WORKBOOK

Metal Forming - Numerical Modeling

LUBLIN 2014

Projekt współfinansowany ze środków Unii Europejskiej w ramach Europejskiego Funduszu Społecznego

Author: Jarosław Bartnicki

Desktop publishing: Jarosław Bartnicki
Technical editor: Jarosław Bartnicki
Cover and graphic design; Jarosław Bartnicki

Publikacja współfinansowana ze środków Unii Europejskiej w ramach Europejskiego Funduszu Społecznego w ramach projektu
Inżynier z gwarancją jakości – dostosowanie oferty Politechniki Lubelskiej do wymagań europejskiego rynku pracy

Lublin 2014

First edition

TABLE OF CONTENTS

Projekt współfinansowany ze środków Unii Europejskiej w ramach Europejskiego Funduszu Społecznego

1. CRYSTAL STRUCTURE OF MATERIALS

Crystal lattice - an arrangement of atoms with clearly specified directions and spacing between them.
There are three basic types of spatial lattice that most metals crystallize into:

- regular, face-centered lattice,
- regular, body-centered lattice,
- hexagonal lattice.

Regular, face-centered lattice (marked with symbol A1) - occurs in metals such as: iron γ, aluminum, copper, nickel, lead, silver, gold, platinum, iridium, palladium.

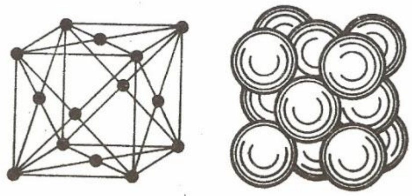


Fig. I Regular, face-centered lattice (W.Weroński, Metal Forming)

Regular, body-centered lattice (marked with symbol A2) - occurs in metals such as: iron α, wolfram, vanadium, molybdenum, chromium, lithium.

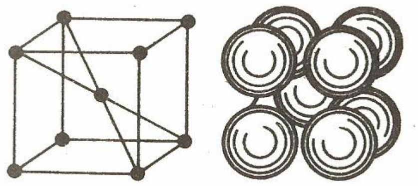


Fig. II Regular, body-centered lattice (W.Weroński, Metal Forming)

Hexagonal lattice (marked with symbol A3) - occurs in metals such as: zinc, cadmium, magnesium, beryllium, titanium α.

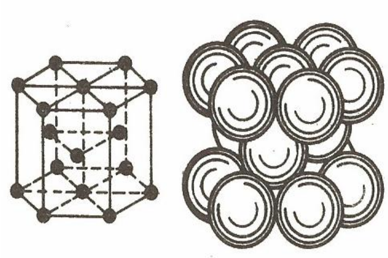


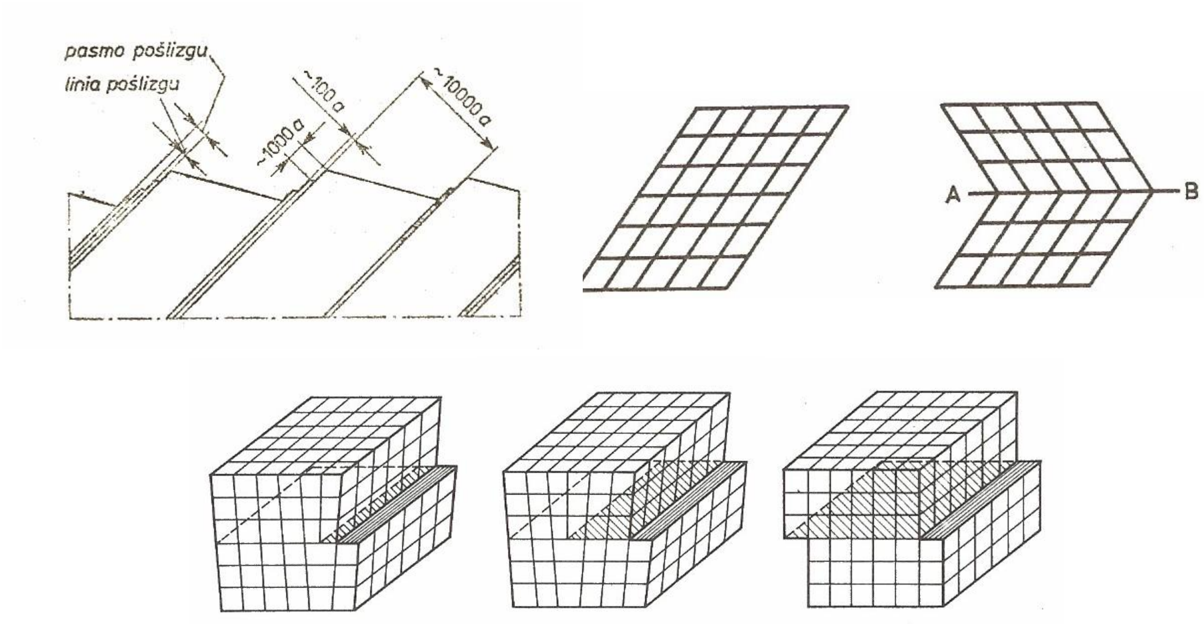
Fig. III Hexagonal lattice (W.Weroński, Metal Forming)

