Plasticity and Deformation Process

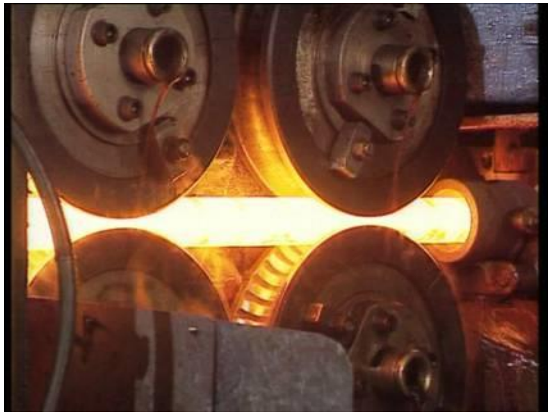
Deformation Processes

Rolling & Forging

At elevated temperatures metals weaken and become more ductile

Massive deformation can occur with continual recrystallization, without fear of fracture due to diminished ductility

In steels, hot forming involves the deformation of the weaker austenite structure which then cools and transforms to the stronger, room temperature stable ferrite



Some of the commonly used hot working processes in modern manufacturing are:

- Rolling
- Forging
- Extrusion
- How drawing
- Piercing

A wide variety of processes to mechanically shape metals is possible

One classification is primary and secondary processes

Primary processes reduce a cast metal into intermediate shapes such as slabs, plates or billets
Secondary processes further convert these shapes into finished or semifinished products like sheets, wires, pipes, etc

Another classification of deformation processes is about how size and shape change:

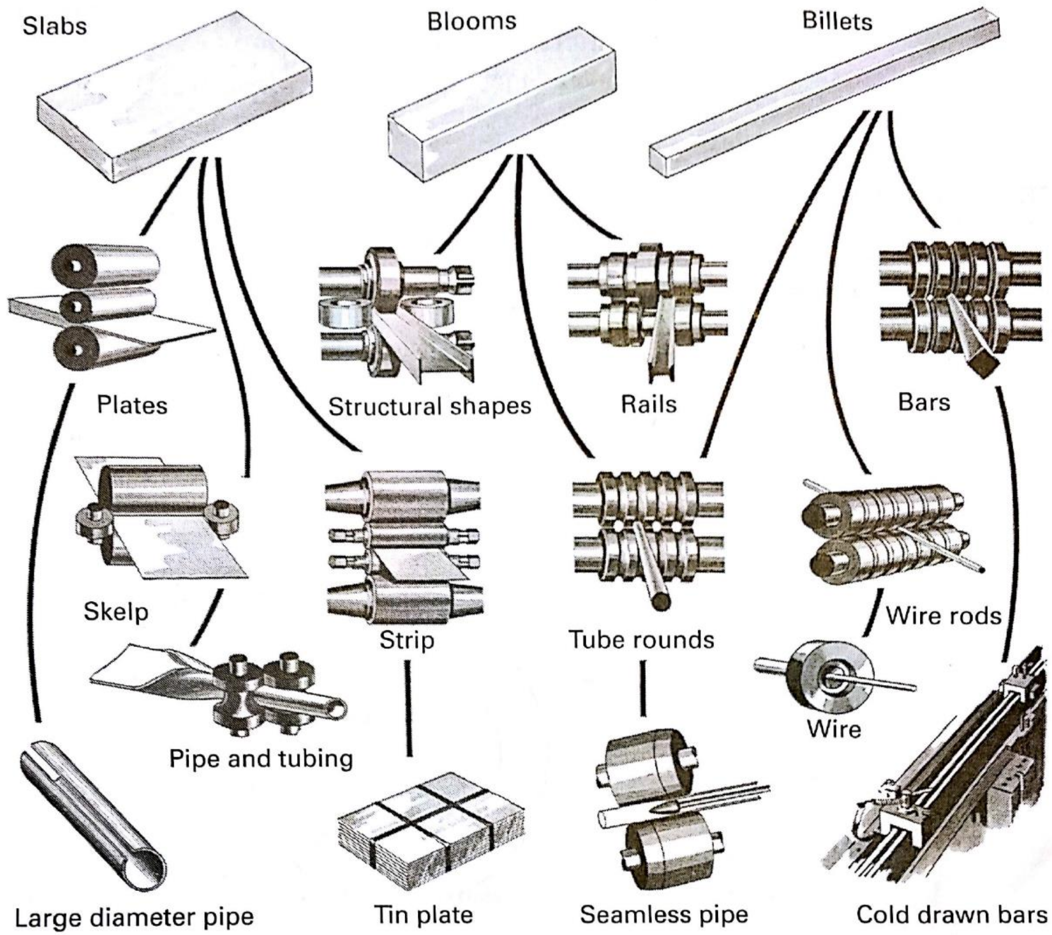
Bulk deformation processes are those where the surface area of the material changes significantly. Thicknesses or cross sections are reduced or shapes are changed. Its dimensions must change since the volume of the material remains constant during plastic deformation. So the surface area increases as the product lengthens

Sheet forming operations involve the deformation of a material where the thickness and surface area remain relatively constant

Deformation processes can also be classified as cold working, warm working and hot working processes

Rolling is both a primary and secondary process

Thick starting metal can be rolled into blooms, billets or slabs
These intermediate products are then rolled to sheets, plates, wires, tubes

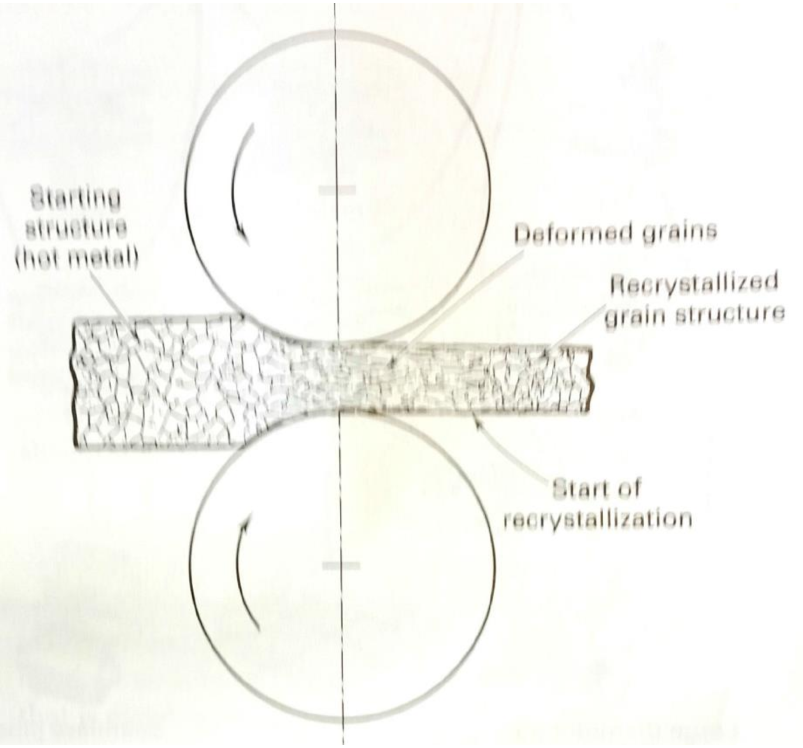


Hot rolling is used the most to shape metals

The dimensional tolerances of hot rolled products vary with the kind of metal and the size of the product. In general the tolerances are within 2 to 5% of the specified height or width

In the basic rolling process, heated metal is passed between two rolls that rotate in opposite directions

The gap between the rolls is less than the thickness of the entering metal



Friction along the contact interface propels the metal forward because the rolls rotate with a surface velocity that exceeds the speed of the incoming metal

Squeezed metal elongates to compensate for the decrease in thickness or cross-sectional area

There is a limit to the amount of deformation in a single pass as it depends on the friction conditions along the interface. Too much deformation may skid the rollers on the material

Temperature control is a requirement for smooth rolling

The starting material should be heated to a uniform high temperature. The subsequent deformation will not be uniform if the temperature is not uniform

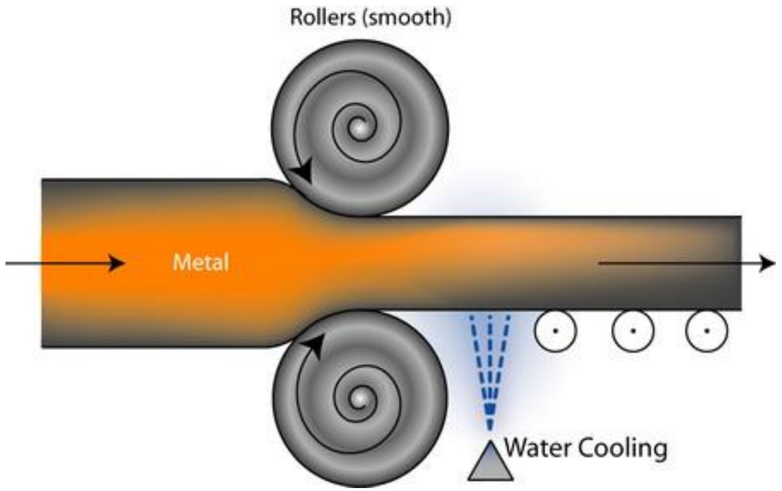
If the soaking time is insufficient, the hotter exterior will flow in preference to the cooler, stronger interior

High volume productions utilize continuous cast feed material which is cooled to enable direct insertion into the hot-rolling operation

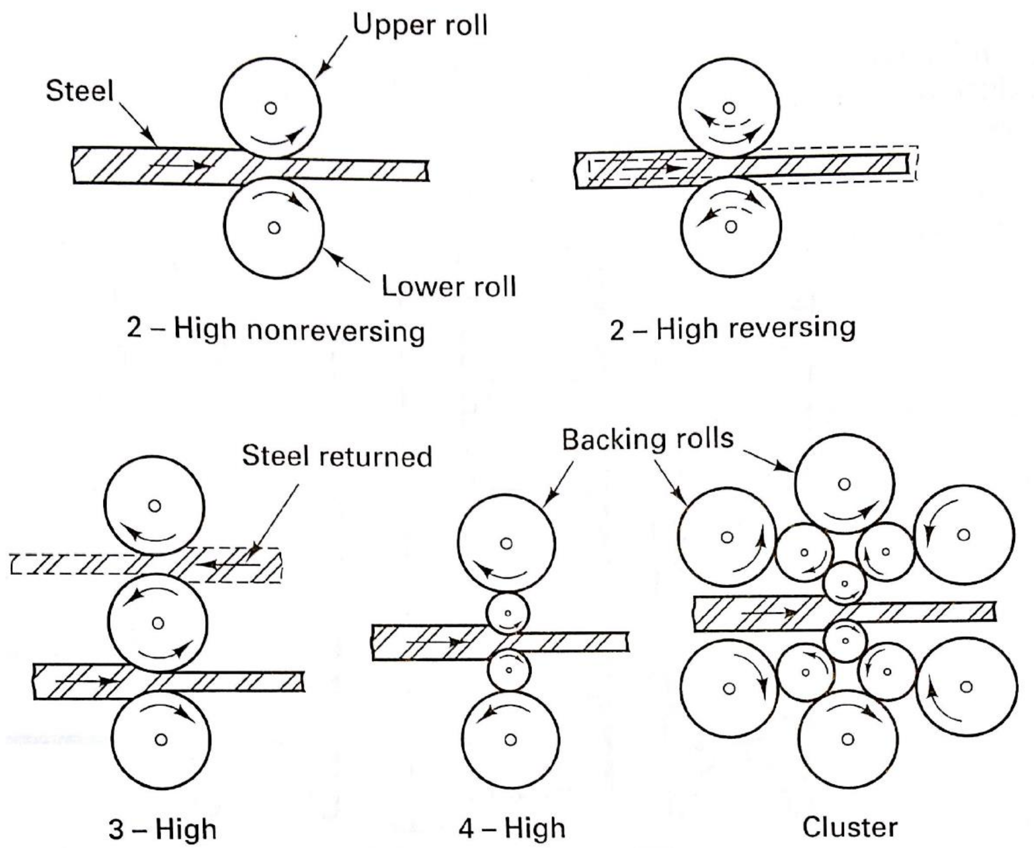
For smaller operations or secondary processing, the starting material is often a room temperature solid such as an ingot, slab or bloom

This material is first brought to the high rolling temperature (> 2/3 of melting T) in furnaces

Hot rolling ends when the temperature falls to 2/3 of melting temperature for production of a uniform fine grain size and to prevent unwanted strain hardening.



