Forging

Overview

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Principle of **open** and **closed** die forging

Technology steps of closed die forging

Process of technology planning

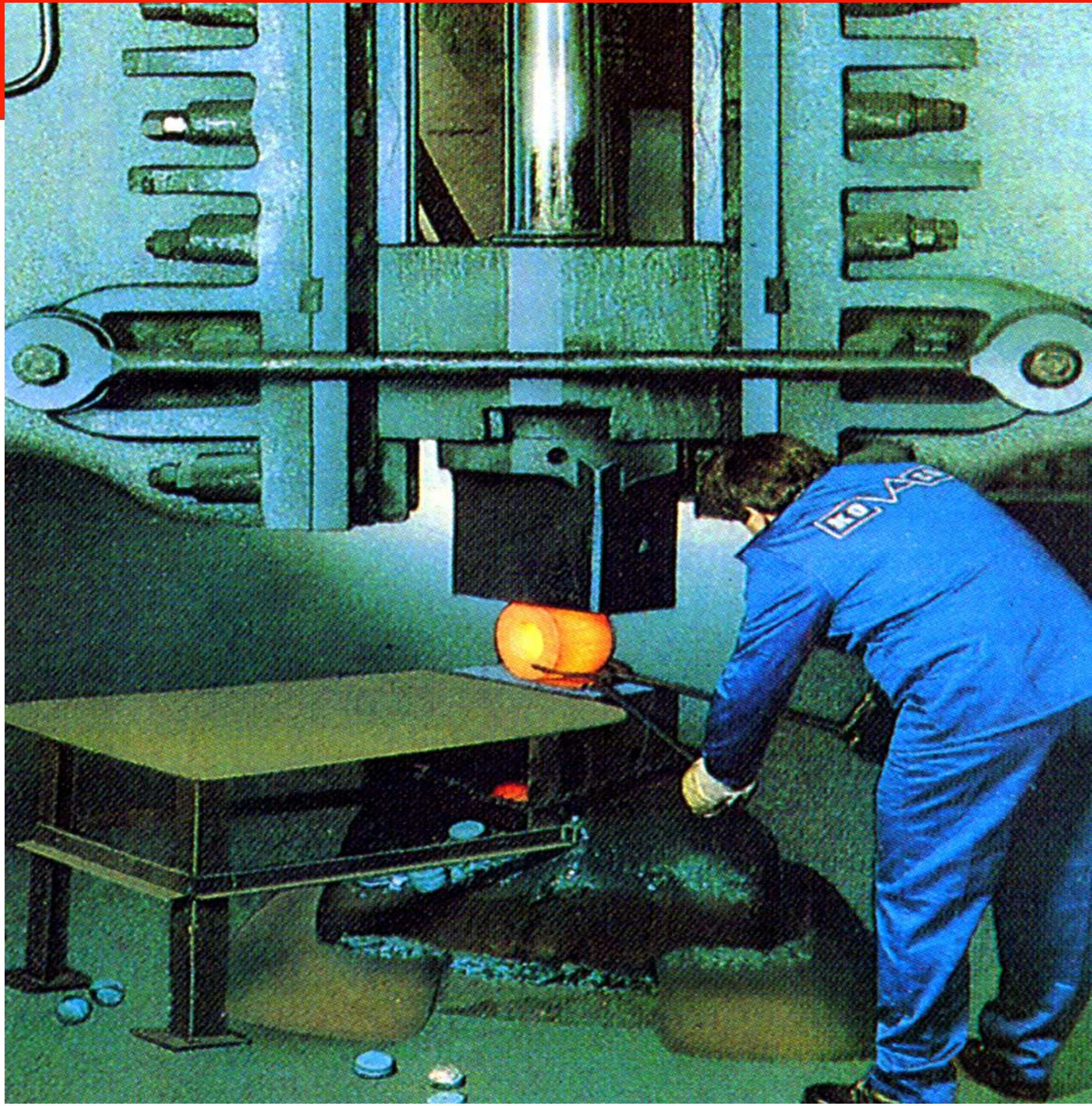
Process of rotary swaging and precision forging

Technology of electric upsetting

Open and closed die forging

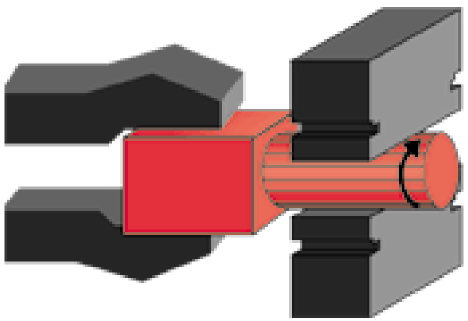
In case of **open die forging** techniques, the operators use numerous **universal tools** and need **free space** around the forging equipment. The quality depends mainly on the **skill of operators**.
The field of application of open die forging is **custom made** and **small series products**. The open die workshops are usually around metallurgical factories, where the **custom large parts** are to be forged directly after casting.

The **closed-die forging** was developed from the open die forging. The quality of the produced workpiece is **determined mainly by the die**, and its technological environment. The manipulation space is not a primary requirement, the **precise guiding of the dies** is critical. It can be realized best by **closed frame machines**.

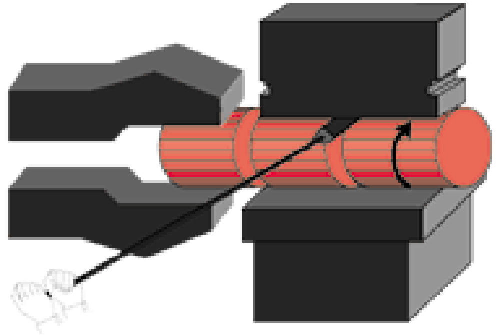


Open die forging

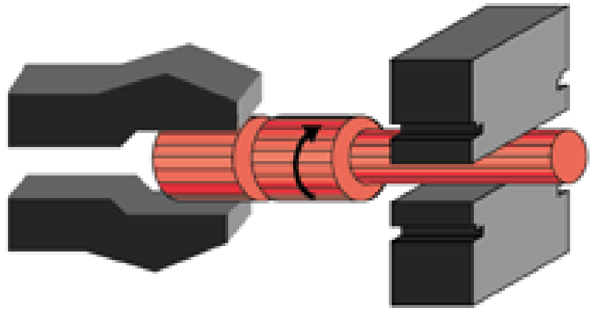
Open die forging - operations



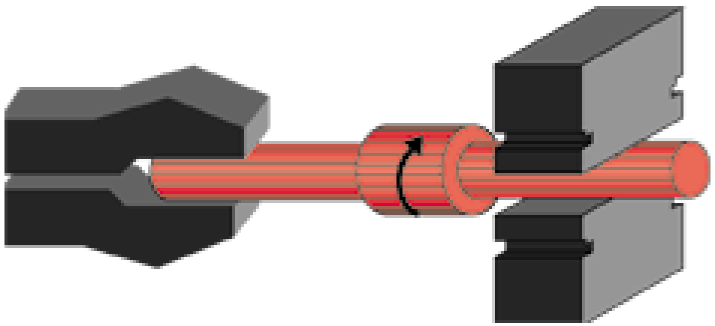
Rough forging



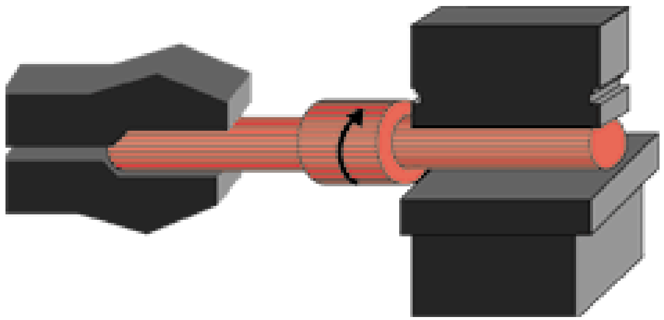
Notching (fullering)



Forging down to size (drawing)



Forging of the other side



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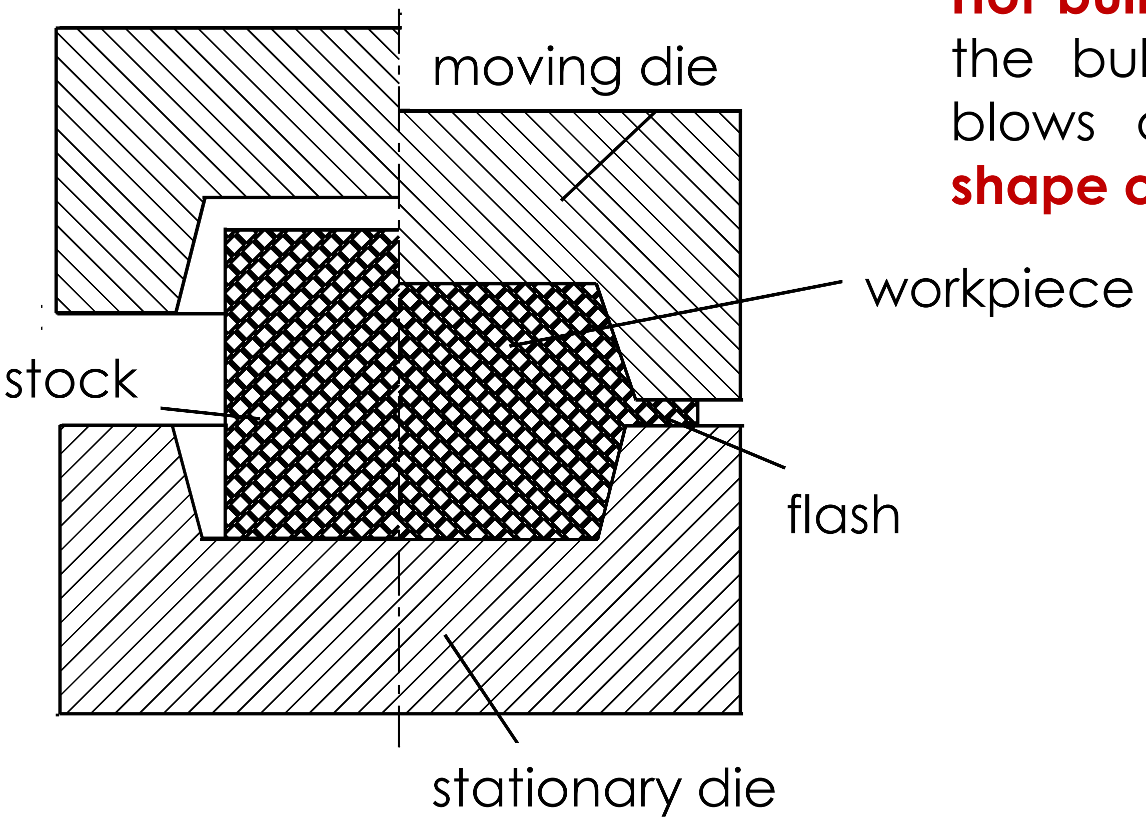
Principle of closed die forging



Hot bulk forming process, where the bulk material **is forced** by blows or pressure **to take the shape of the die cavity**.

The die's materials are **hot work tool steels**, designed for forging, or in special case Ni or Mo based **superalloys**.

The workpiece temperature is **above the recrystallization temperature** of the material.

Technology of closed die forging

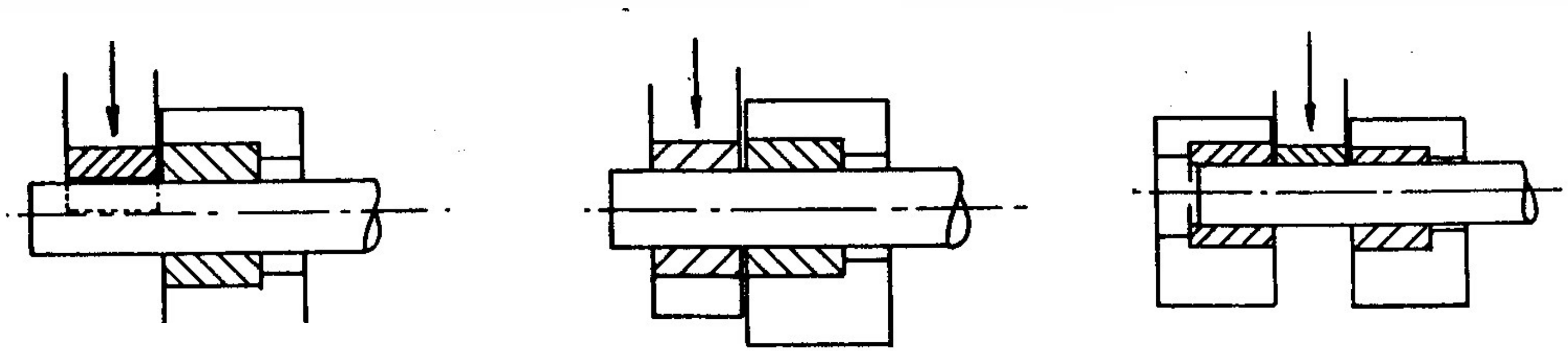
The **forging stock materials** are generally rolled or extruded bars, their properties – as a result of the metallurgical technologies – **are direction-dependent** (i.e. **non isotropic**): better in the longitudinal and worse in the transverse directions. In case of a well-designed closed die forging technology, in the machined and finished part, **the grain flow is aligned** parallel to the highest principal stress trajectory during service.

Highly **reliable machine parts for high dynamic loads** are manufactured by this process.

The **strain distribution is non-uniform** than the recrystallization process is also non-uniform in the cross-section, which **can result in large or coarse grain** microstructure. Because of this, the forging **must be finished** by using an appropriate **heat treatment** procedure:

- heat treatable steels: quenching and tempering;
- case hardening steels: normalization

Parting, shearing



The stock is made from a long product manufactured by hot rolling or extrusion, in case of certain nonferrous metals by cold drawing.
The **bar is cut, broke, or machined (parting, sawing)** into the desired length.

