

Plasticity and Deformation Process

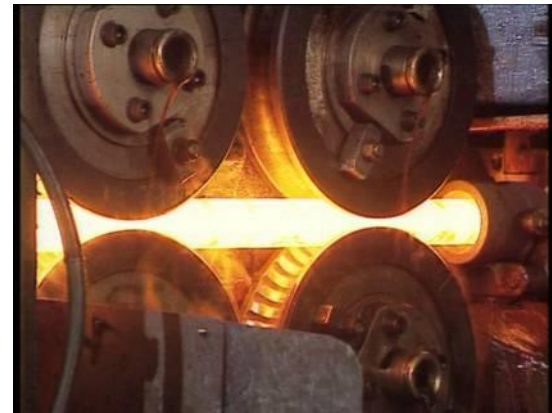
Deformation Processes

Rolling

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
- Hot 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

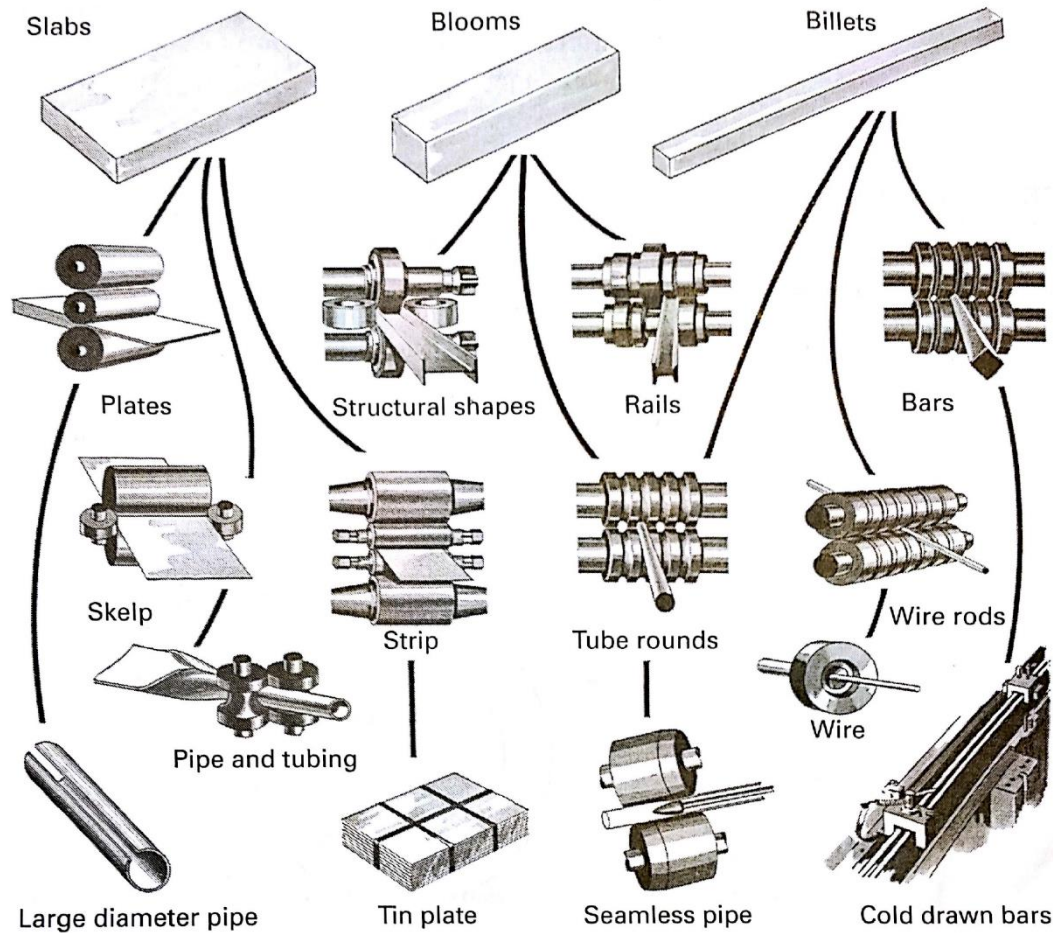
Sheet forming operations involve the deformation of a material where the thickness and surface area remain relatively constant