Metals are **polycrystalline**–composed of large numbers of small crystallites called grains.

There are always multiple defects in the structure of a crystal caused by a presence of foreign atoms, and by irregular arrangement of its own atoms. Is far as geometry of these defects is concerned, there are the following defects:

- point,
- linear,
- planar.

Permanent deformation (plastic) occurs in crystals on the basis of the **slipping** phenomenon**,** or less frequently, **crystal twinning.**



Pasmo poślizgu- slipping band* , *Linia poślizgu-slipping line

Fig. IV Deformation mechanisms (W.Weroński, Metal Forming)

Projekt współfinansowany ze środków Unii Europejskiej w ramach Europejskiego Funduszu Społecznego

2. HEAT TREATMENT AND PHENOMENA

Hardening - an increase in the plasticizing stress values caused by permanent deformations.

The hardening phenomenon is caused by an increased number of dislocations and a simultaneous decrease of the free movement of dislocation. It leads to an increase in the stress levels necessary to trigger the movement of dislocation (permanent deformation).

Change of structure

Deformation causes the grains to elongate, while crystallographic axes orientate towards the largest elongation. A structure with highly organized crystallographic axes of the grains is called the pinch texture. Such a structure has anisotropic properties.

Stored energy – constitutes part of work of plastic deformation, which is not released as heat in the process of deforming of the material.

The **stored energy** is the energy related to the deviation of the atoms from their primary positions due to occurrence of various defects formed during plastic deformation. It constitutes from 2 to 10% of the deformation work.

Recovery

An increase of temperature triggers the diffusion of atoms, which causes the following phenomena:

annihilation (liquidation) of the point defects (the excessive atoms join with the vacancies and are moved to lattice site), annihilation of dislocations of opposite signs,

polygonization (arranging of excessive dislocations of equal signs; they create the structures of lower energy, the so-called low-angle boundaries).

Recrystallization

The process of recrystallization causes structural changes, resulting in the creation of new grains with a relatively small number of dislocations. Recrystallization occurs in higher temperatures than the process of recovery. The process decreases material's plastic resistance as a consequence of eliminating the effects of hardening.

Formation of material in a temperature that is equal or higher than the recrystallization temperature is called **hot metal forming**.

Formation processes in a temperature that is lower than the recrystallization temperature is referred to as **cold metal forming**. The range of temperatures of hot plastic treatment is limited *from the top* by:

- oxidation,
- decarburizing,
- creation of coarse-grained structures,
- from the bottom by:
- plasticizing stress value,
- material's ultimate deformation capacity

Projekt współfinansowany ze środków Unii Europejskiej w ramach Europejskiego Funduszu Społecznego

Heat transfer can occur interiorly–as a process of heat spread from more heated particles to the less heated particles - or between objects of different temperatures, as heat exchange between more and less heated objects.

There are three basic ways of heat transfer:

- leading, thus a **conduction**,
- floating, thus a **convection**,
- radiating, thus a **radiation.**

Thermal impact on metal results in an almost complete loss of elasticity, a decrease of yield strength, and an increase of plasticity. Apart from that, it causes recrystallization and dissolution of the carbides, which accelerates the process of deformation. The thermal conditions are calculated separately for each type of steel, taking into account the original structure of a metal, its volume and cross-section dimensions.

The processing temperature oscillates between the metal's solidification temperature and the end recrystallization temperature. Lower temperature refers to semi-hot and cold plastic treatment.