Shear load is applied, which results to plastic deformation and fracture thereafter. The **volume deviation is 3-4%.**

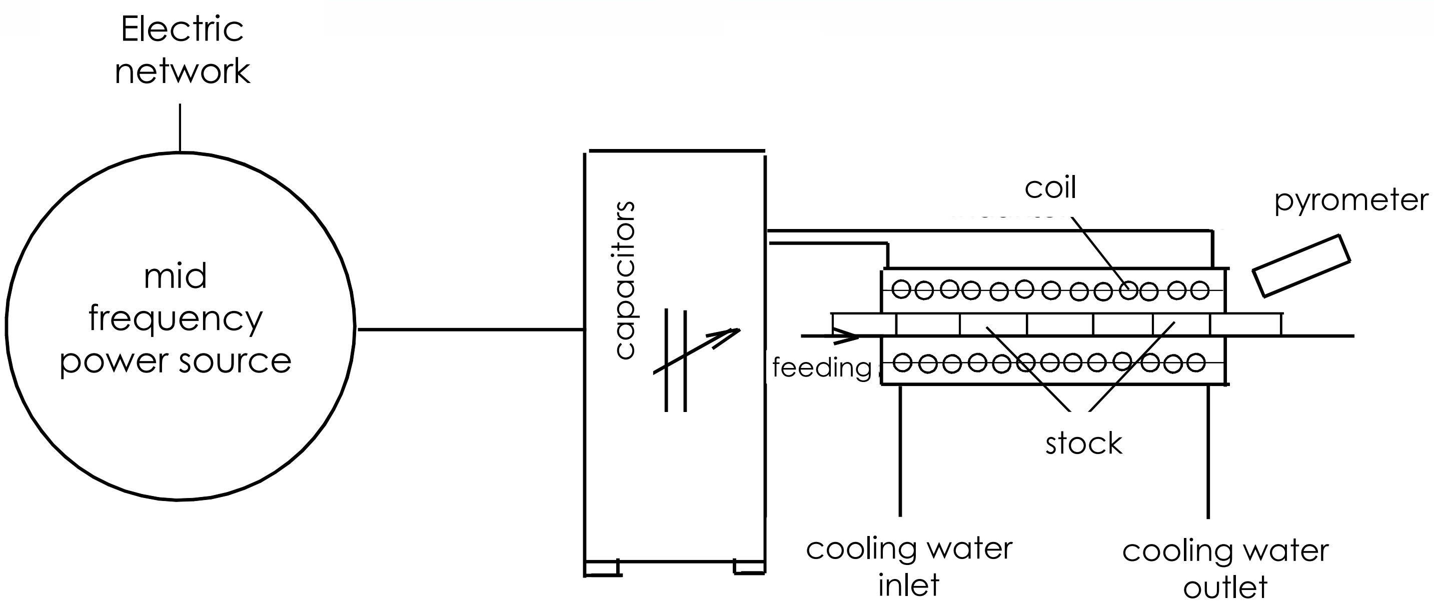
The **volume-identity** can be ensured by **special cutting process**: the mass is measured automatically, and the **feeder is adjusted** if necessary.
The deviation can be **decreased to ~0.1%**

Parting, shearing

For high quality products, the stock cut from hot worked billets, ingots is inspected, and **the defects** – if there is any – **are removed by grinding**.

For products with **smaller tolerances or better surface quality, cold drawn bar is used,** or the **hot rolled bar's surface is removed** by turning. It ensures the **identical cross section and oxide-free surface**.

Heating



The **closed die forging** – because of the high tooling costs – is **economical only for large series** and **mass production**.

The **mid-frequency (0.75 – 15 kHz) induction heating** is also applicable only for large series and mass production. It is **fast, well controllable** and so the most widely used for closed die forging technologies.

Theoretically **to have good electric coupling** for every stock with different geometries **different shaped and sized coil** must be used. Practically a workshop has **a set of coils**, and **the coupling is set** by tuning the oscillating circuit **with adjusting the capacitors**.

Heating

Beside the induction heating, **gas-fired furnaces** are also used (electric furnaces are mostly used as heat treatment furnaces).

In **gas-fired** furnaces a **non-oxidizing atmosphere** can be set. Because of the high health risk of this firing technique (low excess air firing: CO poisoning), it can be realized only if an appropriate controlling system is available.

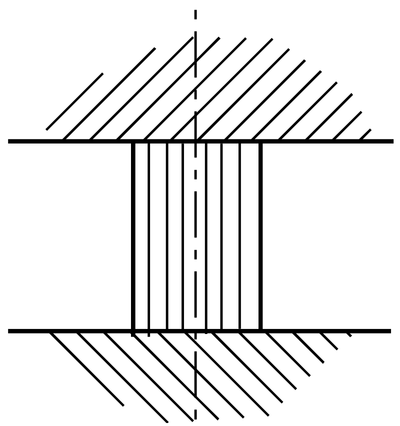
Oil-fired furnaces are also be found in the industry, but **their controllability is lower** than that of gas-fired and electric furnaces. They are used where the oil is cheap or there is no other possibility.

Preforming

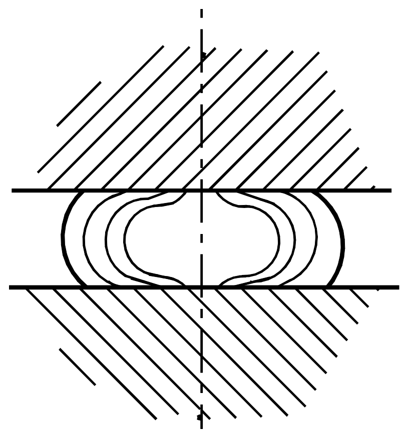
To **avoid unnecessary material loss**, **lower the tool load**, and achieve **proper grain flow**, preforming step(s) must be made.

Material distribution is one of the most important role of preforming: the simple-geometry stock (generally cylindrical or prismatic) is deformed to have a shape required by the final geometry.

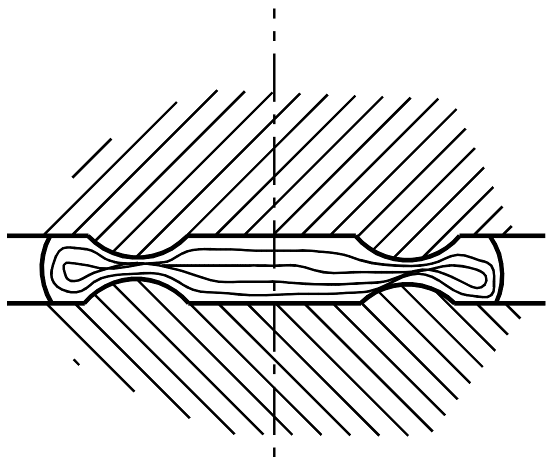
Forging of a disk-shaped workpiece



Grain flow of the parted stock

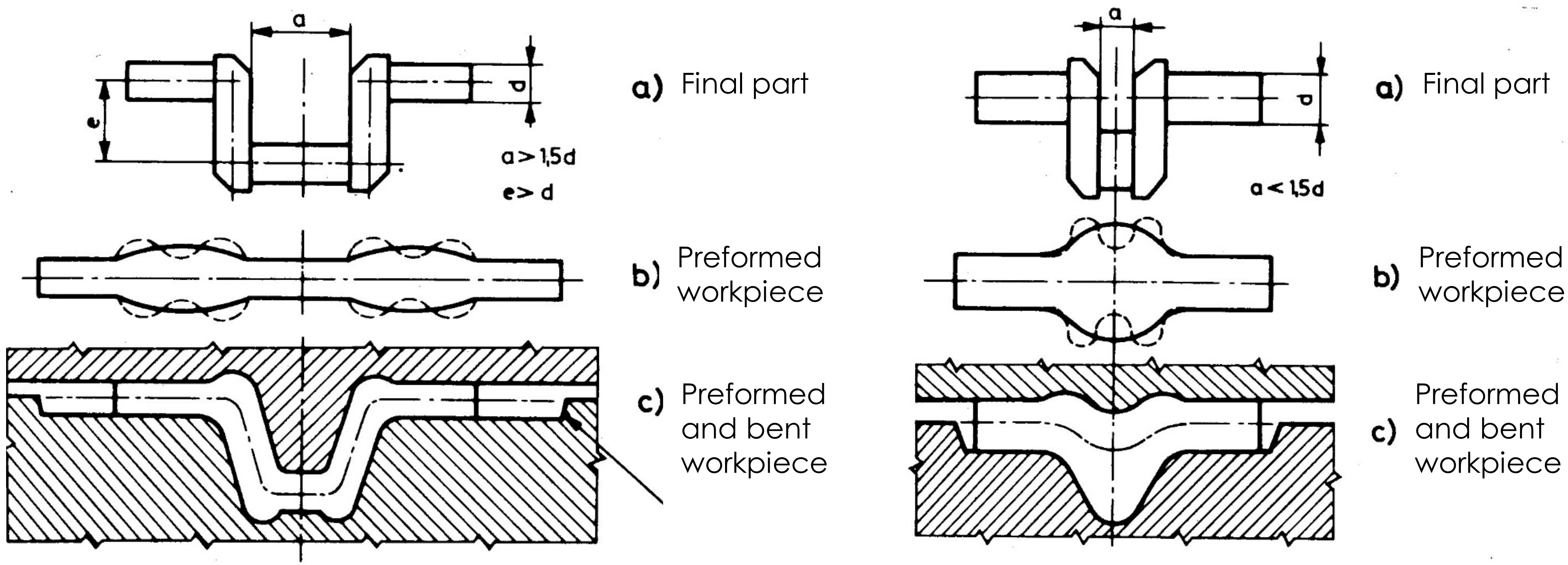


Turning the grain flow by upsetting



Aligning the grain flow to the shape by preforming

Preforming of a long product



Combining bending and material distribution

Removal of the oxide layer (scale) from the stock's surface is essential. The **oxide is brittle** at the forging temperature and **has bad cohesion** to the metal. During plastic forming it is not able to follow the shape change of the workpiece: **it cracks and falls off**. A way to **„explode" the scale off: immersing into cold water** or mixture of water and lubricant.

Preforming

For **parts with complex geometry even 8-12 preforming steps** can be necessary, particularly if the grain flow control is important. On simple way of preforming is the open-die forging.

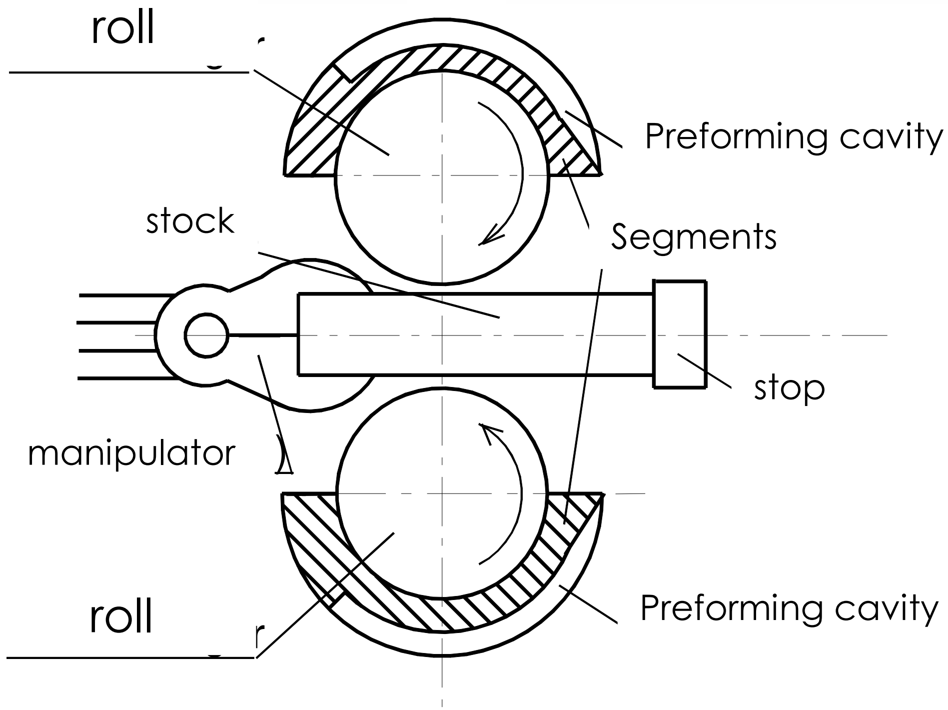
Since the final geometry and its tolerances are defined by the finishing die. In order **to spare the life-time of the finishing die**, **1-2 preforming steps are recommended**, even if there is no other reason.

The **cheapest preforming die is a worn, widened finishing die**.
With the proper number and design of preforming steps a significant amount of material can be saved, which would flow out into the flash otherwise.

The **flash can be sold** as scrap for good price, but it is **always economical to reduce its amount**, because it means cost by the heating.

For **long spindle shaped part in large series** technical and economically the **best technique is the *roll forging***: a periodic working rolling mill with mounted segment pairs, which act as preforming dies.

Preforming – roll forging

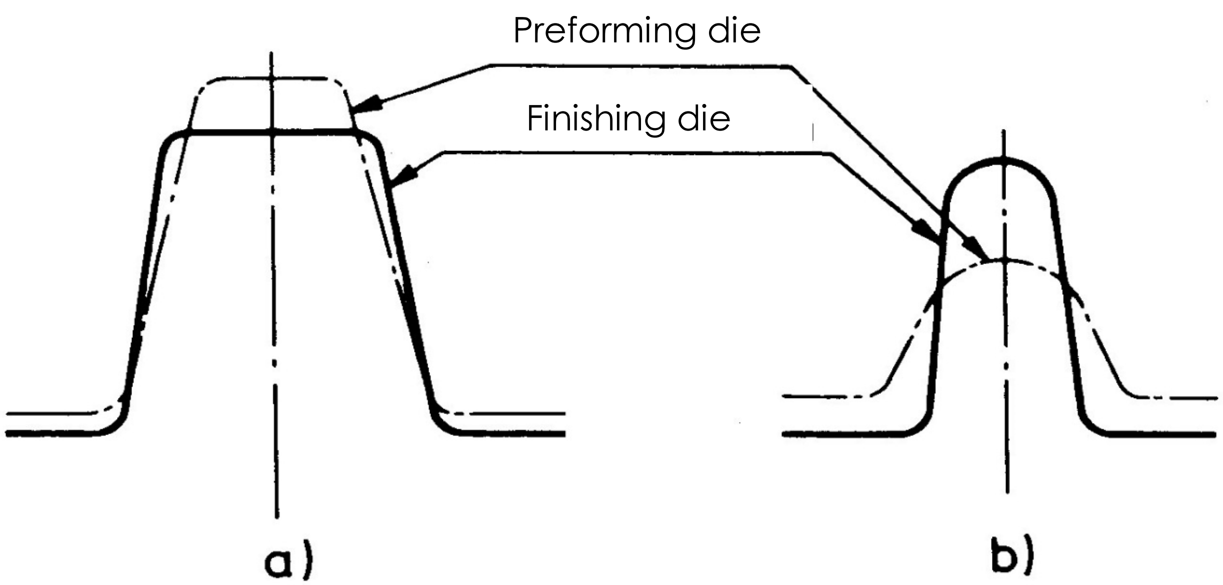


The segment's surface is the **mapping of the forging die's parting plane onto a cylinder**. The preforming cavity is manufactured into the segment's surface.

The central angle of a segment is 87-180°. Up to **4-6 segment pair** can be mounted on one roll, depending on the parts complexity. The manufacturing of the segment cavities is a complicated task.

Moving the part between steps is a **hard physical work**, but it can be automated.

Finishing



Finishing by *a)* upsetting, *b)* impression

The preformed metal fills the cavity of the finishing die. **The filling process depends on the moving tool's velocity**. The process is **different on a mechanical press or on a hammer**. In the former case the process has a static upsetting character, while in the latter one an extrusion/impression character.

