it does not occur when the following inequality is met:

$$\frac{\sqrt{2tg\alpha\, tg\beta}}{\pi}\left(1+\sqrt{\frac{1}{\delta}}\right)(\delta-1)\le 0.2 \qquad (4.25)$$

where: α – forming angle, β – spreading angle, δ – relative reduction. In the case of cross-wedge rolling with upsetting the buckling occurs instead of necking.

Axial cracks phenomenon

Another limitation which often occurs during the CWR process are internal axial cracks in rolled workpieces, called the Mannesmann effect. The shapes of these cracks depend on used CWR method. In the case of a rolling with two rollers, axial-shaped cracks occur (Fig. 4.17) and in the case of process with three rollers, than ring-shaped, longitudinal cracks occur.

The mechanism of internal cracks is complex and it is attributed to low-cycle fatigue of metal. In most cases of CWR process, the layers of the metal (in the central part of the forging) are compressed in the normal direction to the tool surface and in the perpendicular direction to the normal direction – are stretched. After making ¼ of a turn, the stretched layers are compressed, and the compressed ones are stretched. Such scheme of stresses in metals leads with time to fatigue cracks. The condition for the CWR process stability without metal cracks was given by Hayama [12] as:

Figure 4.17. *Cracks in axial zone of the forging formed during CWR process*

$$(0.15+0.0038\alpha)\,\beta^{0.325}\ge M \qquad (4.26)$$

where angles α and β are expressed in degrees and M stands for material constant which should be taken from the range of 0.35÷0.4.

4.2.4. Wedge tools designing

Due to the similar mechanisms of forming process and the big sizes of wedge segments (fixed to the roll barrels) in comparison with the billet size, the tools are designed similarly for all CWR methods. The design process of tools geometry consists of determining the forming angle α and the spreading angle β. On the basis of these mayor parameters the other tool dimensions are designed (of course taking into consideration the size of reheated forging). The following relation may be used to calculate the spreading angle β:

$$\sin\beta = 0.009 \cdot \frac{\mu}{\sin\alpha} \tag{4.27}$$

where: μ – the friction coefficient taken from the range of 0.4÷0.5, α – the obtained forming angle (usually 15° ≤ α ≤ 45°). It should be remember that angles α and β must meet conditions of stable rolling defined by relations (4.24)÷(4.26).

When the value of angles α and β are known, a wedge segment can be designed. The explanation of the order of stages involved in tools construction was presented basing on the example of the forging shown on Fig. 4.18. The given methodology is based on using the three-dimensional system of computer-aided design (CAD 3D). Firstly, a solid with a cross-section corresponding to the sketch of the forging is created (the cross-hatched area, which in shown on Fig. 4.18). This solid is created by extrude (for flat wedges) or the revolve around its own axis (wedges placed on roll barrels) a tool cross-section – Fig. 4.19a. Then, starting from the middle of the segment, its part is cut at an angle β with a plane perpendicular to the surface of the tool basis. In the case of the wedge placed on the roll barrels, the cutting surface is a fragment of the helicoid (Fig. 4.19b). The next stage involves chamfering at an angle α (from the basis) the surface obtained after the previous stage. As a result, the side wedge surface is created, characterized by angles αand β – Fig. 4.19c. The next stages involve obtaining (analogically to the mentioned process) the forming surface on the second half of the tool (Fig. 4.19d). The construction of the wedge segment is completed with introducing the working edge radii and adding the output zone, placed directly behind the sizing zone.

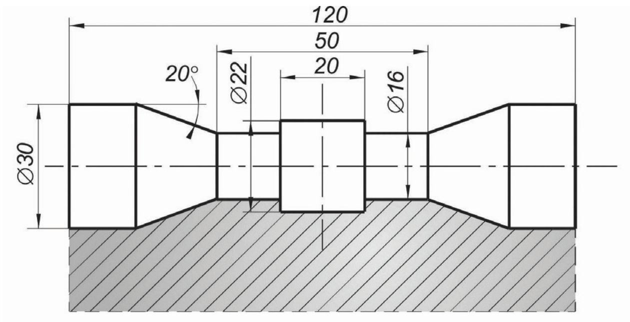


Figure 4.18. *Example of a symmetrical forging shaped with cross-wedge rolling method*