Deformations that result in reduction of size in a cast material (primary process) utilize a two or three-high configuration with 60-140 cm diameter rolls

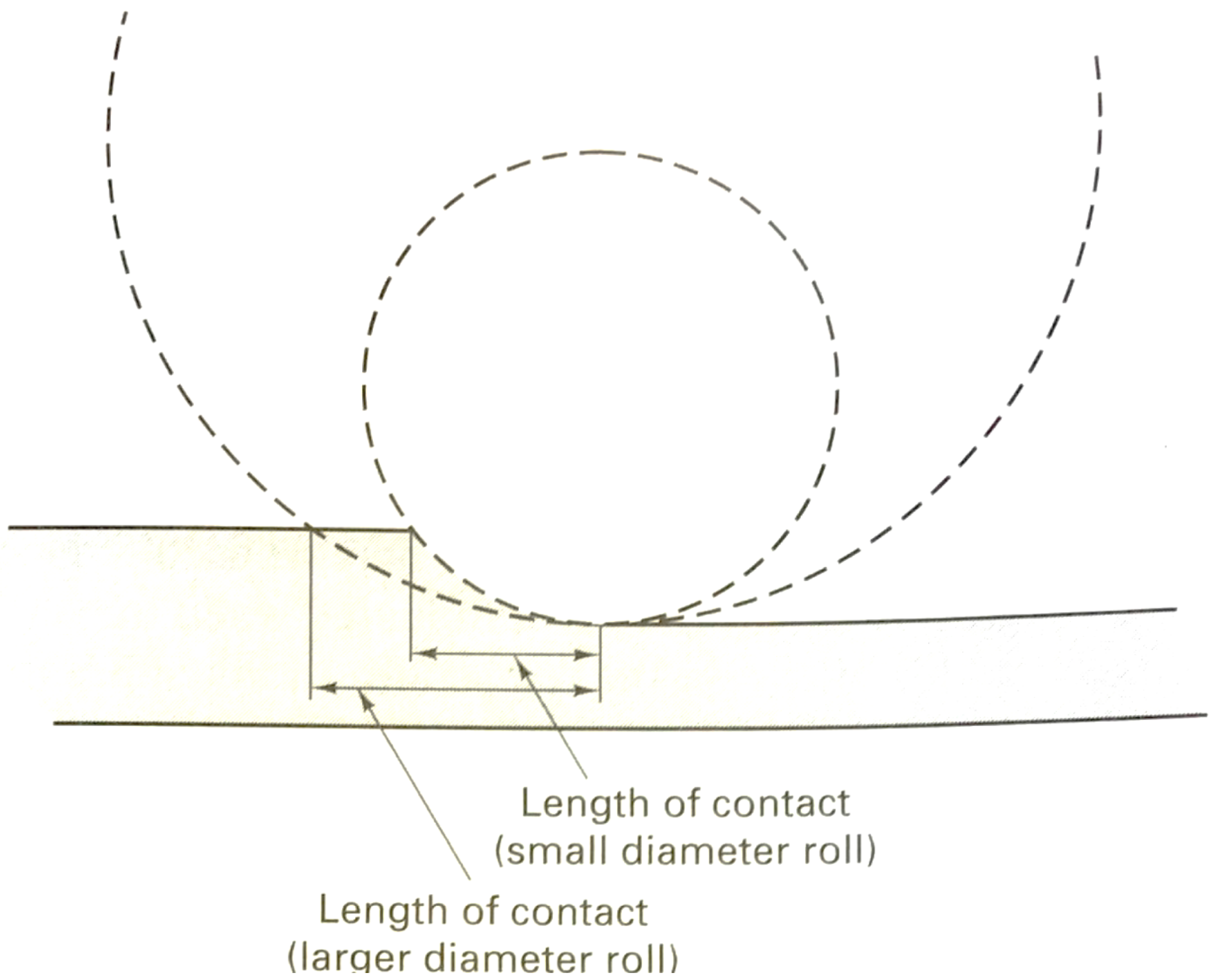


Four-high and cluster arrangements use backup rollers to support the smaller ones to produce wide plate and sheets where small deflections in the roller are not tolerated

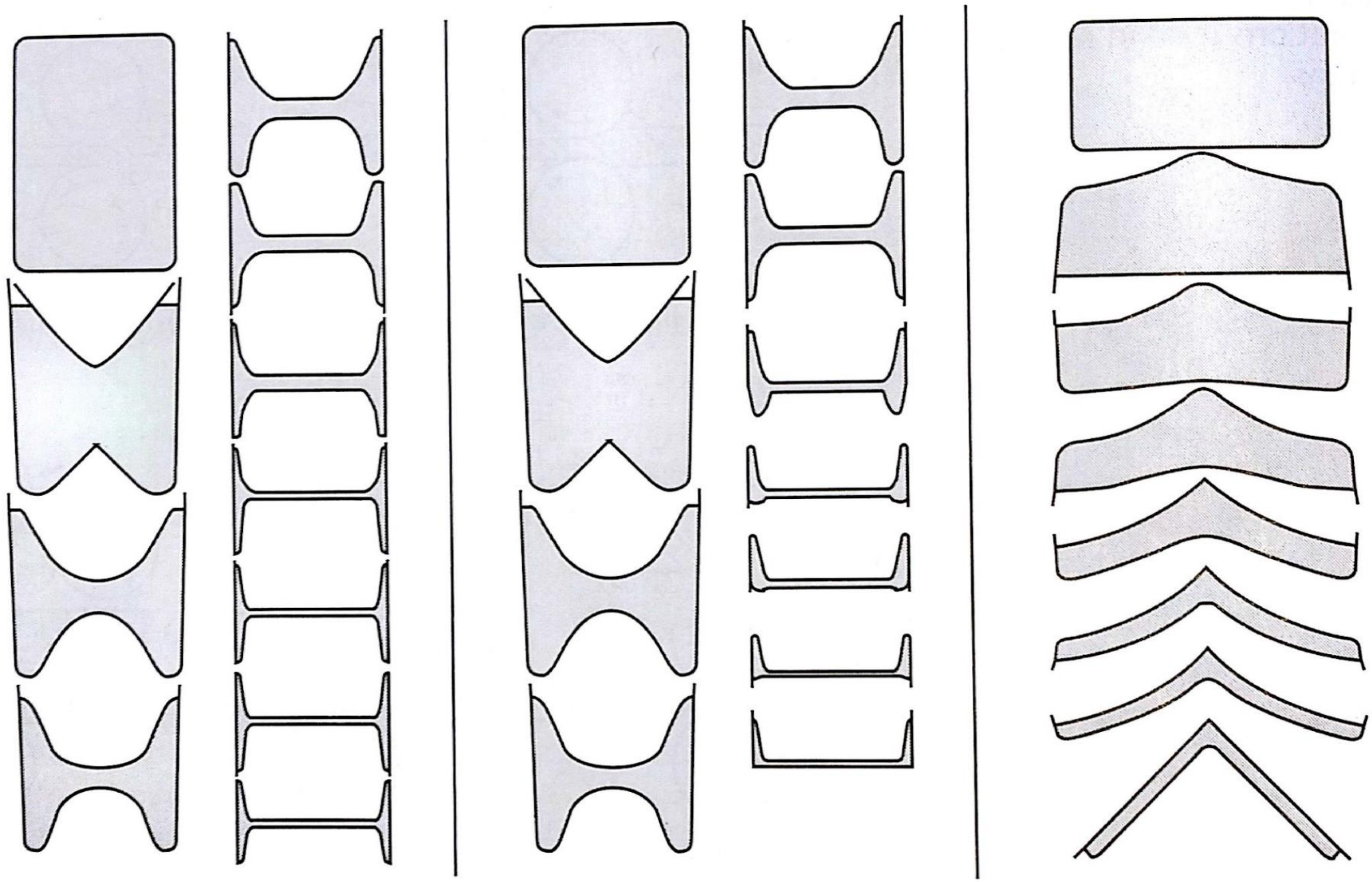
Foil is always rolled on cluster mills since small thickness requires small diameter rolls
The small rollers can have diameters as low as 6mm

Smaller diameter rolls produce less length of contact for a given reduction in thickness and therefore require less force and energy to produce a given change in shape

But the smaller cross section results in reduced roller stiffness and they are prone to flex elastically



In the rolling of nonflat or shaped products such as structural shapes and railroad rail, the sets of rollers contain contoured grooves that sequentially form the desired shape and cross section



When the product is produced by back and forth passes through a single stand, multigrooved rollers are used in the stand

When the volume of a product is high, rolling may be performed on a continuous rolling mill consisting of multiple rolling stations with one set of shaped grooves in each stand

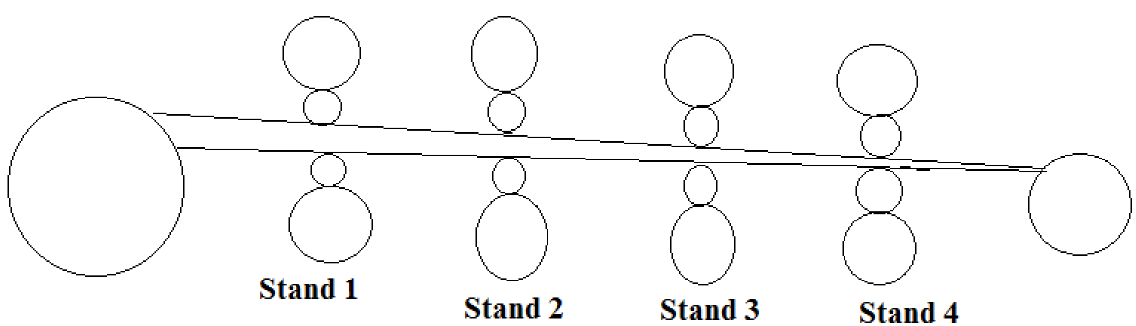
In continuous rolling, billets, blooms or slabs are heated and fed through an integrated series of nonreversing rolling mill stands

If a single piece of material is in multiple rolling stations at the same time, the same amount of material passes through each stand in the same amount of time

If the cross section is reduced, the speed must be increased proportionally

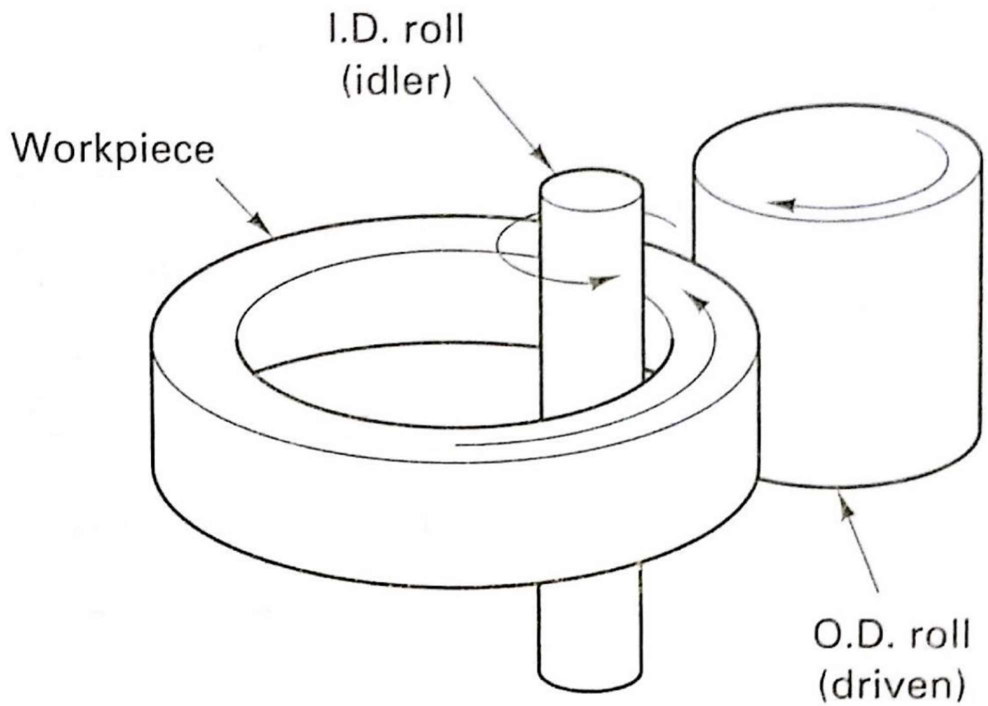
Therefore as a material is reduced in size, the rollers of each successive stand must turn faster than the previous one.

If not, either material accumulation or rupture between the stands will occur



Continous Rolling Mill

Ring rolling is a special rolling process where one roller is placed through the hole of a thick-walled ring, and a second roller presses in from the outside



The wall thickness is reduced and the diameter of the ring increases as the rolls squeeze and rotate

The resulting seamless rings have a circumferential grain orientation and are strong materials for rockets, turbines, airplanes, pressure vessels, etc.

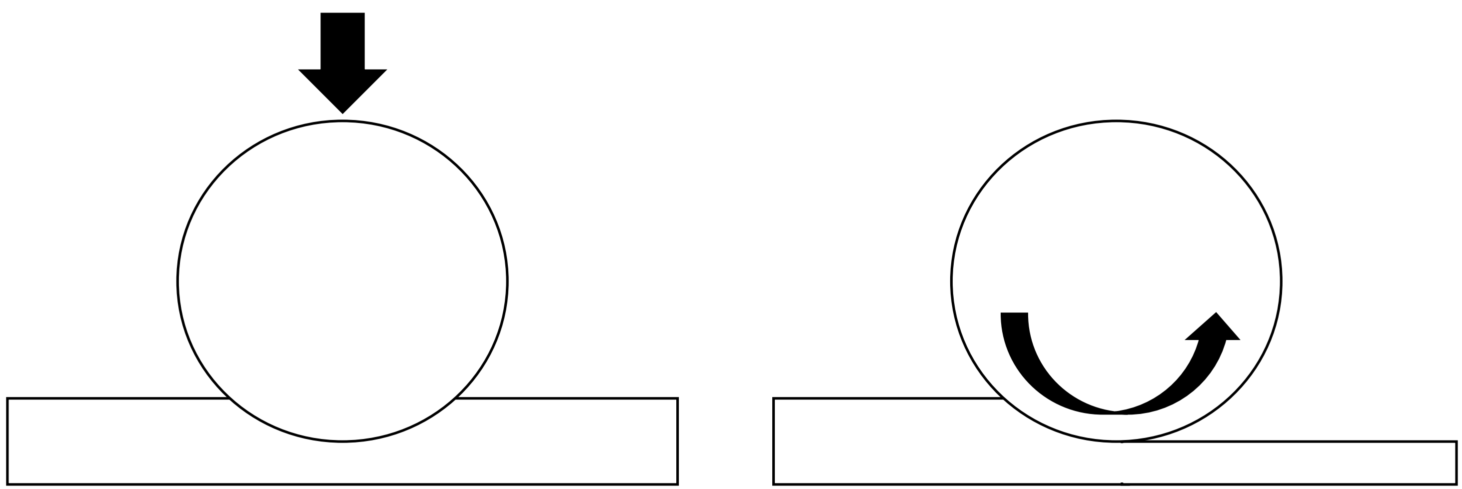
Shaped rollers can produce a wide variety of section profiles