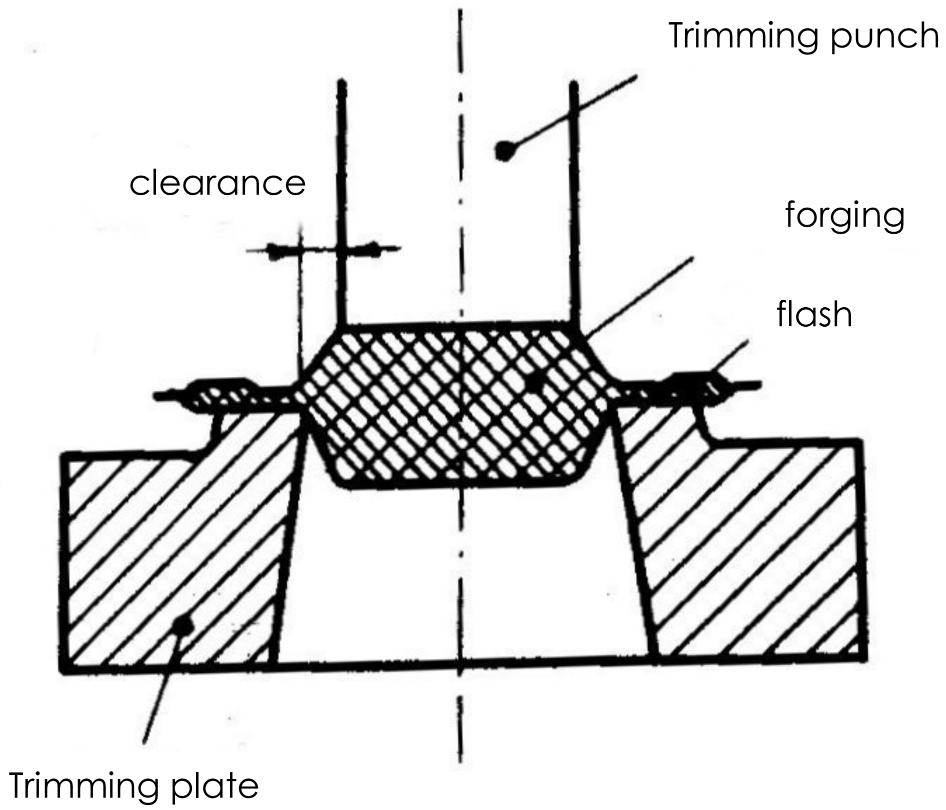
Finishing

The finishing can be done **with or without flash** in die with different gutter geometry. The flash is the material flowing out into the gap between the upper and the lower dies. It **compensate the volume deviation** of the cutting process and **controls the pressure** in the cavity, and **so the filling process**.

Generally, there is **no flash in preforming** steps.

The **line of the resulting force** from the deformation **must coincide** with the line of action of the **forming machine's force**. **Else a moment is generated**, which turns the upper anvil, leading to an **angular defect** of the workpiece and/or **tool break**.

Trimming



Trimming is a shearing operation on the workpiece.

The flash thickness is 1-4 mm.

It is generally done on mechanic presses.

Trimming can be done at **cold, warm or hot** working temperature.

By cold trimming the chance of cracking and fracture is higher but the additional deformation of the workpiece is lower.

Sizing

During trimming the **workpiece can be deformed**, twisted due to the forces acting on it.

To compensate this, a **sizing step (calibration)** is to be applied. The simplest way is to place the workpiece **back into a finishing die** and strike a light blow on it.

For precise parts a separate die must be made for sizing: the workpiece's temperature is lower than the finishing step's temperature, the sizing die must be designed for that temperature.

Heat treatment

The forged part must be heat treated: **normalizing or quenching and tempering for steels**. For **other materials** like austenitic steels, Al alloys or other nonferrous metals **annealing** or – depending on the material – **precipitation hardening**.

Beside the forging workshop **tunnel furnaces can be installed** with programmable zones. Quenching and tempering furnaces are used, with controlled cooling system (water, oil) between them. **Mostly gas-fired furnaces** are used.

If the forging operations' temperature is well controlled, **the heat treatment directly after forging can be carried out**, moreover, some **thermomechanical processes** can be realized as well.

Pickling, removing the oxide

During hot working the metals **surface is oxidizing**. The oxide (scale) can be removed from the forging's surface by **pickling in sulfuric or hydrochloric acid or mechanical process**. The latter one is better due to environmental considerations: **sand blasting and shot peening** is used. Sand blasting is cheaper and gives better surface. Its disadvantage is the **danger of silicosis** for the workers; the protection equipment make the process more expensive.

For **shot peening** the shot is made by **extra hard steel wires** cut to 1-2 mm length pieces **or steel balls** with ~ 1 mm diameter.

Exception: **for austenitic steels glass pearls** are used.

Shot peening is made with special equipment, the wire pieces are accelerated to the **speed of ~ 20 m/s**.

Quality inspection

Beyond the geometry of the workpiece, many characteristics must be investigated: the forged parts are used as high-loaded components where **material discontinuity, overlapping, cracks, and other defects are not allowed**.

The **ultrasonic and magnetic particle inspection** are common for forgings. The mechanical properties must be checked by **hardness testing**.

By **agreement the grain flow** is investigated, and the **mechanical properties** are measured (tensile and impact test: yield stress, tensile strength, elongation, impact energy, etc.)

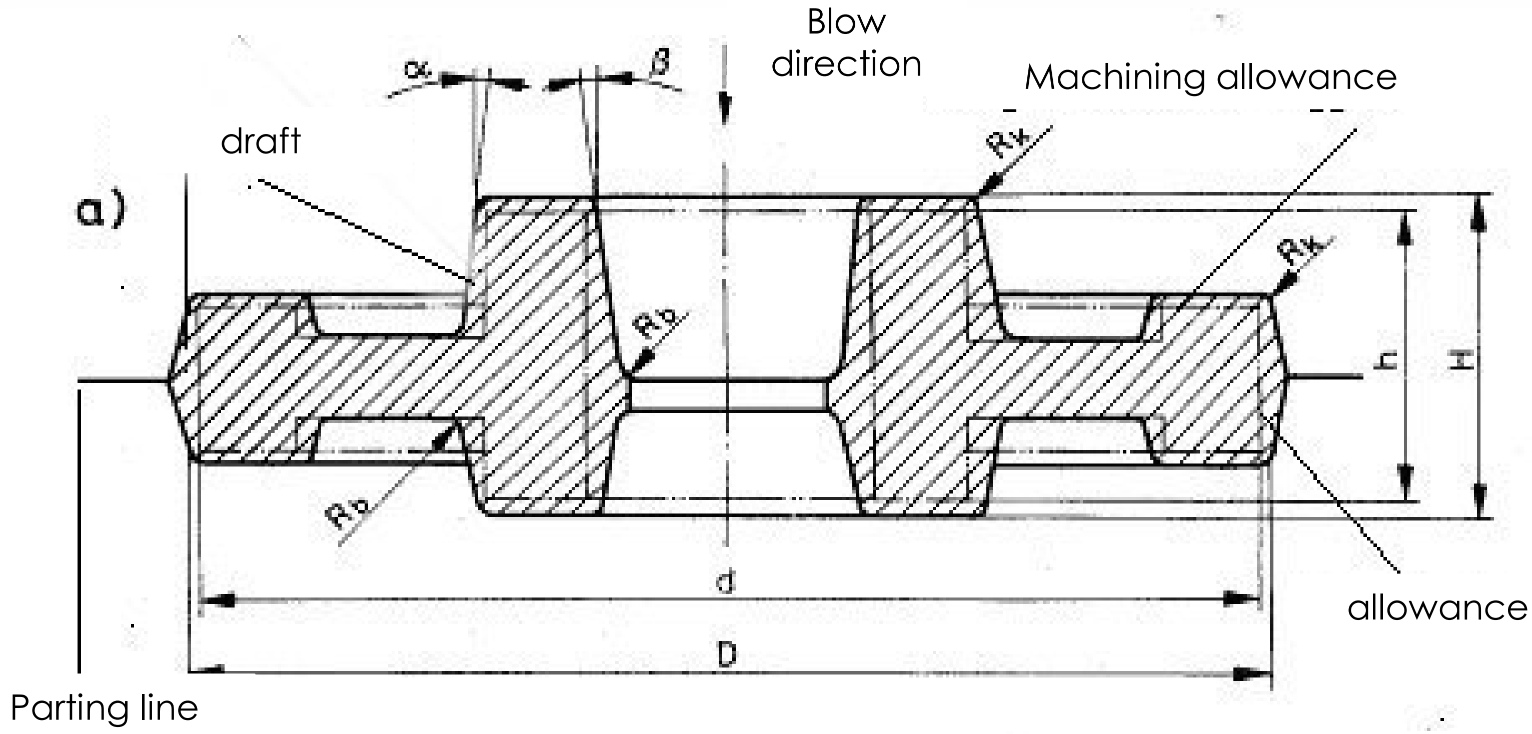
Technology planning and tool design

The **planning steps direction is opposite to the productions direction**: starts from drawing of the finished part and goes backward. (Remember for a former slide.)

Knowing the desired final geometry it must be decided what are the surfaces which must be machined after the forging: small diameter holes, high tolerance surfaces (contact surfaces with other parts), threading, teeth. Except some special case undercut geometries can not be forged. For these features **extra volumes must be added to the geometry:** e.g. filling up the holes, threading and spaces between teeth.

Next step is choosing **a parting line (surface)**. The dies have only one line, except horizontal forging machines, where two perpendicular planes are used. The parting surface can be non-planar but increases the costs significantly. For **disk shapes parts, the parting line is at the largest diameter**.

Disk shaped forging –
Parting line, allowances, draft, radii and fillet



After defining the parting line, the **machining allowances** must be determined. Thereafter the **draft** must be dawn: it ensures that the part will be removable from the die (**no perpendicular surfaces to the parting line**).

Disk shaped forging – Parting line, allowances, draft, radii and fillet

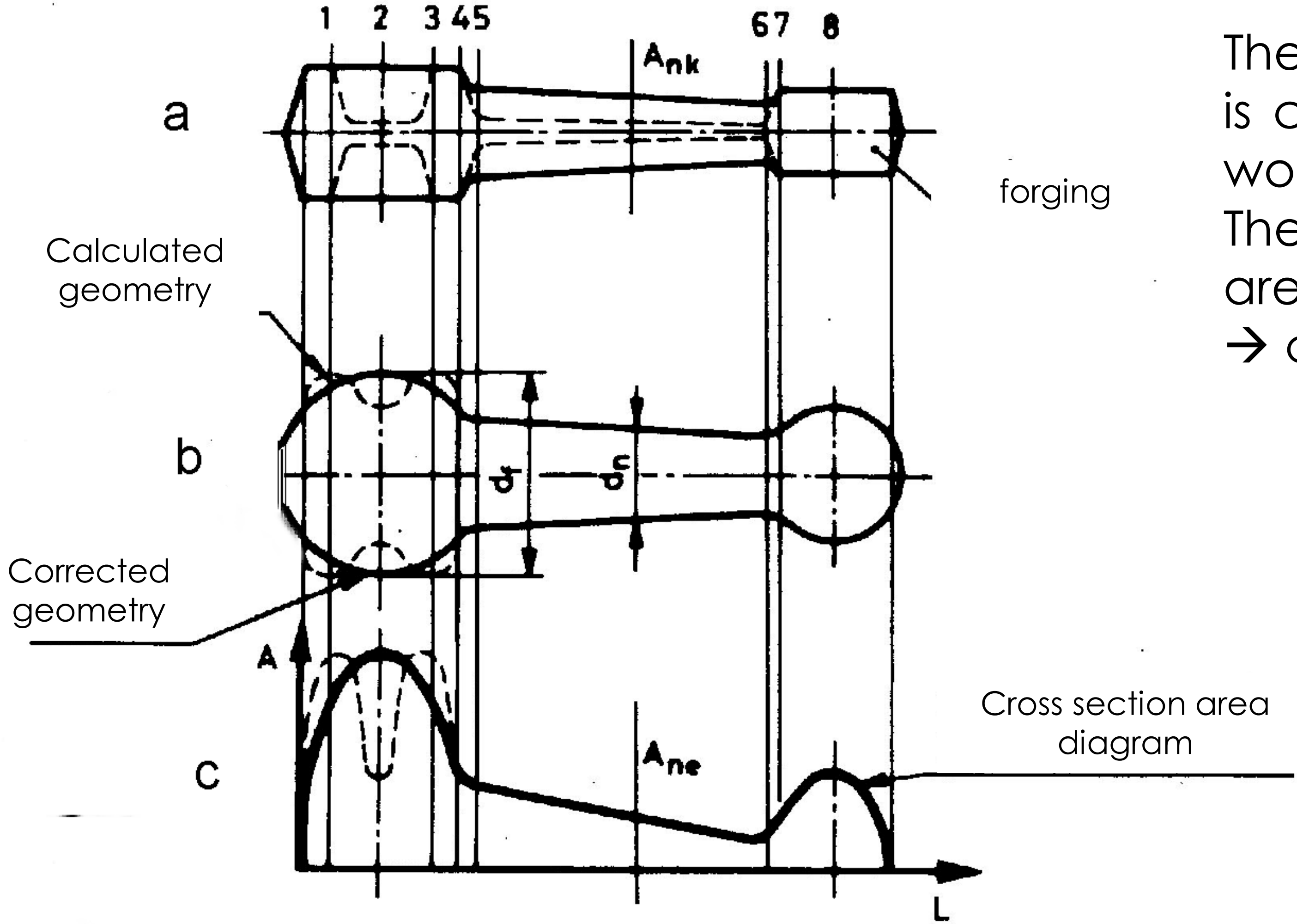
Increasing the draft makes the removal easier but increase the mass of the forging.

After the finishing step **the workpiece starts to cool and shrinks**. Therefore, its dimensions are going to decrease. The **outer surfaces are getting further** from the die's surfaces. Contrary to that, the **inner surfaces shrink onto the die**, making the ejection more difficult. So, the **draft angle is different on the inner and outer surfaces**.

Mechanical machines are equipped with **lower and upper ejectors** thus the draft can be smaller. On screw presses, there is a lower ejector (upper rarely). **Hammers usually don't have** ejectors (modern ones can have), so **the draft is the highest for hammers**.

The volume of the forging must be calculated. This planning step is done together with the design of the preforming steps geometry.