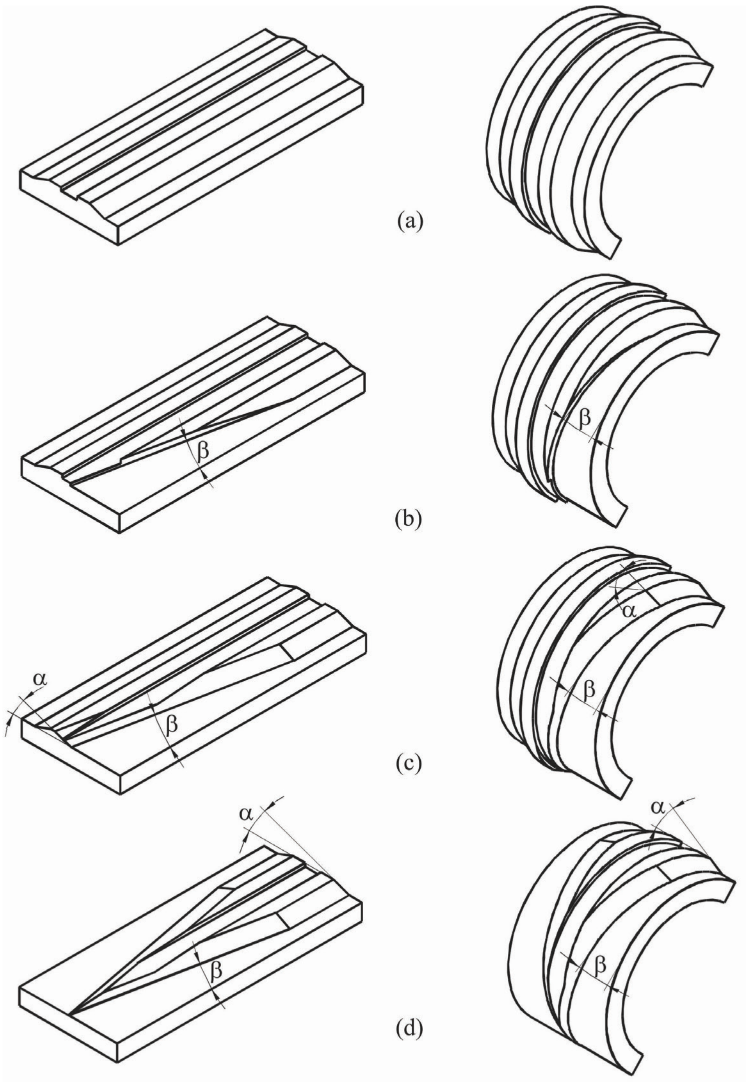


Figure 4.19. *Scheme shows the stages of wedge segment construction, which is destined to rolling a forging shown on previous Fig. 4.18 (description in the text)*

4.2.5. Example of using CWR technology in industry

The example of using CWR technology in industry is the process of rolling a forging of the transmission shaft (Fig. 4.20) with the ULS 70 cross-wedge rolling mill (Fig. 4.21). This mill is equipped in the rollers with the diameter of 700 mm. Due to the fact that the outermost steps of the shaft are shaped with the reduction ratio δ = 2.45, it was accepted that the cross-wedge rolling process would proceed in two stages (operations).

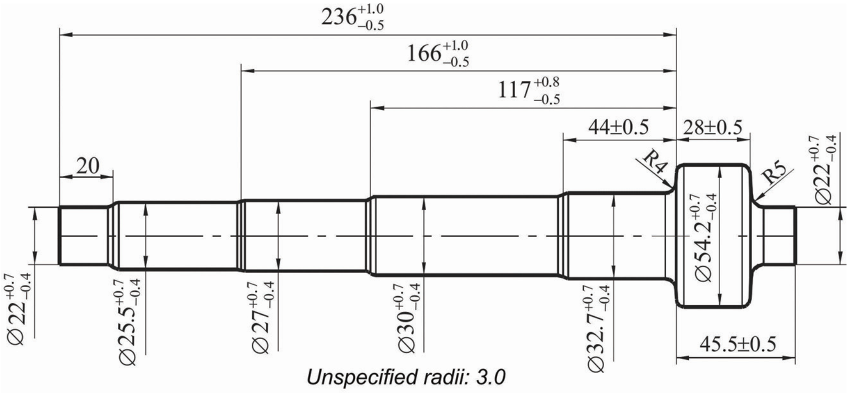


Figure 4.20. *Forging of transmission shaft rolled in configuration two rollers*

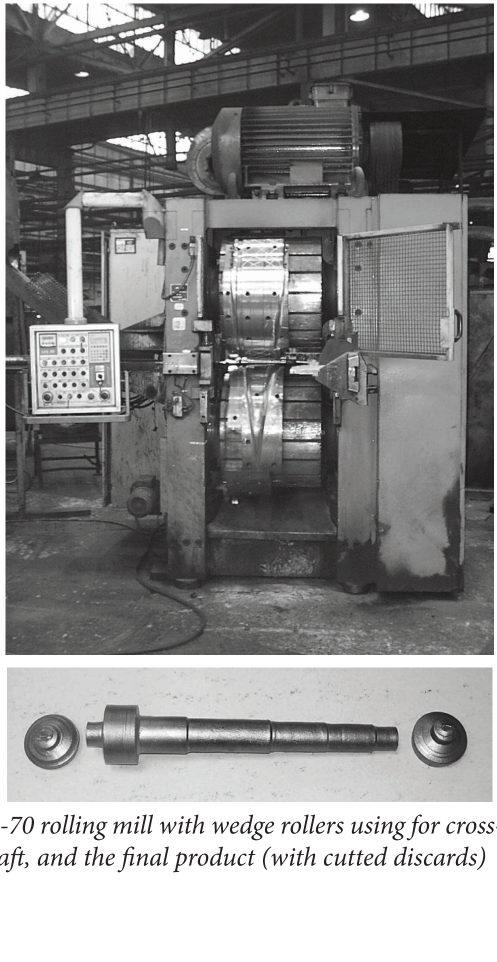


Figure 4.21. *The ULS-70 rolling mill with wedge rollers using for cross-wedge rolling forgings of transmission shaft, and the final product (with cutted discards)*