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

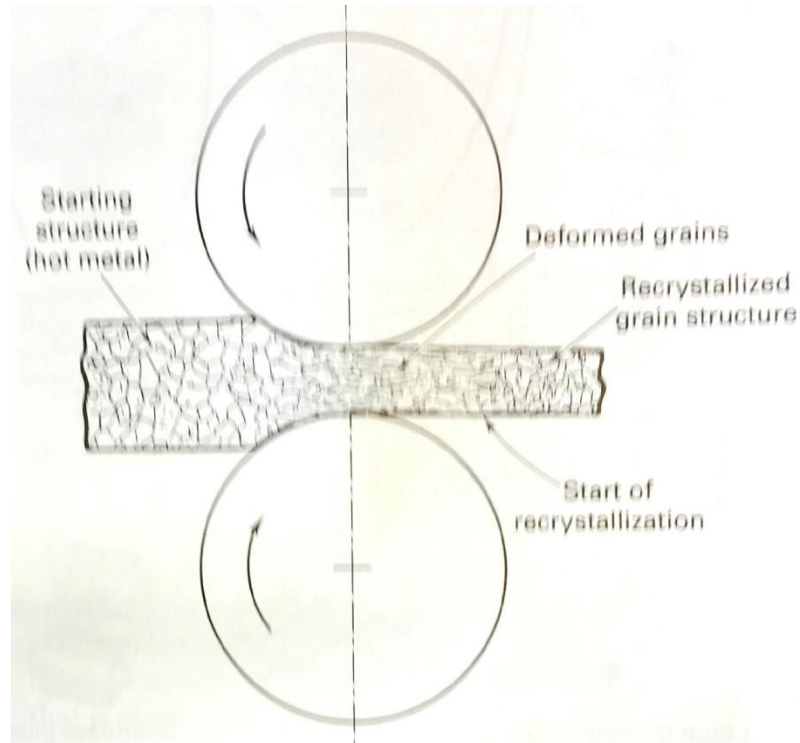


Hot rolling is used the most to shape metals

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

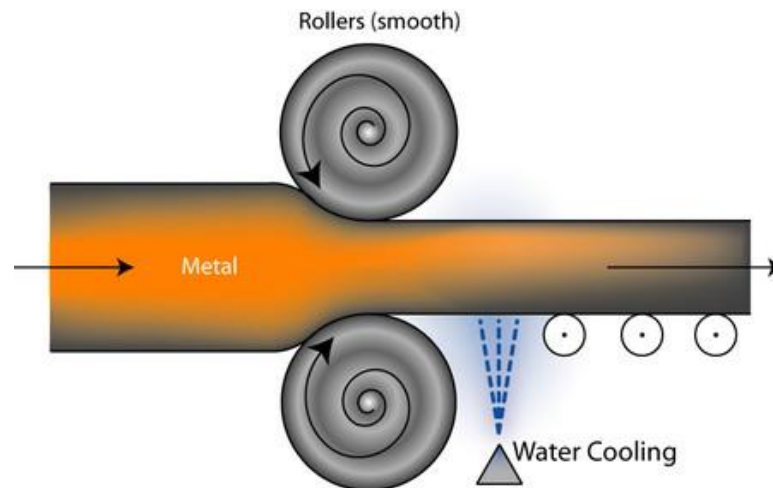
If the soaking time is insufficient, the hotter exterior will flow in preference to the cooler, stronger interior

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

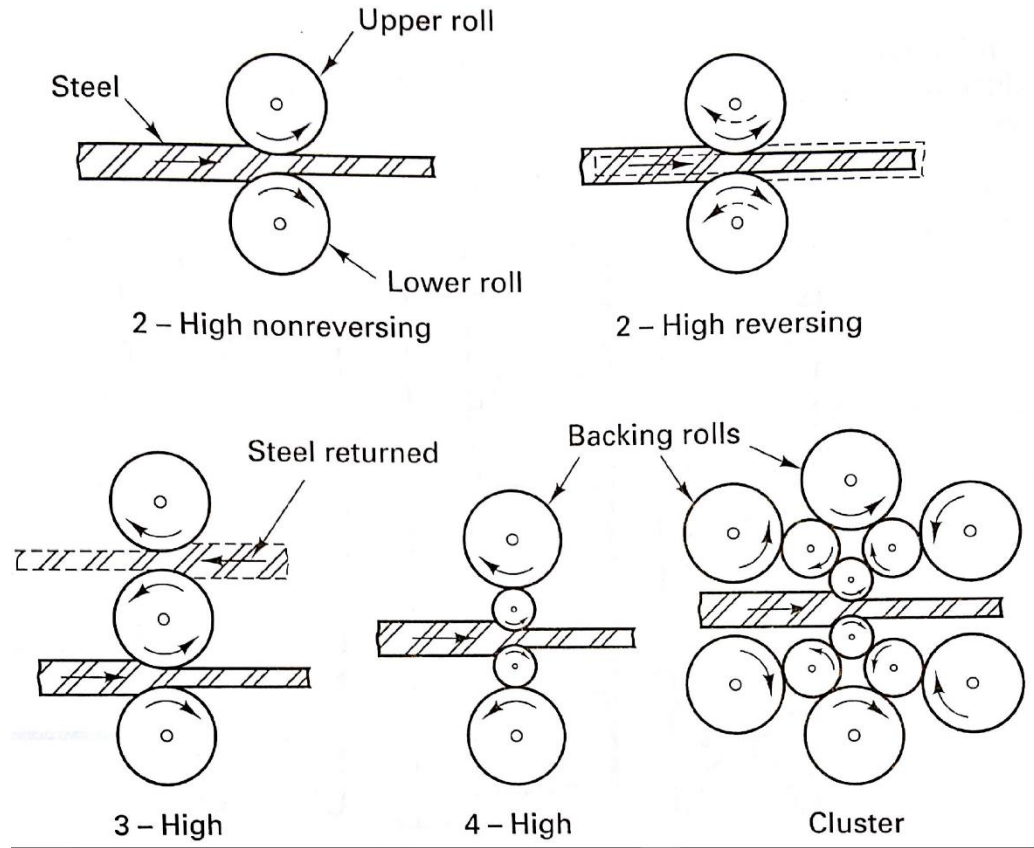
For smaller operations or secondary processing, the starting material is often a room temperature solid such as an ingot, slab or bloom