Design of the preformed geometry of a connection rod



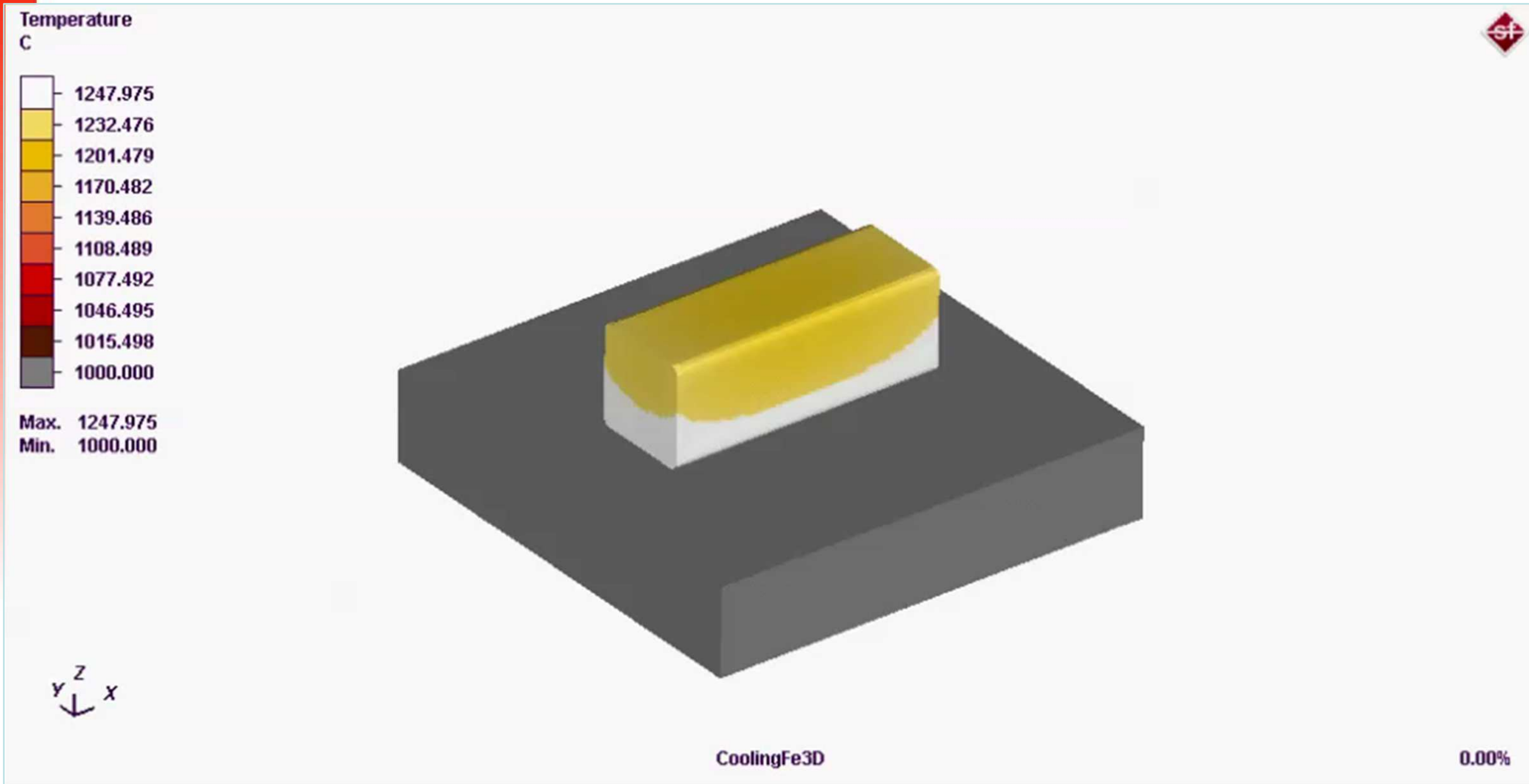
The sections area A(x) is calculated along the workpiece's axis (x).
The stepwise changes are smoothed to get a → corrected geometry.

$$A(x) = \frac{d(x)^2}{4}\pi$$

$$V_0 = \int_0^L A(x)dx$$

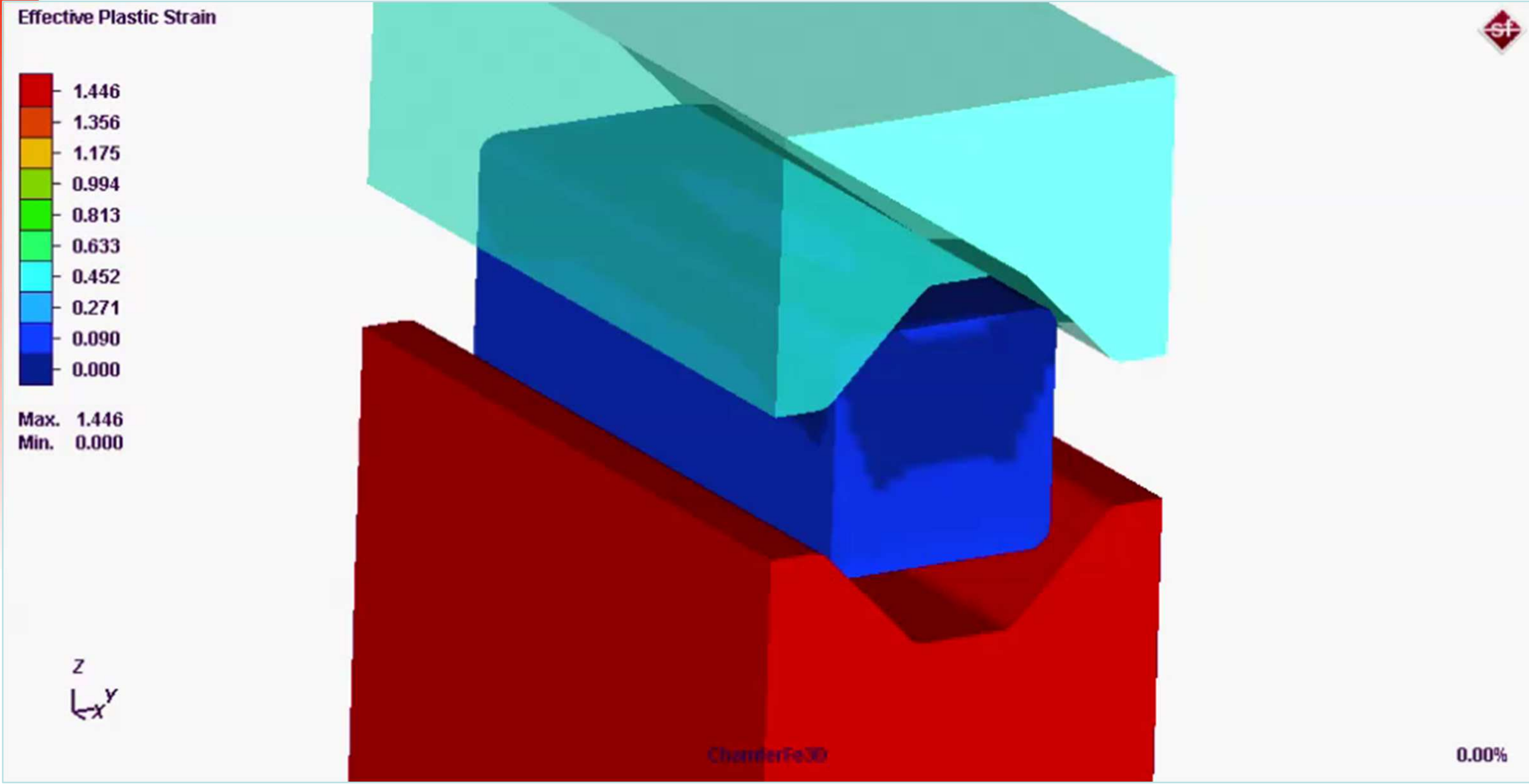
This geometry **does not include the material which will go to flash, burn and the wasted at parting**.

