Plasticity and Deformation Process

Effect of temperature on plastic deformation processes & Forging

Metal forming processes are classified based on both the temperature and the material being formed:

- **Hot working**

Plastic deformation is performed under high temperature where recrystallization occurs simultaneously with the deformation
The temperature of deformation is greater than 2/3 times the melting temperature of the material on an absolute temperature scale

- **Cold working**

Cold working is deformation under conditions where the recovery processes are not active
The working temperature is usually less than 1/3 of the workpiece melting temperature

- **Warm working**

Warm working is done between 1/3 and 2/3 of the melting temperature to improve the efficiency of cold working processes

Hot working temperature depends on the recrystallization temperature of the metal under consideration.
Tin is near hot-working temperature at room temperature, steel requires temperature greater than 1000 C and tungsten does not undergo recrystallization until above 2000 C

- At the temperatures of hot-working, recrystallization eliminates the effects of strain hardening so there is no considerable increase in strength and hardness or decrease in ductility
- The metal can be drastically deformed without the requirement of excessively high forces or fear of fracture
- The stress-strain curve is nearly flat after the yield point
- The elevated temperatures promote diffusion that can remove or reduce chemical inhomogeneities, close the pores or reduce their size
- Hot working is beneficial especially for steels as they transform to weak and ductile austenite phase as opposed to the stronger ferrite that is stable at lower temperatures

- On the negative side, high hot-working temperatures may promote undesirable reactions between the metal and the environment
- Tolerances are poorer due to thermal contractions and possible warping or distortion that result from nonuniformity in the cooling
- The metallurgical structure may be nonuniform since the final grain size depends on the amount of deformation, temperature at last deformation, and cooling history after the deformation all of which may vary throughout a workpiece

The plastic deformation of metals much below the recrystallization temperature is known as cold working
Cold working has a number of distinct advantages from a manufacturing point of view

- No heating is required
- Better surface finish is obtained
- Better dimensional control is achieved in the absence of expansion of tooling. Little or no secondary machining is required as a result
- Products possess better reproducibility and interchangeability
- Strength, fatigue and wear properties are all improved through strain hardening
- Directional properties can be imparted
- Contamination is minimized

On the other hand there are numerous drawbacks of cold-working processes compared to hot working

- Higher forces are required to initiate and complete the deformation
- Heavier and more powerful equipment and stronger tooling are required
- Less ductility is available
- Metal surfaces must be clean and scale-free
- Intermediate anneals may be required to compensate for the loss of ductility
- The imparted directional properties may be detrimental
- Undesirable residual stresses may be produced

Because cold-forming processes require powerful equipment and product specific tools or dies, they are best suited for large-volume production of precision parts

Warm forming offers several advantages compared to cold forming:

- Reduced loads on the tooling and equipment
- Increased material ductility
- Reduction in the number of anneals due to a reduction in the amount of strain hardening

The use of higher forming temperatures can expand the range of materials and geometries that can be formed by a given cold forming process

Warm working is preferred over cold working for intermediate sized parts (≤10 kg) and steels with high alloy content due to concerns on energy and material conservation

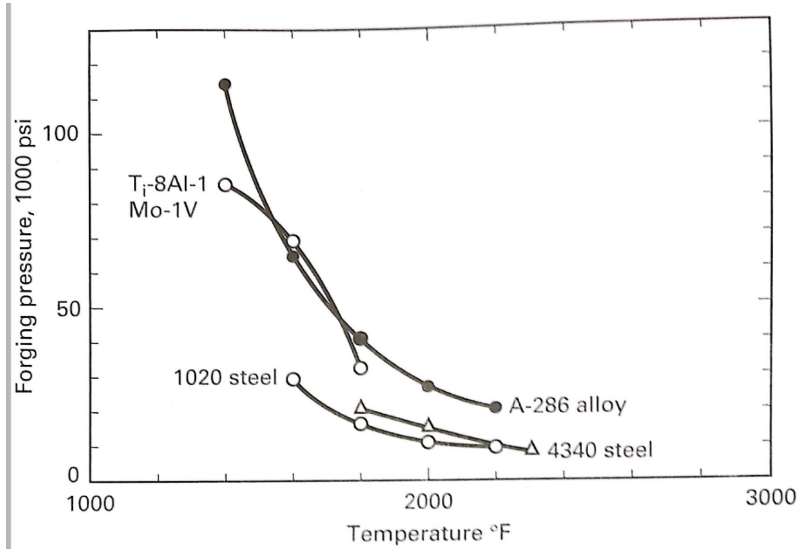
It has the following advantages compared to hot forming:

- The lower temperatures produce less scaling and decarburization
- Products with better dimensional precision and smoother surfaces
- The as-formed properties may be adequate for many applications because of the finer structures and presence of some strain hardening, eliminating final heat treatment operations
- The lower temperatures and less processed material with high precision requires less energy
- Tools last longer because thermal shocks and fatigue are lower while they exert 25 to 60% higher forces

Hot working and warm forming are usually applied to the bulk forming processes like rolling, forging, extrusion where the workpiece is not prone to rapid changes in temperature

Hot and warm forming operations need to be done at constant temperature for some materials strength of which depends strongly on temperature

Cooling of as little as 100 C can produce a doubling in strength for materials such as titanium alloy or nickel alloy



In this case cooler surfaces surround a hotter interior and the variations in strength can result in nonuniform deformation and cracking of the less ductile surface

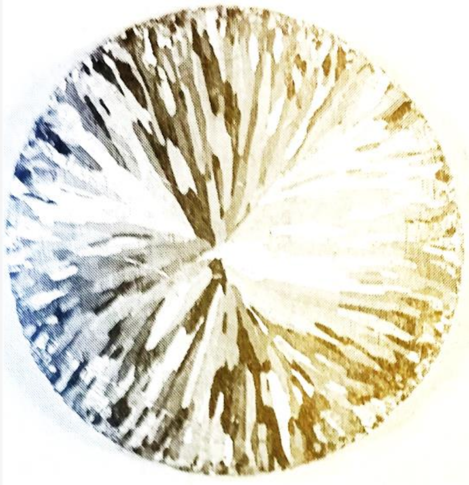
In isothermal forming, deformation is performed under isothermal conditions to successfully deform temperature sensitive materials
The dies or tooling must be heated to the same temperature as the workpiece, sacrificing die life

In addition deformation rates are slowed so that the heat generated by deformation is reduced and distributed uniformly over the product at constant temperature

Inert atmospheres may be required to avoid reactions at long processing periods at elevated temperatures

These costly methods are often the only means of producing from certain products
The advantages of isothermal forming due to these unique conditions are

- Close tolerances
- Low residual stresses
- Uniform metal flow



Nonideal microstructures are often observed in solidifying metals as coarse structure tend to form with a certain amount of chemical segregation

The size of the grains is usually not uniform and undesirable grain shapes are common like columnar grains

Small gas cavities or shrinkage porosity can form during solidification

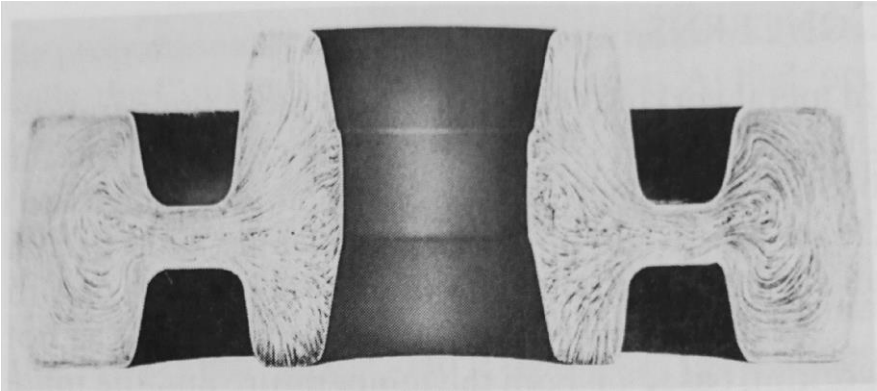
Many impurities tend to locate along grain boundary interfaces as solids as they are mostly oxides and have high melting temperatures

These can initiate a crack or assist its propagation through a metal if they are unfavorably oriented or intersect surfaces

When a metal is plastically deformed, the impurities tend to flow along with the metal, or fracture into rows of fragments that are aligned in the direction of working

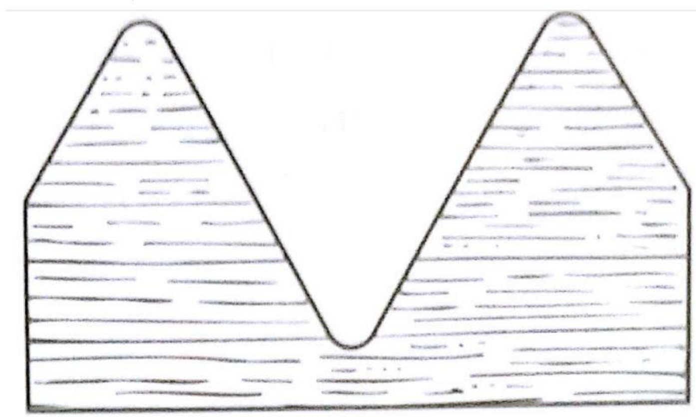
These impurities retain their distorted shape and orientation while the deformed metal constantly recrystallizes during hot forming