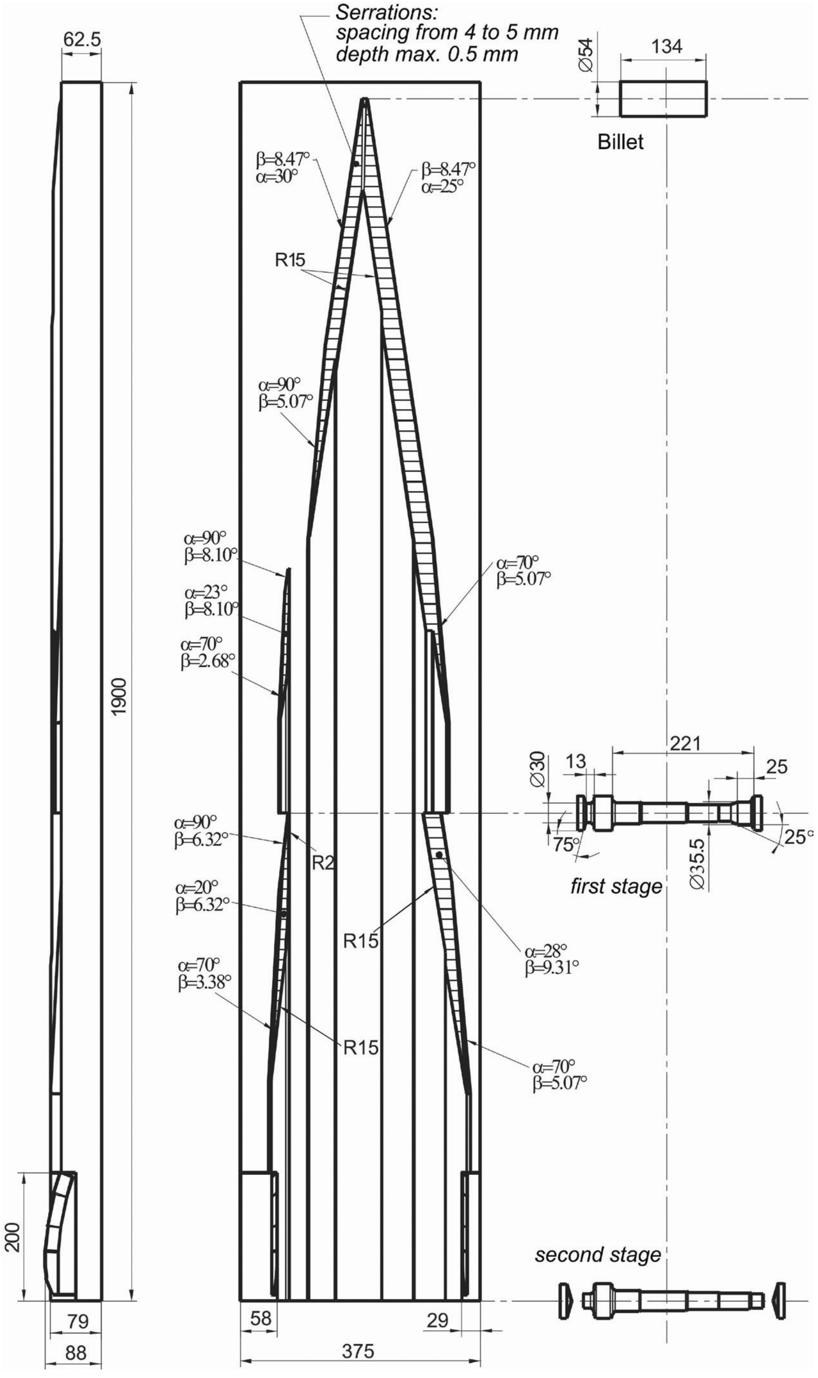


Figure 4.22. *Wedge segment for cross-wedge rolling a forging of transmission shaft (in the developed view)*

On Fig. 4.22 there is a wedge segment (in the developed view), enables the realisation of cross-wedge rolling a forging shown on Fig. 4.21. On the drawing there are also dimensions of the billet, some of dimensions of the forging after the first stage and the values of angle parameters describing the geometry of forming and auxiliary surfaces of wedges. Because of the shape of the forging, it was necessary to use the scheme of the rolling with cutting discards – i.e. deformed ends of forging, in which the funnels were formed. This discards, because of its location at the forging ends and the size of the diameter (equal to the billet diameter), plays also during the rolling the stabilizing role, protecting the forging from skewing.