From the top, the processing temperature is limited by *metal combustion* . It occurs as a result of diffusion of oxygen along the grain boundaries of austenite. As a consequence, inclusions of oxides occur which weaken the bonds between the grains.

A precise calculation of the minimum forging temperature is quite complicated. Forging should be performed in one phase. In such a case plastic deformation is smoother and the forged material has better mechanical properties.

For carbon steel, the range of forging temperatures is shown on an iron-carbon phase diagram. The maximum forging temperature is 100-150°C below the solidus. The minimum forging temperature for all types of carbon steel is approx. 800°C.

In the industrial practice, the following ranges of temperatures are used for plastic processing:

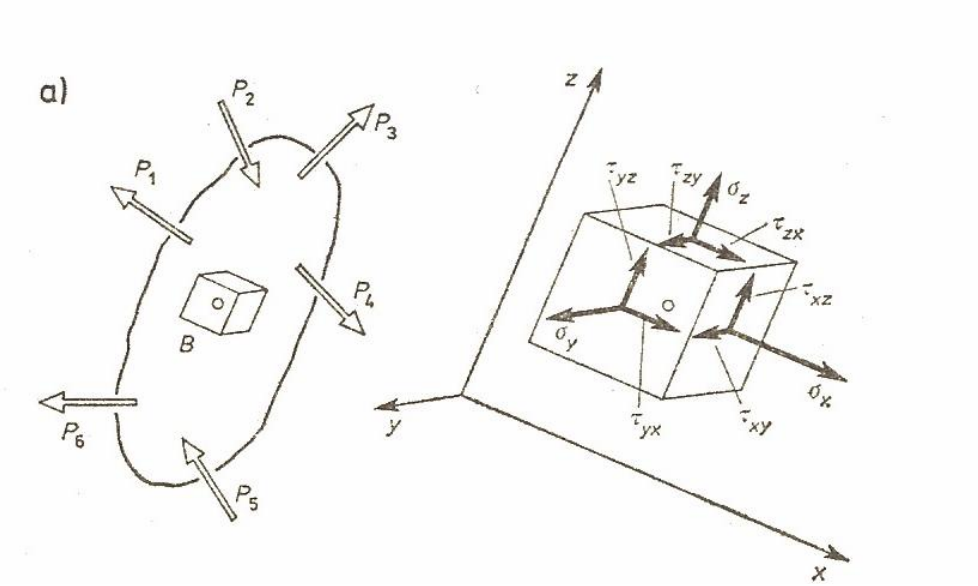
- carbon steel 1250÷800°C
- Al alloys 500÷400°C
- Mg alloys 480÷350°C
- Bronze 850÷750°C
- Brass 750÷700°C

KAPITAŁ LUDZKI NARODOWA STRATEGIA SPÓJNOŚCI
UNIA EUROPEJSKA EUROPEJSKI FUNDUSZ SPOŁECZNY
Projekt współfinansowany ze środków Unii Europejskiej w ramach Europejskiego Funduszu Społecznego

3. BASICS ABOUT STRESS, STRAIN, YIELD CRITERION, FRICTION

The state of stress in a given point of an object, with a given external force applied to it, can be described by six independent components: σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{zx}.

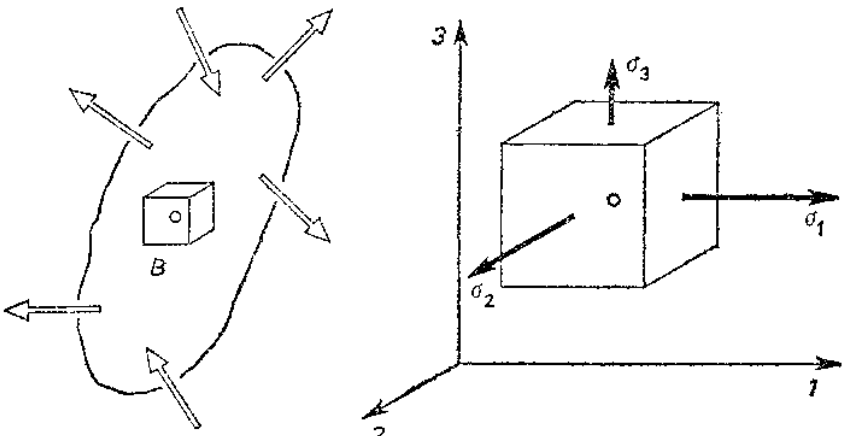
$\tau_{xy}= \tau_{yx}$, $\tau_{zx}=\tau_{xz}$, $\tau_{zy}=\tau_{yz}$.