Process analysis

Consider rolling of an aluminum slab of dimensions 10*1*0.2 m at room temperature. It is being reduced in thickness by a roller in a sheet forming process

Plain strain condition applies as the width of the metal is much larger than the thickness
$\varepsilon_y, \gamma_{yz}, \gamma_{xz}, \tau_{yz}, \tau_{xz} = 0,$

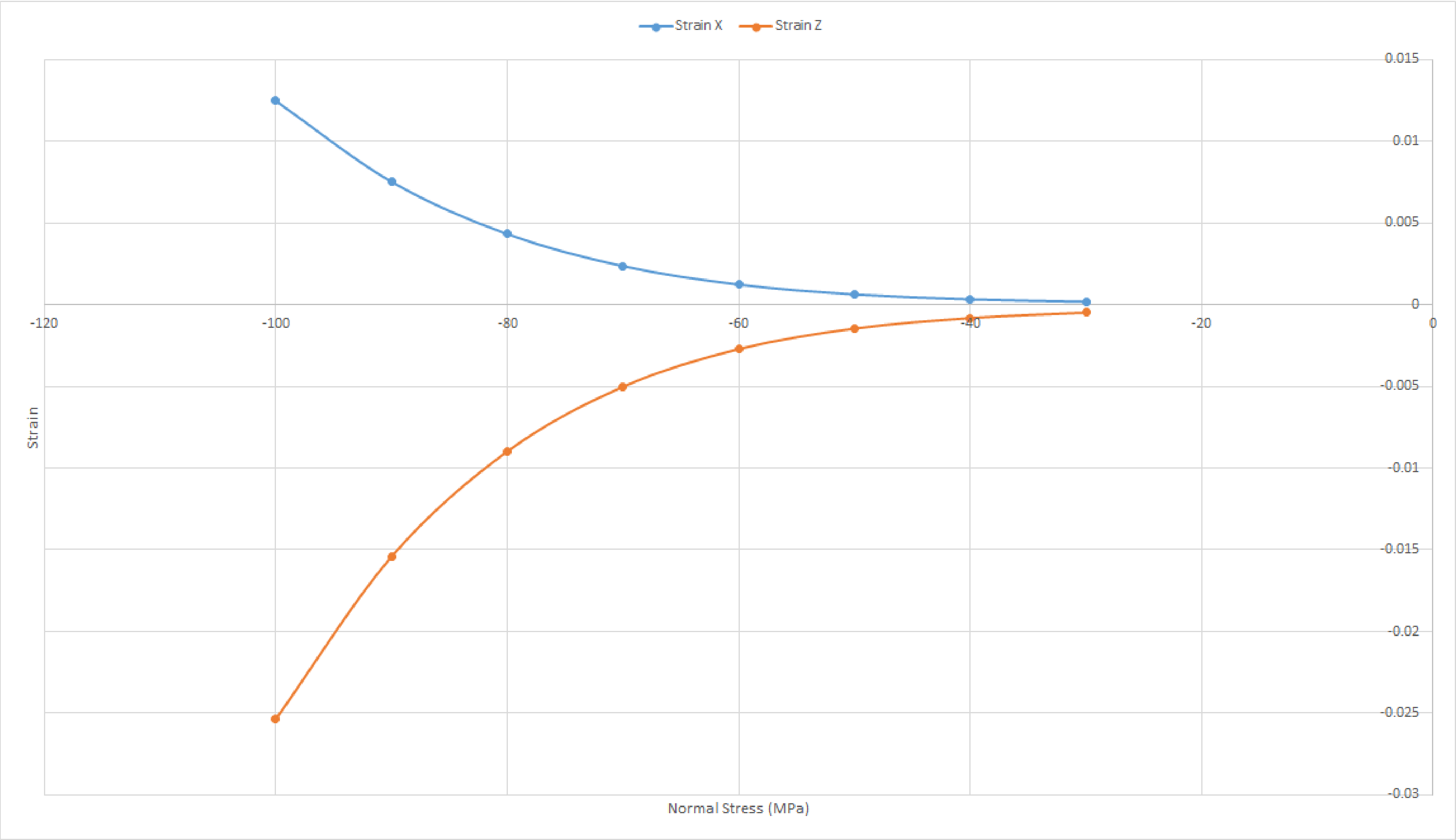
The deformation can be visualized as the sum of two stages:
dipping (deformation by roller moving in the z direction) and rolling (deformation by stationary roller rotating at an angular velocity)



Ramberg-Osgood material model is used to describe plastic deformation behavior of alumina which has the following mechanical properties:

$$\sigma_Y = 30\ MPa, \qquad \varepsilon_Y = 0.000429, \qquad E = 70\ GPa, \qquad \nu = 0.35, \qquad UTS \approx 100\ MPa$$

Strains developing in the deformed zone are in x and z directions during dipping stage
Strains in y direction are considered zero as the width is much greater than the thickness

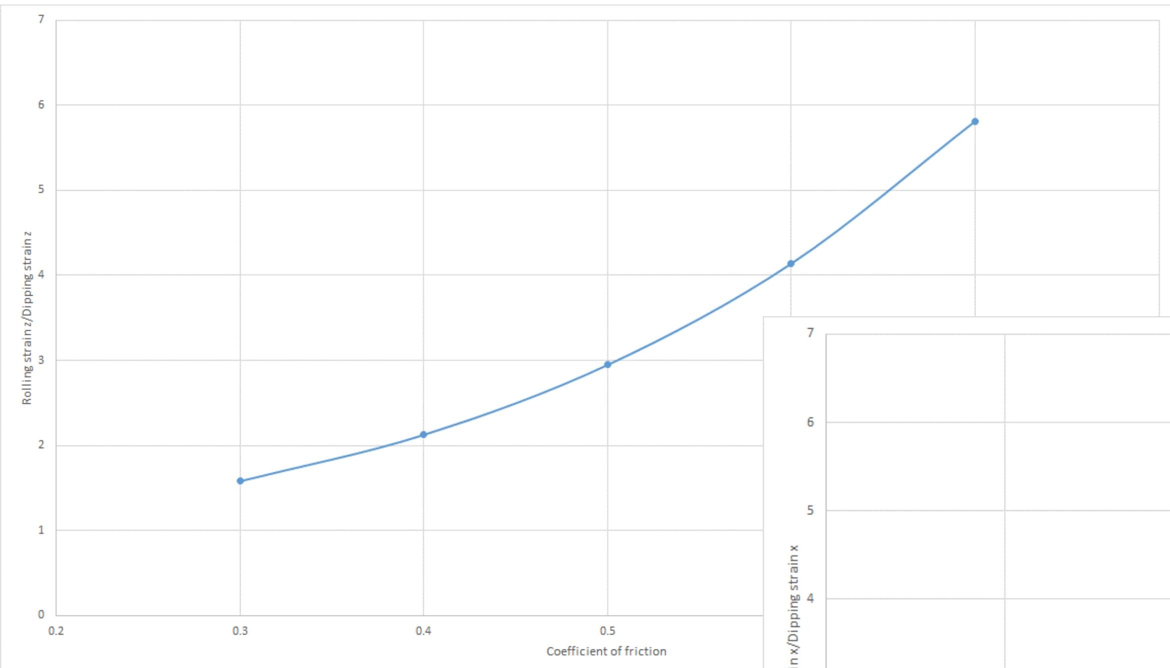


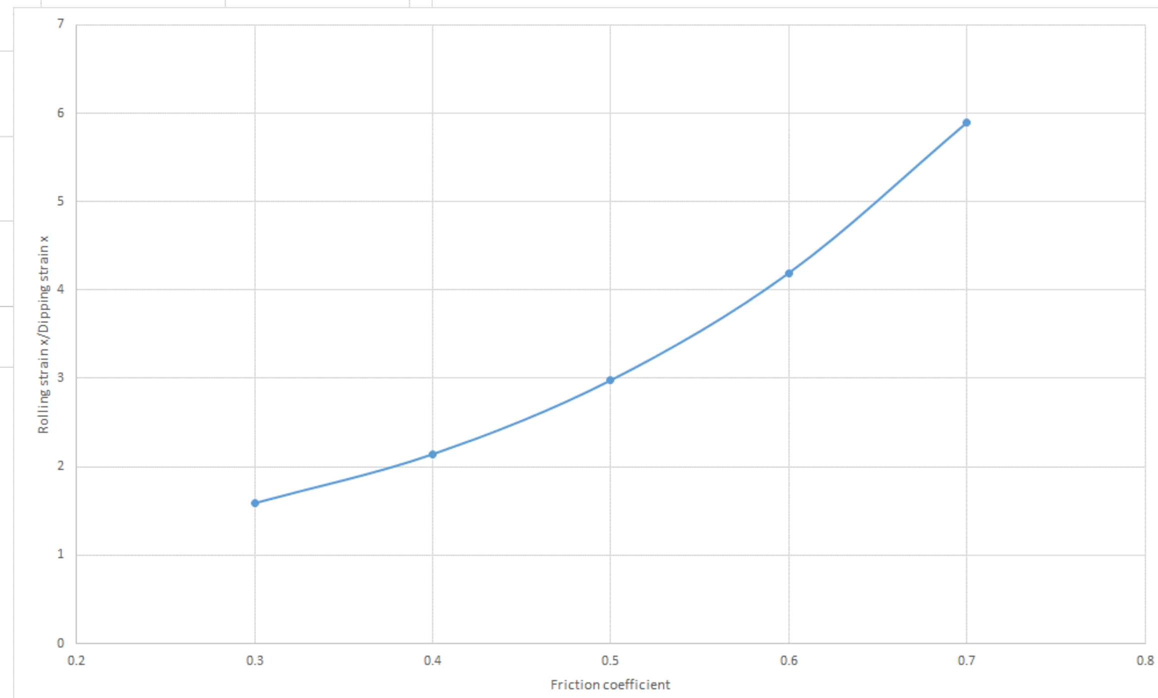
The deformation process aims to reduce the thickness by 25%, a strain of -0.25
It is apparent that the material is not ductile enough at room temperature

The stress applied by the dipping roller is kept constant for the duration of dipping

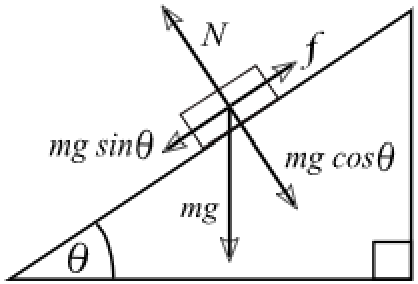
The total strain is equal to thickness final/thickness initial

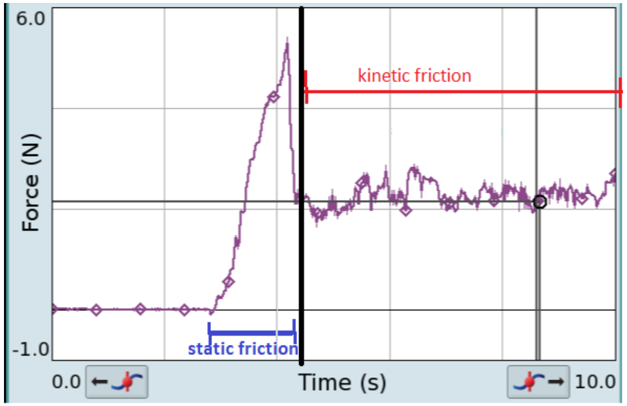
Dipping will result in less strain when considered alone
When rotation is applied to dipping roller, both strains and deformation increase because of the shearing force as a result of friction between roller and metal



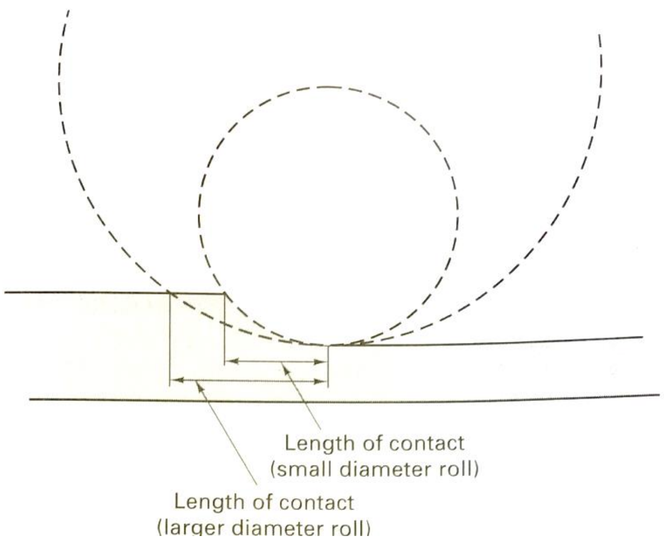


Rotation applied during rolling stage shears the material due to frictional force resulting from the normal force that exists in the material due to dipping