Virtual manufacturing - FEM



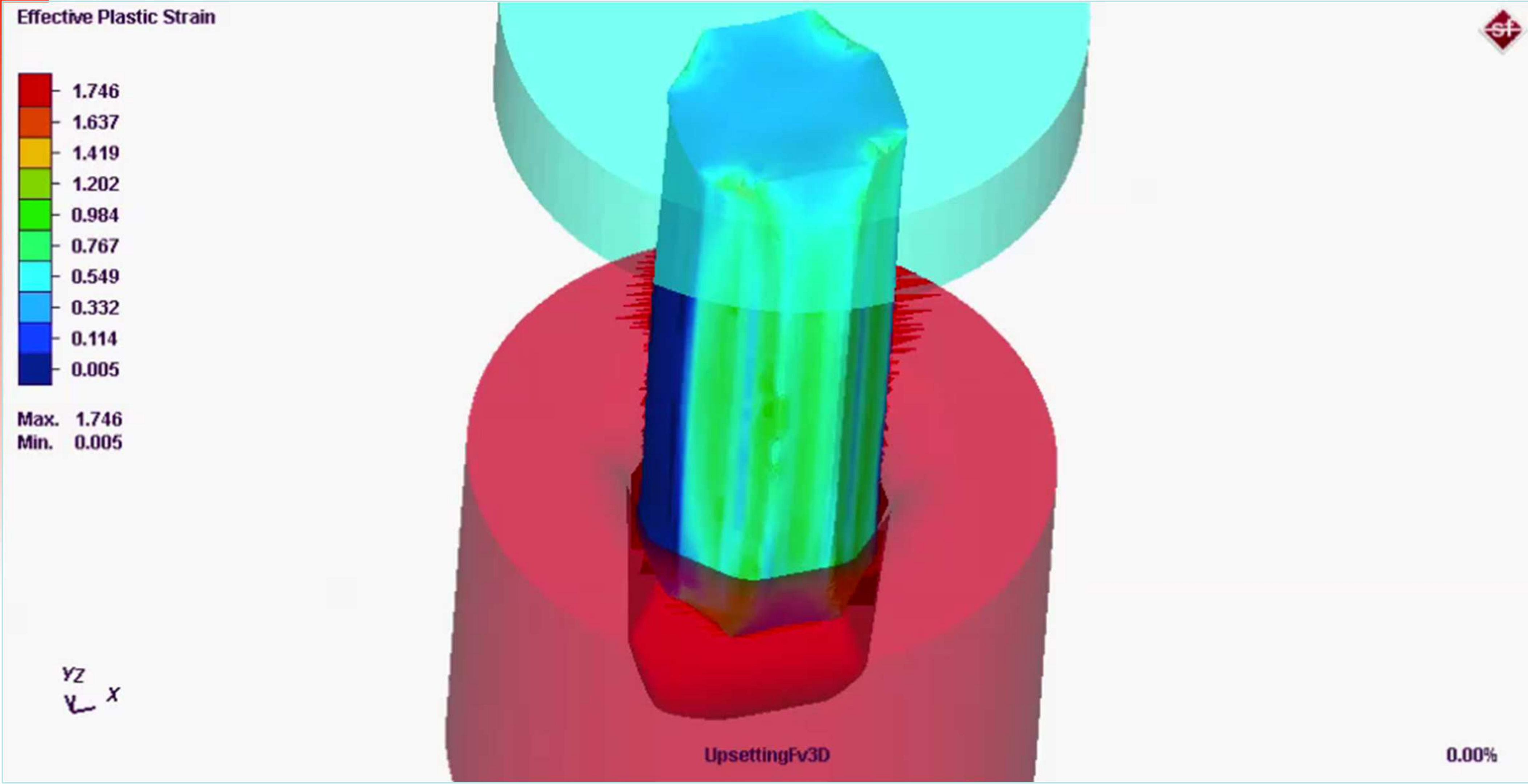
Cooling of the part during transport

Virtual manufacturing - FEM



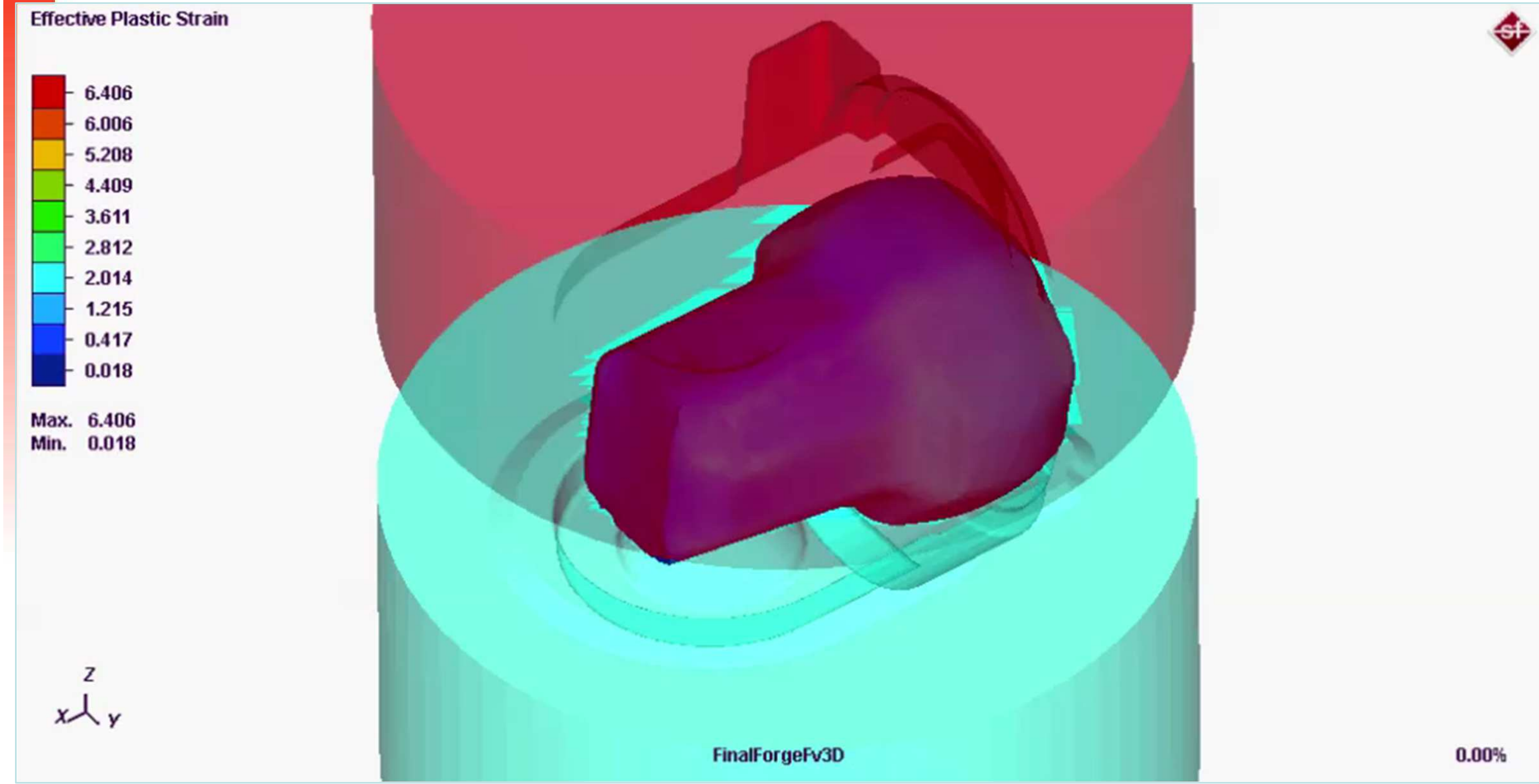
Forming step 1 - Chamfer

Virtual manufacturing - FEM



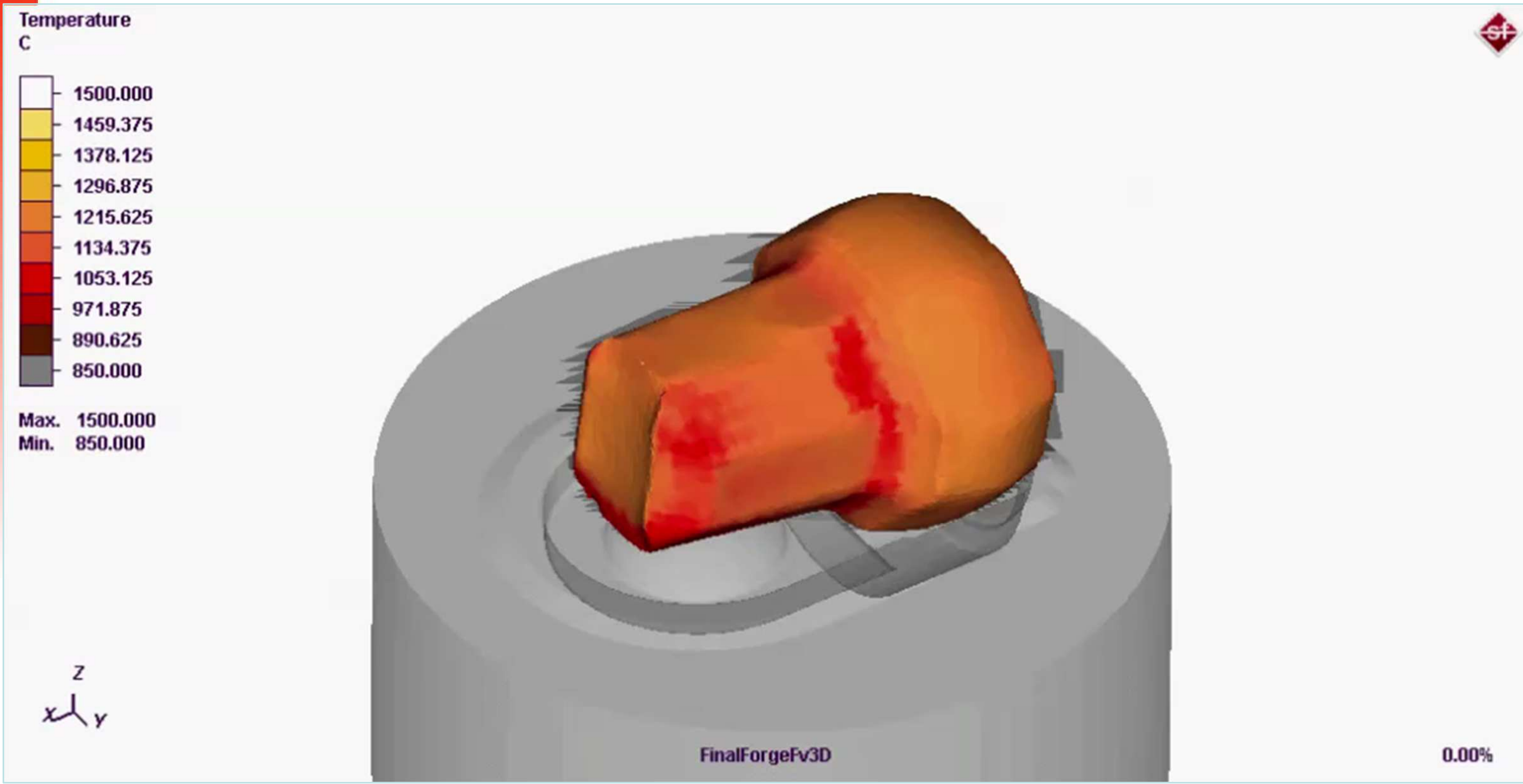
Forming step 2 - Upsetting

Virtual manufacturing - FEM



Forming step 3 – Forging

Virtual manufacturing - FEM

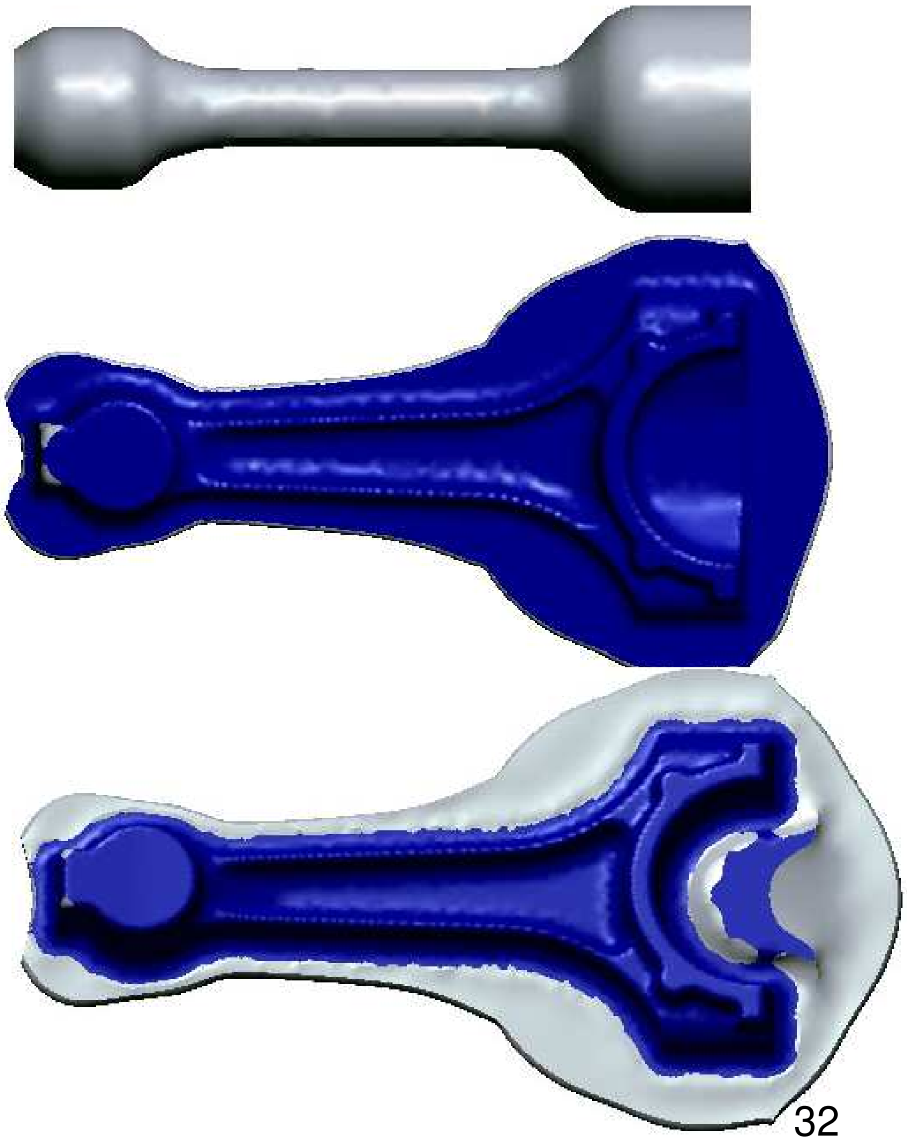


Forming step 3 – Forging

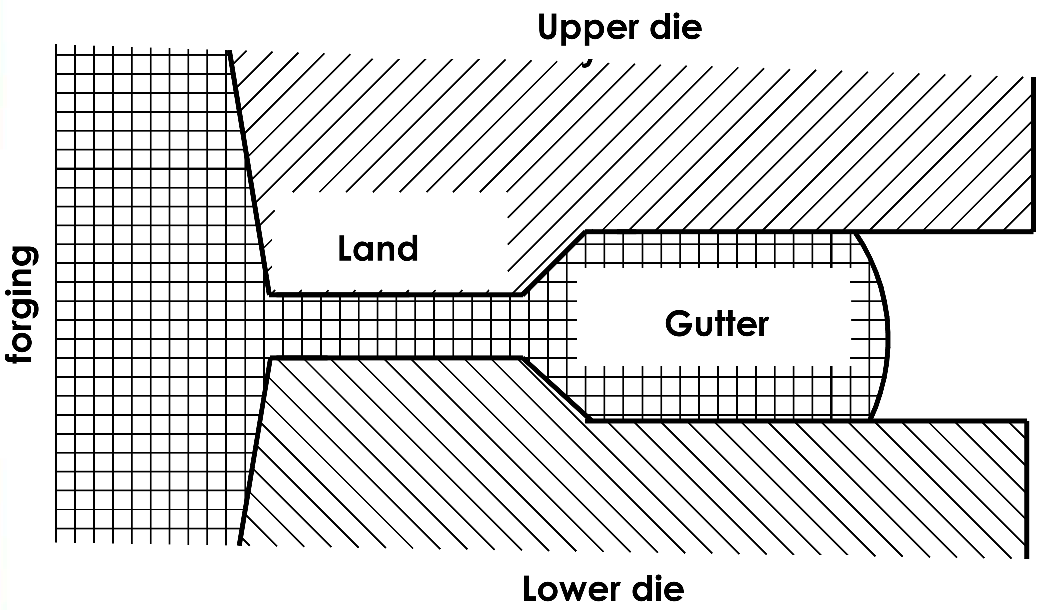
FEM calculation

Original

Optimized preforming



Design of flash land and gutter



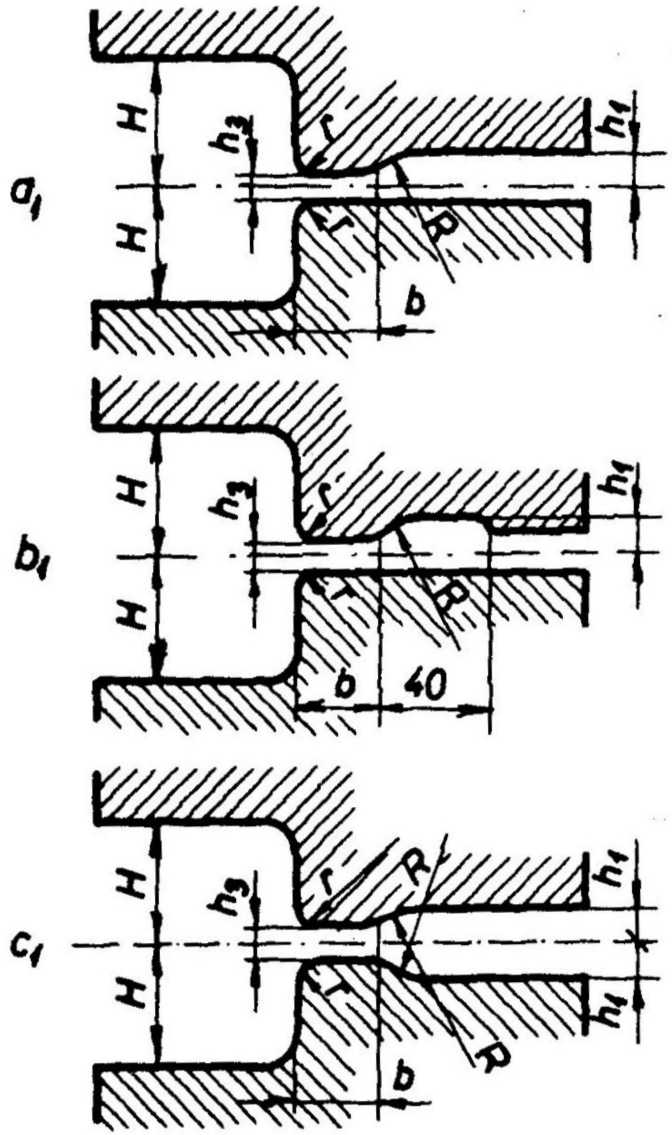
Land and gutter geometry is designed, A_s is calculated, assumed that is filled up to 70%.

$$\Delta d = \frac{0.7 A_S}{d\pi}$$

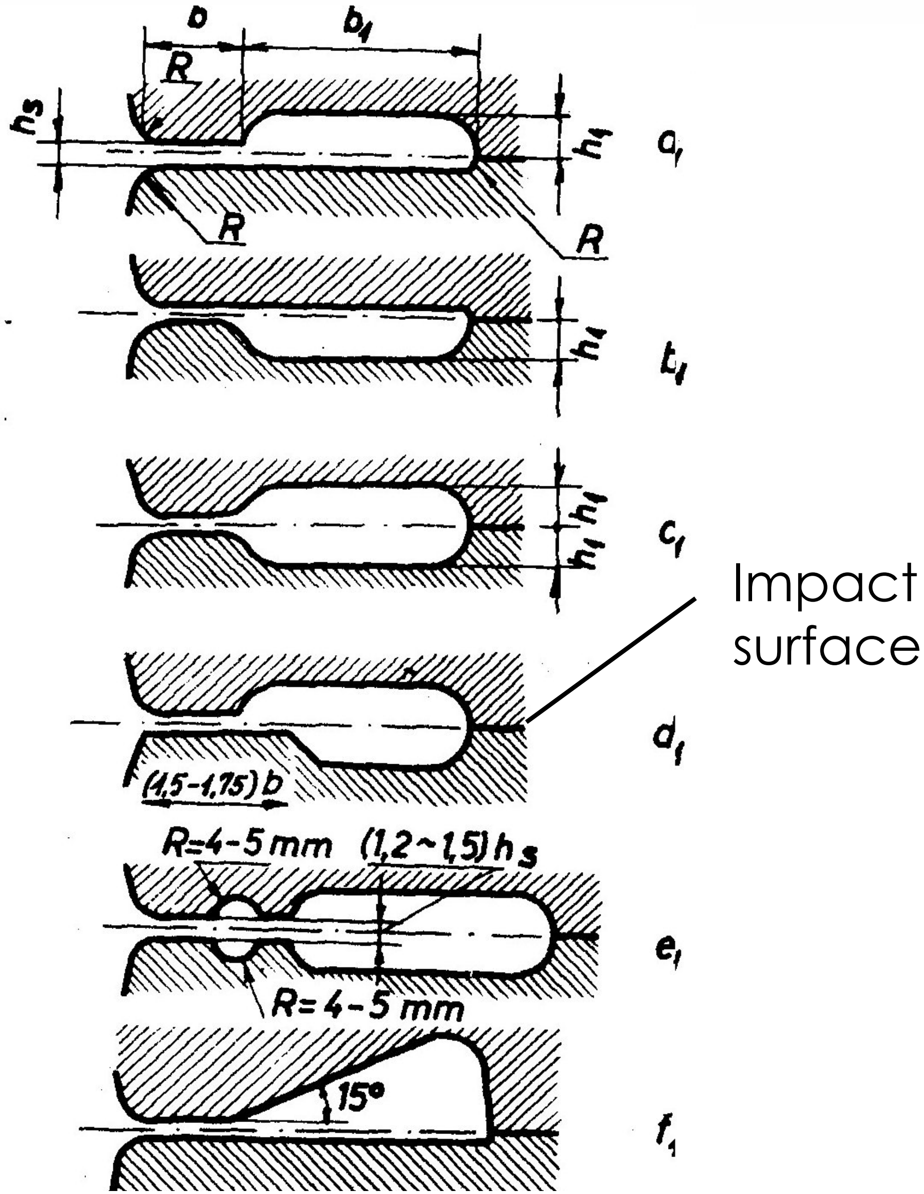
The Δd diameter increment must be added to every diameter on the cross-section area diagram

Common **problem** that the material does **not fill the cavity properly**. The volume of the part must be increased: **the increased amount of material flows into flash**, this way **forces the rest to fill the cavity**. In extreme cases up to 50% of the volume can go into flash. It can be reduced by increasing of the number of preforming steps – if possible.

Design of flash land and gutter



Machanical presses
Open design



Screw presses, hammers
Closed design

Design of preformed geometry

The **volume is calculated**, which **includes the flash**. The **wasted material by parting and burning must be added**.

The **volume divergence of shearing is ~ 3-4%.** It can be increase by using modern processes (e.g band saw). Much more materials can be wasted by oxidation. **In gas-fired furnaces it can reach 13-14%,** while in well controlled **induction furnaces can be decreased below 1%.** For some materials (e.g. titanium alloys) shielding gas can be applied.