(W.Weroński, Metal Forming)

Fig. V Components of stress state in point B for arbitrary directions in the coordinate system

For any point, with a given load, such directions of coordinate system axis may always be set, so that on each face of an elementary cuboid, the shear stress will equal zero and only the normal stress will remain.

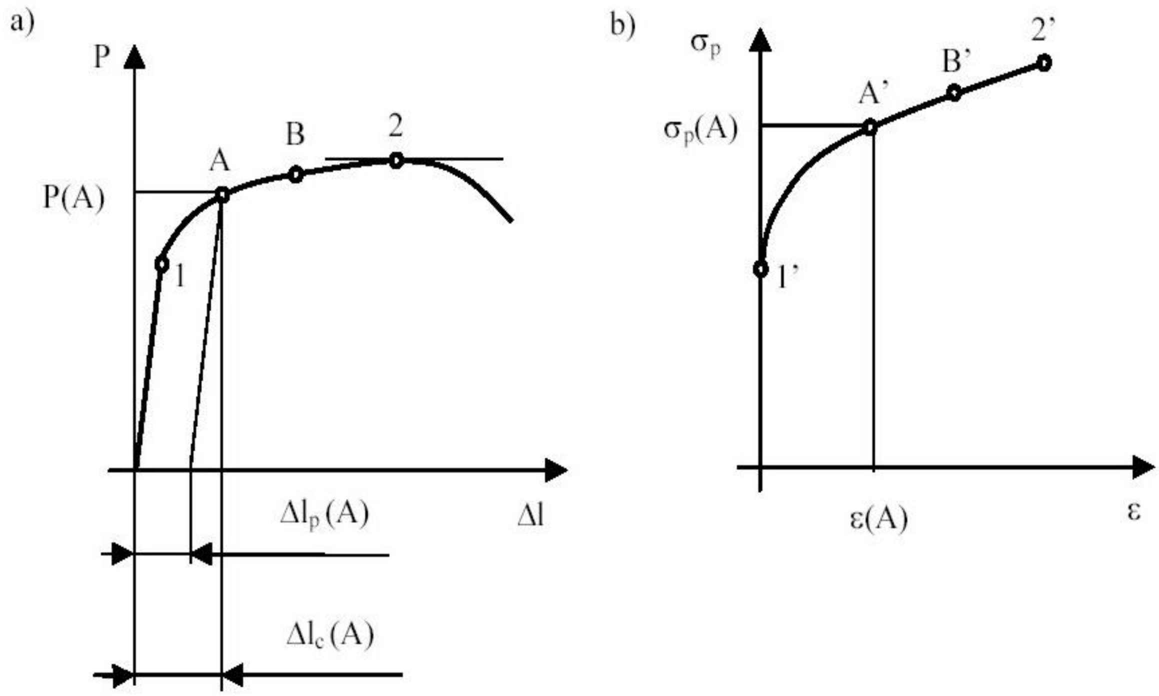


(W.Weroński, Metal Forming)

Fig. VI Components of stress state in point B for the main coordinates

Such coordinates are called **the main coordinates**, and the stress normally applied in these coordinates **- the principal stress,** marked with symbols σ_1, σ_2, σ_3.

Graph presenting tensile test of a steel sample



(W.Weroński, Metal Forming)

Fig. VII A graph of tensile (a) and a corresponding hardening curve (b)

The simplest example of load is a uniaxial stress, in which case $\sigma 2 = \sigma 3 = 0$.

Yield stress

A processed sample is permanently deformed after reaching a certain stress value, called the yield strength. If a material can be constantly deformed under a fixed value of stress equaling the yield strength, then such a material is called **perfectly plastic**. For most materials, exceeding the yield strength signifies changing the value of stress necessary for plastic flow. This kind of stress is called **plasticizing stress**, and in case of uniaxial tensile, it is calculated by means of a formula:

$$\sigma_p = \frac{P}{S},$$

where: *P* - tensile force value, *S*– sample's cross-section.

For uniaxial tensile the criterion necessary for obtaining the first plastic deformations, called the yield criterion, is as follows:

$$\sigma_1 = \sigma_p.$$

The yield criterion is obtained by comparing the equivalent stress (determined according to the accepted hypothesis, and being a certain function of stress components) with the plasticizing stress σp.