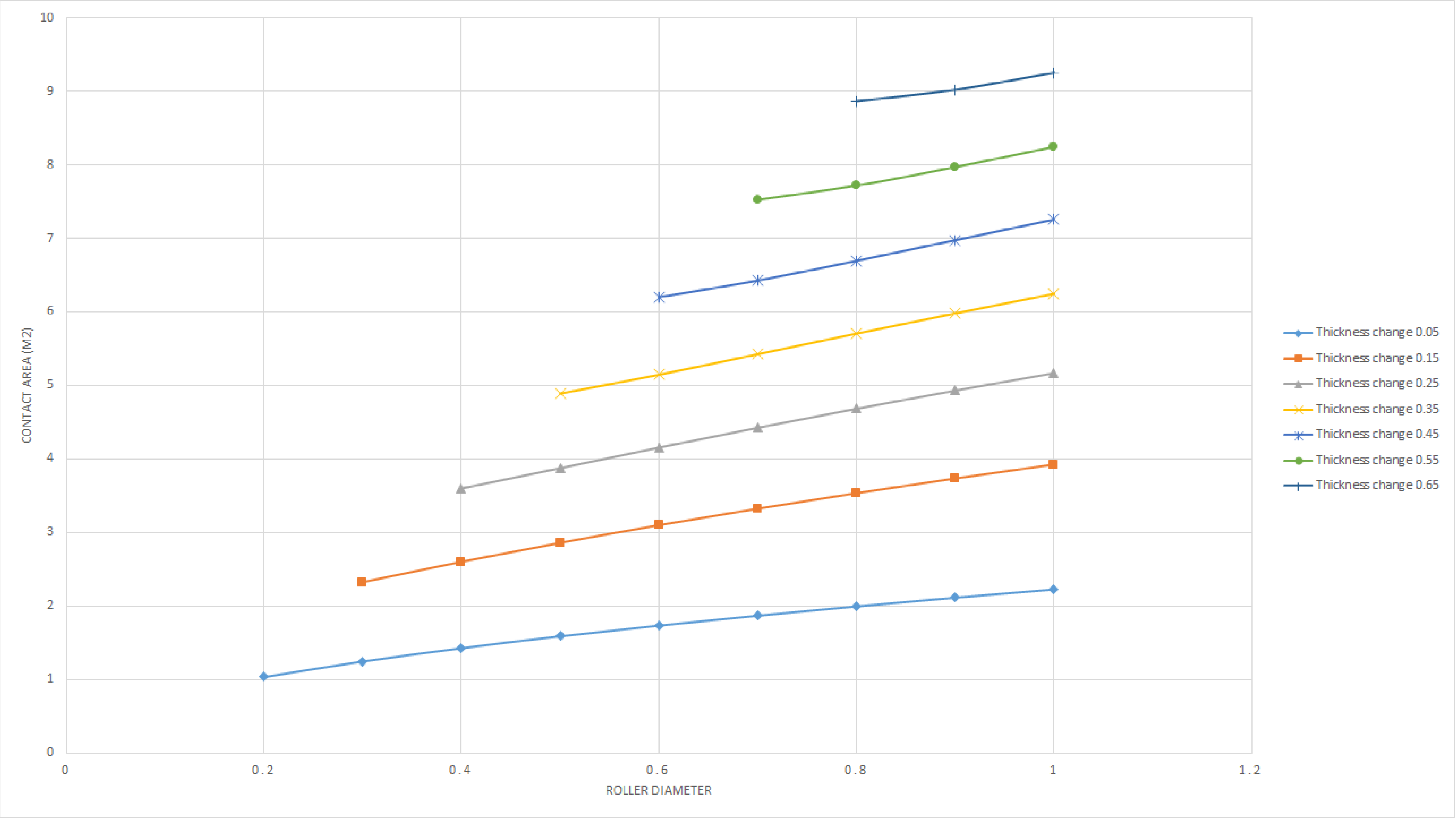




In this stage the normal force converts to shearing force that deforms the material in the vicinity of the contact area

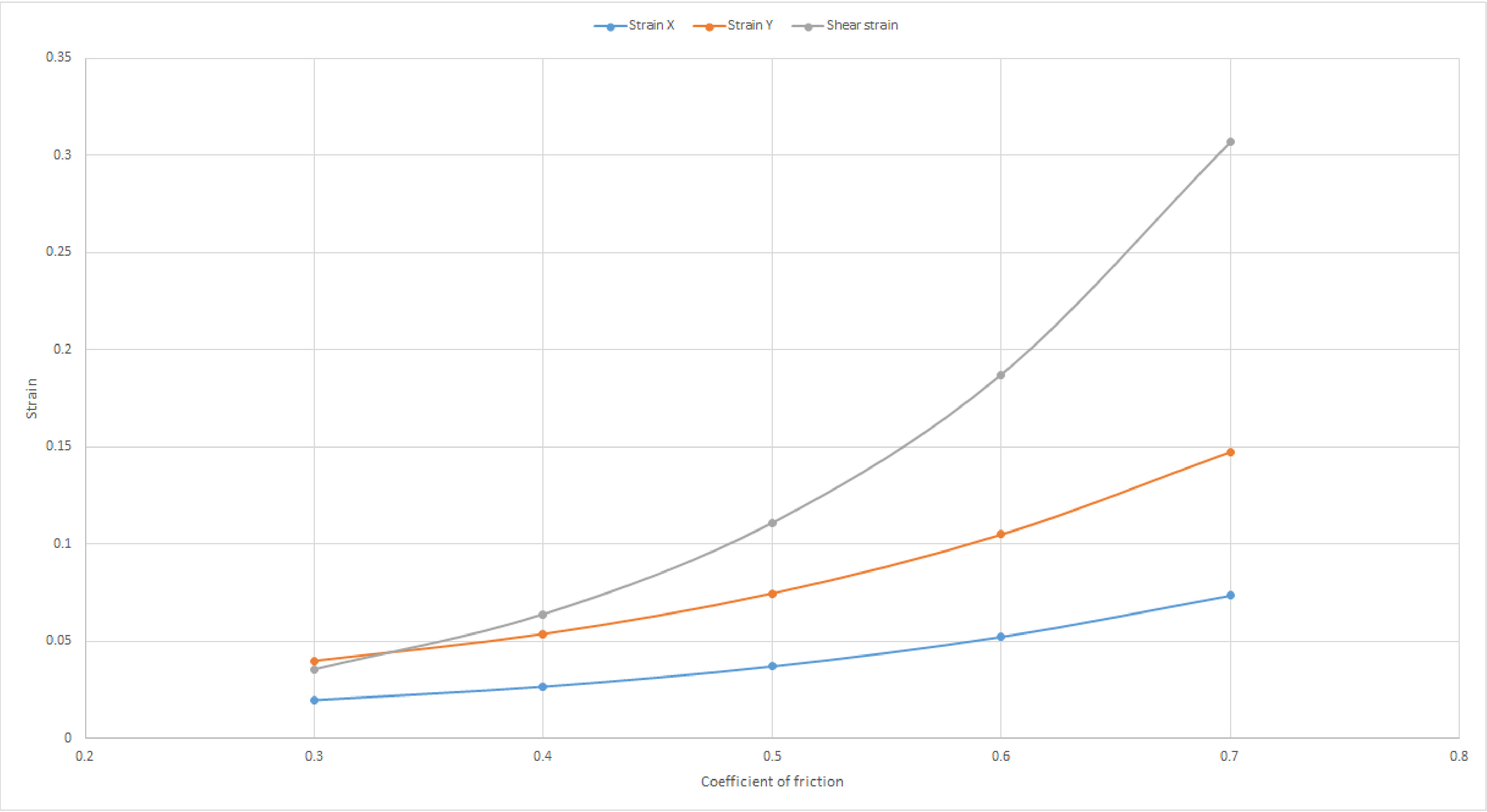


Contact area is proportional to the roller diameter and the reduction in slab thickness



The roller diameters are assumed the same as the initial thickness of the slab

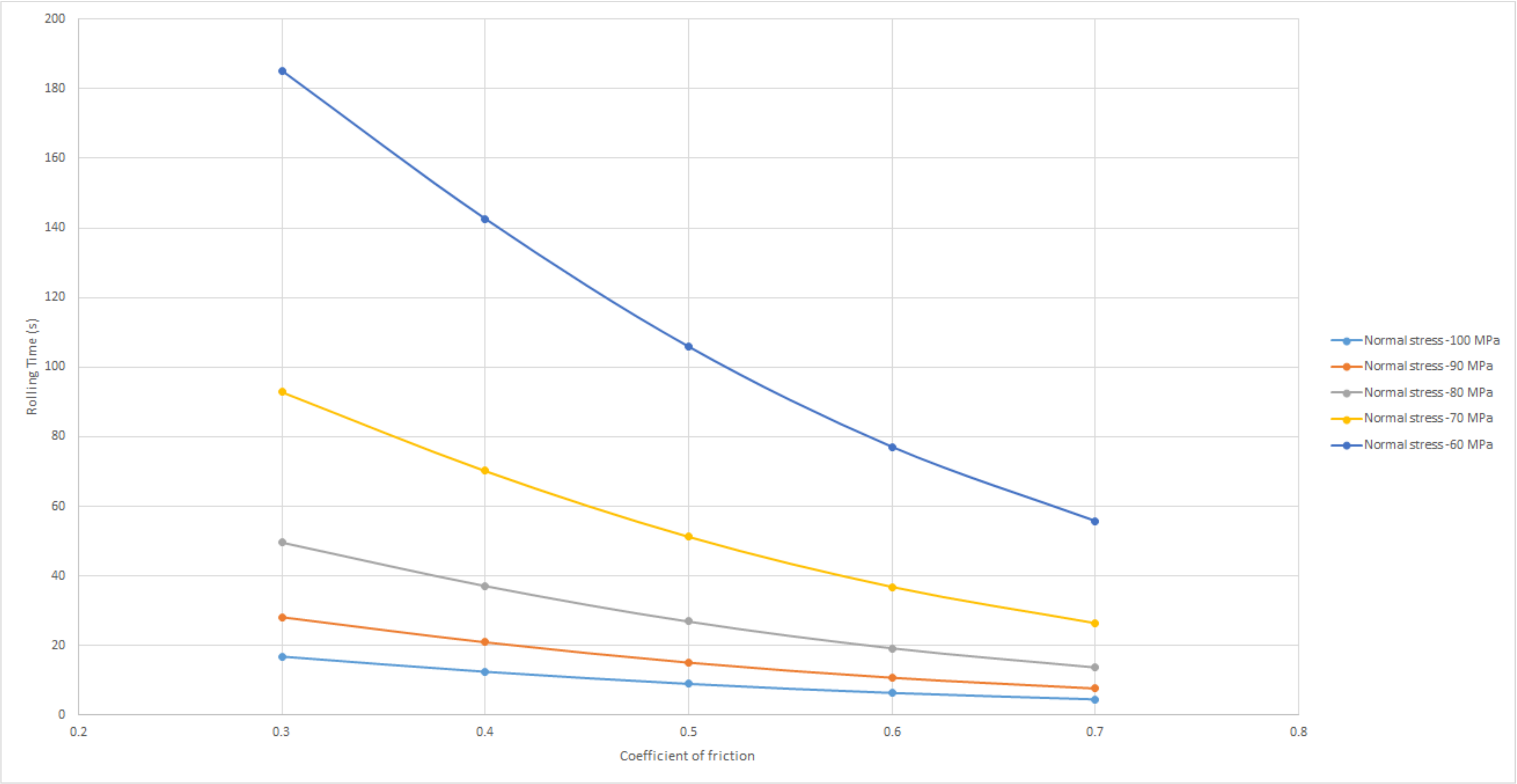
The contact area affects the applied normal stress
Both contact area and coefficient of friction between the roller and metal affect the applied shear stress



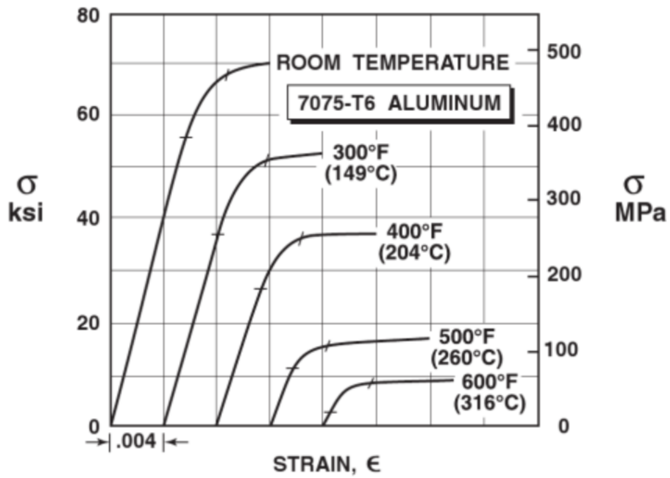
Rolling deforms the metal by shear stress and also moves it in the x direction as a result of the elongation

If we consider the rolling stage as deformation instants applied to the whole length of the metal, we can calculate the approximate time it will take to reduce the thickness of the slab

The following data is for an angular velocity of 60˚/s

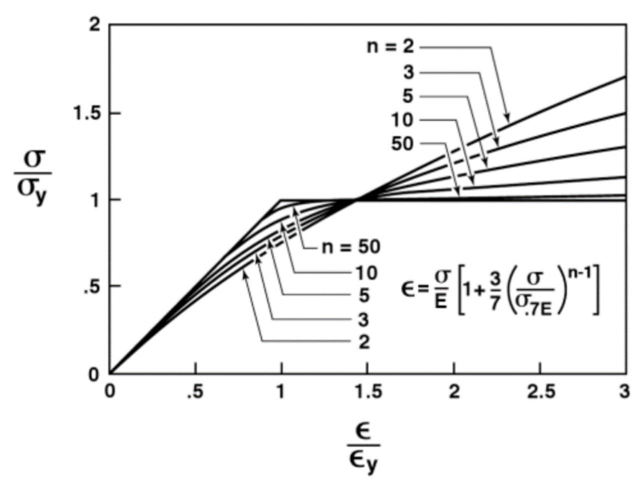


To achieve the desired reduction in thickness by rolling, metal should be heated above their recrystallization temperature to enable flowability and avoid strain hardening