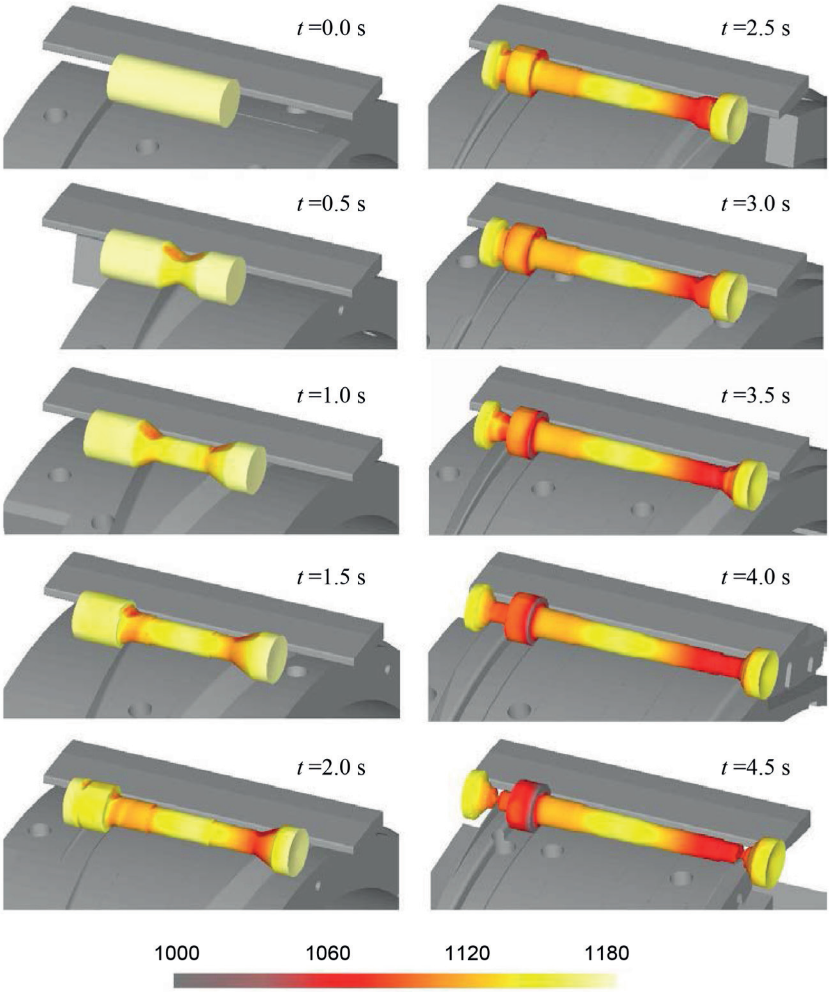


Figure 4.23. *Progress of forging shape during rolling process and distribution of temperature in material (in °C); to improve clarity, upper roller and one of work guiders were hidde*

The industrial tests performed in the ULS 70 rolling mill confirmed the correctness of the obtained assumption. The forging of transmission shaft shaped during the rolling process (Fig. 4.21) had dimensions in accordance with the tolerances.

In order to get to known what is happening during the implementation of the cross-wedge rolling process a the transmission shaft forging, its numerical simulation was performed with using the finite element method (FEM). On Fig. 4.23, there are shown the changes in the forging shape during the rolling process.

In the initial phase of the process, the wedges cut in the middle part of the billet and reduce its diameter. After forming three steps of the forging, located on the right of its head, the forging step located on the left (for time $t \approx 2.0$ s) is rolled to the intermediate diameter of Ø30 mm. The first stage ends after 2.6 s and the forging is sized on the short tool section (for $t \approx 2.5 \div 2.8$ s). Then the second stage begins. The outermost steps of the forging with diameters of Ø22 mm are shaped. This process ends after $t \approx 3.8$ s and then the forging is put in the next sizing zone ($t \approx 3.8 \div 4.2$ s) which aim is to remove the mistakes in shape (which were made during the previous rolling phases). In the final phase of the CWR process ($t > 4.2$ s) the discards are cut.

The Fig. 4.23 additionally shows how the metal temperature changes (the billet was reheated to the temperature $T = 1170$°C) during the CWR process. Despite the long time of rolling ($t \approx 4.5$ s), during which the forging touches the tools of lower temperatures (assumed $T = 250$°C), the fall of the metal temperature below the lower limit of the forging temperature was not observed. The lowest metal temperature occurs in the shaft head, which turns freely on rollers surfaces, giving them heat. However, in the formed steps the significant fall of the temperature was not noticed. This is an effect of compensating the heat carried to tools with the heat produced as the change of plastic deformation work and friction work.