The cooled product exhibits a flow structure and properties vary in different directions



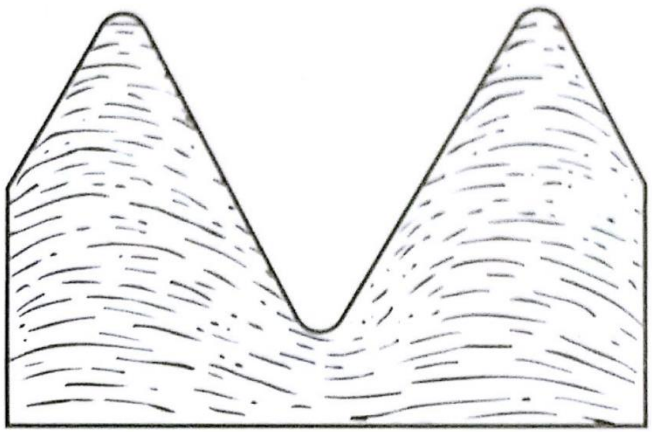
Through proper design of deformation the impurities can often be reoriented into a crack-arresting configuration where they are perpendicular to the direction of crack propagation

Hot forming processes like rolling and forging improve strength and fracture resistance of impurity containing metals by reorienting the axial defects in the starting metal rod to be parallel to the rolling surface



(a)

Machined cold-worked component



(b)

Hot-forged component

Such a deformation control is beneficial in cold-working processes to impart useful anisotropy

Over 90% of the energy imparted to a deforming workpiece is converted into heat and it may increase the temperature of the metal if deformation rate is high

Heat is lost through the workpiece surfaces after the deformation, with the majority of cooling occurring at contact points between the metal and the lower temperature tooling

The success of a hot deformation process depends on the ability to control the temperatures within the deformed metal

Nonuniform temperatures resulting from the deformation and cooling may cause flow of the hotter, weaker interior and cracking of the colder, less ductile surfaces. The flow behavior is further complicated by thin sections that cool faster than thick sections

To keep the workpiece temperature as uniform as possible, dies and tooling are heated so that the rate of hear transfer is reduced

Dies are frequently heated to 325-450 C when used in hot forming of steel. Tolerances can be improved and contact times can be increased if the tool temperatures are raised to 550-650 C but tool degrades so rapidly that these conditions are unattractive economically

In addition cooling is done slowly and uniformly to minimize residual stresses in hot-worked products and avoid warping, distortion and cracking

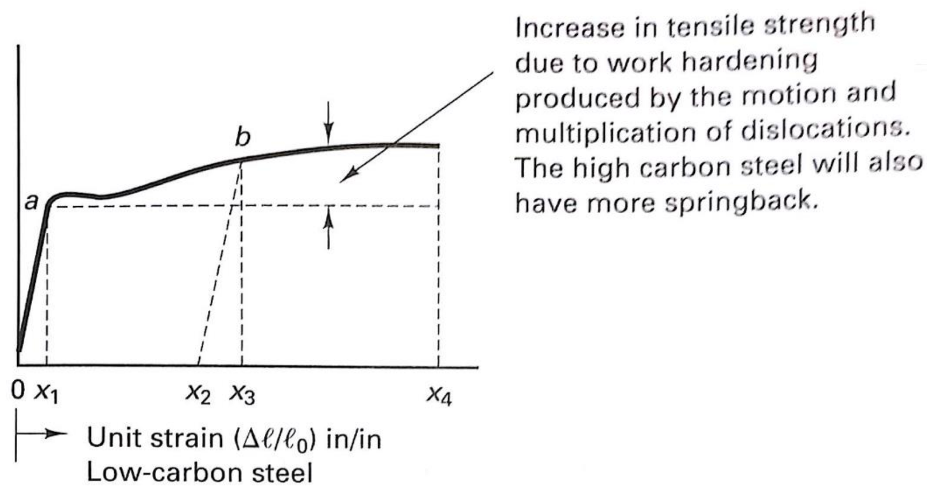
On the other hand the success of a cold working operation depends largely on the quality of the starting metal

It should be clean and free of oxide or scale that might cause abrasion and damage to the dies or rolls which in turn affects the dimensional precision and surface finish adversely

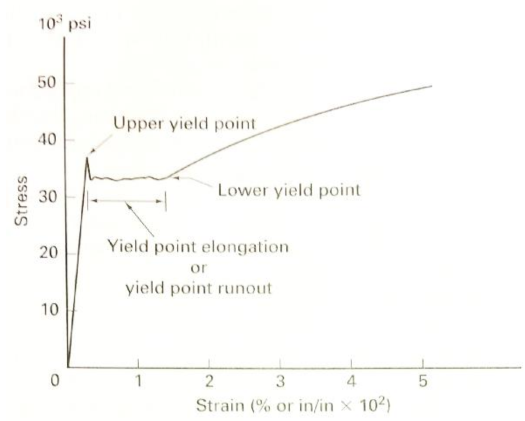
Scale in the starting metal is removed commonly by dipping in acid and washing

In addition sheet metal and plate may be rolled lightly prior to the major deformation to ensure uniform starting thickness and smooth surface

Initial light cold-rolling is beneficial to avoid the yield-point phenomenon and the associated problems of nonuniform deformation and surface irregularities in the product.



Many low carbon steels exhibit a yield-point runout after loading to the upper yield point
In this case the metal can strain up to several percent with no additional force being required

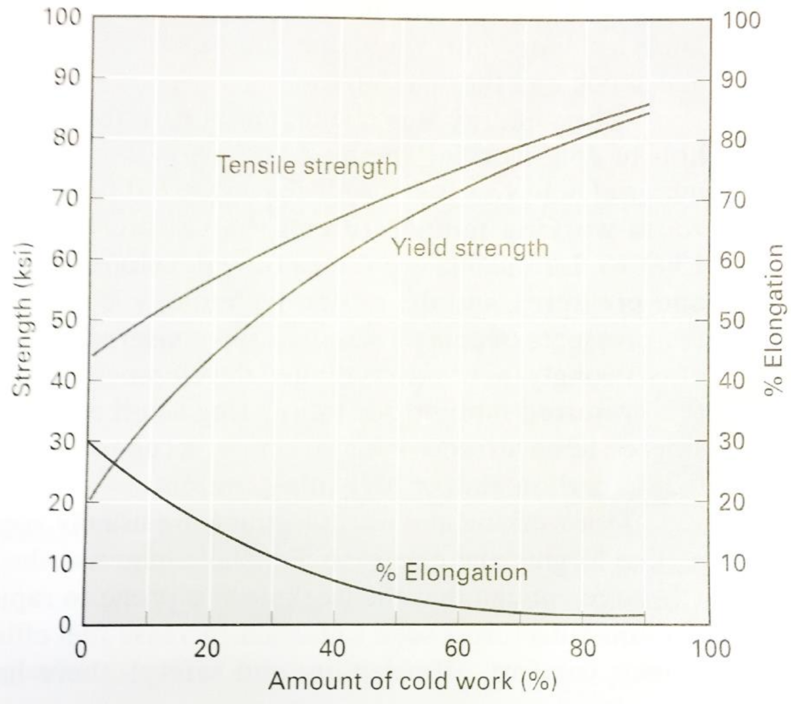


A piece of sheet metal that is formed into an automotive body panel is showed in the figure. When the panel is stretched around the yield point strain, a stress equal to the yield stress is applied and different parts of the metal deform at varying extents

Under this stress the material is free not to deform, to deform the entire amount of the yield-point runout or to stay at some point in between. Some regions deform the entire amount and undergo thinning while adjacent regions resist deformation and stay thick

The resulting stretcher bands are very difficult to remove. The only way to avoid it is to cold roll the material to a strain near or past the yield-point runout so that the subsequent forming occurs in a smooth-line region of the curve

The effect of cold working on the mechanical properties of pure copper is true for all metals



Hardness in general is also increased and electrical conductivity and corrosion resistance decreases with the extent of cold-working

Annealing heat treatment is often applied to metals prior to cold working as a means of maximizing the starting ductility

Intermediate anneals may be performed to restore ductility if the required amount of deformation exceeds the fracture limit

The time of last anneal is important to make use of the stronger cold worked structure in the product