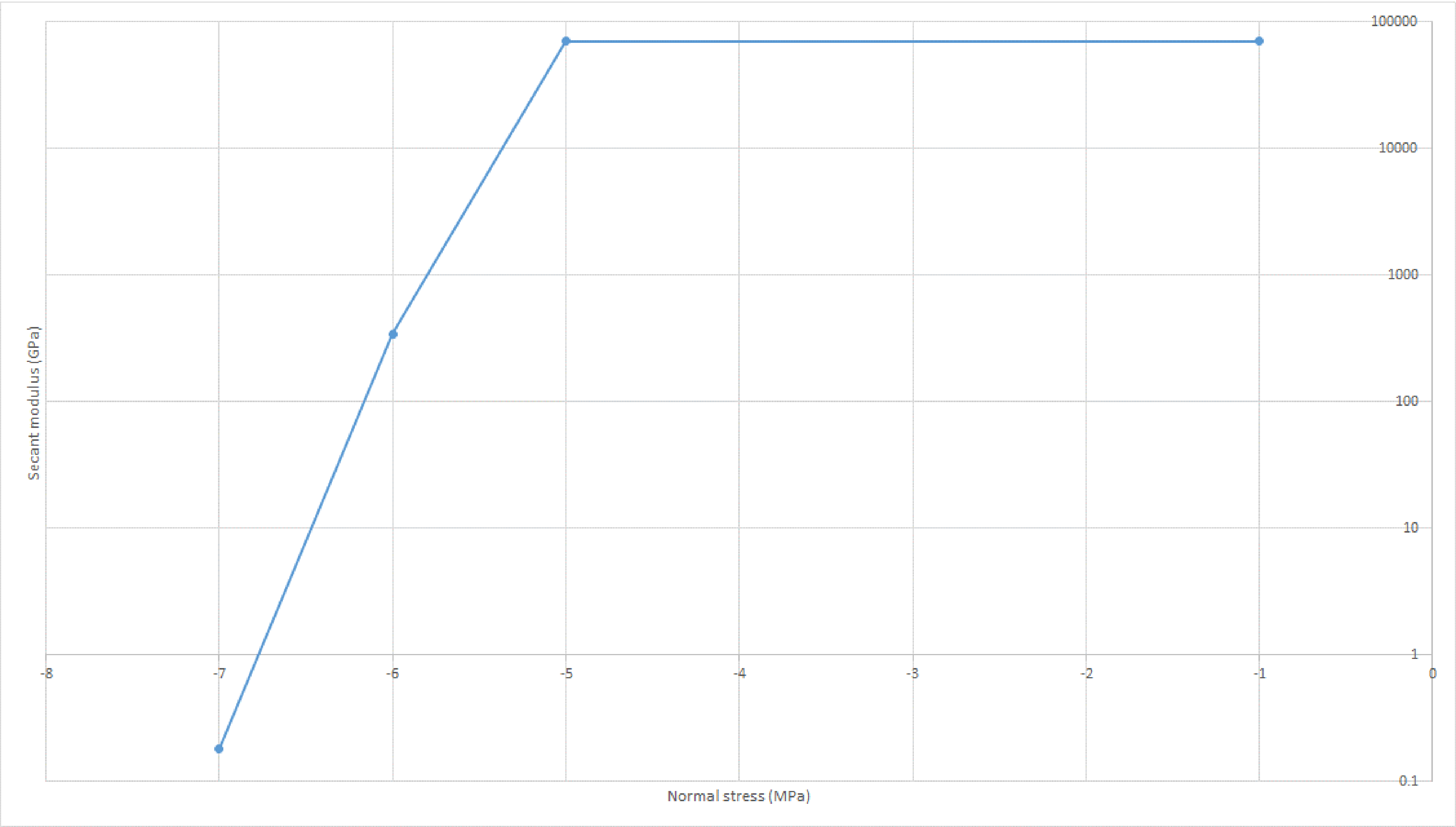
Compressive Stress-Strain Curves for 7075-T6 Aluminum as a Function of Temperature *(After Mathauser and Brooks*

In this case an elasto-plastic material model or Ramberg-Osgood model with high n approximately describes the material



Consider heating pure aluminum to a high enough temperature that its yield strength decreases to about 5 Mpa and it undergoes no strain hardening

Ramberg-Osgood material model with n=50 and $\sigma_{0.7} = 7MPa$ produces the following secant moduli and strains as a function of dipping normal stress



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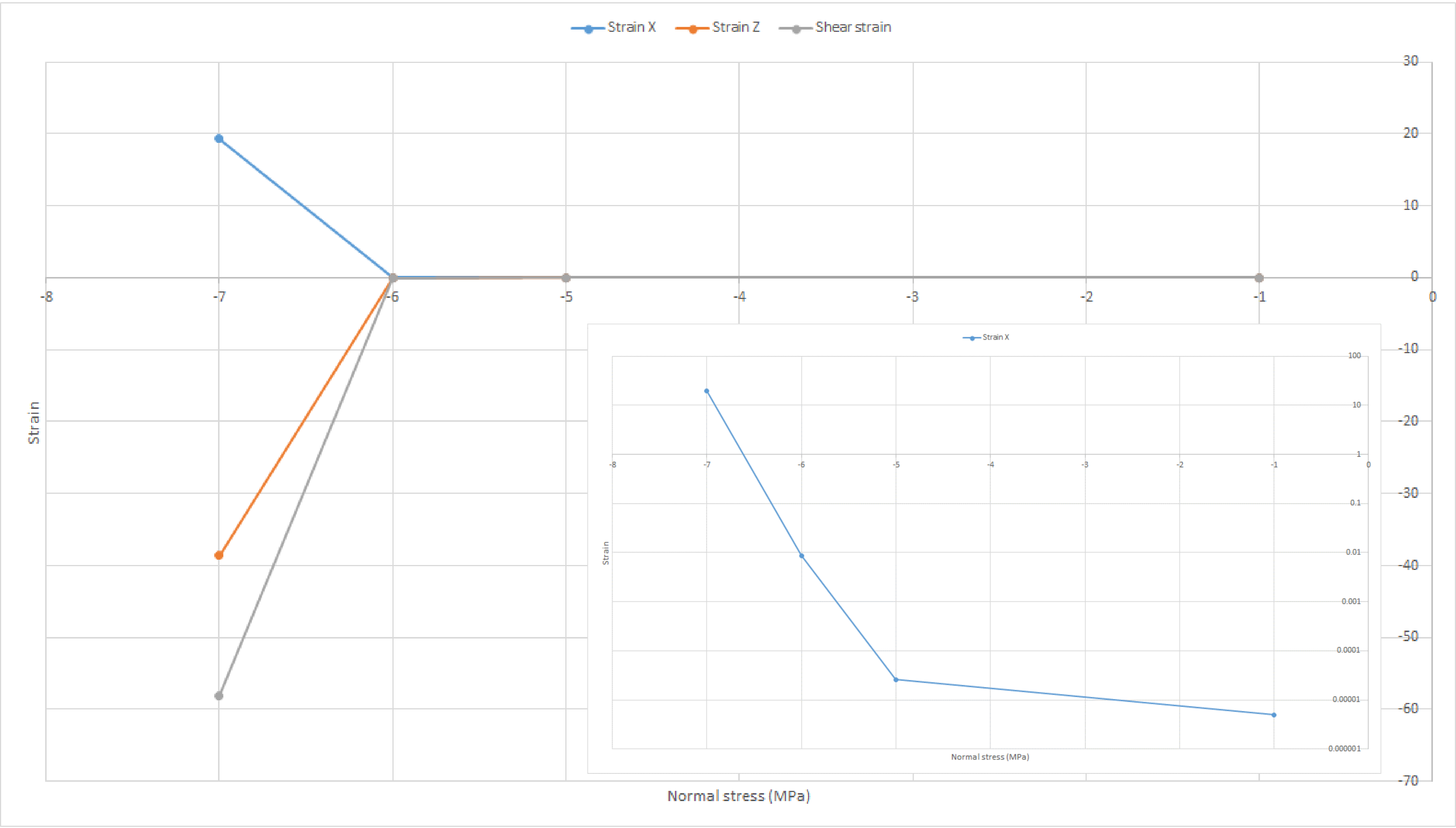
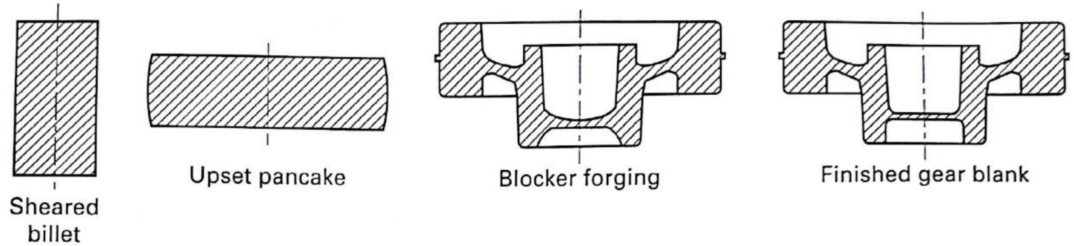


Forging is the oldest and most well-known deformation process that can be done in the hot, cold, warm or isothermal mode, although hot forging is the most common

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:

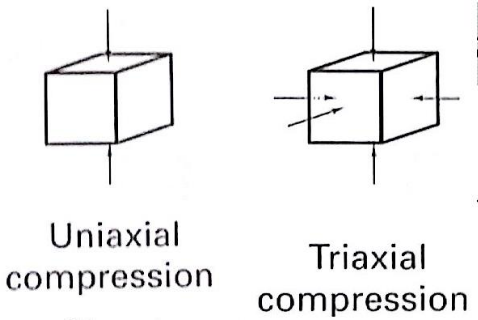
- Open die drop-hammer forging
- Impression die drop-hammer forging
- Press forging
- Upset forging
- Automatic hot forging
- Roll forging
- Swaging



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



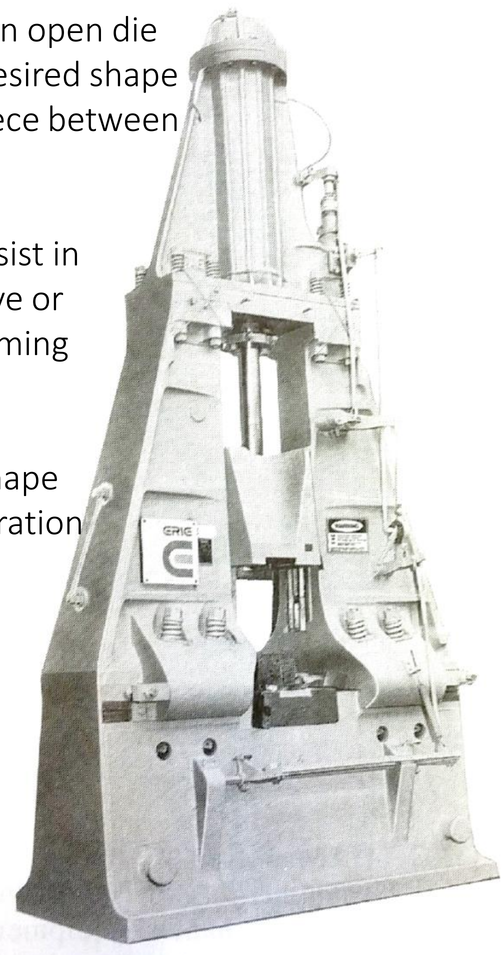
The general open die forging operation starts by feeding the heated metal to an open die

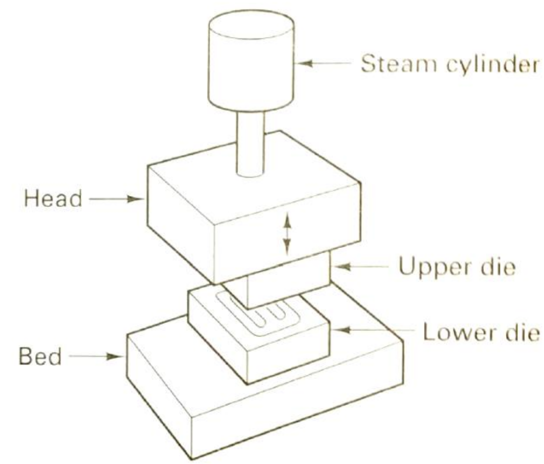
The impact is then delivered by some type of mechanical hammer, the simplest being a gravity drop. Steam or air hammers which use pressure to both raise and propel the hammer are the most common. Programmable, computer controlled hammers can provide blows of differing impact energy for various stages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