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

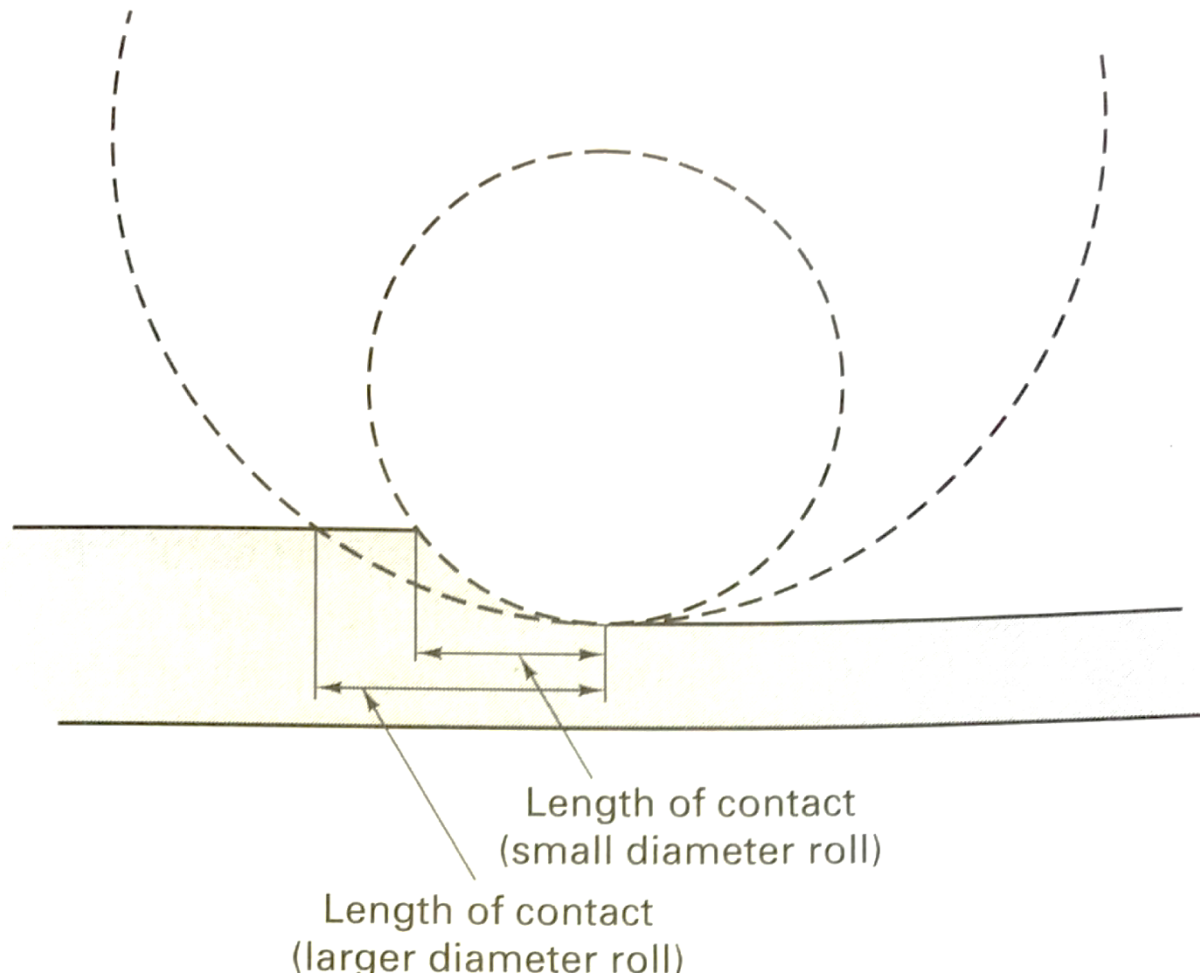


Four-high and cluster arrangements use backup rollers to support the smaller ones to produce wide plate and sheets where small deflections in the roller are not tolerated

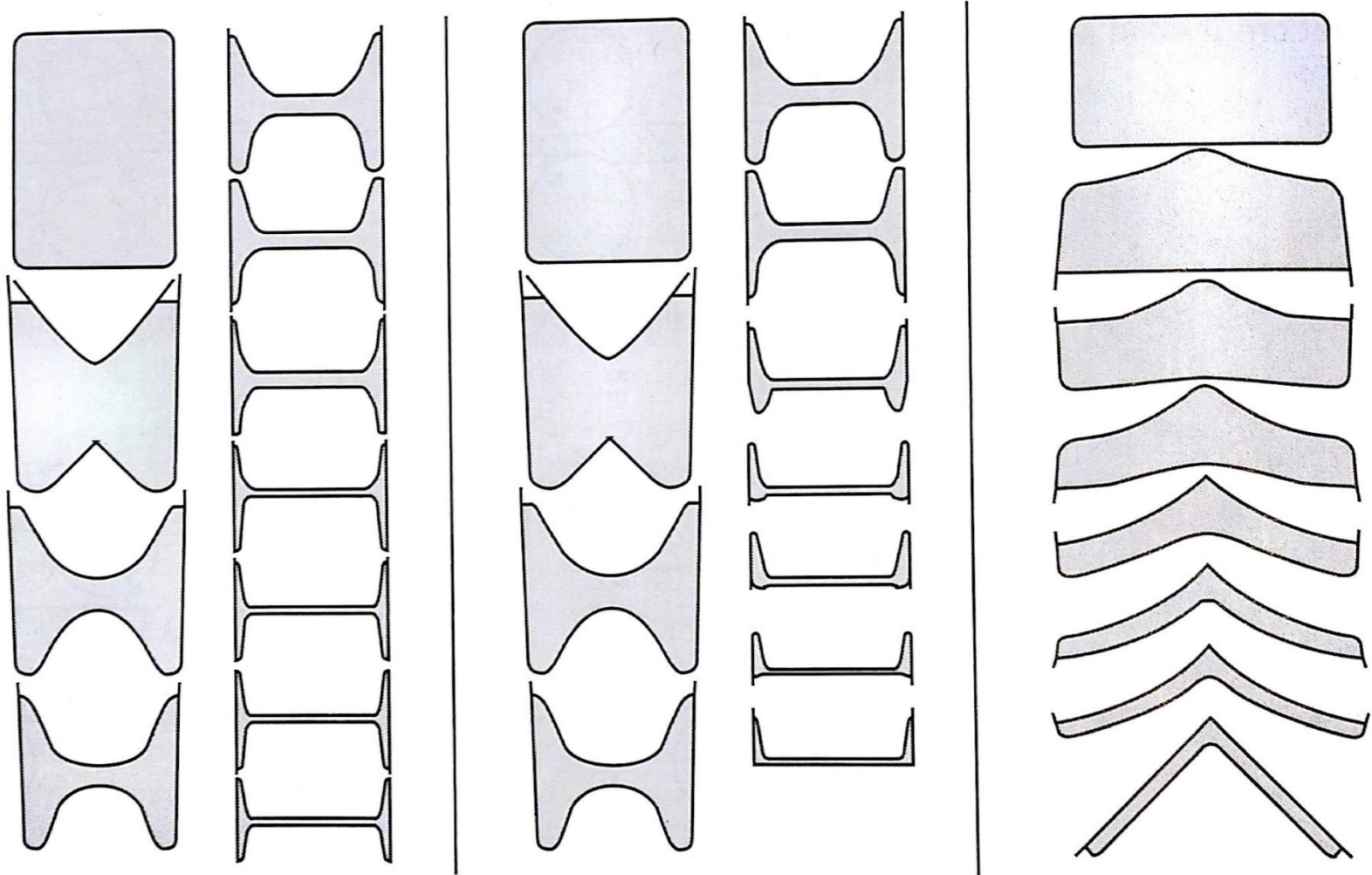
Foil is always rolled on cluster mills since small thickness requires small diameter rolls
The small rollers can have diameters as low as 6mm