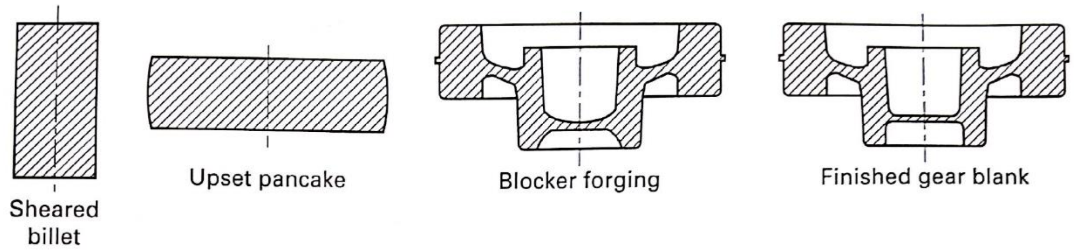
All annealing operations should be done carefully to control the grain size of the resulting material

Forging is the oldest and most well-known deformation process that can be done in the hot, cold, warm or isothermal mode, although hot forging is the most common

It refers to a family of processes where the deformation is induced by localized compressive forces by the use of hammers, presses or special machines

Various forging processes have been developed that suit the economic production of a single piece or millions of identical parts:

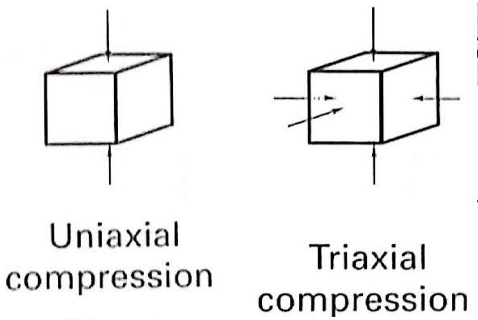
- Open die drop-hammer forging
- Impression die drop-hammer forging
- Press forging
- Upset forging
- Automatic hot forging
- Roll forging
- Swaging



By these methods the metal may be

- Drawn out to increase its length and decrease its cross section
- Upset to decrease the length and increase the cross section
- Squeezed in closed impression dies to produce multidirectional flow

The state of stress in the workpiece is primarily uniaxial or multiaxial compression



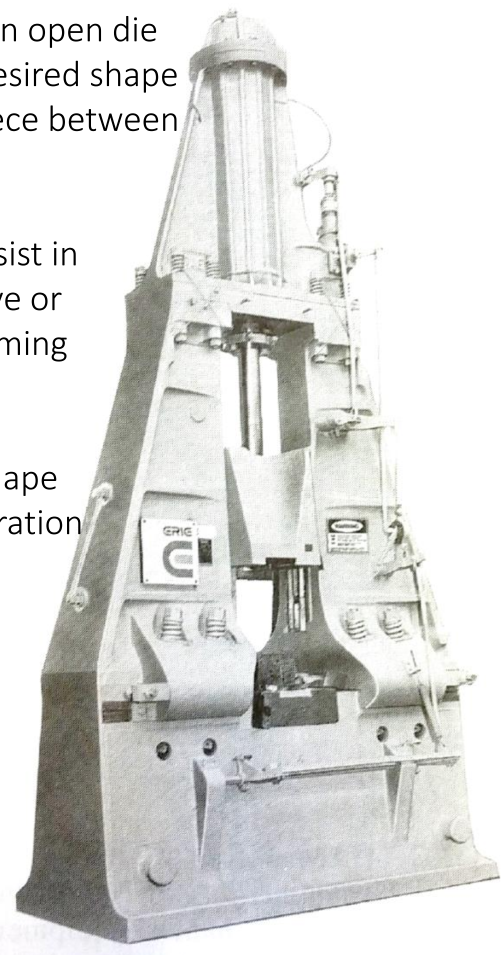
The general open die forging operation starts by feeding the heated metal to an open die

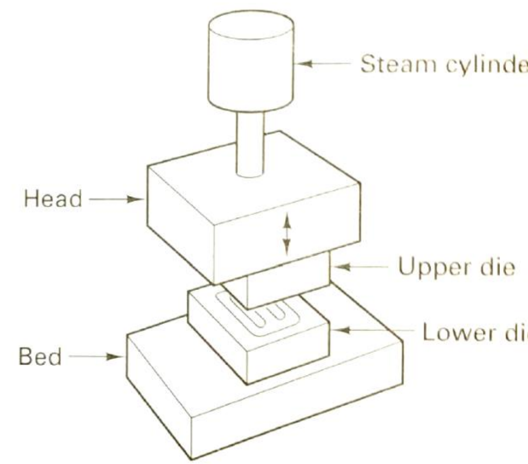
The impact is then delivered by some type of mechanical hammer, the simples being a gravity drop.
Steam or air hammers which use pressure to both raise and propel the hammer are the most common.
Programmable, computer controlled hammers can provide blows of differing impact energy for various stages of operation which greatly increases the efficiency of the process

The flow of metal is not fully controlled in open die forging. The operator must obtain the desired shape by orienting and positioning the workpiece between blows

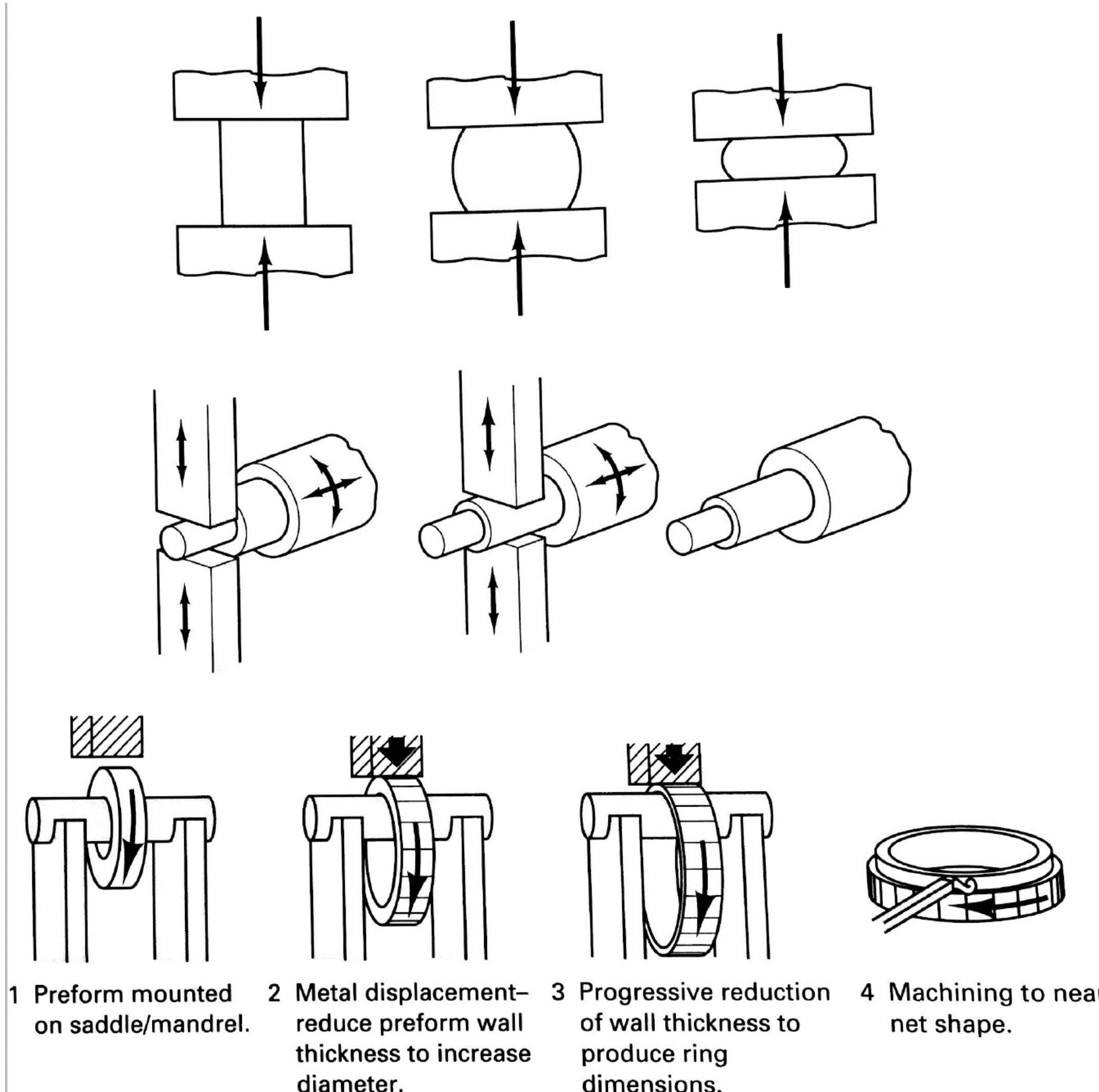
Specially shaped tools can be used to assist in making simple shapes like round, concave or corvex surfaces, forming holes or performing Cutoff

Open die forging is usually used to preshape the metal in preparation for further operation