Based on volume constancy the cut stock's volume can be calculated. If the largest cross section area of the preformed piece is A_{premax} the stock's cross section A_{stock} must be equal or somewhat larger than A_{premax}

$$A_{stock} = (1...1,05)A_{pre\max}$$

Design of preforming die

The cross section of the billets is usually rectangular for steels, ands circular for light and heavy metals. (steel billet are made rolling, heavy and light metals by extrusion). For light and heavy metals cast ingots are also used.

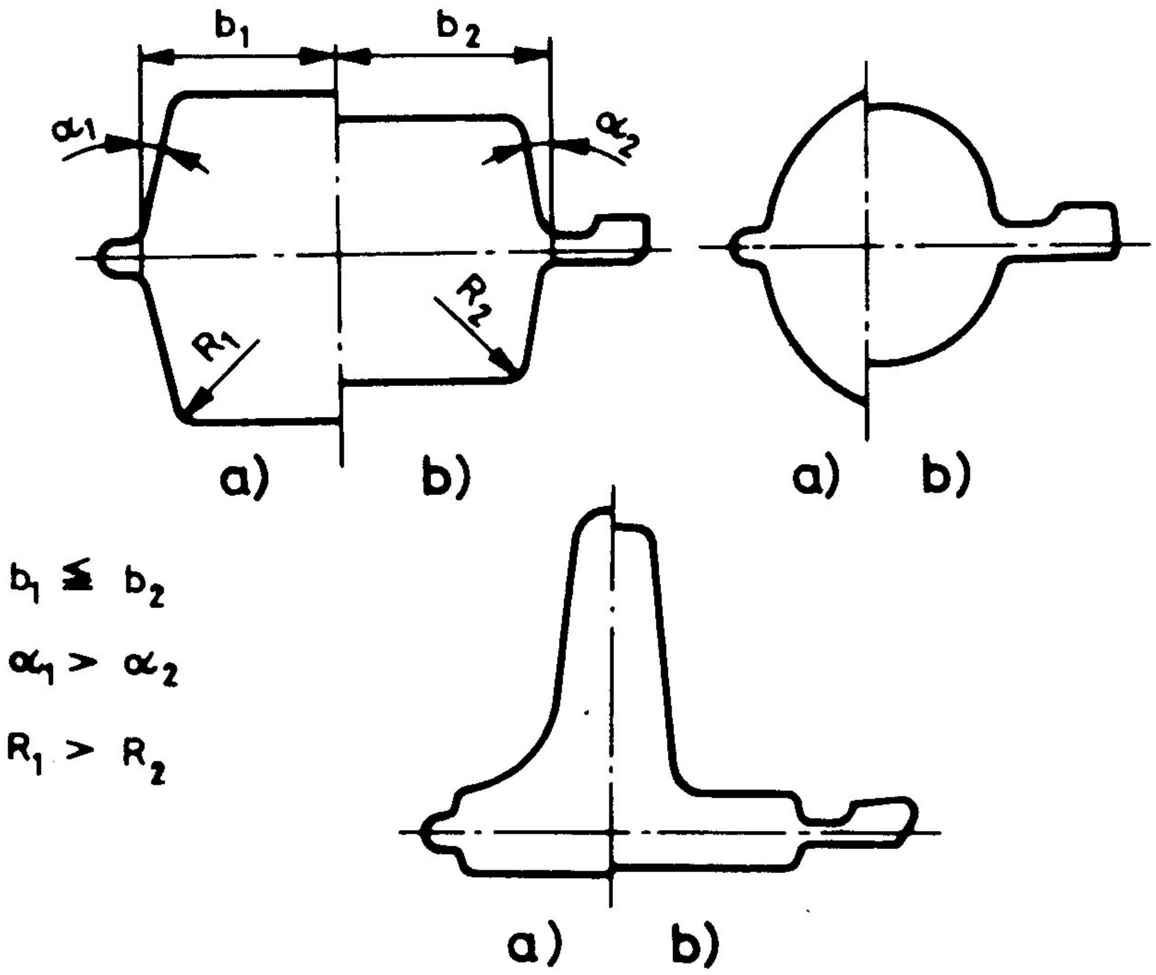
The **preformed part is forged directly form the cut stock or after forming with roll forging.**

The cavity design is based on the finishing die's geometry.

3 principles:
1) volume constancy
2) correction of the shape
3) altering the grain flow
   - disks: upsetting
   - non-straight long parts: bending

The **cavity must be filled without flash** land and gutter: **the radii and draft angles are higher** than that of in the finishing cavity.

Design of preforming die



a Preforming die

b Finishing die

Design of finishing die – thermal expansion

The finishing die's cavity is the negative of the forging.
The cavity's geometry and the workpieces geometry at room temperature are different. Their geometry is the same only at the final moment of finishing.

Workpiece:	low alloyed steel,	T=900–1250 °C
Tools:	high alloyed steel,	T=150–300 °C

Their temperature and thermal expansion coefficients are different.

L_{m0}:	workpiece's dimension at T_0
L_m:	workpiece's dimension at forging temperature
S_{m0}:	tool's dimension at T_0
S_m:	tool's dimension at forging temperature
α_m, α_s	thermal expansion coefficients of workpiece and the tool

At the final moment of finishing:
$L_m=L_s$ while the workpiece has T_m and the tool T_s temperature.

$$L_m = L_{m0}\left[1+\alpha_m\left(T_m - T_0\right)\right],\quad L_s = L_{s0}\left[1+\alpha_s\left(T_s - T_0\right)\right]$$

$$L_{s0} = L_{m0}\frac{1+\alpha_m\left(T_m - T_0\right)}{1+\alpha_s\left(T_s - T_0\right)} = L_{m0}\,(1.007\ldots1.015\,)$$

Role of the flash

An important part of the finishing die's design is the flash land and gutter: **flash is not only excess material**.

The flash cools faster, so its actual yield stress if higher. Because of the geometric conditions, there is a high resistance against the flow.

The amount of flash is limited by the deformation of the die: **the pressure on the cavity increases due to the flash** and so the mechanic load on the dies. It leads to excessive deformation and wear: after a few produced part the die's geometry steps out of the desired tolerance and must be replaced (increased costs).

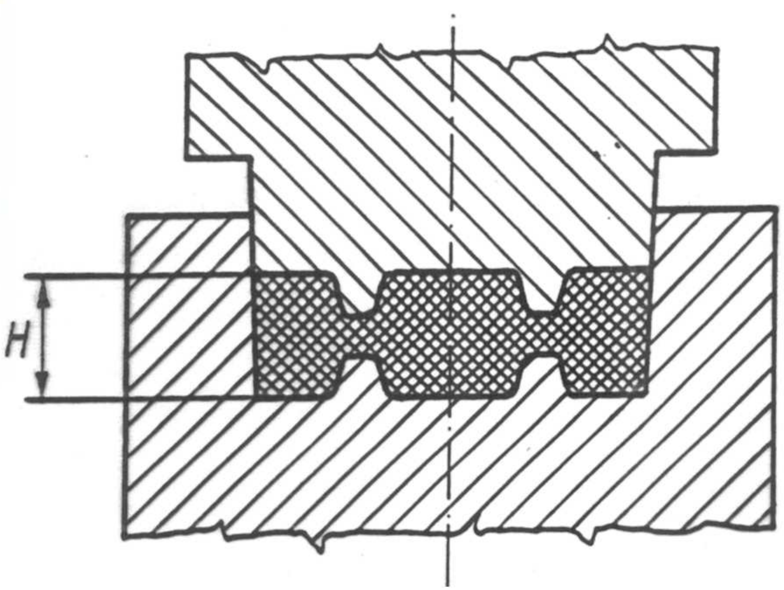
Orientation in the trimming tool.

Ejection of the forging: **the ejectors lift the part by the flash**, no mark on the forging surface.

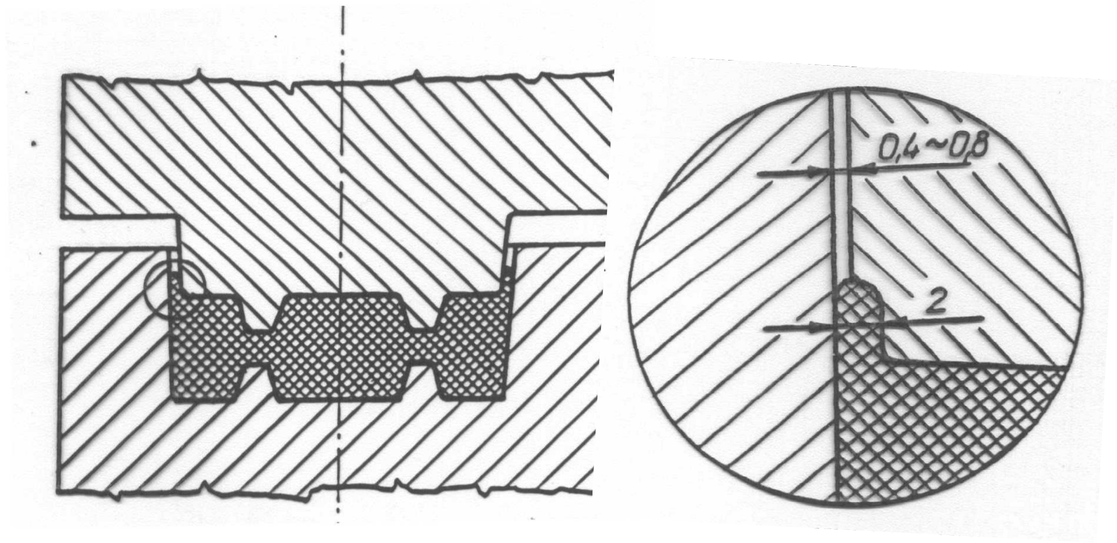
Forging without flash

The **flash is wasted material and energy**. Under strict conditions, it can be avoided:

1) volume constant parting
2) overload protected forging equipment (hydraulic presses are such equipment – but not commonly used in closed-die forging)

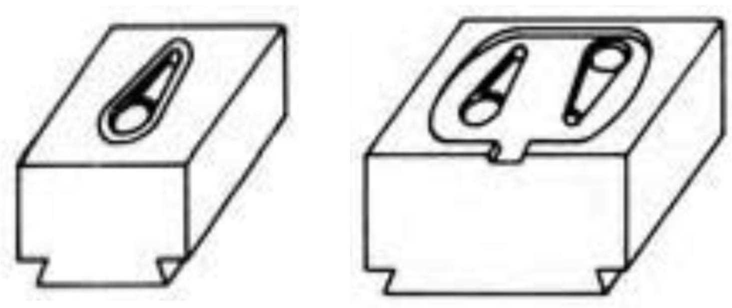


Die without flash

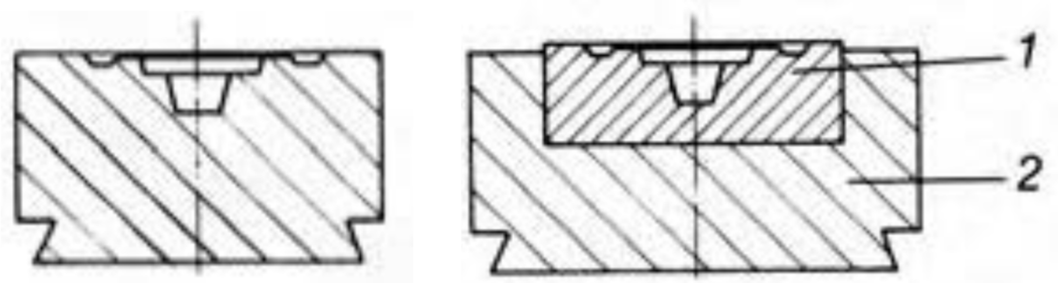


Compensating the uncertainty of the volume

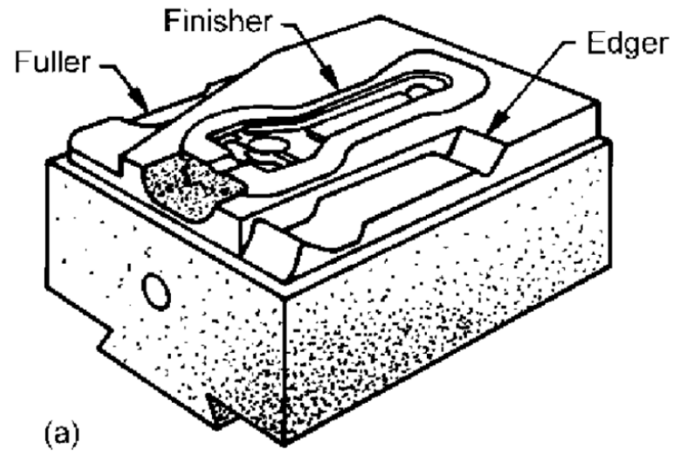
Design of the die – single and multiple dies