4.3. Skew-rolling

The skew-rolling process will be presented using the example of rolling a ring – Fig. 4.24. This technology is widely used in bearing factories in Russia and the Timken company in USA. In the comparison with the punching, it has many advantages. They mainly include: lower metal consumption as a result of lack of bottom, which gives the total yield on the level 92÷94%; significantly higher efficiency reaching to 100÷2800 rings per hour, less number of tools and shorter time of tooling set-up on the rolling mill.

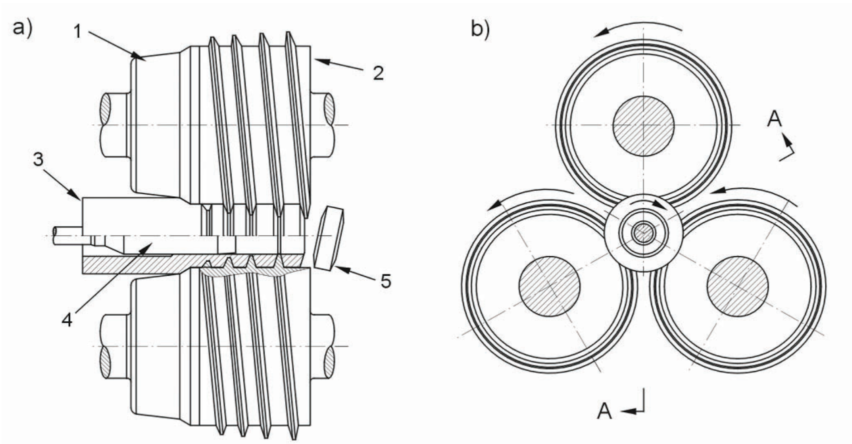


Figure 4.24. *Scheme of rolling rings in the three-roller skew-rolling mill: a) section along the deformation zone, b) front view, where: 1 – input cone for initial rolling, 2 – forming roller, 3 – tube billet, 4 – mandrel, 5 – final ring*

4.3.1. Skew-roll pass design

The roller (Fig. 4.24) used during the process of skew-rolling the ring consists of the input (conical) part and forming (helical pass) part. The input part gives the initial axial velocity (as a result of skew rollers location at an angle 3° to the axis of the billet) and the circumferential velocity of a tube billet on a cylindrical mandrel. Then the reduction of the billet diameter (its wall thickness) occurs and because of that, the good quality of inside and outside surfaces is obtained. The forming part of the roller is designed with a projection on the surface, in order to enable making products of specific shapes.

Skew-roll pass design process is very complex and difficult. During designing the pass, the rule of constant metal volume is obligatory ($V_{\Theta} = V_{\Theta + 360°}$ – where: Θ – an angle of the roller rotation). CAD software may be used for this aim. Assuming with a small simplification that the product during the whole forming process is the axially symmetric solid, its dimensions should be change in a way (in the function of a roller rotation angle Θ), which enables retaining its volume.

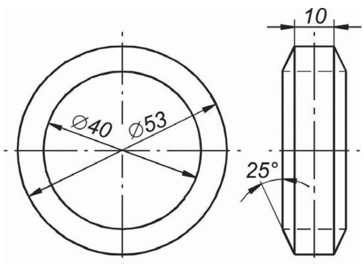


Figure 4.25. *The ring as a product of skew-rolling process*

On Fig. 4.25 there is a ring shown, formed during the skew-rolling process with three rollers of dimensions shown on next Fig. 4.26 [14]. The parameters change during rolling (depth of helical groove *h*, width of helical groove crest b, pitch of flank 1 and 2) are shown in function of a roller rotation angle Θ in a table 4.1

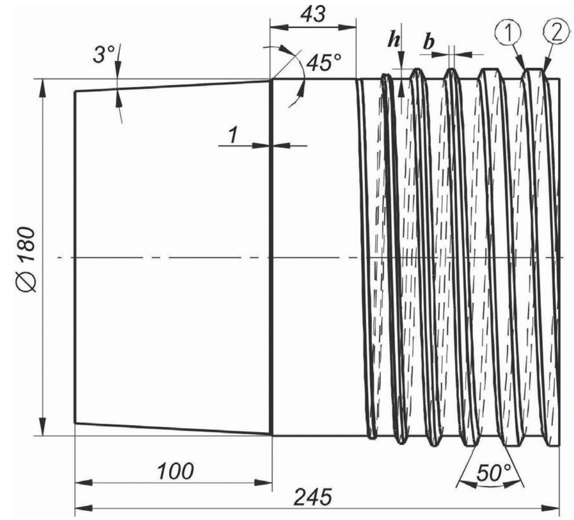


Figure 4.26. *Scheme of roller used during the skew-rolling a ring forging, where the major parameters are: b – width of groove crest; h – depth of groove; 1 and 2 – designation of groove flanks*