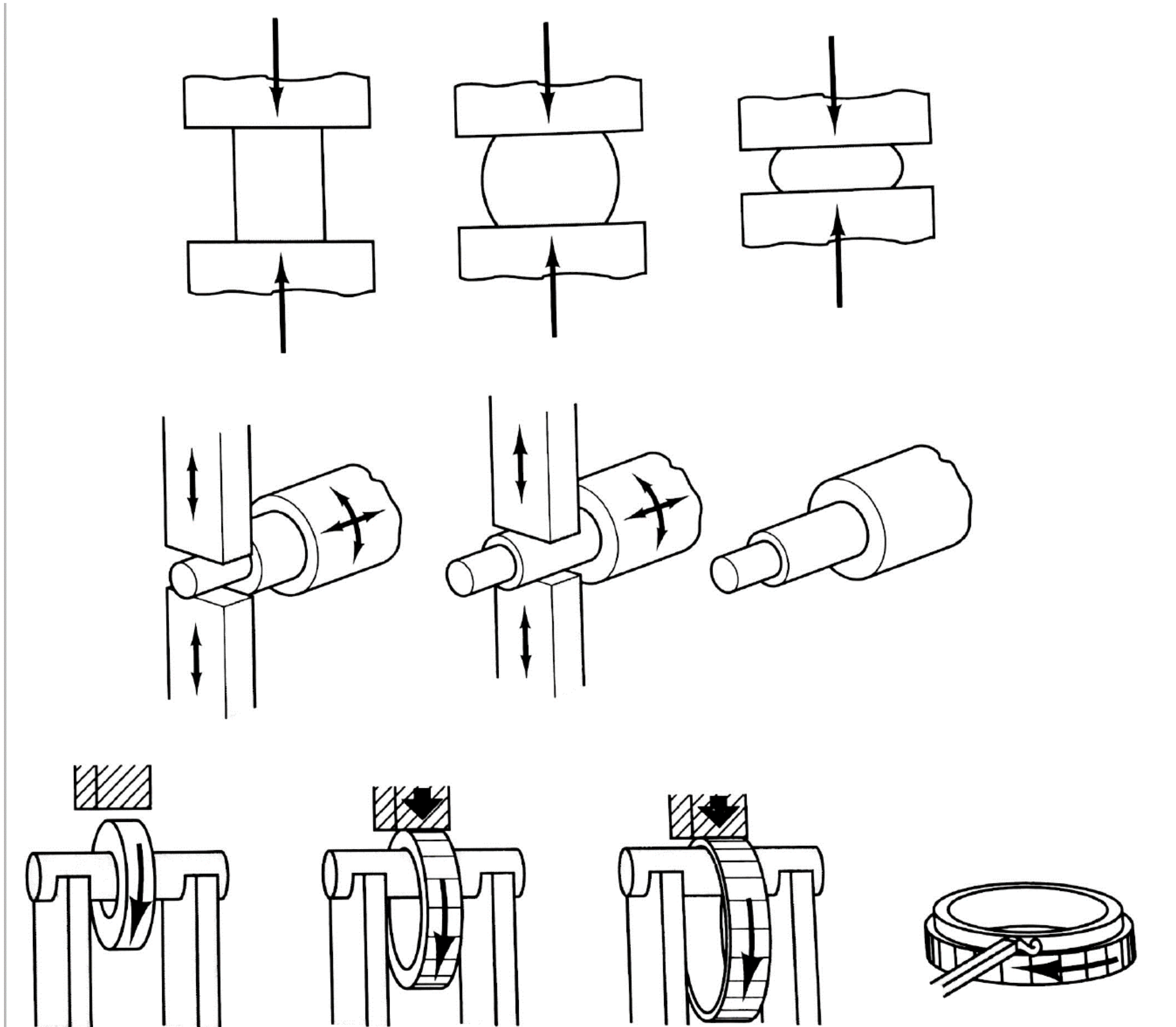
Specially shaped tools can be used to assist in making simple shapes like round, concave or corvex surfaces, forming holes or performing cutoff

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



1 Preform mounted on saddle/mandrel.

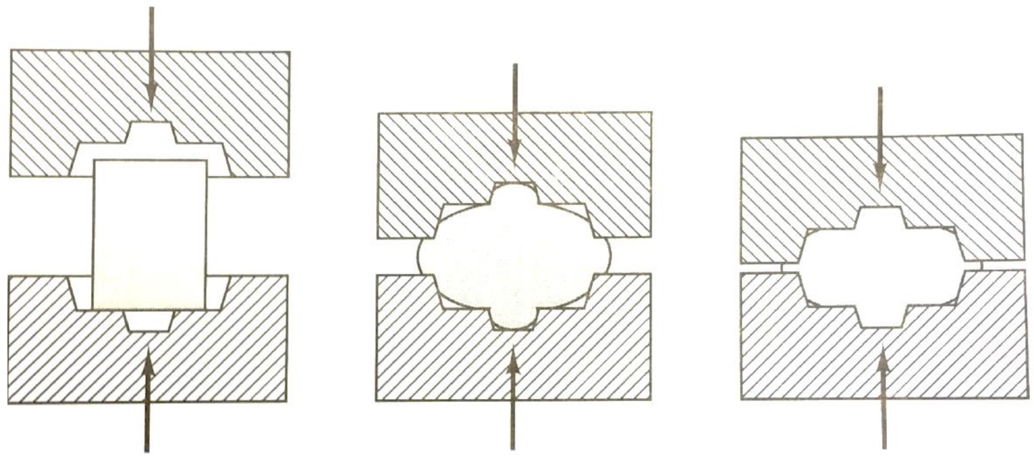
2 Metal displacement– reduce preform wall thickness to increase diameter.

3 Progressive reduction of wall thickness to produce ring dimensions.

4 Machining to near net shape.

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

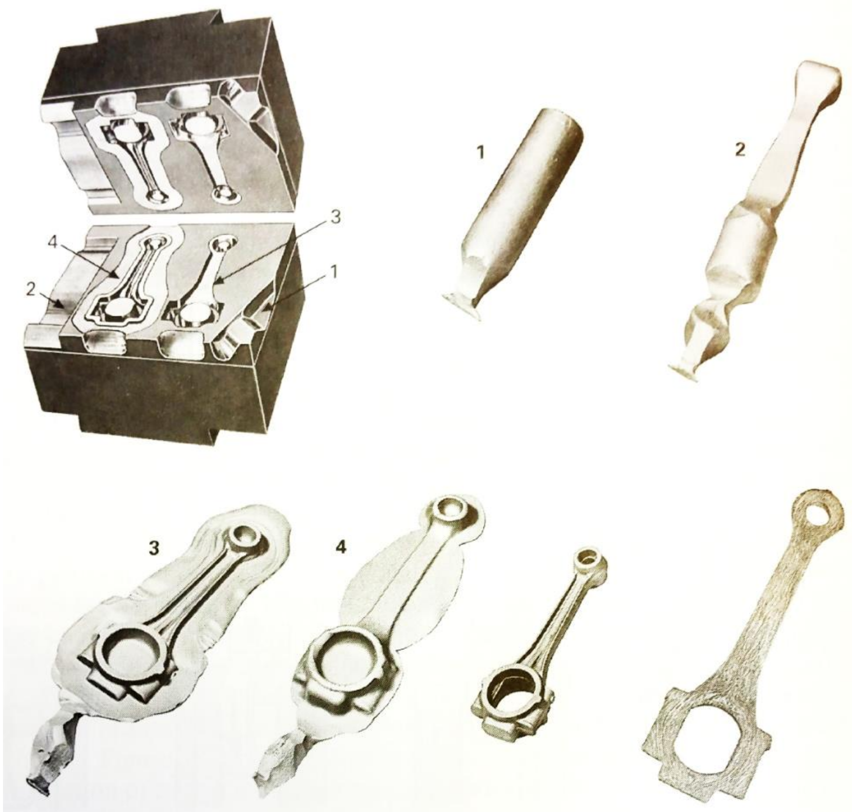
Most conventional forgings are impression-die with flash and are produced in dies with a series of cavities where one or more blows of the hammer are used for each step

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

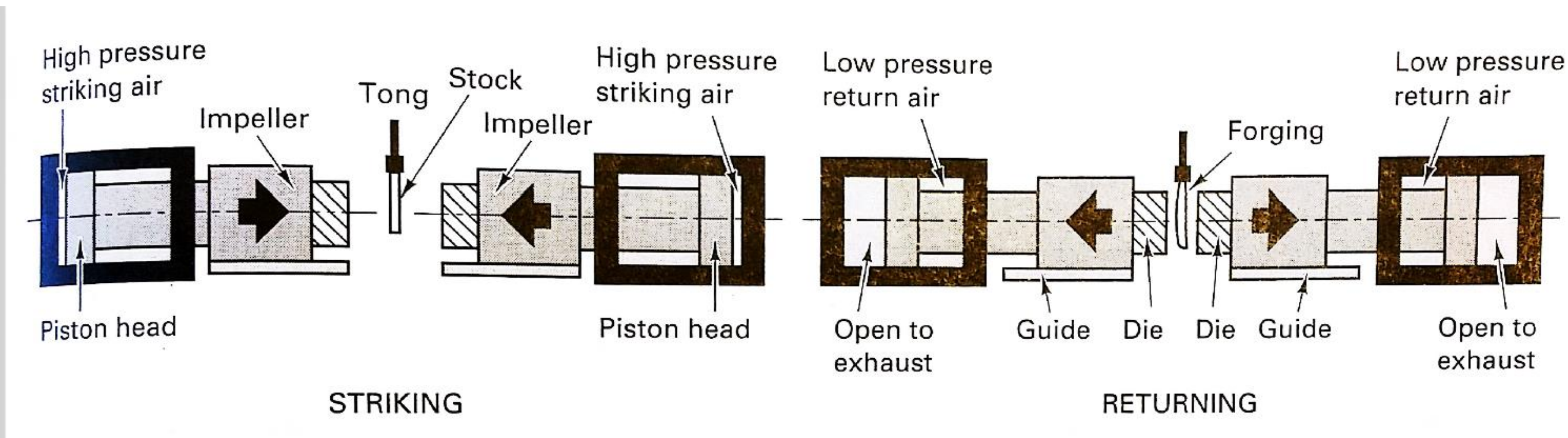
This is majorly because of the control on the flow of material by various cavities and the resulting oriented structure

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

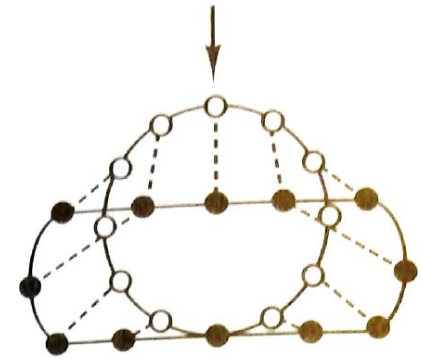
Furthermore hot working provides a fine recrystallized grain structure
Impactor provides even more uniform structure with a different arrangement than the vertical hammer and anvil approach



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

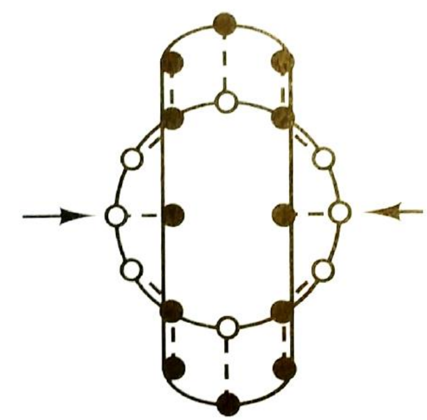
Excess energy does not go to the machine foundation which requires a heavy machine base

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



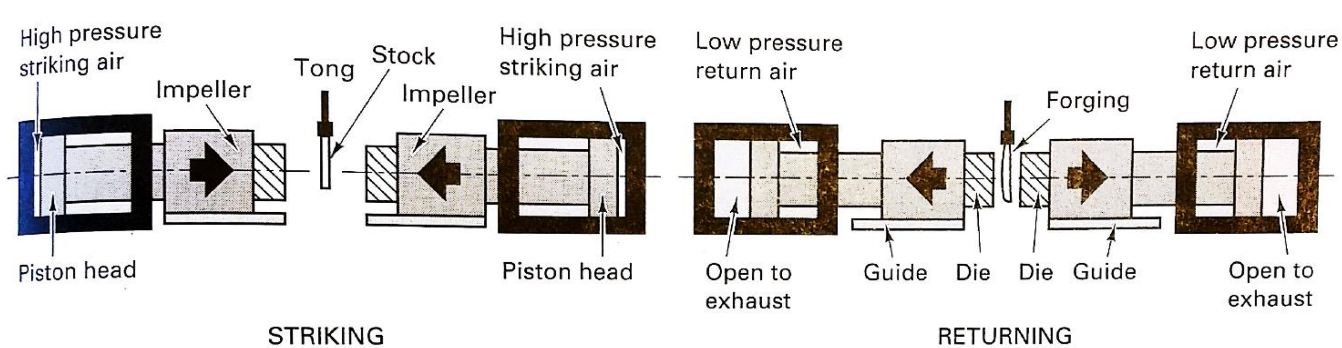
(a)

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 dissipate 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 have 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

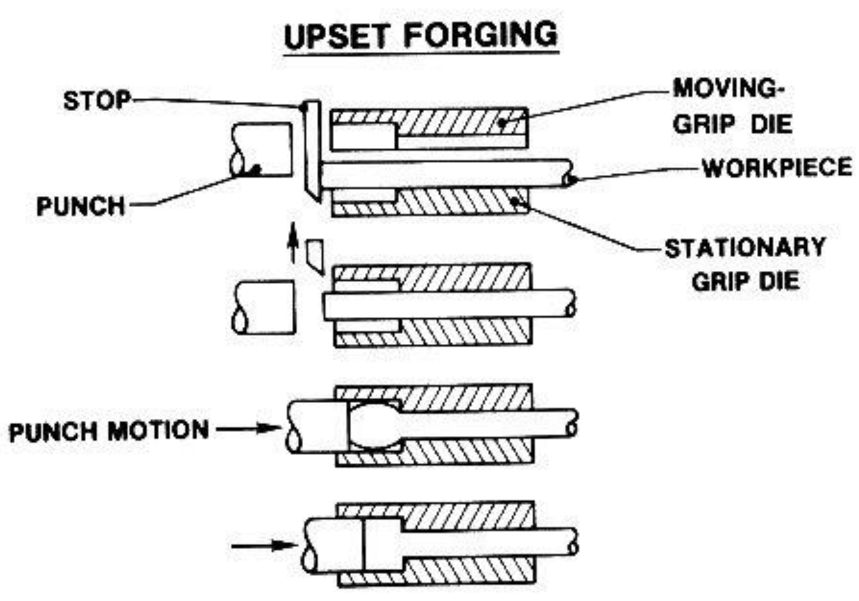
Upset forging involves increasing the diameter of a material by compressing its length