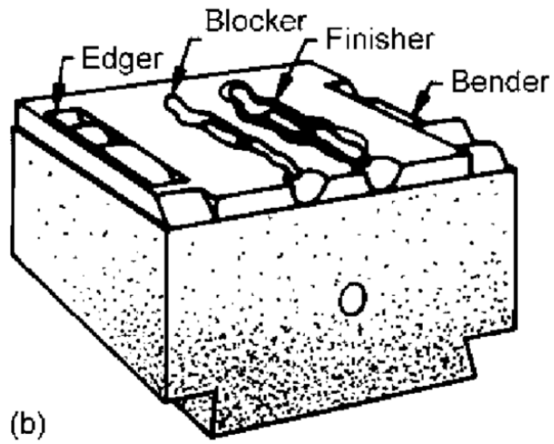


Single and multiple die



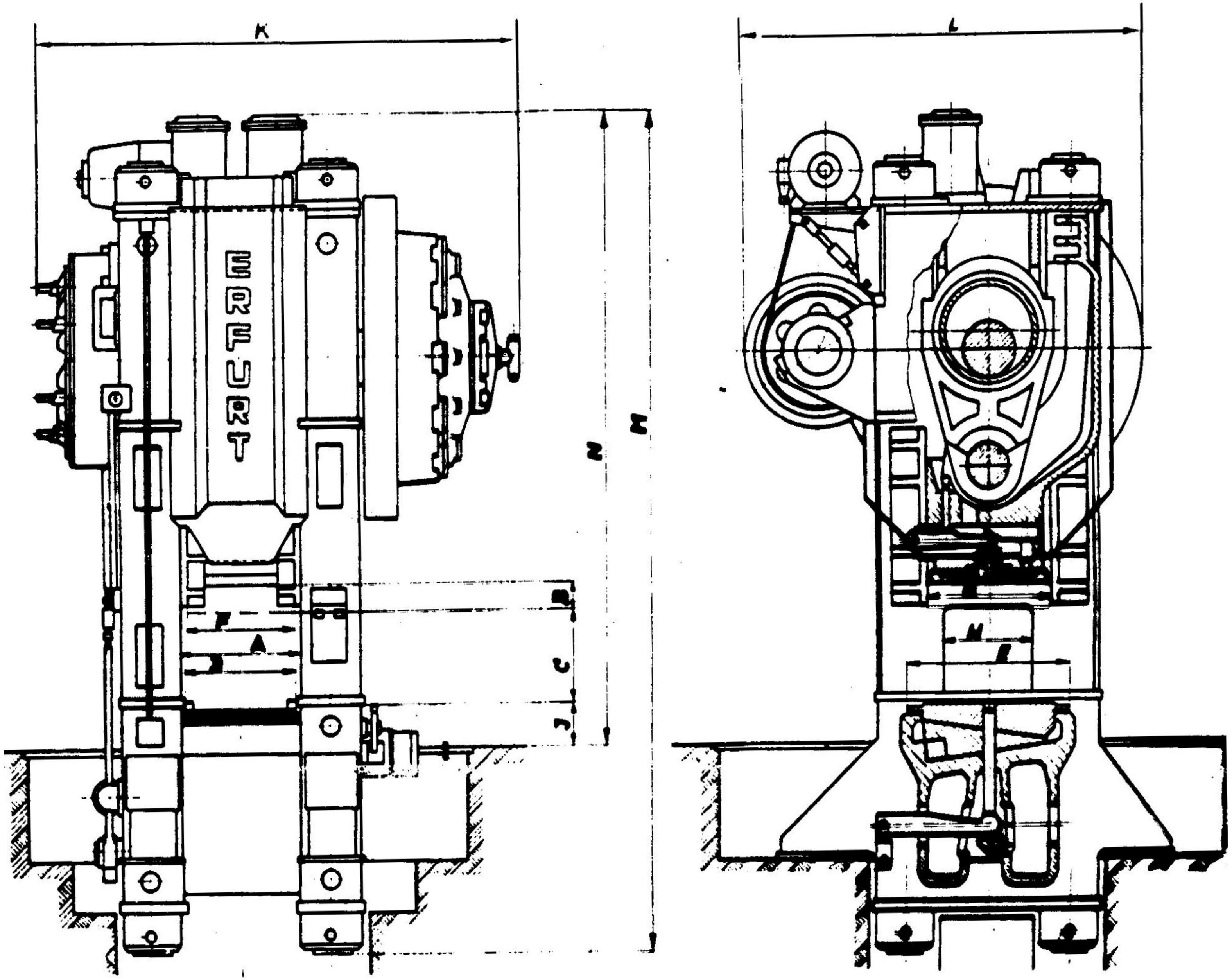
Solid die and die with insert



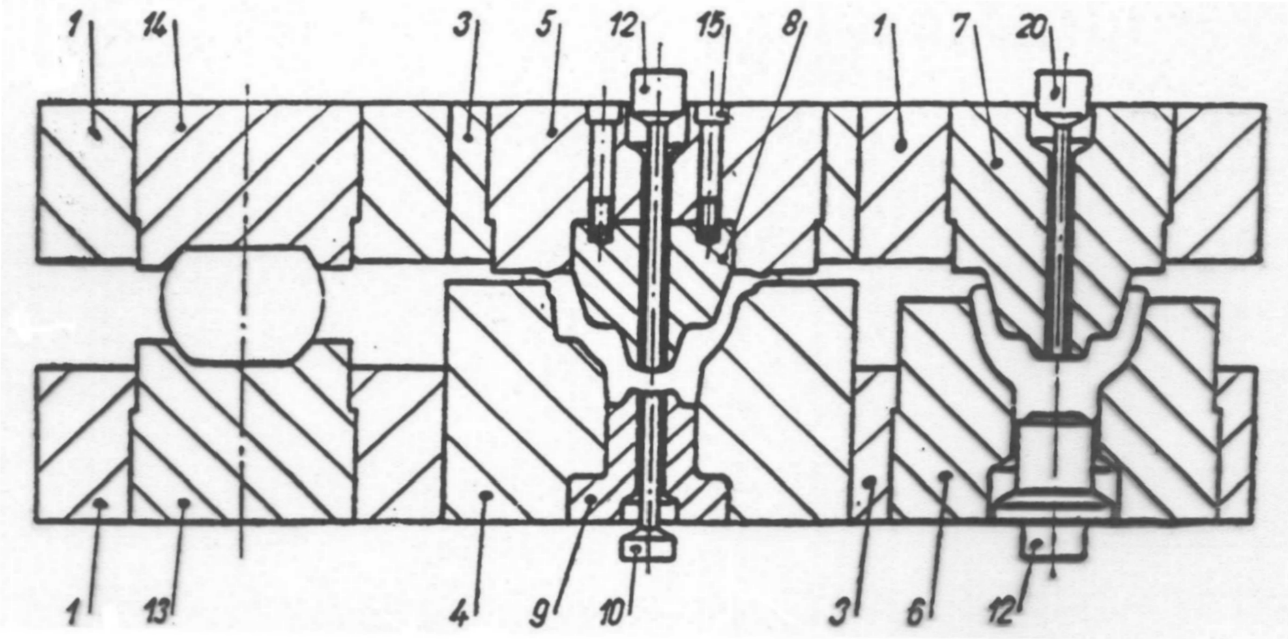


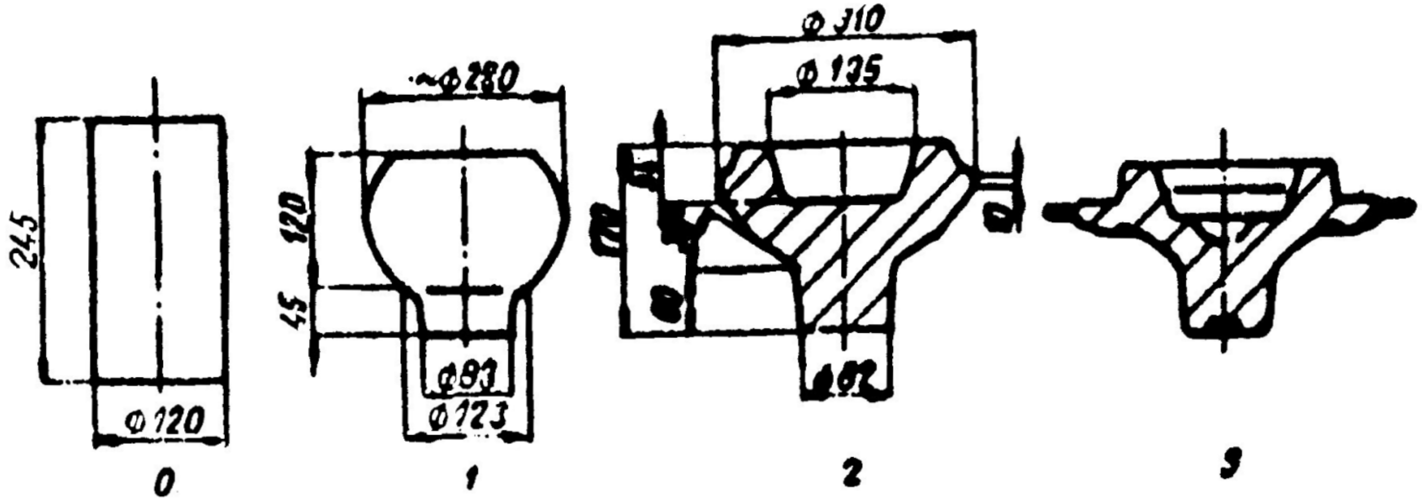
Multiple operation in one die

Mechanical forging press



Arrangement of preforming and finishing operations on mechanical presses





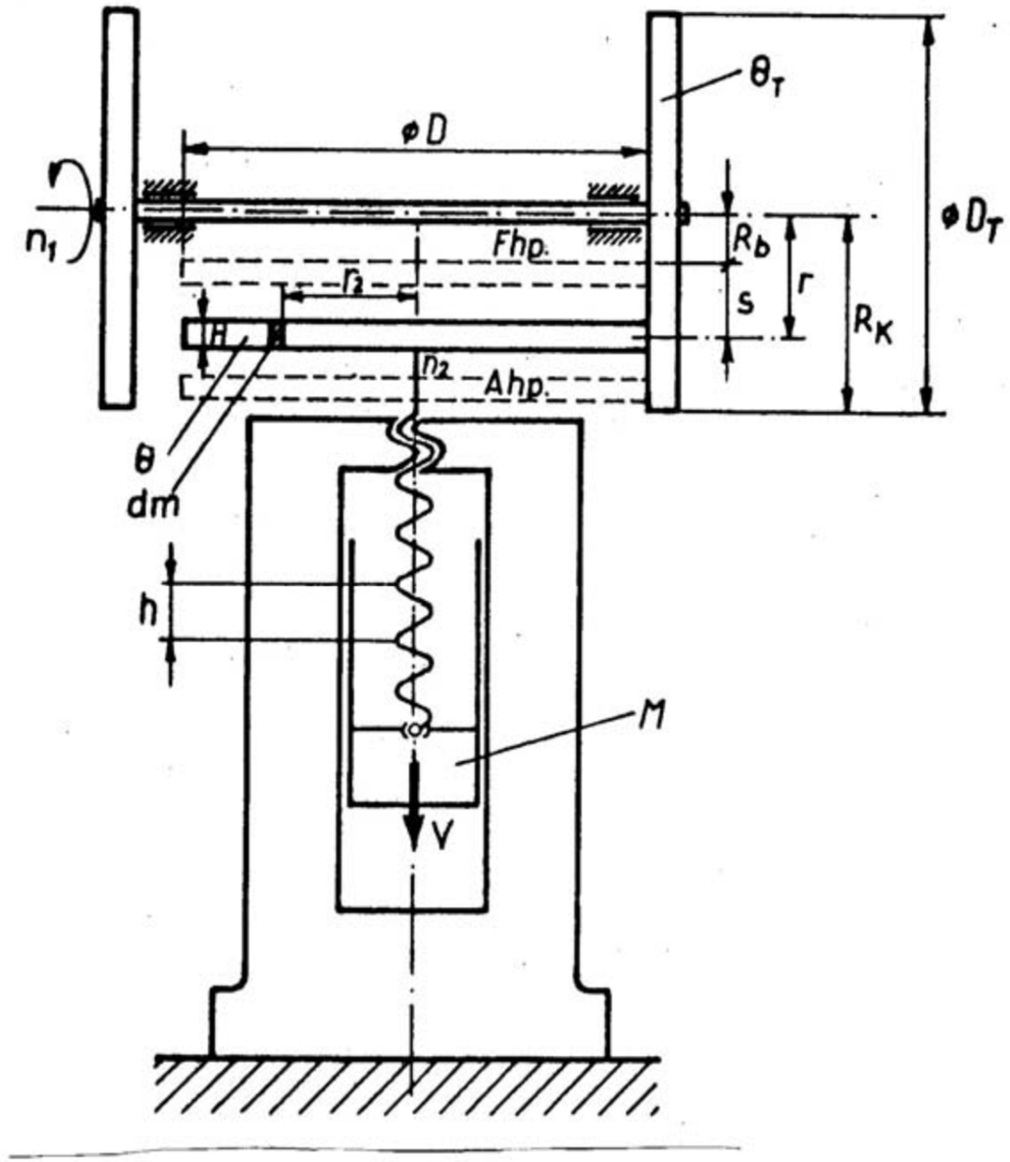
Dies for screw presses

The spindel can be **loaded only in axial direction**.

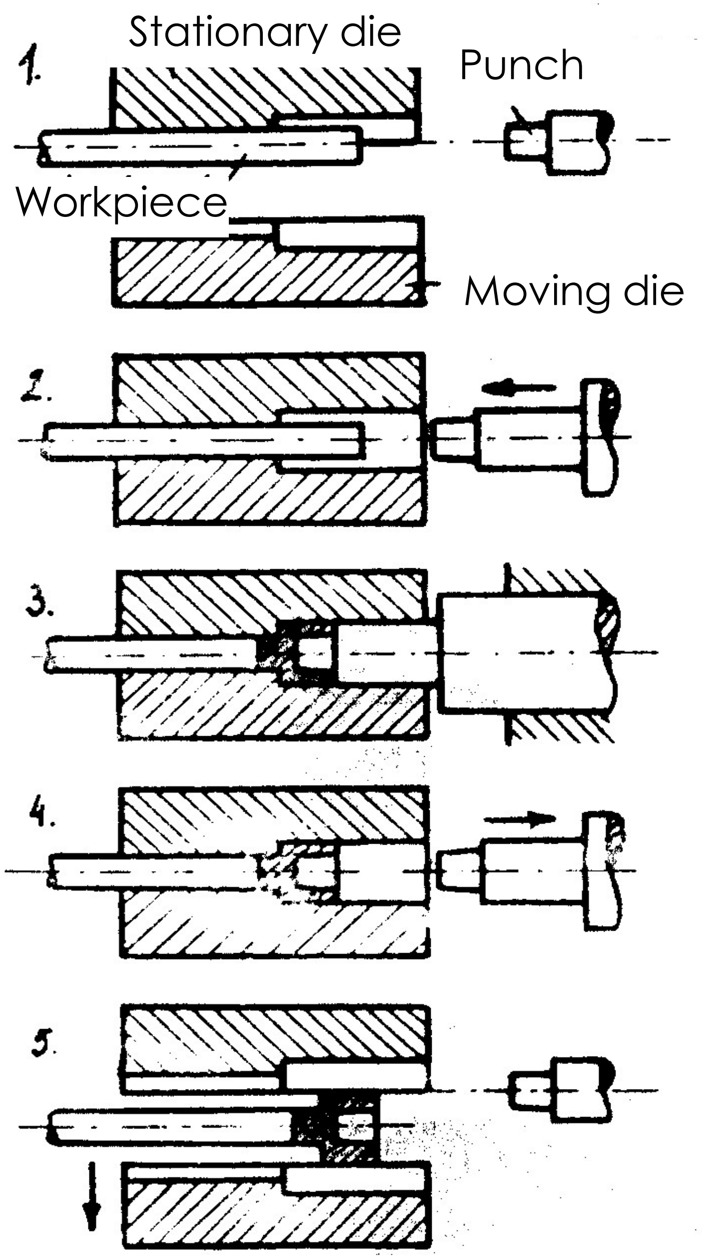
The resulting **force must be alligned** with the spindle's axis.

Only one operation per press is suggested.

The flash **gutter is closed**.



Horizontal forging press



Dies: two dies - one punch

Synchronized motion of dies

Two perpendicular parting lines

Geometrical limitation: buckling

Advantages of a horizontal forging press

Parts with **more complicated shapes** can be forged.