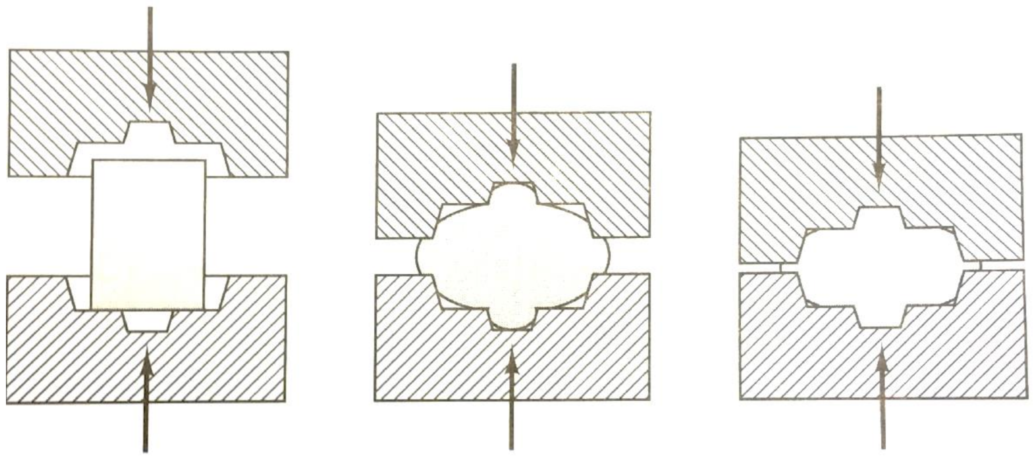


Open-die forging is used to induce oriented plastic flow and minimize the amount of subsequent machining



Open-die hammer forging is a simple and flexible process but it is not practical for large scale production. It is a slow operation and the size, shape and dimensional precision of the resulting workpiece is dependent on the skill of the operator

Impression-die or closed-die drop hammer forging overcomes these difficulties by using shaped dies to control the flow of metal



The strikes on the hot metal in the die causes it to flow and completely fill the die cavity

Excess metal is squeezed out around the periphery of the cavity to form a flash. This part cools rapidly, increases in strength, and effectively blocks the formation of additional flash. The flash ensures filling of all of the cavity details by trapping material within the die. It is ultimately trimmed from the product

In flashless forming also known as true closed-die forming, the metal is deformed in a cavity that provides total confinement

Accurate workpiece sizing is required since complete filling of the cavity with no excess material is needed
By this approach scrap generated during flash formation (20-45% of the starting material) is eliminated

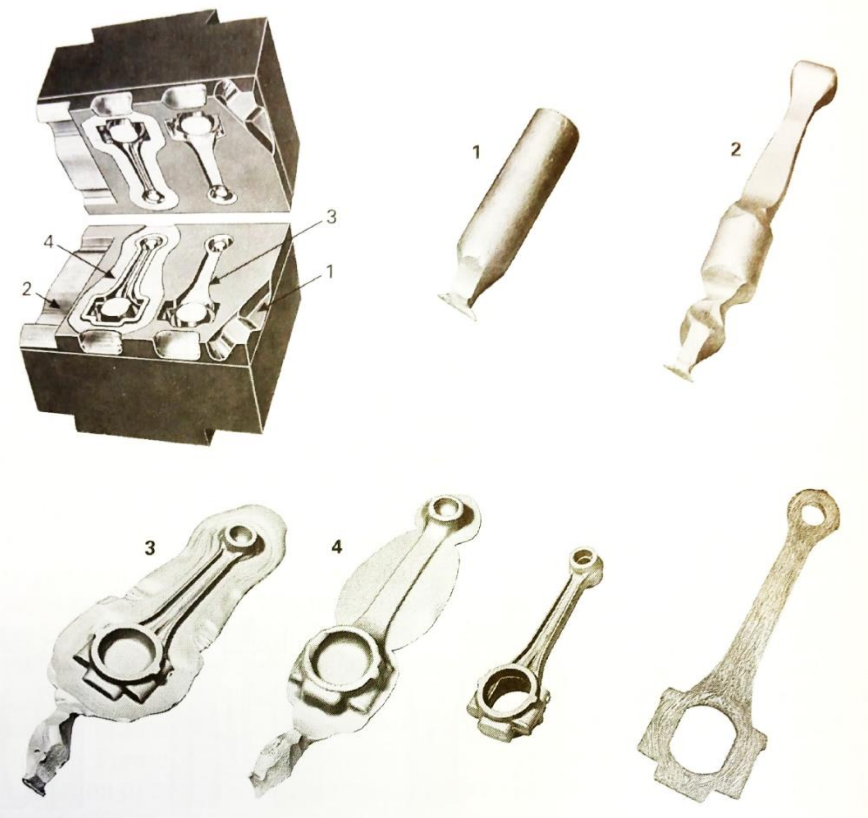
Most conventional forgings are impression-die with flash and are produced in dies with a series of cavities where one or more blows of the hammer are used for each step

The first impression is often an edging impression to distribute the metal roughly in accordance with the requirements of the later cavities

Intermediate impressions are for blocking the metal to approximately its final shape with thick corner and fillet radii

The final shape and size are set by additional forging in a finisher impression

For small production numbers, the blocker-type forgings are finished by machining rather than making further cavities in the die



Forgings often have about 20% higher strength/weight ratios compared to cast or machined parts

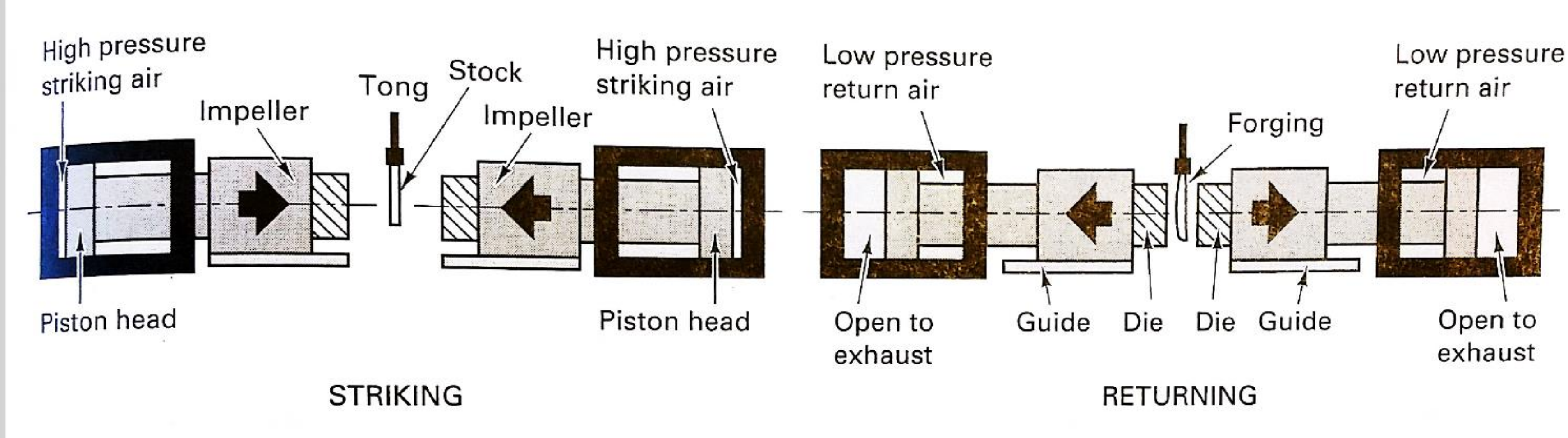
This is majorly because of the control on the flow of material by various cavities and the resulting oriented structure

Grain flow that follows the outline of the component is in the crack arresting orientation, improving strength, ductility and resistance to impact and fatigue

The size and shape of various cross sections are also well controlled so the metal is distributed as needed to resist the applied loads

Any voids are overcome due to compressive forming stresses

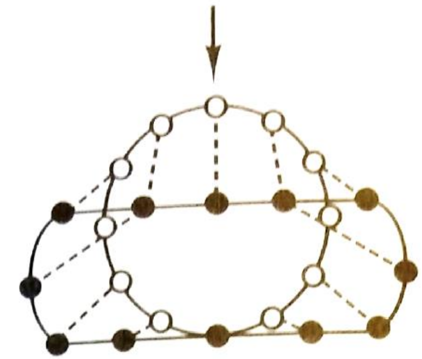
Furthermore hot working provides a fine recrystallized grain structure
Impactor provides even more uniform structure with a different arrangement than the vertical hammer and anvil approach



Two horizontal hammers simultaneously impact a workpiece that is positioned between them

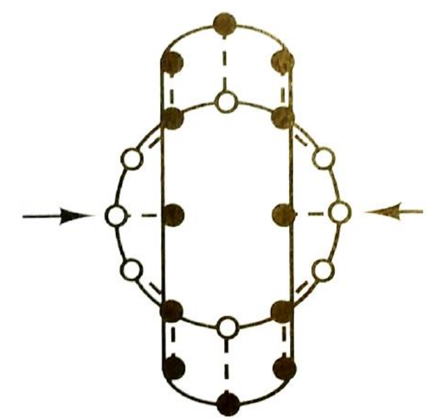
Excess energy does not go to the machine foundation which requires a heavy machine base

They also operate with less noise and vibration and produce distinctly different flow patterns