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

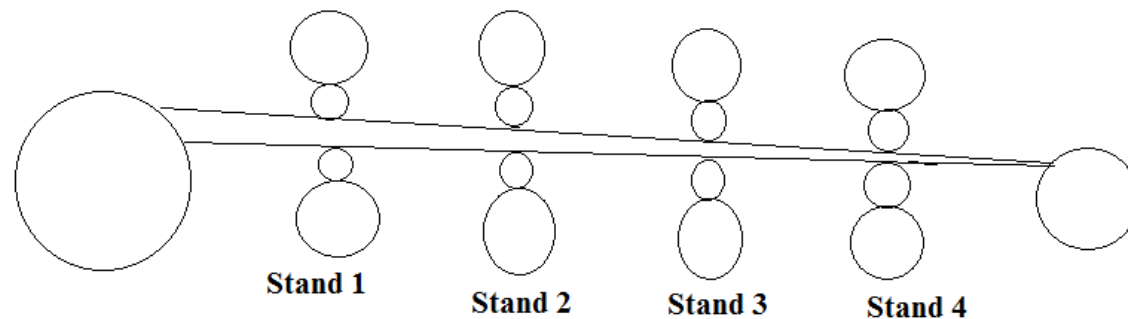
In continuous rolling, billets, blooms or slabs are heated and fed through an integrated series of nonreversing rolling mill stands

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

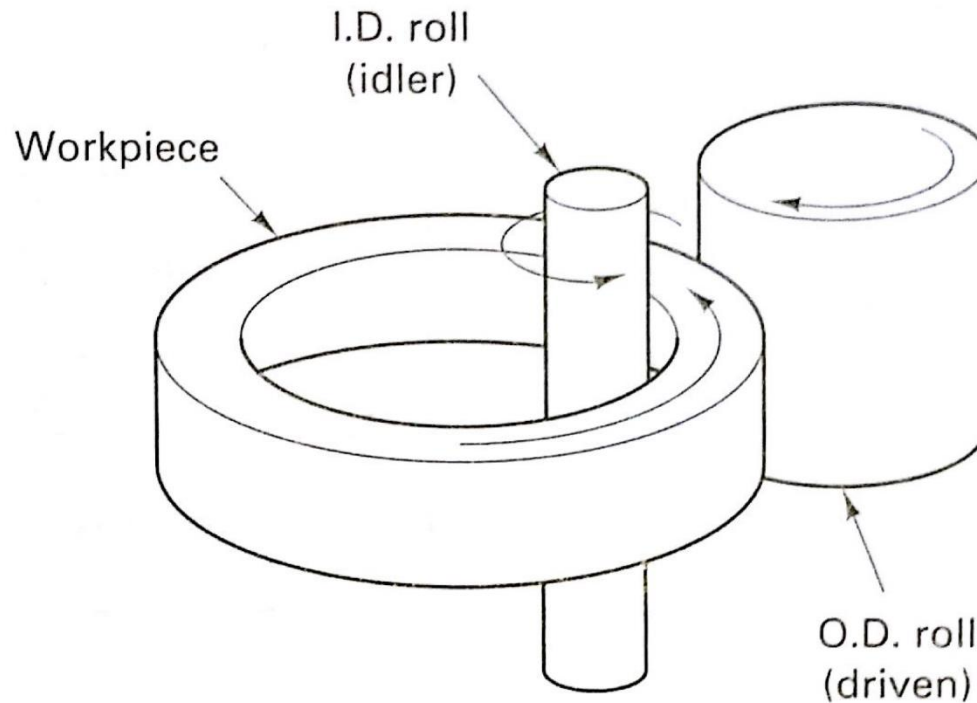
Therefore as a material is reduced in size, the rollers of each successive stand must turn faster than the previous one.