According to Huber's hypothesis, also called the hypothesis of the specific energy of shear deformation, the equivalent stress is:

$$\sigma_H = \frac{\sqrt{2}}{2}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}\ .$$

Strain

The elementary increase of strain $d\varphi$ equals the ratio of the increase of length dl to the length of a sample l:

$$d\varphi = \frac{dl}{l}\ .$$

A total strain of the sample as a result of increasing the length from $l0$ do l is calculated by integrating the equation:

$$\varphi = \int_{l_0}^{l}\frac{dl}{l} = \ln\frac{l}{l_0}\ .$$

The strain as shown by the above dependency is called **logarithmic strain**

Strain rate

Strain rate is defined as a growth of deformation value $d\varphi$ in time dt:

$$\dot{\varphi} = \frac{d\varphi}{dt}\ .$$

Strain rate is expressed as [s^{-1}]. In order to determine the influence of strain rate on plasticizing stress, flow curves are most often determined with the fixed value of the parameter. In tests, the controlled parameter having a direct impact on the deformation strain test, is the linear velocity of the tensile sample. Because of that, the following correlation is often used:

$$\dot{\varphi} = \frac{dl}{l\cdot dt} = \frac{v}{l}\ ,$$

where: v - linear velocity of the sample stretching (pressing).

Friction models

Amontons' model

In the 17th century a French scientist, Guillaueme Amontons, formulated a theory which initiated scientific development concerning the laws of friction. According to him, the friction force T is proportional to normal load and does not depend on the contact surface of the objects, which he showed in an equation:

$$T = \mu \cdot N$$

where: m - coefficient of friction, N - pressure force.

Coulomb's model

In the 18th century a French physician, Charles Augustin de Coulomb (better known for his achievements in electrostatics), further developed Amontons' law, claiming that the moment an object is set into motion, the friction force does not depend on the velocity. Apart from the component depending on the normal load, it depends on the intermolecular forces, which he showed in the correlation:

$$T = \mu \cdot N + A,$$

where A - intermolecular forces.

Intermolecular forces however are very weak compared to the pressure, and are omitted in the practical calculations (A=0), which reduces Coulomb's dependency to Amontons' law. This is why Amontons' law is often referred to in specialist literature as Coulomb's law.

Referring the forces to the surfaces on which they are applied, Amontons' law can be expressed by the equation:

$$\tau = \mu \cdot q_n,$$

where: τ - friction force on the contact surface,

qn – normal stress on the contact surface.

Although the laws of Amontons and Coulomb were one of the first concepts, they lasted much longer than many different theories in subject of friction. They are frequently used in the analysis of plastic processing methods.

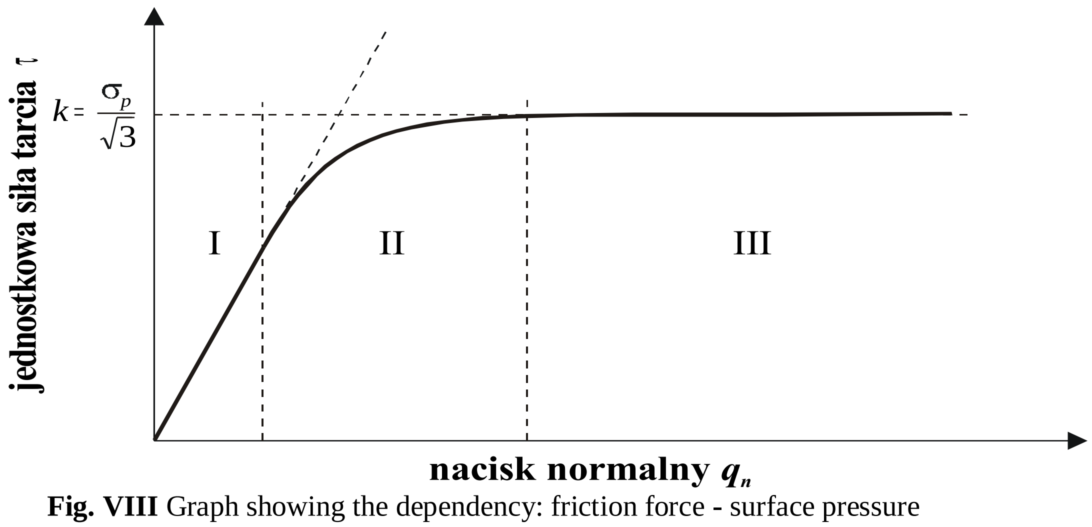


Fig. VIII Graph showing the dependency: friction force - surface pressure

(W.Weroński, Metal Forming)