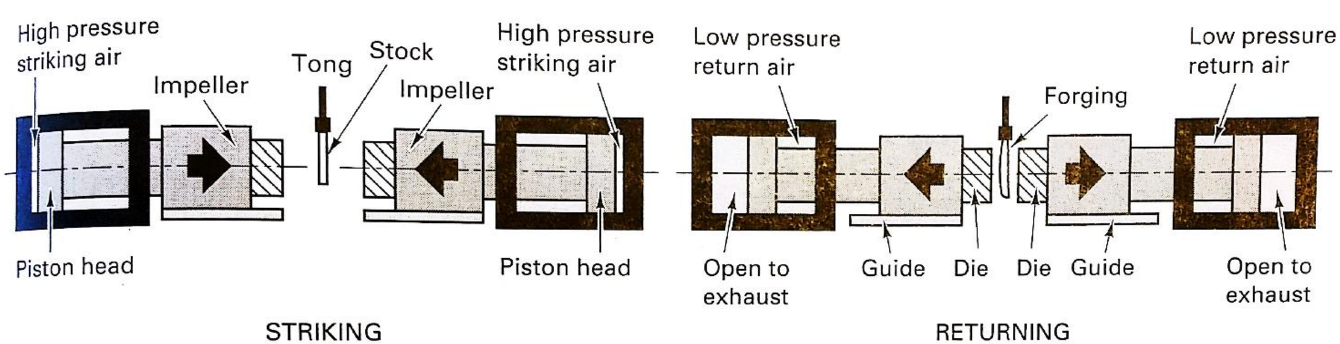
(a)

Conventional forged disc with paths of flow



(b)

Disc formed by impacter with paths of flow



In drop-hammer or impact forging the metal flows to dissipiate the energy imparted in the collision

Contact times under load are on the order of milliseconds, there is little time for heat transfer and cooling of the workpiece

However it is possible that all of the energy be dissipated by deformation of just the surface of the metal and absorption by the anvil

The interior of the workpiece may remain undeformed

This problem is overcome especially for large and thick pieces by press forging

The slow squeezing action penetrates completely through the metal, producing a more uniform deformation and flow

The deformation in press forging is analyzed in terms of forces or pressures rather than energy

Heated dies are generally used to reduce heat loss, promote surface flow and enable the production of finer details

Two basic types of forging presses are mechanical and hydraulic

Mechanical presses use cams, cranks to produce a reproducible stroke.
They are quite fast, capable of up to 50 strokes per minute and hava capacities up to 18000 tons

Hydraulic presses move in response to fluid pressure in a piston and are generally slower, more massive and costly. They have capacities as high as 50000 tons

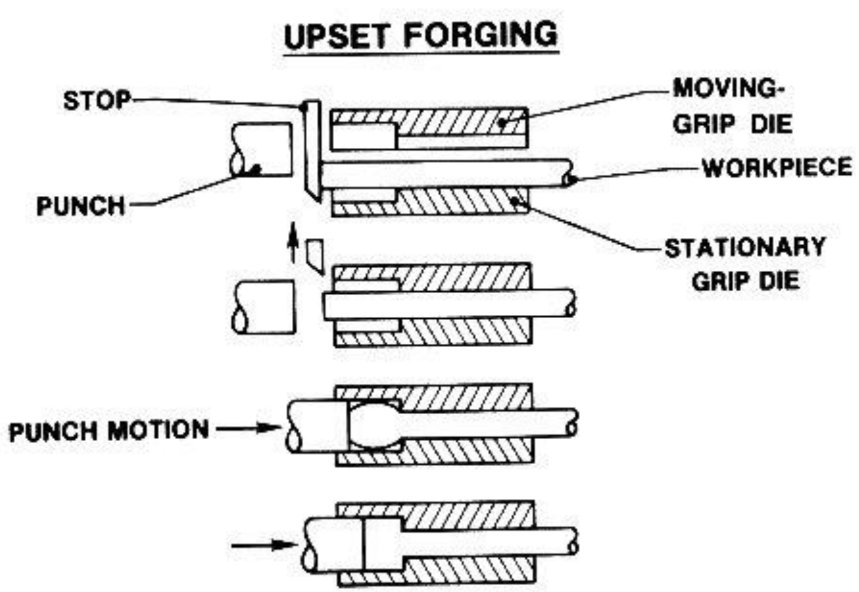
Upset forging involves increasing the diameter of a material by compressing its length

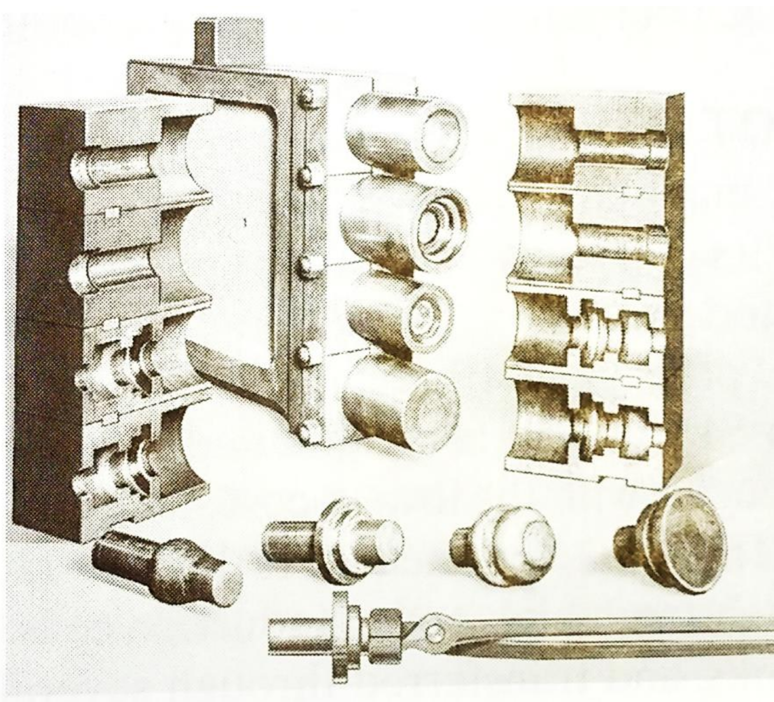
It is the most widely used of all forging processes in terms of the number of pieces produced

Parts can be upset forged both hot and cold, with the operation generally being performed on special high-speed machines where the forging motion is horizontal

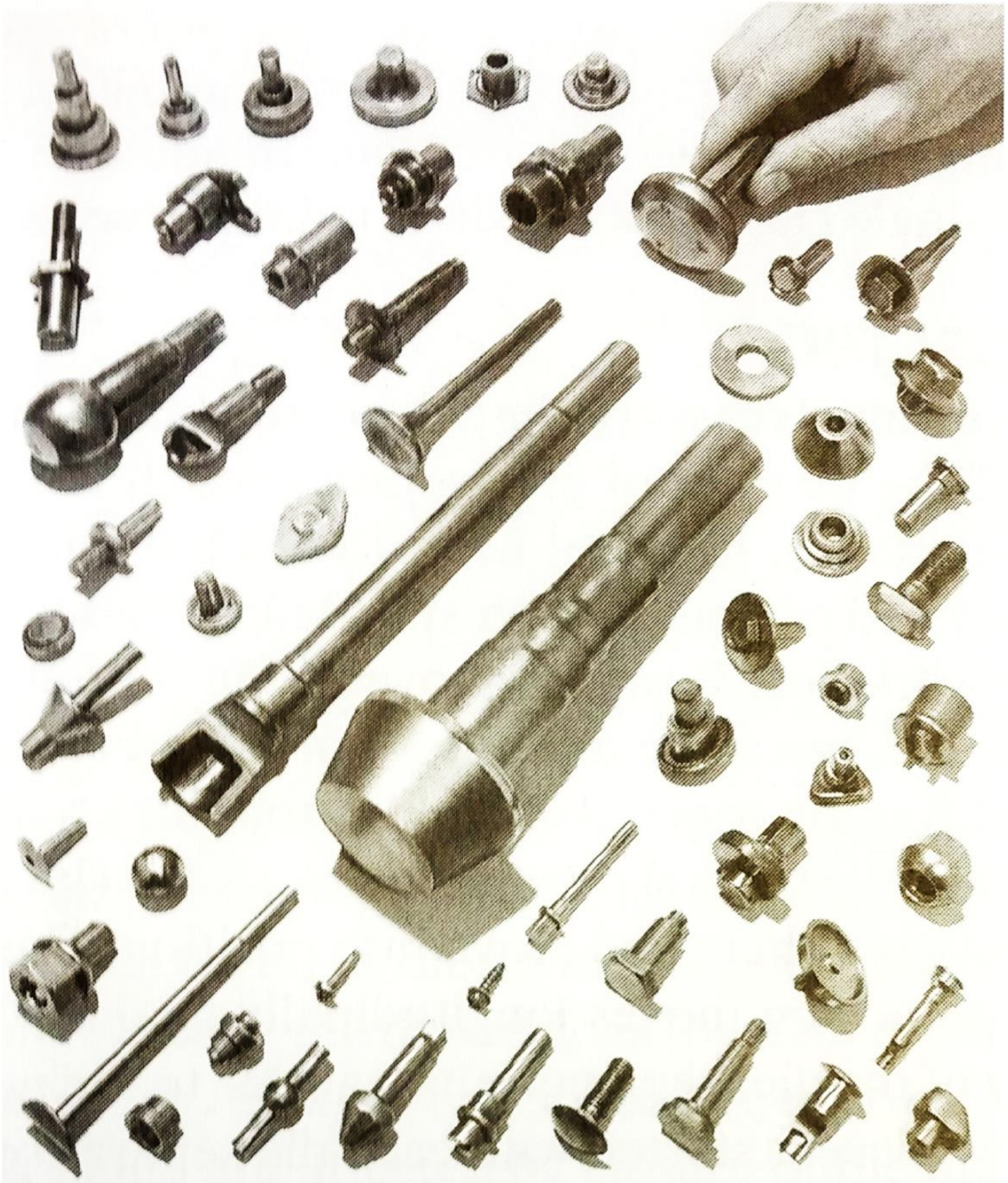
The starting stock is usually wire or rod but bars up to 25 cm in diameter can also be forged