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



Continuous 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

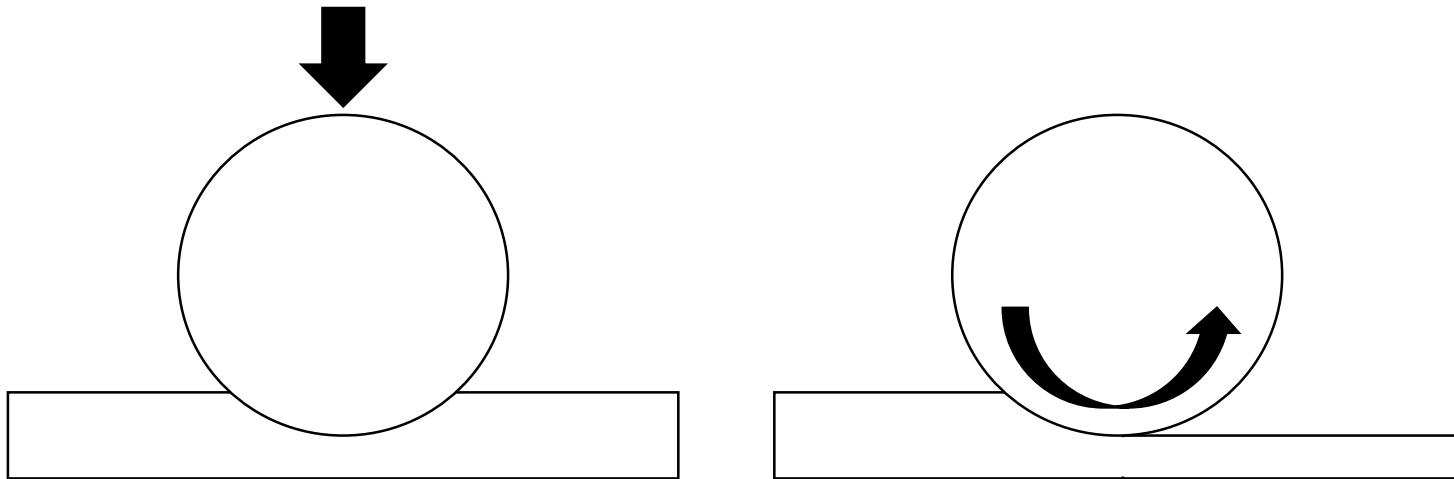
Consider rolling of an aluminum slab of dimensions $10 \times 1 \times 0.2$ m at room temperature. It is being reduced in thickness by a roller in a sheet forming process

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:

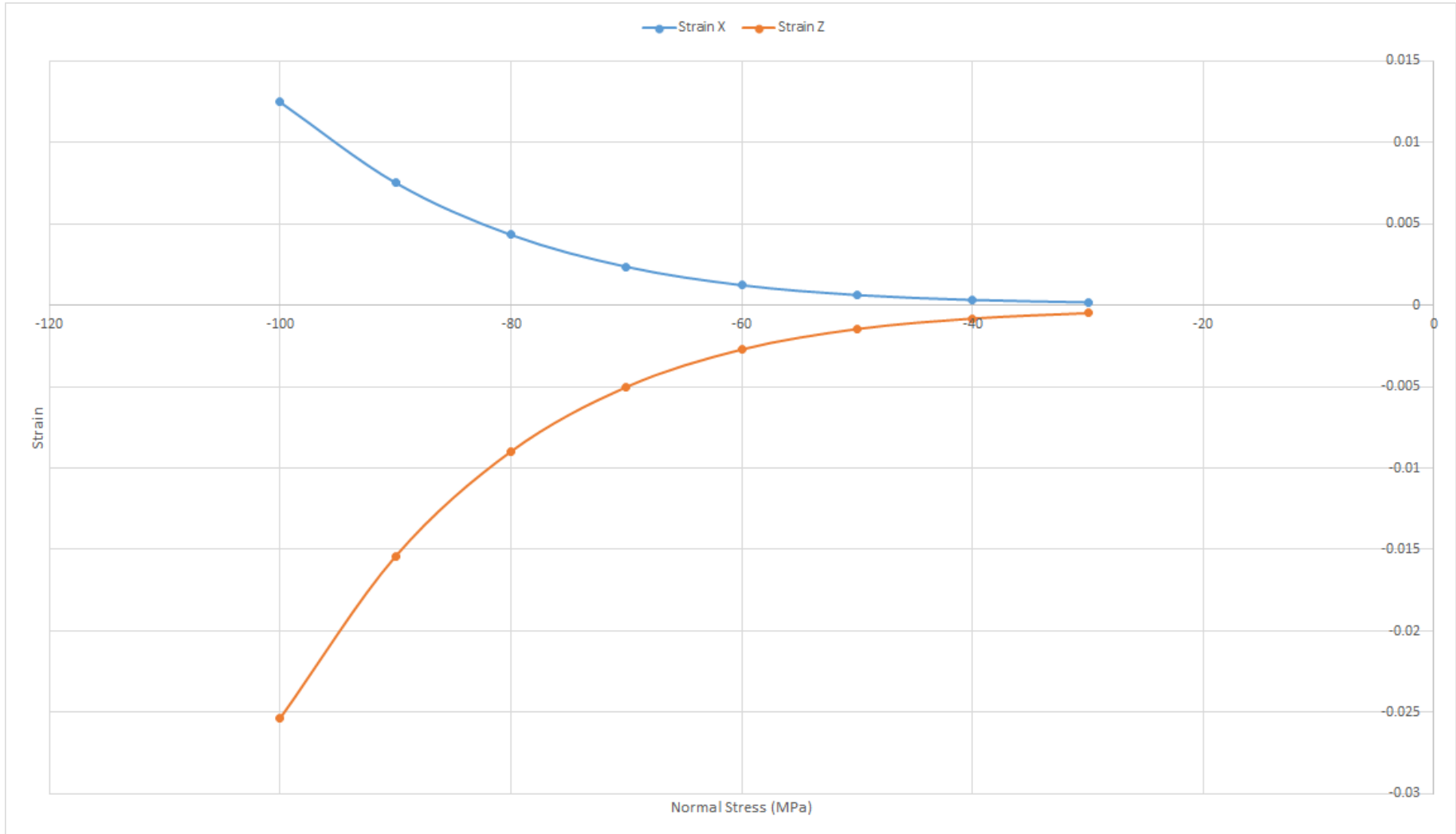
dipping (deformation by roller moving in the z direction) and rolling (deformation by stationary roller rotating at an angular velocity)