Jednostowa siła tarcia-Unit friction force, Nacisk normalny-normal stress

In case of high normal stresses (area III), the unit friction force reaches a constant value, which equals the yield strength in pure shear k. In this range, applying Amontons' law would lead to considerable errors as the unit friction force would reach very high, unrealistic values. That is why for larger normal stresses, the phenomenon of friction is better described by *law of constant friction,* as shown in the dependency:

$$\tau = m \cdot k ,$$

where: m - friction factor ($0 \le m \le 1$),

k - yield strength in pure shear

In this model, the unit friction force t depends not on the stress states, but on the properties of the material. The friction factor value m determines the quality of the friction contact and indicates to what extent does the value t differ from k. In a case where there is a full contact between a material and a tool, the less durable, therefore plastic, material is sheared. The friction force t equals the yield strength in pure shearing k:

$$\tau = k .$$

For such a case, the value of the friction factor m=1. Based on Huber's hypothesis, the yield strength in pure shearing equals:

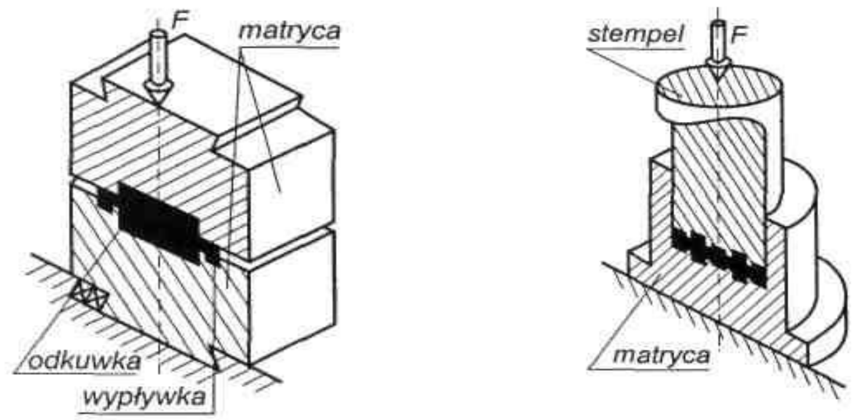
$$k = \frac{\sigma_p}{\sqrt{3}} ,$$

where σ_p – yield stress

4. CHOSEN METHODS OF METAL FORMING.

Forging

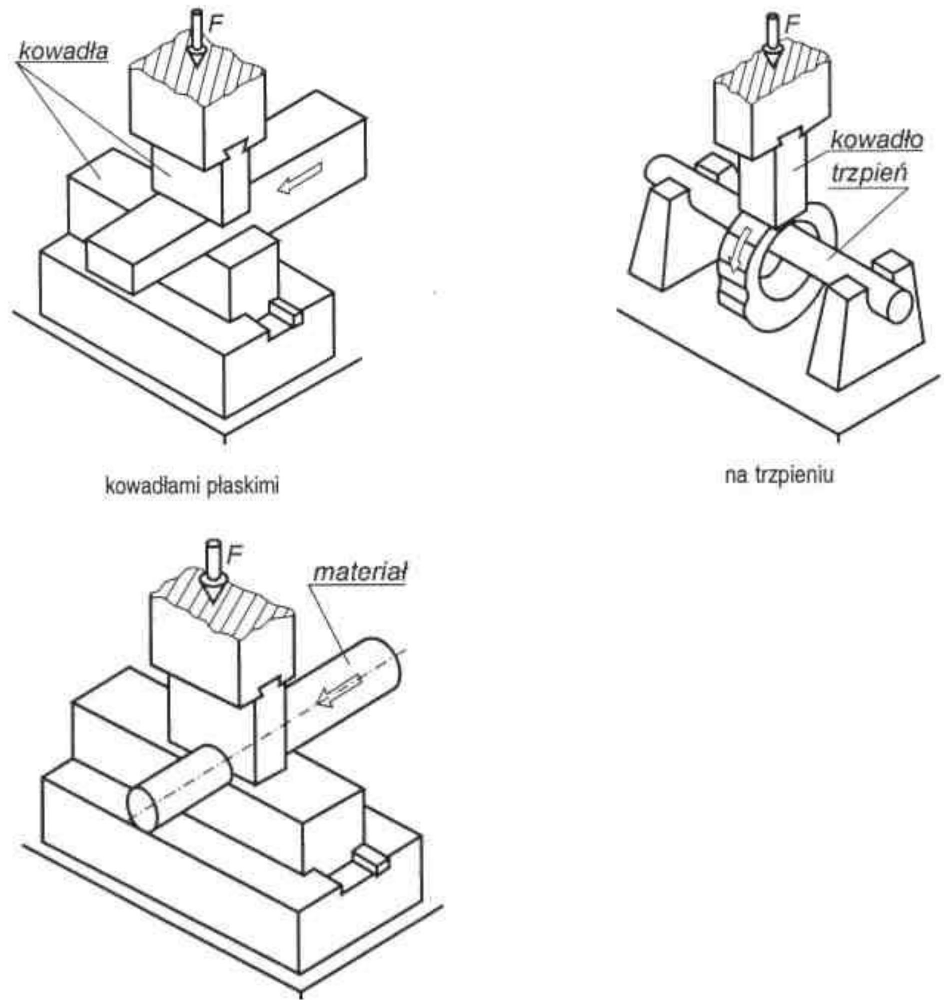
The process of forging can be divided into free forging, semi-free forging and drop-forging. The free forging consist in deforming the material between two tools (top and bottom anvil) without restraining its flow. In the semi-free process, the flow of the material is constrained at least from one side by a mold. The drop-forging consist in precisely filling a mold with the material, using a blow of a hammer, or a press pressure. The forging processes can be performed using a press or a hammer.