Split dies that contain multiple positions and cavities are usually used. The rod moves into position between separate dies and then they are clamped together and a ram moves longitudinally against the bar, upsetting it into the cavity.





Separation of the dies then permits transfer to the next position or removal of the product



Automatic hot forging allow efficient mass production of parts up to 6 kg at a rate up to 180 parts per minute from steel bars as long as 7 meters

The process begins with a low cost hot-rolled steel bar. It is heated to around 1200 C in 60 seconds as it passes through high-power induction coils. It is then descaled by rolls, sheared into small lengths and passed through several successive forming stages during which it is upset, preformed, final-forged and pierced if necessary

Other than high production speed and low-cost input material, the process has the following advantages

- Minimum labor
- No flash produced, material savings up to 20-30%
- Air cooling after a finishing temperature near 1050 C produce a structure suitable for machining. The need for additional annealing or normalizing treatment is eliminated
- Tolerances around 0.3 mm
- Clean surfaces
- Tool life is nearly double that of conventional forging because the contact times are only about 1/10 of a second

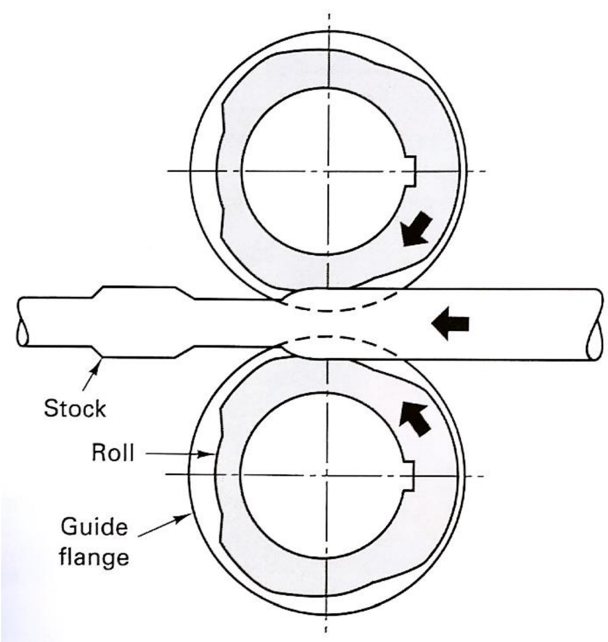
Round or flat bars are reduced in thickness and increased in length in roll forging to produce axles, tapered levers, leaf springs

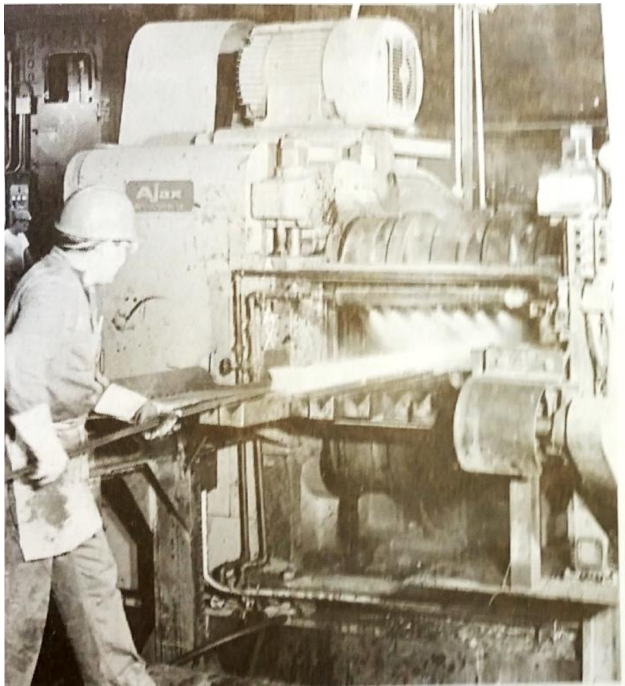
Roll forging is performed on machines that have two cylindrical or semicylindrical rolls each containing one or more shaped grooves

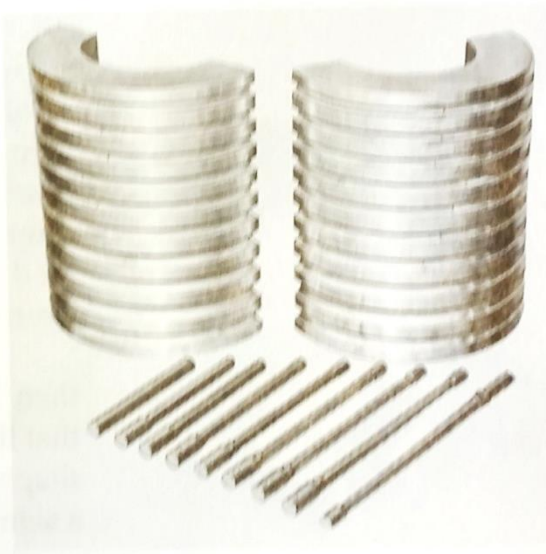
A heated bar is inserted between the rolls

The rolls rotate when the bar encounters a stop and the bar is progressively shaped as it is rolled out toward the operator. The piece is then transferred to the next set of grooves or rotated and reinserted in the same groove for further roll forging until the desired size and shape is produced

The advantages are that there is no flash and the oriented structure imparts favorable properties



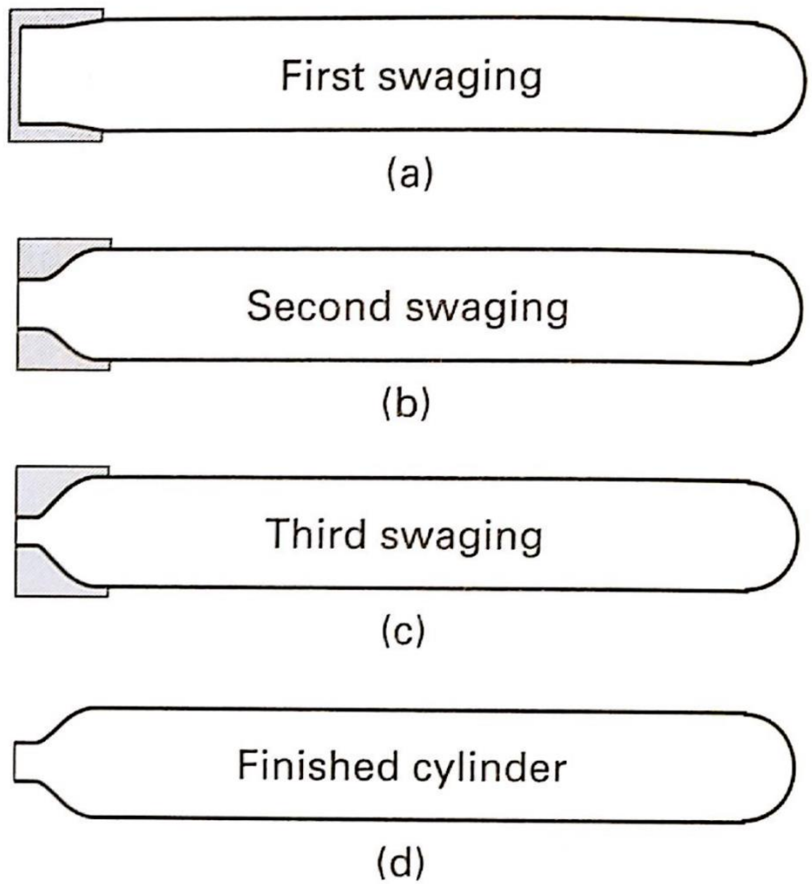




Swaging involves hammering of a tube or a rod by a die to reduce its diameter

Repeated blows are delivered from various angles, causing the metal to flow inward and assume the contour of the die