Table 4.1. *The parameters describing the shape of helical pass (grooves) made on the skew-roller shown on Fig. 4.26, as a function of a roller rotation angle Θ calculated from the moment of initiating the groove.*

Roller rotation angle Θ, °	Width of groove crest *b*, mm	Depth of groove *h*, mm	Pitch of flank 1, mm	Pitch of flank 2, mm
0 ÷ 360	2.50	0.00 → 2.50	14.03	14.03
360 ÷ 540	2.50	2.50 → 3.75	15.29	15.29
540 ÷ 630	2.50	3.75 → 4.37	16.00	16.00
630 ÷ 720	2.50	4.37 → 5.00	16.75	16.75
720 ÷ 1080	2.50	5.00	17.16	17.16
1080 ÷ 1440	2.50 → 7.50	5.00	17.16	17.16 → 27.16
above 1440	7.50	5.00	22.13	22.13

With using such rollers, forming the furrow on a workpiece surface (as an effect of increasing depth of helical groove *h*) is finished after two rollers rotations (when the angle Θ = 0°÷720°). Then, during the next rotation (when Θ = 720°÷1080°), with remaining the roll parameters, the ring forging is sized to obtain the deserved shape. During the fourth rollers rotation (Θ = 1080°÷1440°) the width of helical groove increases three times. As a result, the necking land (which connecting particular rings) should be ruptured. In the next zone of the forming part of roller (for Θ > 1440°), the roll parameters do not change and the final product (ring) separated from the tube workpiece is moved out of the roll gap.

4.3.2. Rolling progression

The skew-rolling process of rings using a three-roller rolling mill was modeled using FEM method. On Fig. 4.27, the geometrical model of this process is shown. It consists of three skew rollers (Fig. 4.26), the stationary mandrel with the outside diameter of Ø40 mm, the billet and the pusher (necessary to moving workpiece into the roll gap). The billet is the thick-walled tube with the outside diameter of Ø57.2 mm, the inside diameter of Ø44.4 mm, the length of 100 mm and is made of 100Cr6 steel. The rollers are located 120° from each other on the radius of 116 mm, in the relation with the middle

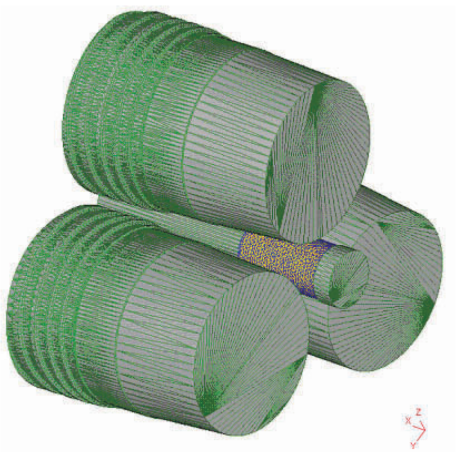


Figure 4.27. *The geometrical model of skew-rolling process, using in FEM simulation (DEFORM-3D software)*

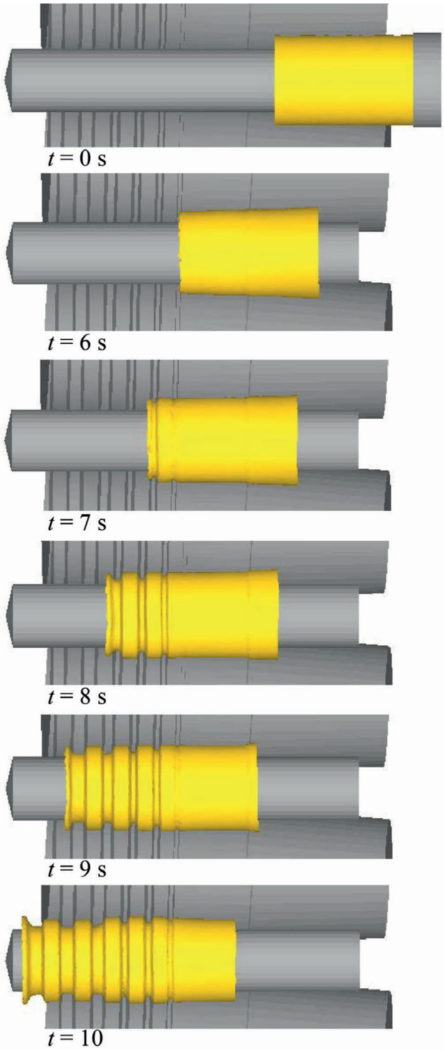


Figure 4.28. *Change of workpiece shape during rolling rings in three-roller skew-rolling mill (upper roller was hidden), at time t, which is shown on figure*

of the billet. The main roller axis is skewed in the relation with the billet axis at an angle 3°.

Due to using the FEM method for simulation of rolling process, it can be seen how the product shape changes during the progress of rolling rings in the three-roller skew-rolling mill. Such changes are shown on Fig. 4.28.