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

$$\sigma_Y = 30 \text{ MPa}, \quad \varepsilon_Y = 0.000429, \quad E = 70 \text{ GPa}, \quad \nu = 0.35, \quad UTS \approx 100 \text{ MPa}$$

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



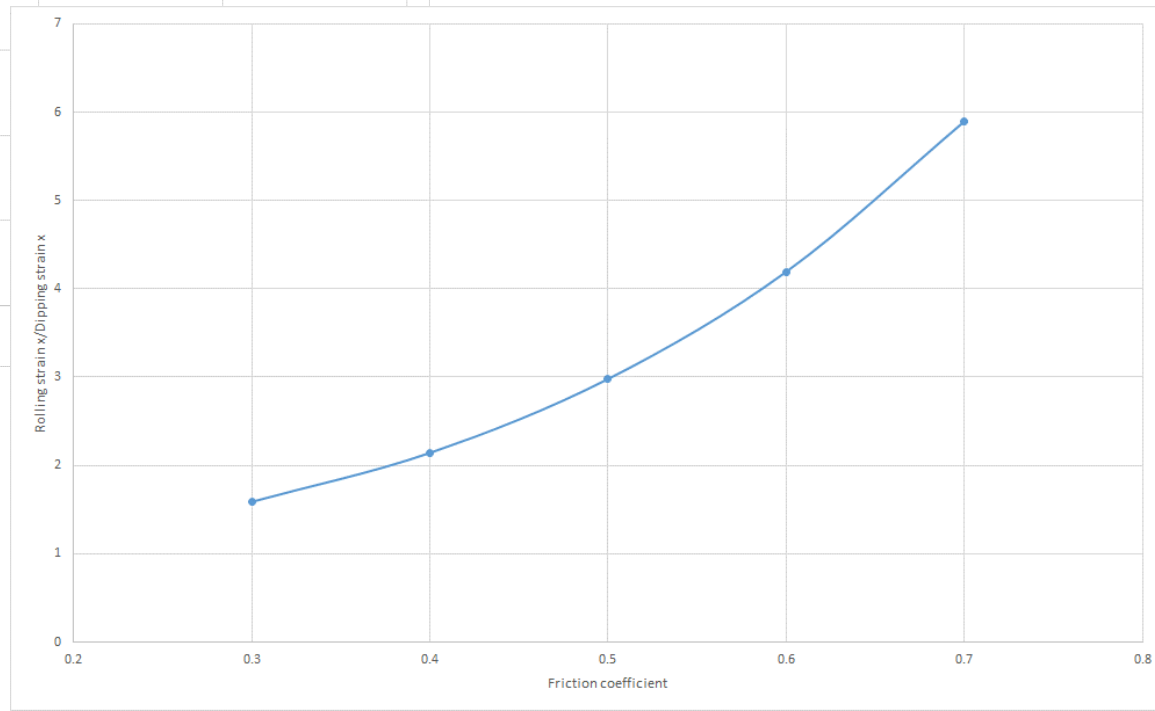
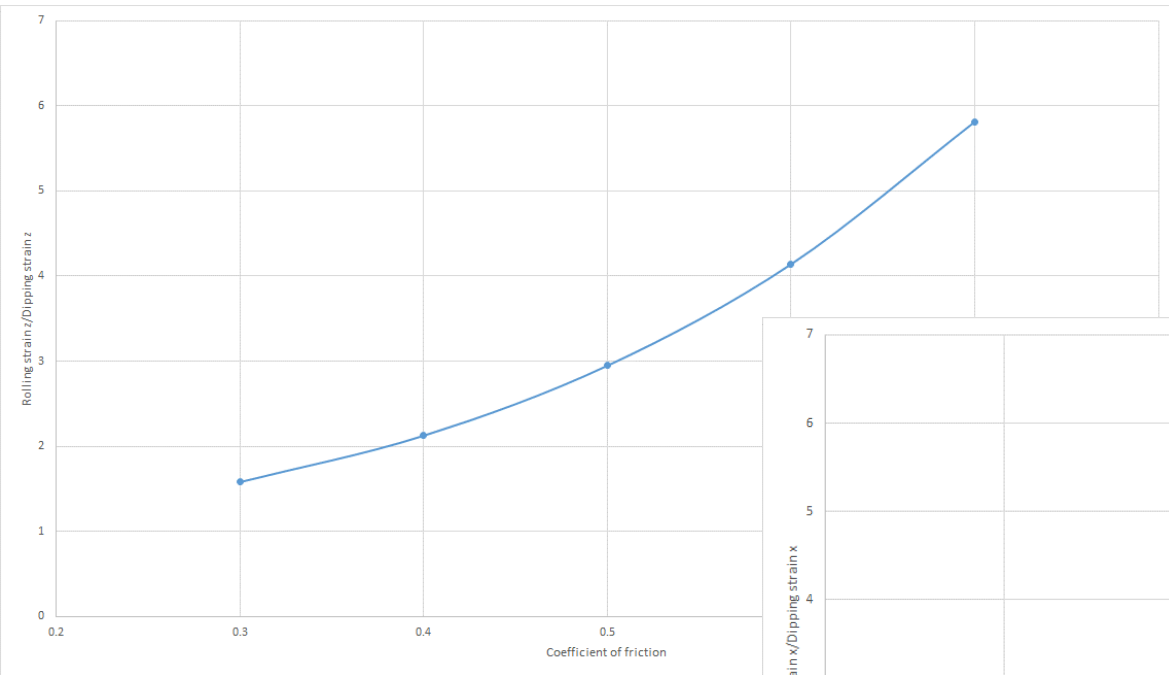
The deformation process aims to reduce the thickness by 25%, a strain of -0.25
It is apparent that the material is not ductile enough at room temperature