Most swaging processes are performed cold but hot swaging involves forcing the metal into a confining die to reduce its diameter



Process analysis

Consider press forging a mild steel cube at room temperature with the following mechanical properties:

$$\sigma_Y = 270\ MPa, \qquad \varepsilon_Y = 0.00135, \qquad E = 200\ GPa, \qquad \nu = 0.29, \qquad UTS \approx 390\ MPa$$

The stress condition on the material is typically uniaxial compression

The only stress component is σ_z and the effective stress is

$$\sigma_{eff} = \frac{\sqrt{2}}{2}\sqrt{(-\sigma_z)^2 + (\sigma_z)^2} = \sigma_z$$

We find strains in three directions as a result of stresses applied in the proce
By using the Ramberg-Osgood material model with n=14 and $\sigma_{0.7}$=270 MPa

Ramberg-Osgood equation $\varepsilon = \frac{\sigma}{E}\left(1 + \frac{0.3}{0.7}\left(\frac{\sigma}{\sigma_{0.7}}\right)^{n-1}\right)$

$\frac{1}{E_{sec}} = \frac{1}{200000}\left(1 + \frac{0.3}{0.7}\left(\frac{\sigma}{270}\right)^{14-1}\right)$ for mild steel

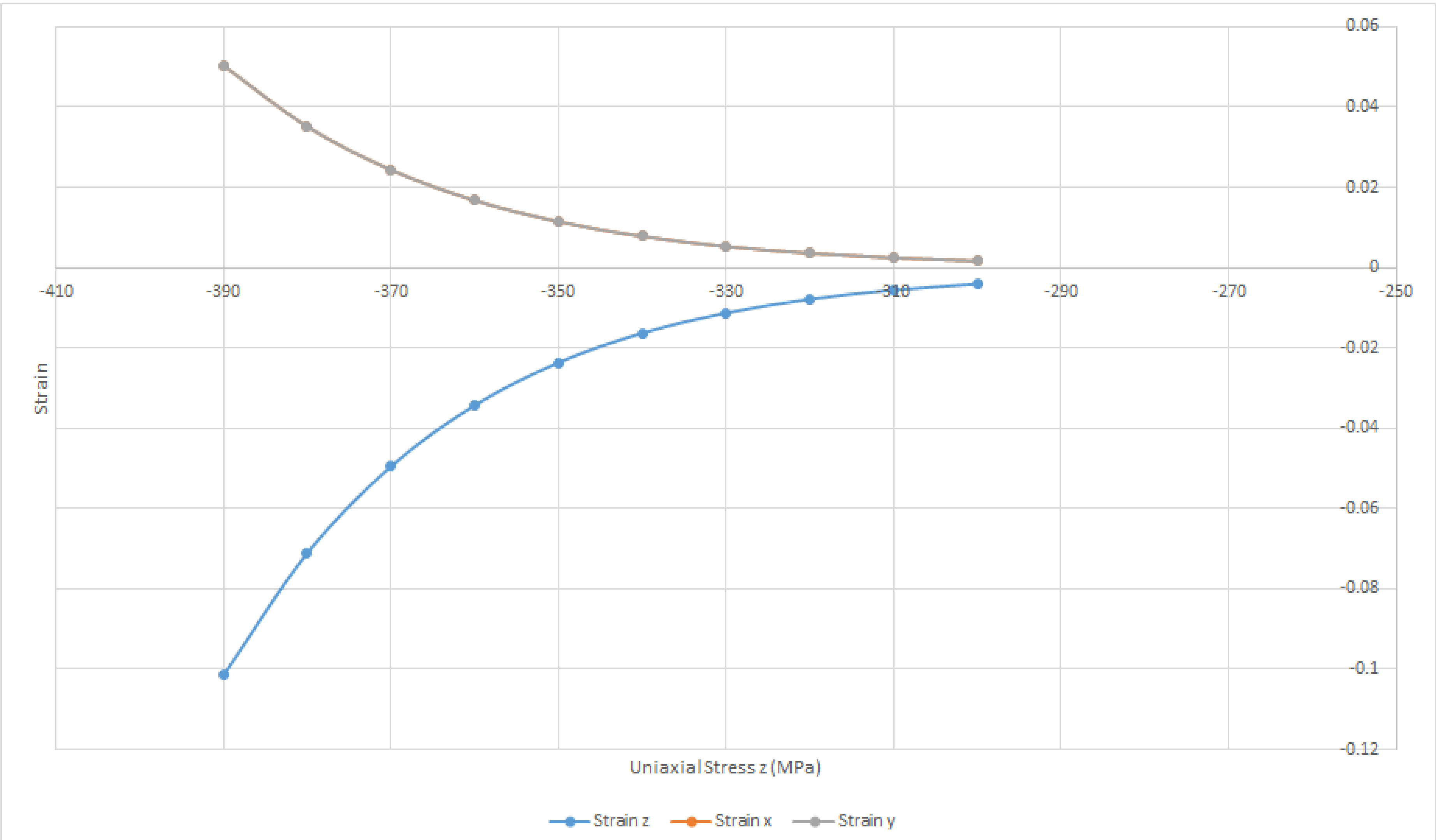
$$\nu = \frac{1}{2} - \frac{E_{sec}}{E}\left(\frac{1}{2} - \nu^e\right)$$

$$\varepsilon_x = \frac{1}{E_{sec}}\left(-\nu(\sigma_z)\right)$$

$$\varepsilon_y = \frac{1}{E_{sec}}\left(-\nu(\sigma_z)\right)$$

$$\varepsilon_z = \frac{1}{E_{sec}}(\sigma_z)$$

What happens when we press forge a mild steel cube that is at room temperature with $\sigma_Y = 270\ MPa$, $\varepsilon_Y = 0.00135$, $E = 200\ GPa$, $\nu = 0.29$, $UTS \approx 390\ MPa$