At the beginning, the charge is bite with rollers, which make it rotate and move it axially. The process of rotary compression with three tools begins and lasts until the mandrel touches the workpiece. Then the thickness of the workpiece wall is reduced and it is the most intensive when the metal is formed with pass of rollers. In the next rolling stage, as a result of interacting the cylindrical roller part, the workpiece is sized, obtaining the desired ring shape. Then, the pass (grooves) rolled helically on roll berrel interact with the metal (it is at time $t = 6$ s – Fig. 4.28). As a result of cutting the crests of roll pass into the workpiece, the cross section of the billet is deformed (triangulated) again. This effect can be seen on Fig. 4.29 (at time $t = 10$ s), where the rings from the conical part of the roller have bigger diameters than the rings on their way-out, in which triangulation was successfully removed.

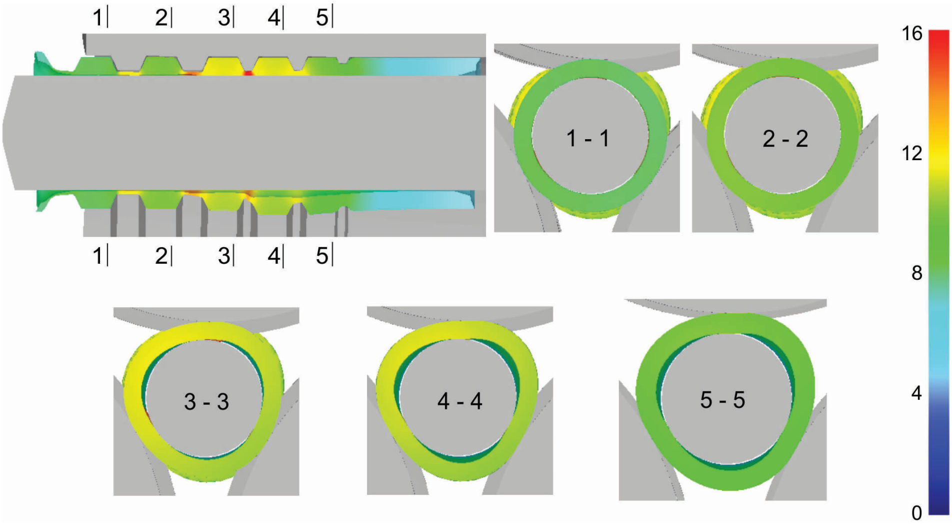


Figure 4.29. *The deformation zone during steady phase of skew-rolling process (t = 10 s) of rings; the effective strain distribution is shown*

The effective strain distribution on the longitudinal section (going through the upper roller axis, the billet axis and between the bottom rollers) and on cross section was shown on Fig. 4.29. It can be concluded from the figure that strains in the ring have relatively constant value and do not depend on radial coordinate. Relatively large value of strains in rings is explained by the intensive metal flow in the unwanted tangent direction. The biggest strains appear in necking land connecting particular rings, where the metal is intensively compressed and where the material should be separated.

On the basis of next Fig. 4.29 it can be closely tracked how the cross-section of the ring during the forming phases changes. From the data put on this figure it may be said that occurring deformations (triangulation) is successively removed during the sizing phase when the ring obtains the desired shape. Moreover, as a result of rolling the ring, its inside diameter slightly increases. As a result, the clearance between the ring and the mandrel appears and there are no problems connected with moving the final products out of the roll gap.

The screw-rolling process is also used in mass production of balls used as grinding media in ball mills. The issues concerning this kind of forming process is extensively described in the monograph [24].