Better tolerances

Less or no flash

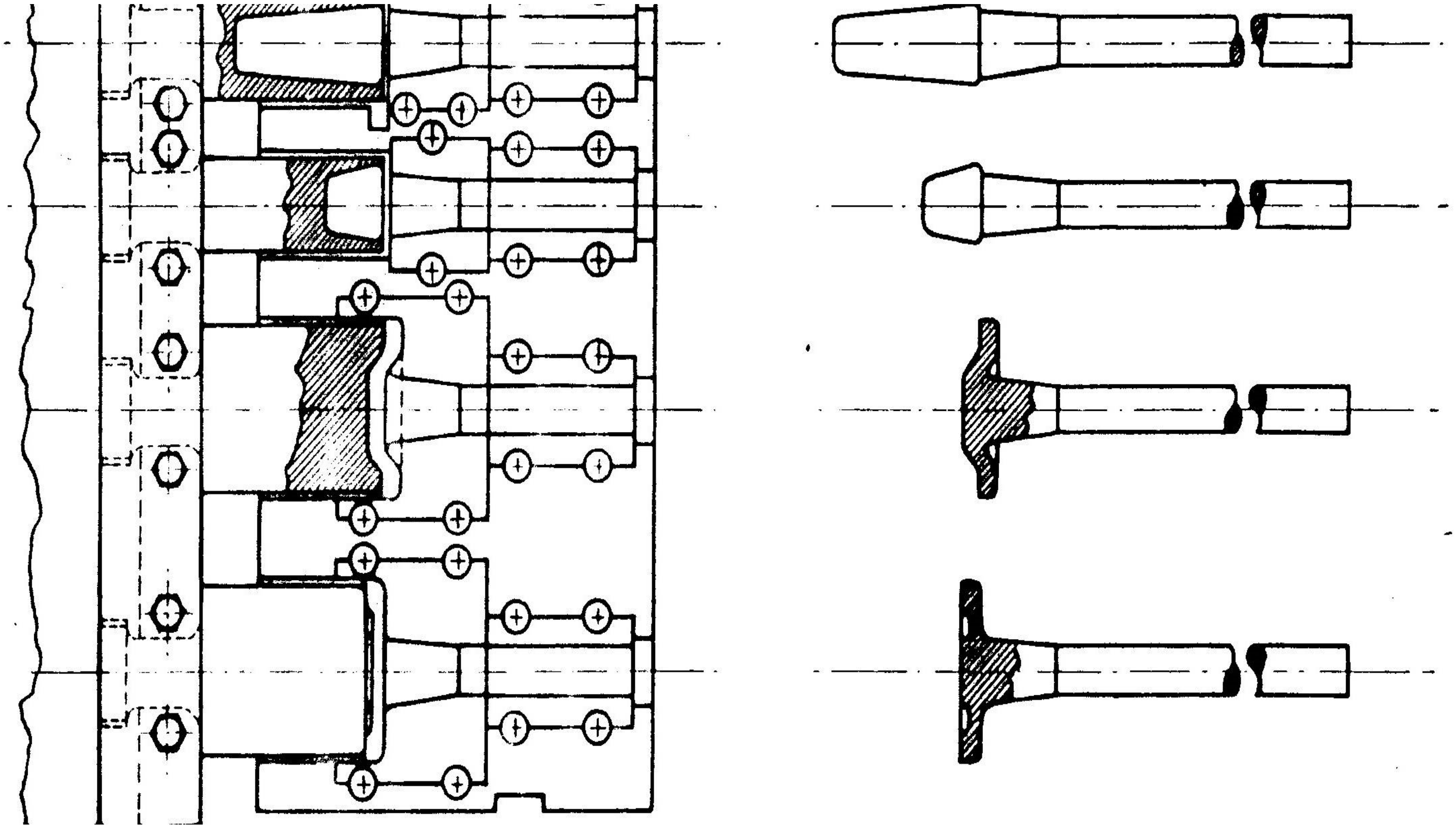
No draft angle is necessary on inner surfaces.
Outer surface: same as on mechanical presses.

Good grain flow

Working directly from wire or bar.
No separate partig step is necessary.

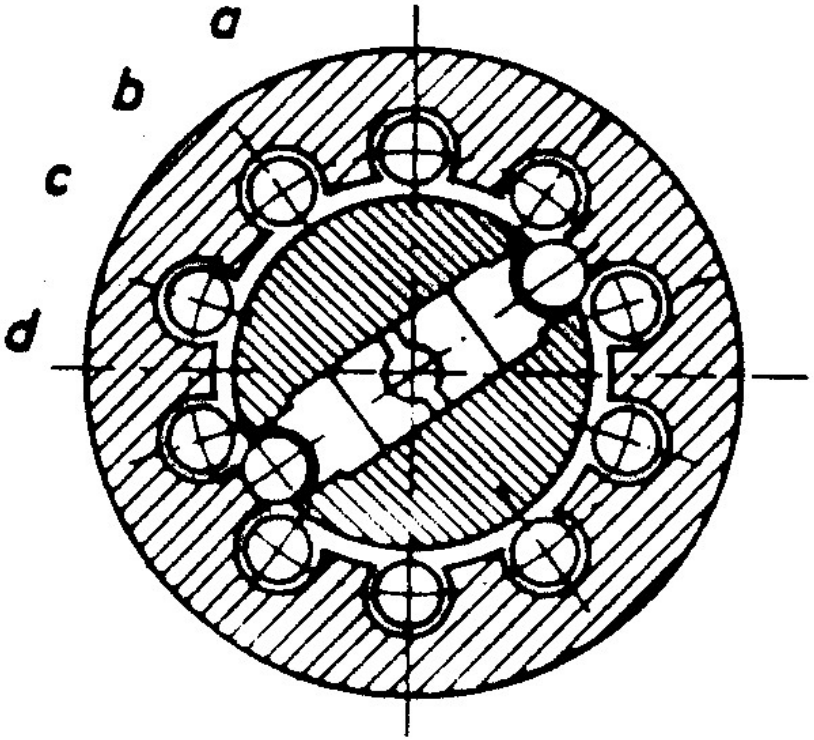
Changable die inserts

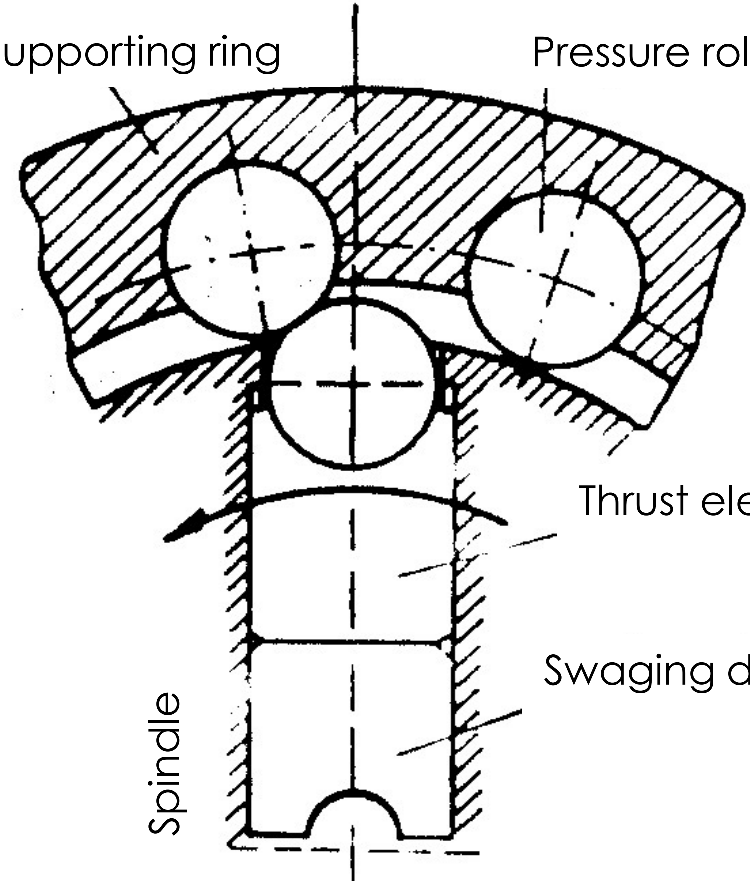
Forging in 4 steps



Forging of long axisymmatrical parts

Rotary swaging
Solid or hollow parts with strict tolerances
For both cold and hot forming
Stroke: 1800 - 3900 stroke/minute.
Application example: rifled barrels

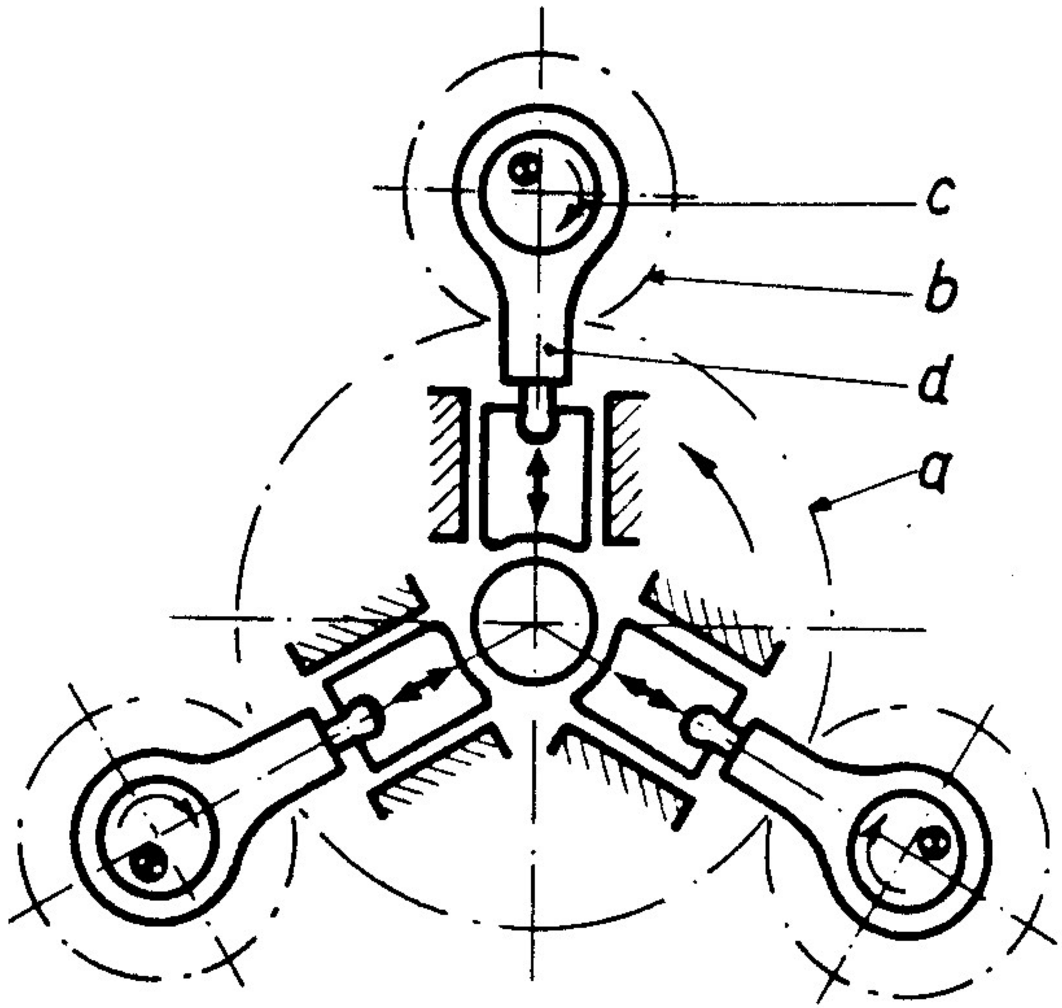




Rotary forging

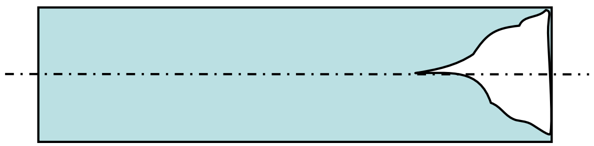
Rotating workpiece: circular cross section
Stationare workpiece: poligonal cross section

The strain is small, while the deformation takes place mainly on the surface.



B

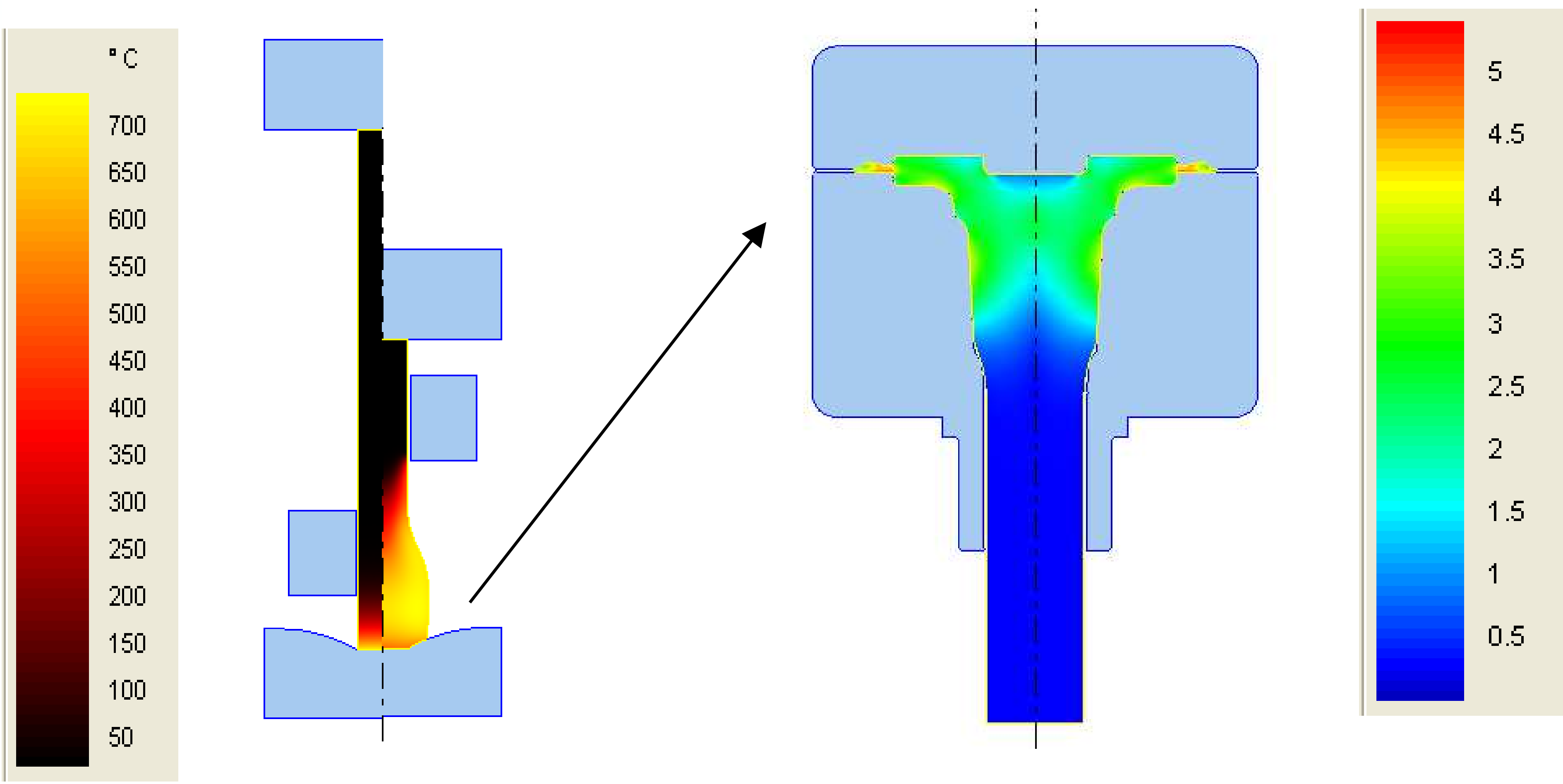
The end of workpiece after forming:



Upsetting with local heating

For valve-shaped parts.

Induction heating.



Heating + upsetting **Upsetting/forging**

Thank you for your attention!