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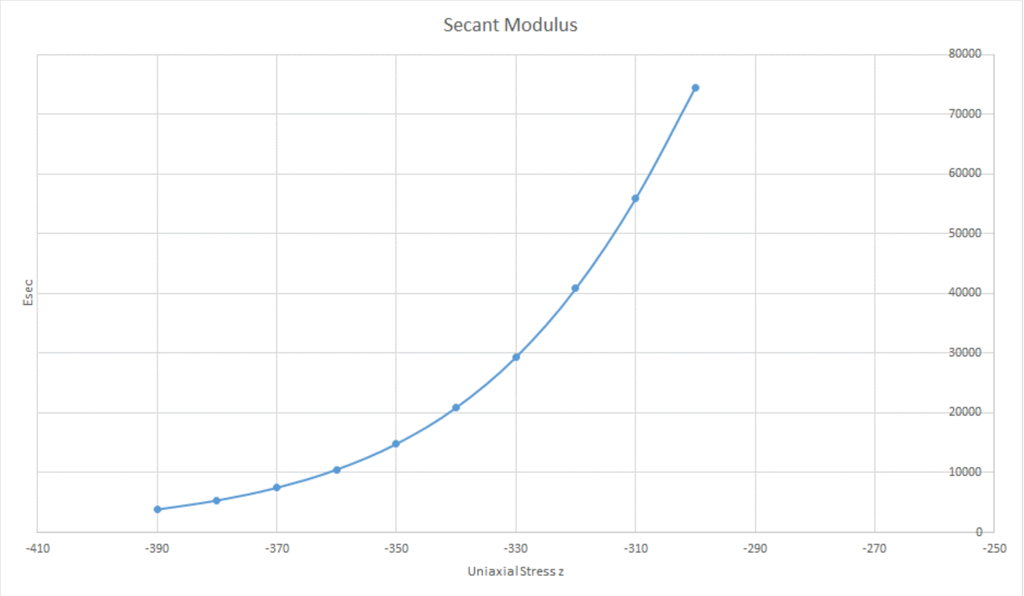
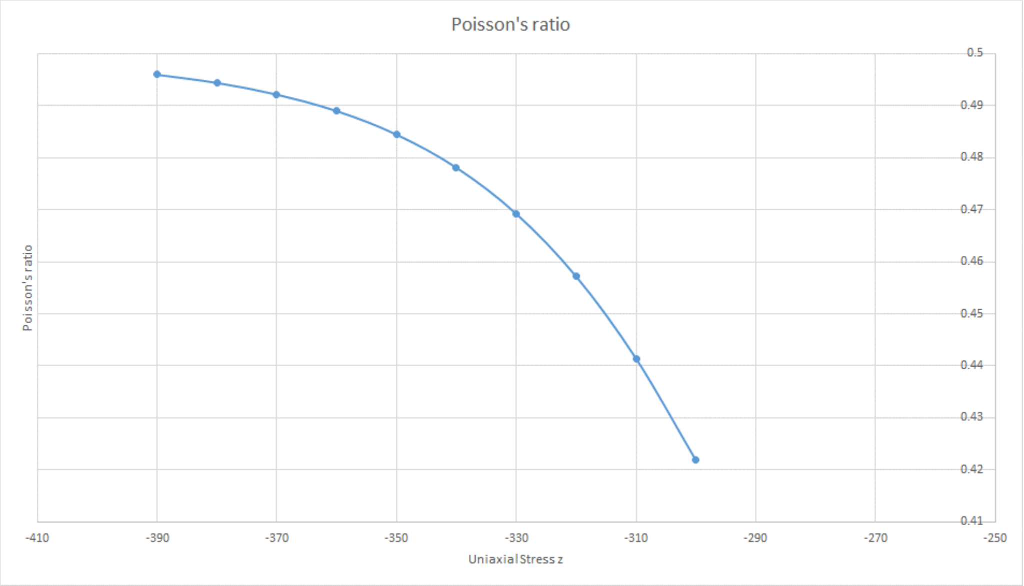
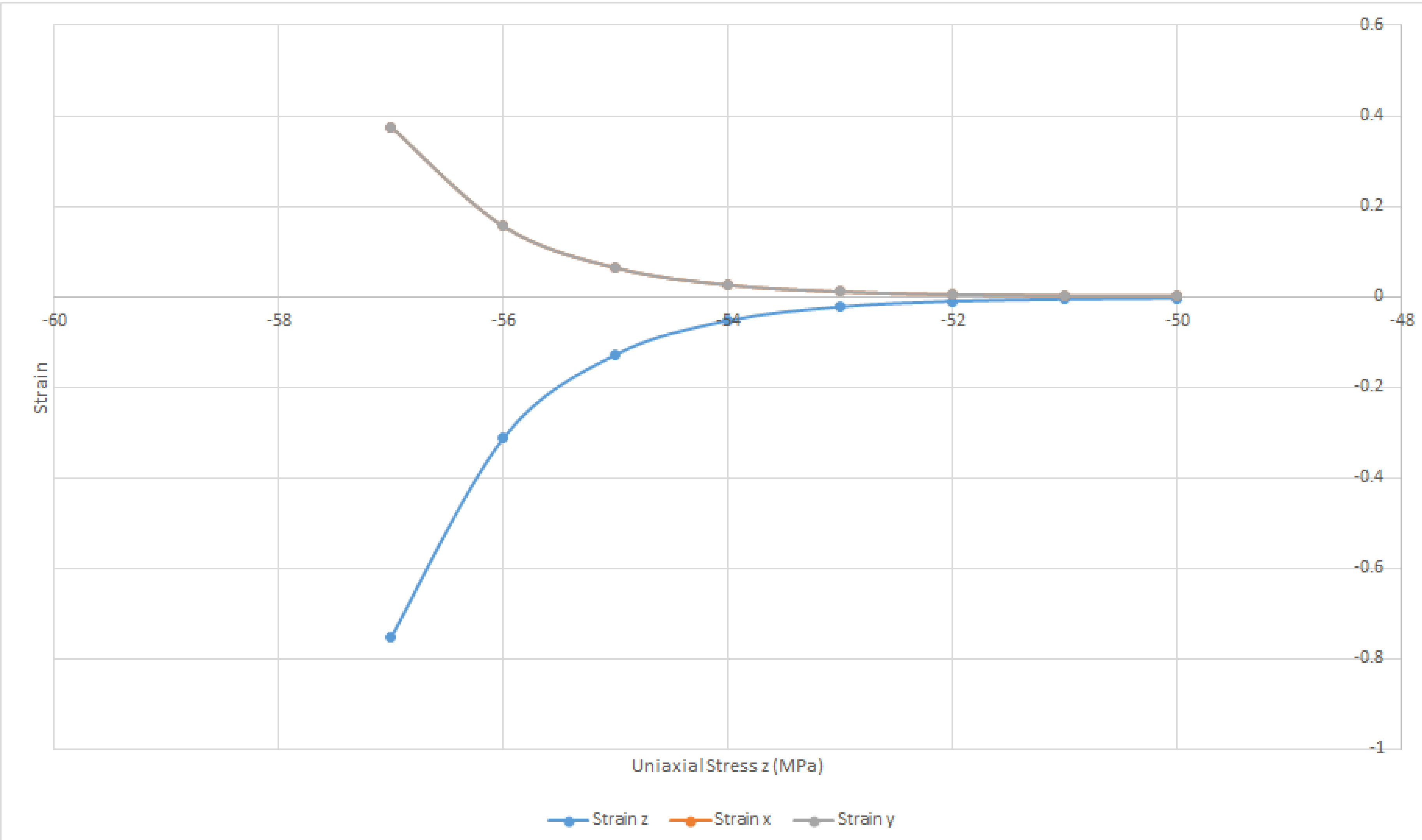




What happens when we press forge a mild steel cube that is above recrystallization temperature with

$$\sigma_Y = 50\ MPa, \qquad \varepsilon_Y = 0.00135, \qquad E = 20\ GPa, \qquad \boldsymbol{\nu = 0.29}$$



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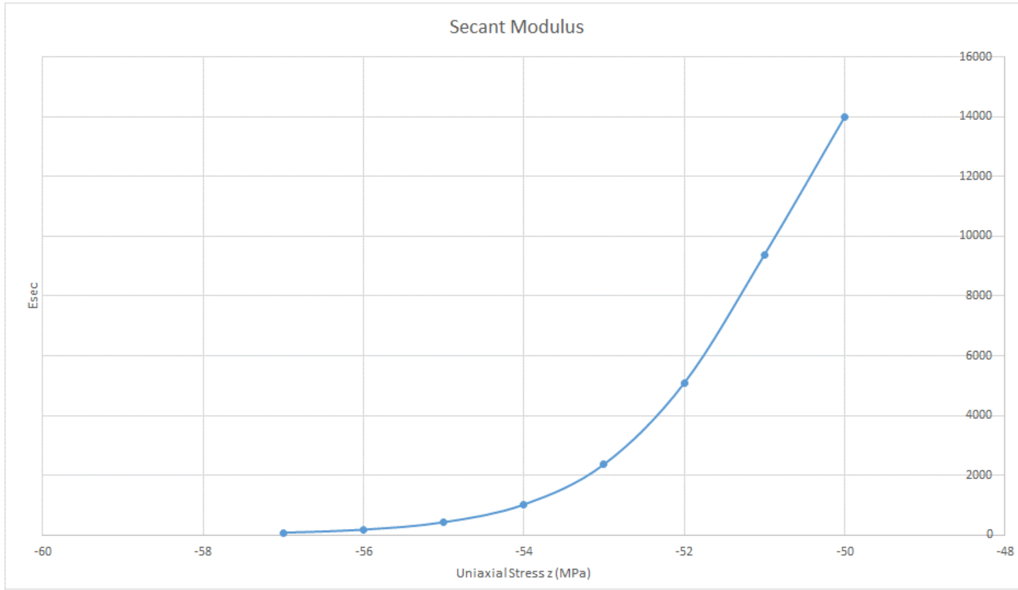

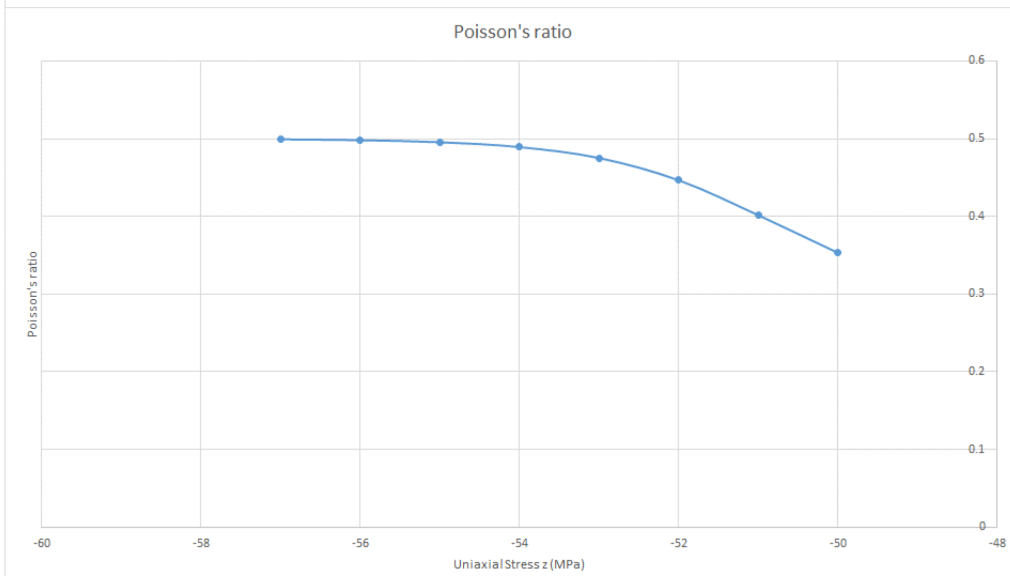

What happens when we press forge a mild steel cube that is above recrystallization temperature with

$$\sigma_Y = 50\ MPa, \qquad \varepsilon_Y = 0.00135, \qquad E = 20\ GPa, \qquad \boldsymbol{\nu} = \mathbf{0.4}$$