Literature

1. Avitzur B. *Metal Forming. Processes and Analysis*. New York, Wyd. Mc Graw-Hill Book Co. 1968.
2. Bochniak W., Korbel A., Błaż L., Brzostowicz A. *Wytwarzanie drobnoziarnistych wyrobów ze stopu aluminium 7075 w procesie wyciskania metodą KOBO*. Przegląd Mechaniczny, 2009 nr 10, s. 33-37.
3. Bochniak W., Korbel A. *Refinement and control of the metal structure elements by plastic deformation*. Scripta Materialia, 2004 vol. 8, s. 755-759.
4. Bosiacki K. *Kucie matrycowe na młotach*. Warszawa, Państwowe Wydawnictwo Techniczne 1956.
5. Danchenko V., Dyja H., Lesik L., Mashkin L., Milenin A. *Technologia i modelowanie procesów walcowania w wykrojach*. Częstochowa, Wyd. Wydziału Inżynierii Procesowej, Materiałowej i Fizyki Stosowanej Politechniki Częstochowskiej 2002.
6. Devjatov V., Dyja H., Stolubov V., Trusov P., Łabuda E. *Matematyczne modelowanie i optymalizacja procesów wyciskania*. Częstochowa, Wyd. Wydziału Inżynierii Procesowej, Materiałowej i Fizyki Stosowanej Politechniki Częstochowskiej 2004.
7. Dobrucki W. *Zarys obróbki plastycznej metali*. Katowice, Wyd. Śląsk 1975.
8. Dyja H., Banaszek G., Grynkevych V., Danchenko V. *Modelowanie procesów kucia swobodnego*. Częstochowa, Wyd. Wydziału Inżynierii Procesowej, Materiałowej i Fizyki Stosowanej Politechniki Częstochowskiej 2004.
9. *Extrusion and Drawing of Metals [online]*, University of Notre Dame, czerwiec: 2007, s. 1-26 [dostęp lipiec 2013]. Dostępny w World Wide Web: http://www3.nd.edu/~manufact/MET%20pdf_files/MET_Ch15.pdf
10. *Forging of Metals [online]*, University of Notre Dame, czerwiec: 2007, s. 1-26 [dostęp wrzesień 2013]. Dostępny w World Wide Web: http://www3.nd.edu/~manufact/MET%20pdf_files/MET_Ch14.pdf
11. Gołowin W.A., Mitkin A.N., Rieznikow A.G. *Wyciskanie metali na zimno*. Warszawa, Wyd. WNT 1973.
12. Hayama M. *Optimum working conditions in the cross rolling of stepped shaft*. Journal of Mechanical Working Technology, 1979 vol. 3, s. 31-46.

13. *Hot Forging Dies*, [W:] suite of Mechasoft Co., India, [dostęp maj 2013]. Dostępny w World Wide Web: http://www.mechasoft.in/img/pbg7.JPG
14. Kazanecki J., Pater Z. *Analiza termomechaniczna procesu walcowania pierścieni w trójwalcowej walcarce skośnej*. Rudy i Metale Nieżelazne, 2007 nr 11, s. 861-866.
15. Kuzman K. *Metal working. Cold extrusion*, [W:] Encyclopedia of Materials: Science and Technology, Wyd. Elsevier Science Ltd., 2001, s. 5495-5500.
16. Krzekotowski Z., Gałuszka M., Serwicki H. *Zarys kuźnictwa*. Katowice, Wyd. Górniczo-Hutnicze 1959.
17. Laueand K., Stenger H. *Extrusion-Processes, Machinery, Tooling*. Ohio, American Society for Metals, Metals Park, 1981.
18. Leśniak D. *Analiza warunków zgrzewania podczas wyciskania stopów AlCuMg*. Seria Monografie nr 5/2012. Kraków, Wyd. Naukowe AKAPIT 2012.
19. Lisowski J. *Walcowanie kuźnicze*. Warszawa, WNT 1974.
20. Muller K. *Metal working. Extrusion*, [W:] Encyclopedia of Materials: Science and Technology, Wyd. Elsevier Science Ltd., 2001, s. 5510-5515.
21. Pater Z. *Walcowanie poprzeczno-klinowe*. Lublin, Wyd. Politechniki Lubelskiej 2009.
22. Pater Z., Gontarz A., Weroński W. *Wybrane zagadnienia z teorii i technologii walcowania poprzeczno - klinowego*. Lublin, Wyd. LTN 2001.
23. Pater Z., Samołyk G. Podstawy technologii obróbki plastycznej metali. Lublin, Wyd. Politechniki Lubelskiej 2013.
24. Pater Z., Tomczak J. *Walcowanie śrubowe kul do młynów kulowych*. Lublin, Wyd. Politechniki Lubelskiej 2012.
25. Samołyk G., Pater Z. *Rowek na wypływkę w kuciu matrycowym*. Lublin, Wyd. LTN 2005.
26. Sińczak J. i in. *Procesy przeróbki plastycznej*. Kraków, Wyd. Naukowe AKAPIT 2003.
27. Tomczak J. *Theoretical and experimental analysis of forming process of conical toothed wheels on a crank forging press*. Steel Research International, 2012 Spec. Ed., s. 151-154.
28. Tsukamoto H., Morimoto K., Juge T., Takahashi K, *Application study on cross roll method for axi-symmetrical stepped shaft*. Advanced Technology of Plasticity, 1984 vol. 2, s. 936-941.
29. Wasiunyk P. *Kucie matrycowe*. Warszawa, WNT 1980.
30. Wasiunyk P. *Walcownictwo i ciągarstwo*. Warszawa, WSiP 1981.
31. Wasiunyk P., Jarocki J. *Kuźnictwo i prasownictwo*. Warszawa, Wyd. PWSZ 1969.
32. Weroński W. i in. *Obróbka plastyczna – Technologia*. Lublin, Wyd. Politechniki Lubelskiej 1991.
33. *Wyciskanie części maszyn i wyrobów hutniczych [online]*, Politechnika Wrocławska, styczeń: 2008, s. 26-49 [dostęp czerwiec 2013]. Dostępny w World Wide Web: http://www.metalplast.pwr.wroc.pl/pliki/lab2.pdf.