(S. Erbel, Manufacturing technologies)

Fig. IX Scheme of drop-forging: a) with flashes, b) flashless

Matryca-mold, Stempel-punch, Wypływka-flash, Odkuwka-forging



(S. Erbel, Manufacturing technologies)

Fig. X Schemes of forging: a)b) free: c) semi-free
Materiał-material, Na trzepieniu-on the pin, Kowadłami płaskimi-Flat anvils, Kowadło-anvil Trzpień-pin

Stamping

Stamping is a pressing operation, during which a stamp presses the material causing it to squeeze through holes in the tool or die cavities, shaped as the cross-section of the final product. Such processing is used to make different kinds of pipes, vessels or shaped rods. In stamping, only materials with low yield strength are used (e.g. lead, tin, zinc, aluminum, copper and some of their alloys), due to the fact that when high pressure is applied in the process, the material is pressed in all directions.

One of the vital factors impacting the outcomes of the process is the material temperature. It is very important for the material not to reach the temperature in which it will become brittle, as in such as it would lose its plasticity. Another factor is the velocity of the squeezed object. If it is too low, the material might crack.

A scheme of producing pipes using stamping methods is shown below. After the material has swelled in the cylinder, it is pierced by an interior stamp. When the stamp reaches the die cavity - it stops, and an exterior stamp presses the material out of the cylinder thus shaping the material into a pipe.