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

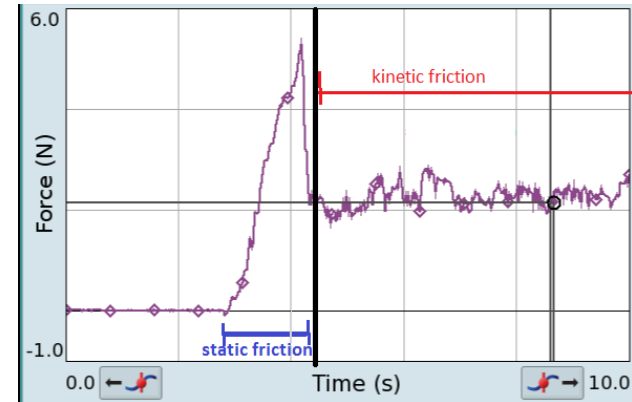
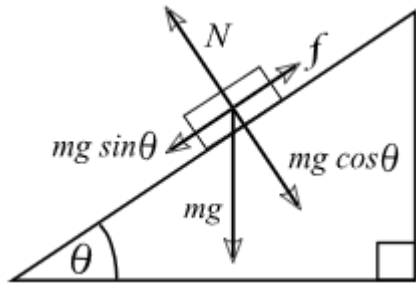
The total strain is equal to thickness final/thickness initial

Dipping will result in less strain when considered alone

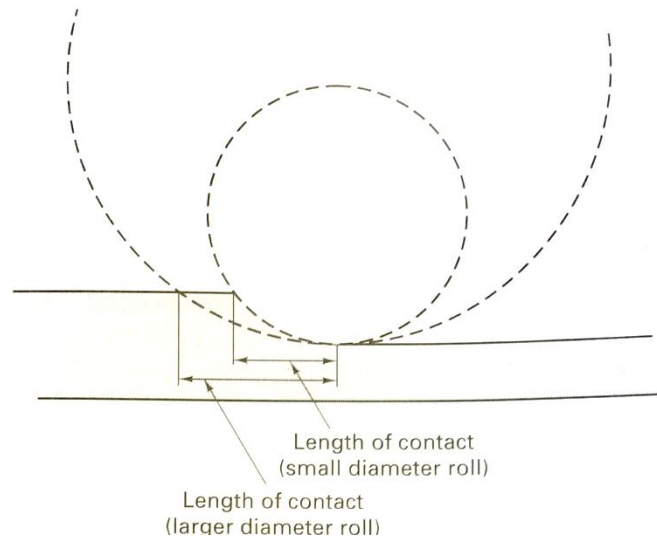
When rotation is applied to dipping roller, both strains and deformation increase because of the shearing force as a result of friction between roller and metal



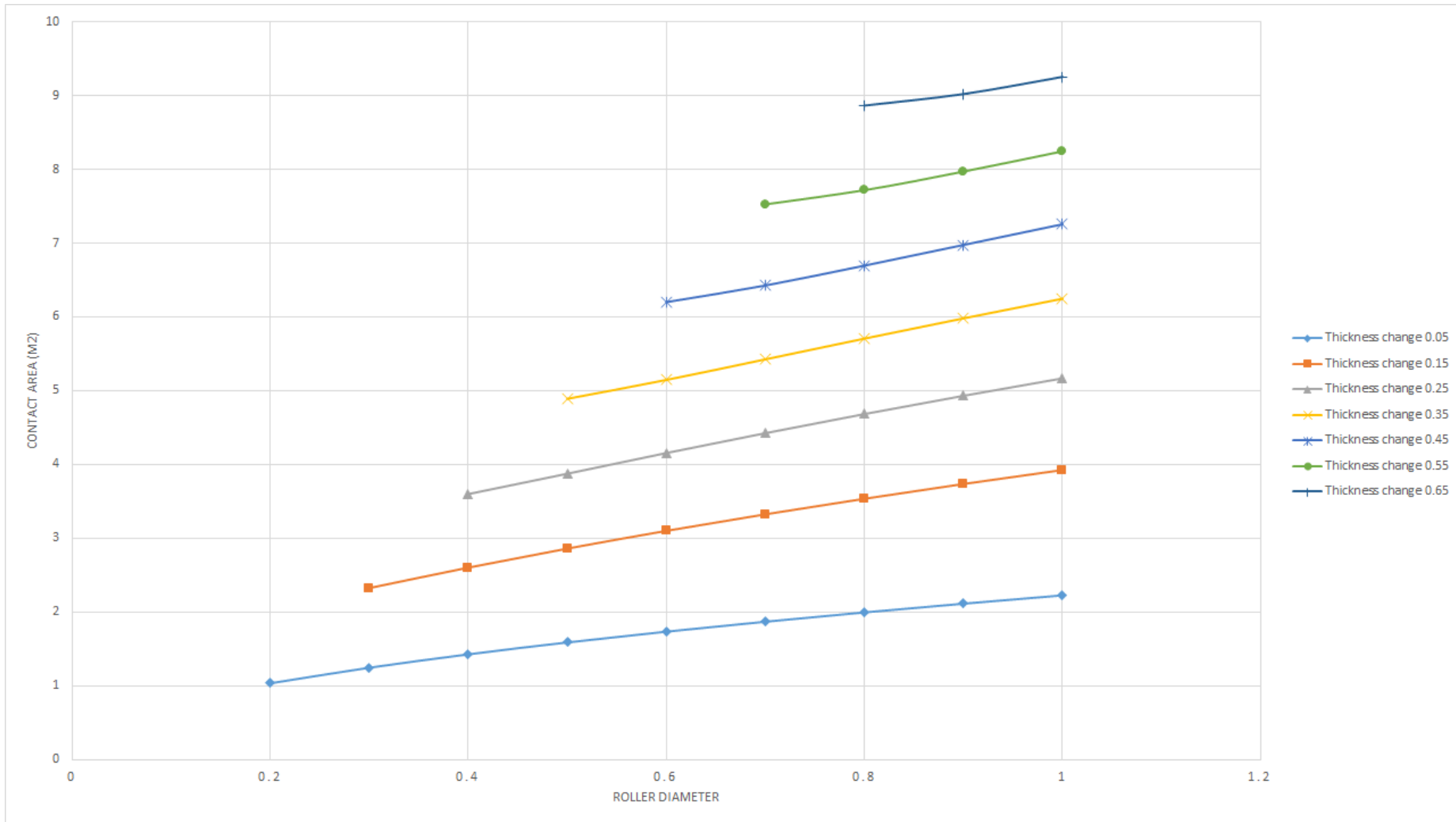
Rotation applied during rolling stage shears the material due to frictional force resulting from the normal force that exists in the material due to dipping