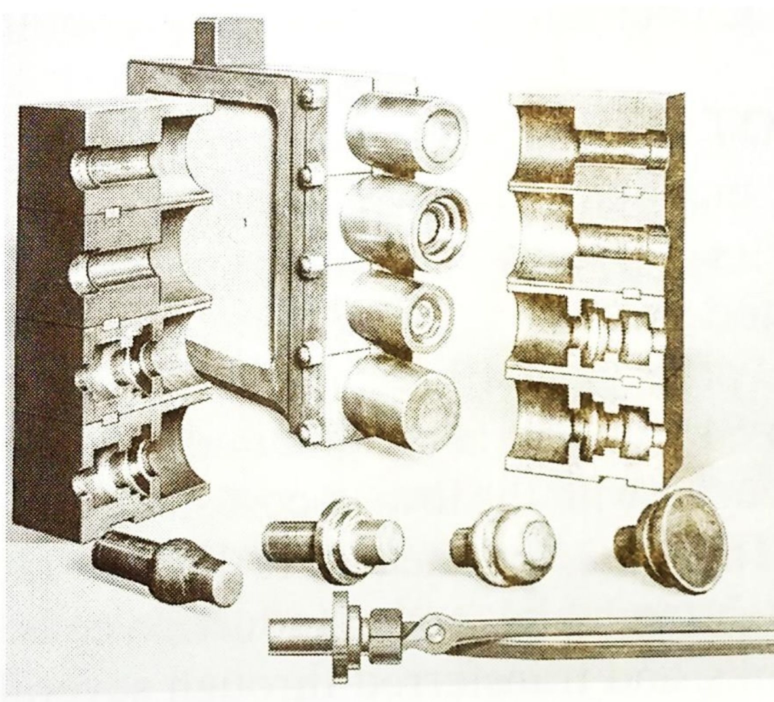
It is the most widely used of all forging processes in terms of the number of pieces produced

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

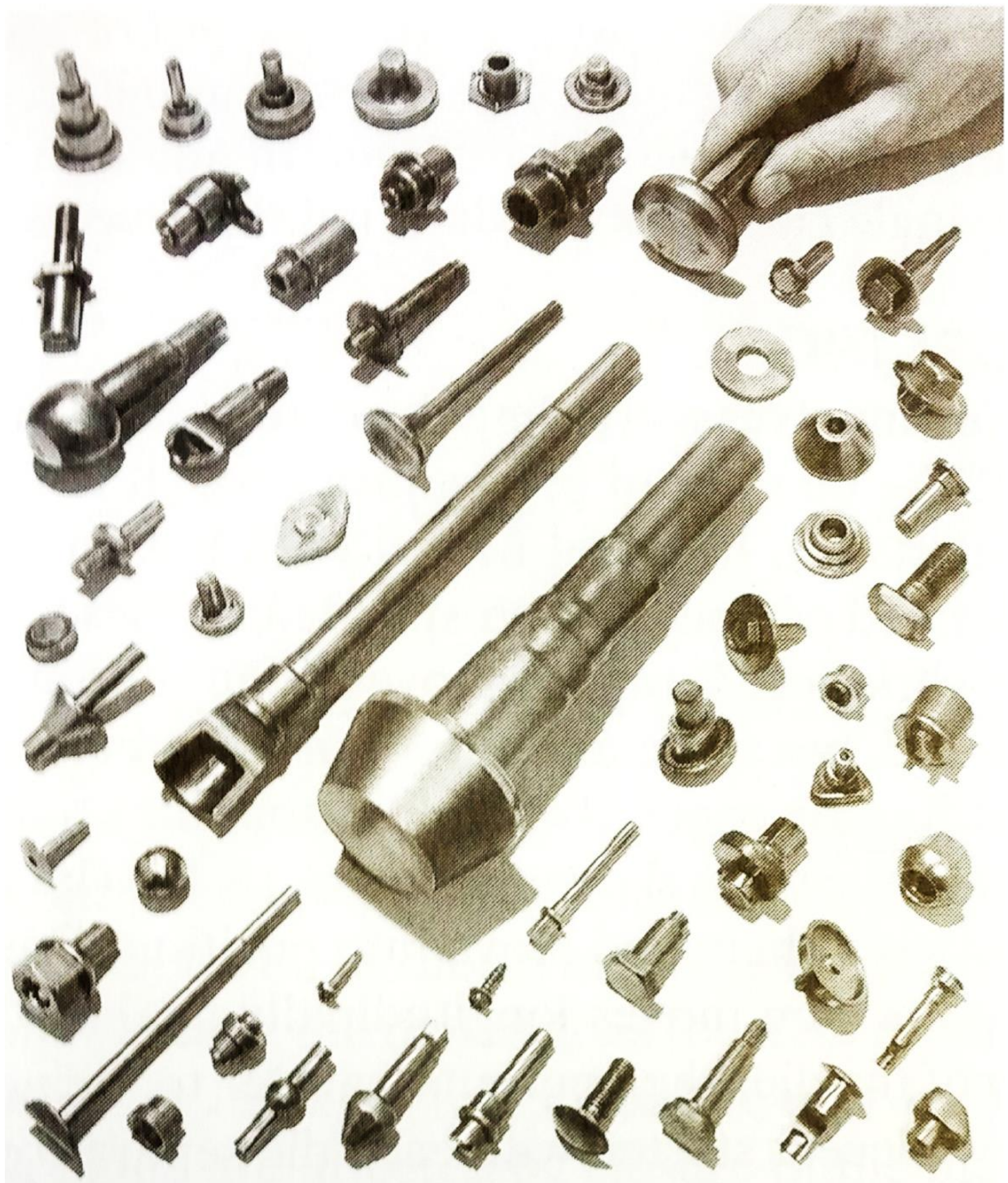
The starting stock is usually wire or rod but bars up to 25 cm in diameter can also be forged

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

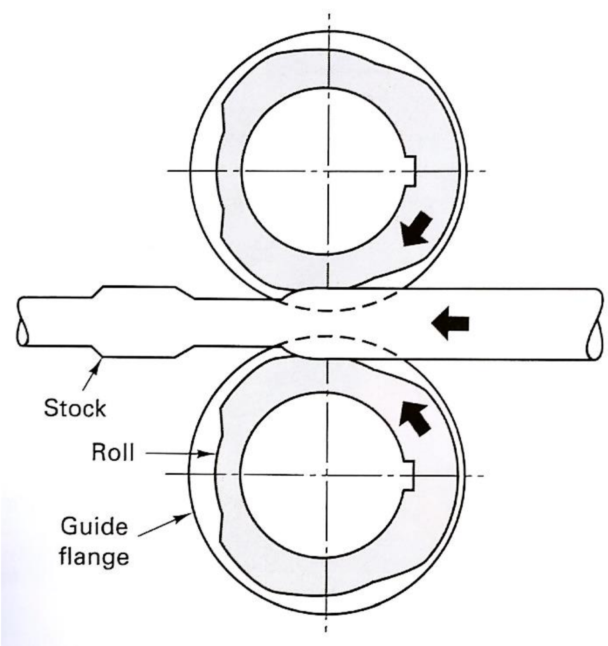
Round or flat bars are reduced in thickness and increased in length in roll forging to produce axles, tapered levers, leaf springs

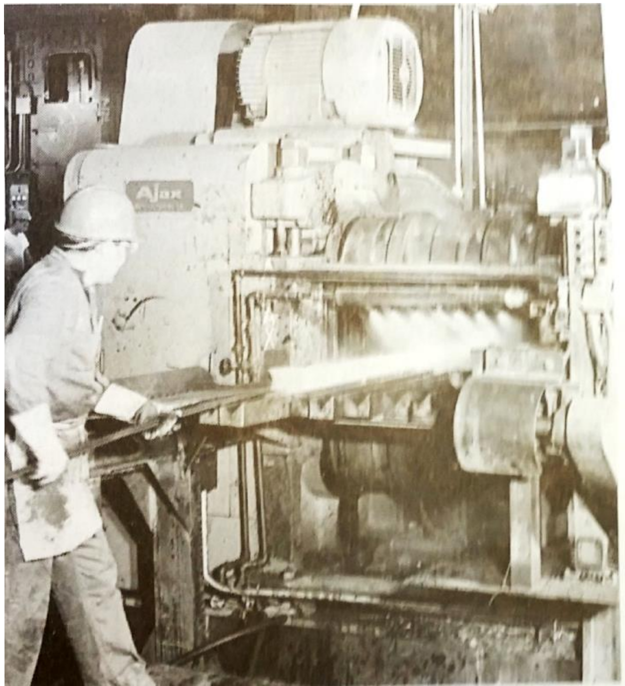
Roll forging is performed on machines that have two cylindrical or semicylindrical rolls each containing one or more shaped grooves

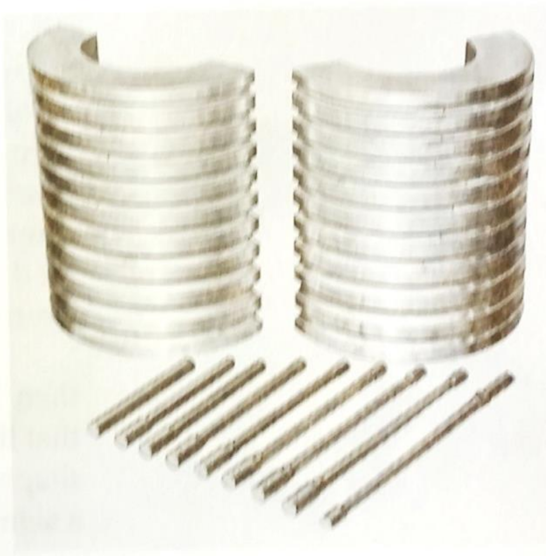
A heated bar is inserted between the rolls

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



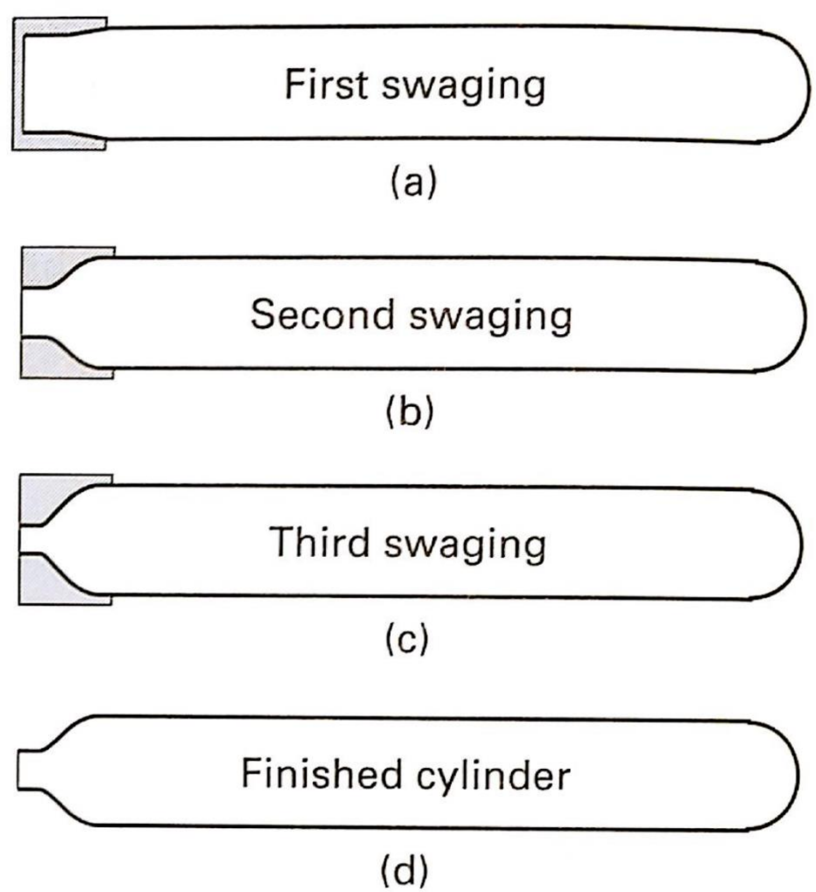




Swaging involves hammering of a tube or a rod by a die to reduce its diameter

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

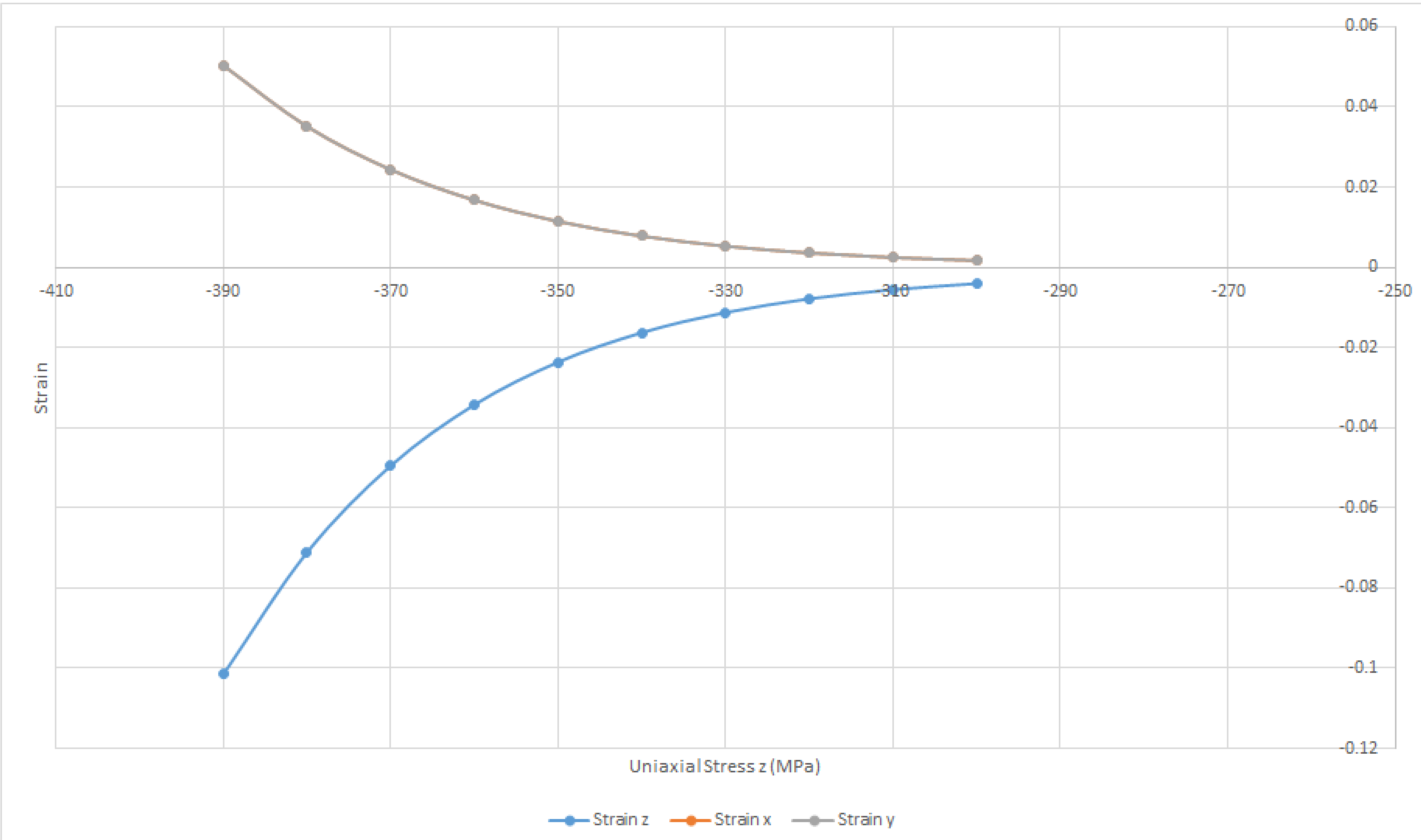
$$\nu = \frac{1}{2} - \frac{E_{sec}}{E}\left(\frac{1}{2} - \nu^e\right)$$