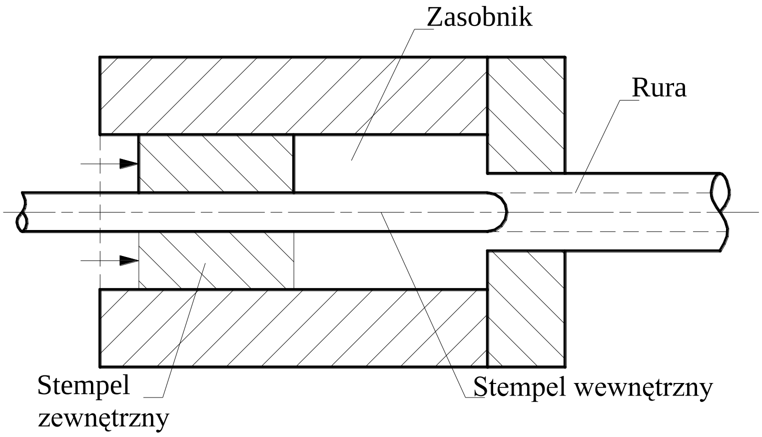


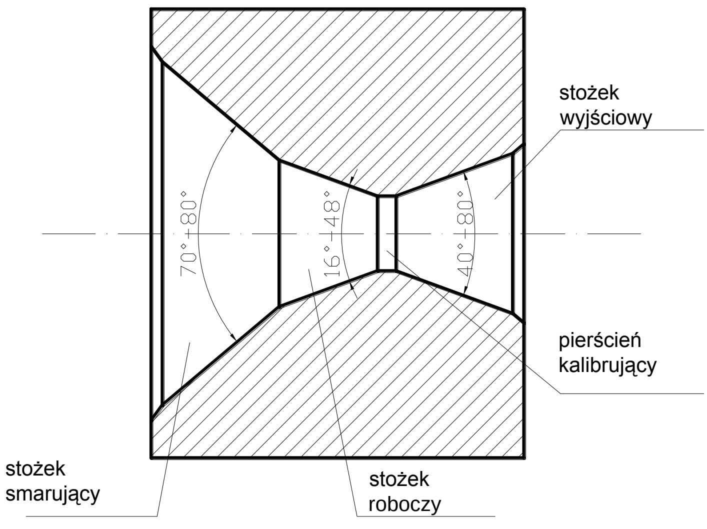
Fig. XI A scheme of pipe stamping

Stempel wewnętrzny-*internal stamp, Stempel zewnętrzny*-*external stamp*

Zasobnik-cylinder, Rura-pipe

Drawing

The drawing process consists in drawing the material through a stationary tool (a die) in order to increase its length and reduce its diameter. The process can also be used to reshape the processed material. It is a cold work process.



(J. Łuksza, Drawing basics)

Fig. XII A scheme of a die

Stożek smarujący-*lubricating cone, Stożek roboczy*-*working cone, Pierścień kalibrujący*-*calibration ring, Stożek wyjściowy*-*exit cone*

Materials made of steel and non-ferrous metals, and their alloys may be subject to drawing. Drawing is used to change the size or shape of the material's cross-section, to achieve the minimal measurement deviations, to get a smooth, clean surface, and to enhance the mechanical properties of the material.

In such processing, rods of circular, hexagonal, or square cross-section are used, as well as rolled or hot forged pipes. Objects processed via this method are characterized by high dimensional accuracy and smoothness of the surface. In the drawing process, different types of wire machines are used for different purposes (wires, pipes and rods).

Material defects that occur most often are non-metallic contaminants, peeling (caused by rolling and blistering), and residues of the shrinking cavity. If the process is performed incorrectly, cracks in the material may occur, caused by excessive pressure, the material might become brittle due to excessive cold work pressing, or there might be scratch marks on the surface, made by a damaged die.

Rolling

Rolling is plastic processing of metals consisting in reducing the material's thickness (of its cross-section) with its simultaneous lengthening and widening. The process of rolling can be performed in room or elevated temperatures, depending on the processed material and the properties to be achieved. Cold work rolling is mostly used for sheets and strips of material and for materials that have been previously hot worked.

In rolling, the material passes between rotating, cooperating rollers, discs or cylinders, using the friction forces occurring between the surface of the tools and the material. In the process of rolling, steal containing up to 1% C is used. The velocity of rolling, as well as the level of pressure depends on material's plasticity. The less plastic the material, the lower the velocity.

Rolling mill - a machine used in cold or hot working of metals, in which the material is shaped between the rotating rollers, discs or cylinders. **Rolling line** consists of two or more cooperating rolling mills.

The rolls can be divided, depending on their role, into *work rolls* and *backup rolls*.

The work rolls are in a direct contact with the material in the rolling process. The backup rolls are used solely to give support to the work rolls and to prevent them from bending. Backup rolls are used in four-, six-, or multiple-roller mills. They allow for the use of greater pressure on the work rolls, and in order to achieve a better dimensional accuracy and thicker products. Depending on the structure of the mill, either the work or backup rolls are driven.

There are different types of rolling, depending on the way the rolled material moves, and on the shape and configuration of rollers:

- longitudinal;
- cross;
- skew;
- special, which is a combination of the above methods.

KAPITAŁ LUDZKI
NARODOWA STRATEGIA SPÓJNOŚCI
UNIA EUROPEJSKA
EUROPEJSKI FUNDUSZ SPOŁECZNY
Projekt współfinansowany ze środków Unii Europejskiej w ramach Europejskiego Funduszu Społecznego