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

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

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

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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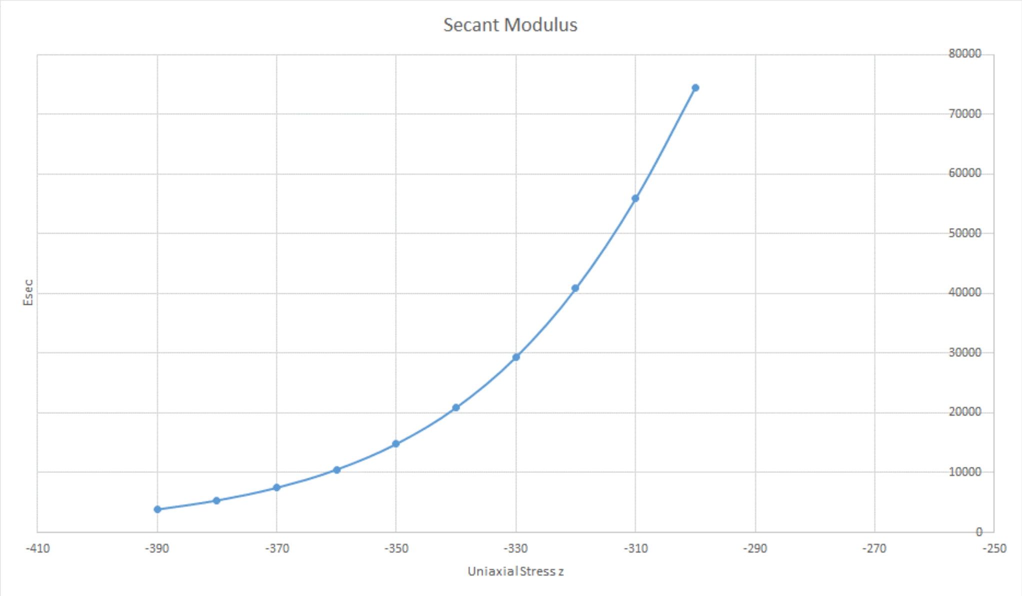
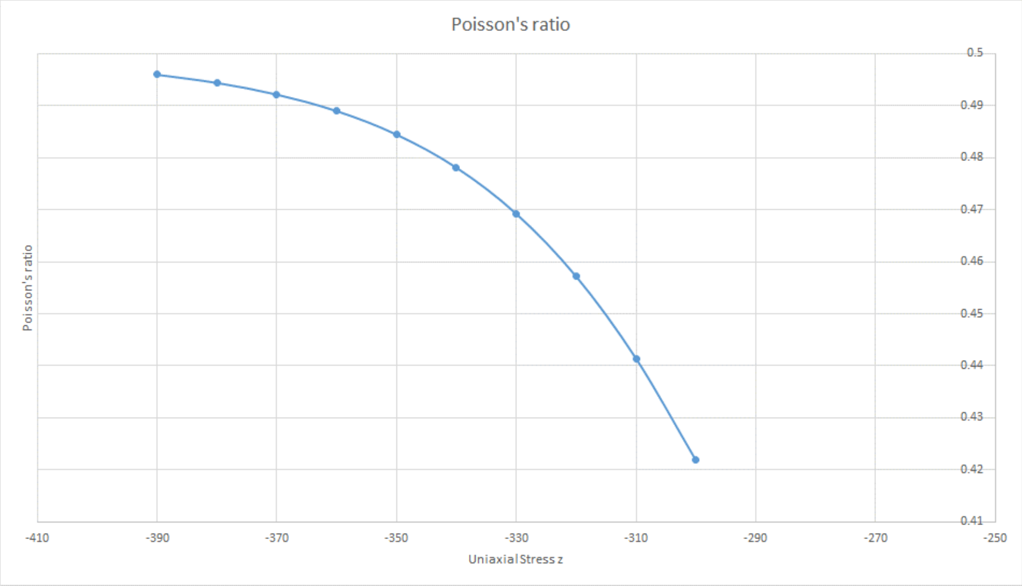
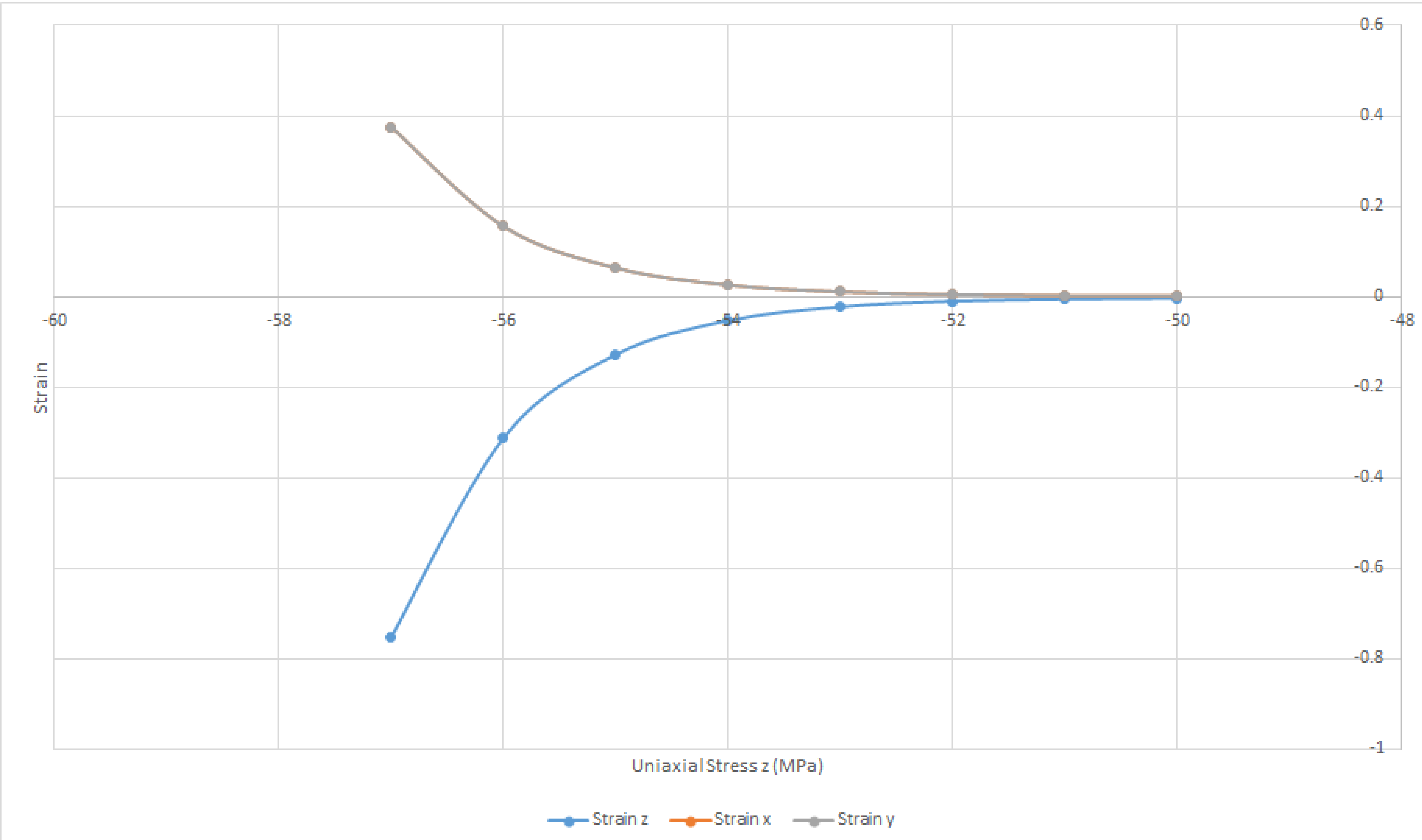




What happens when we press forge a mild steel cube that is above recrystallization temperature with

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



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

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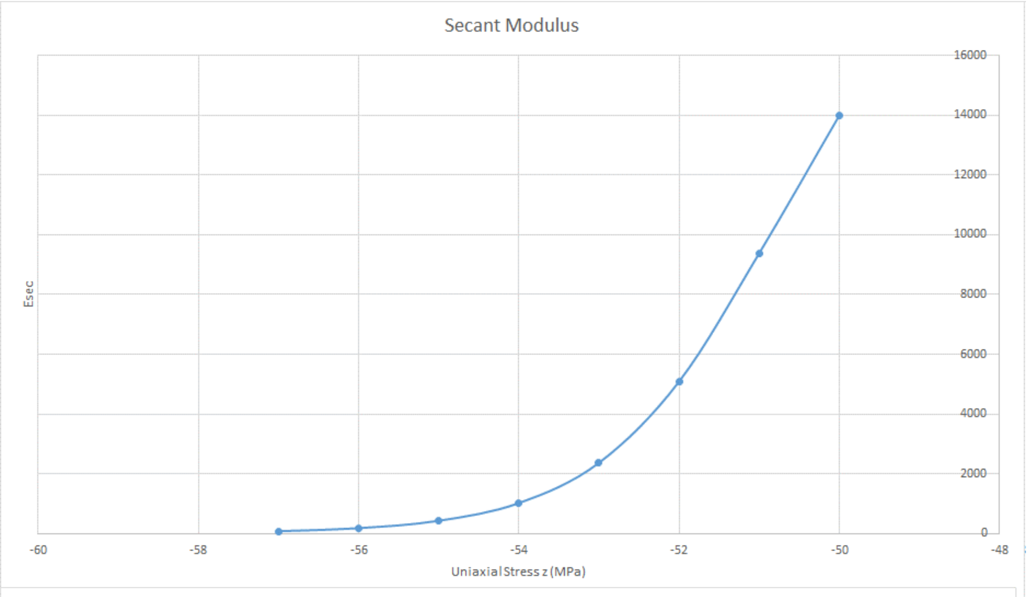

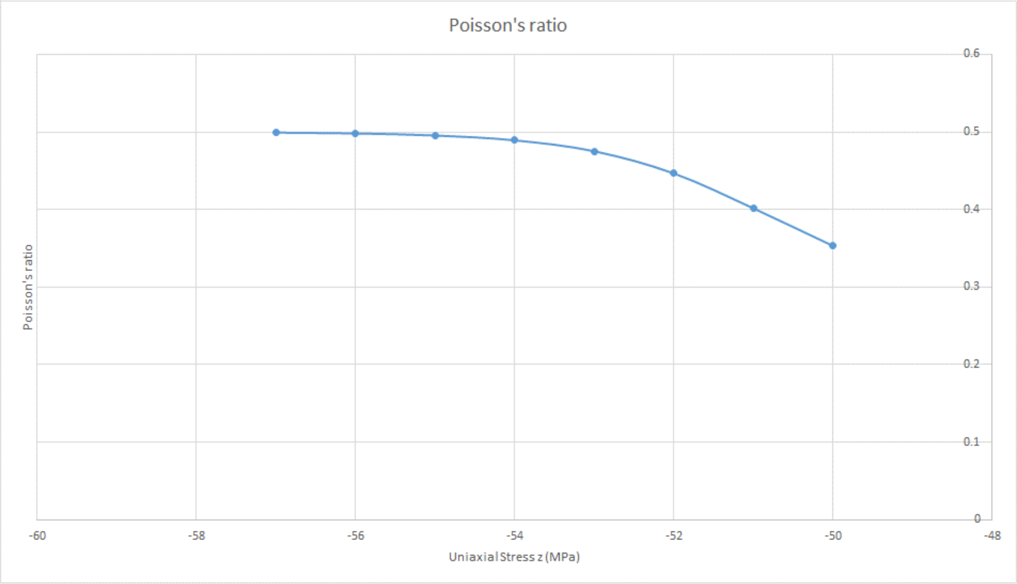

What happens when we press forge a mild steel cube that is above recrystallization temperature with

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