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



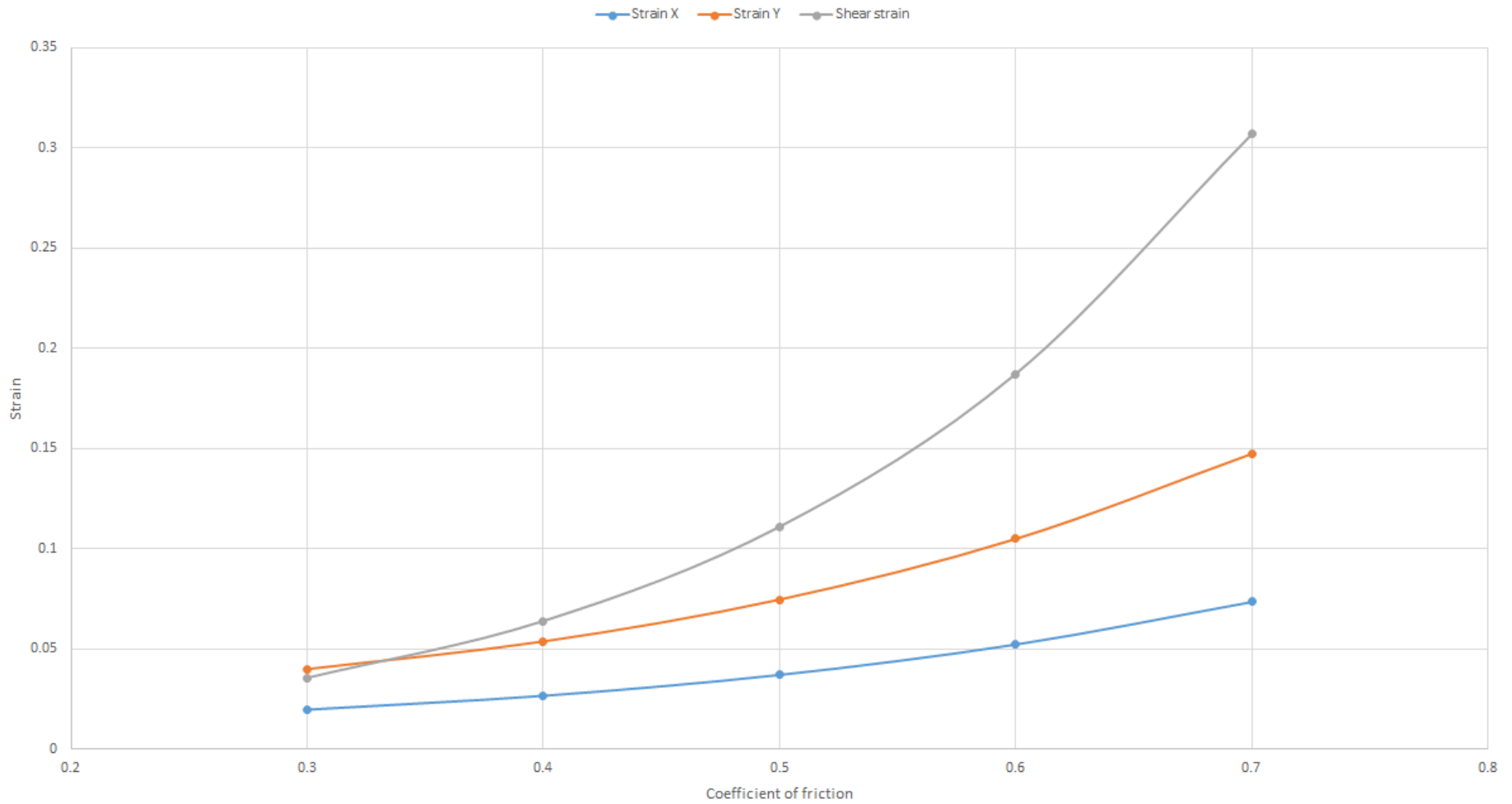
Contact area is proportional to the roller diameter and the reduction in slab thickness



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

The contact area affects the applied normal stress

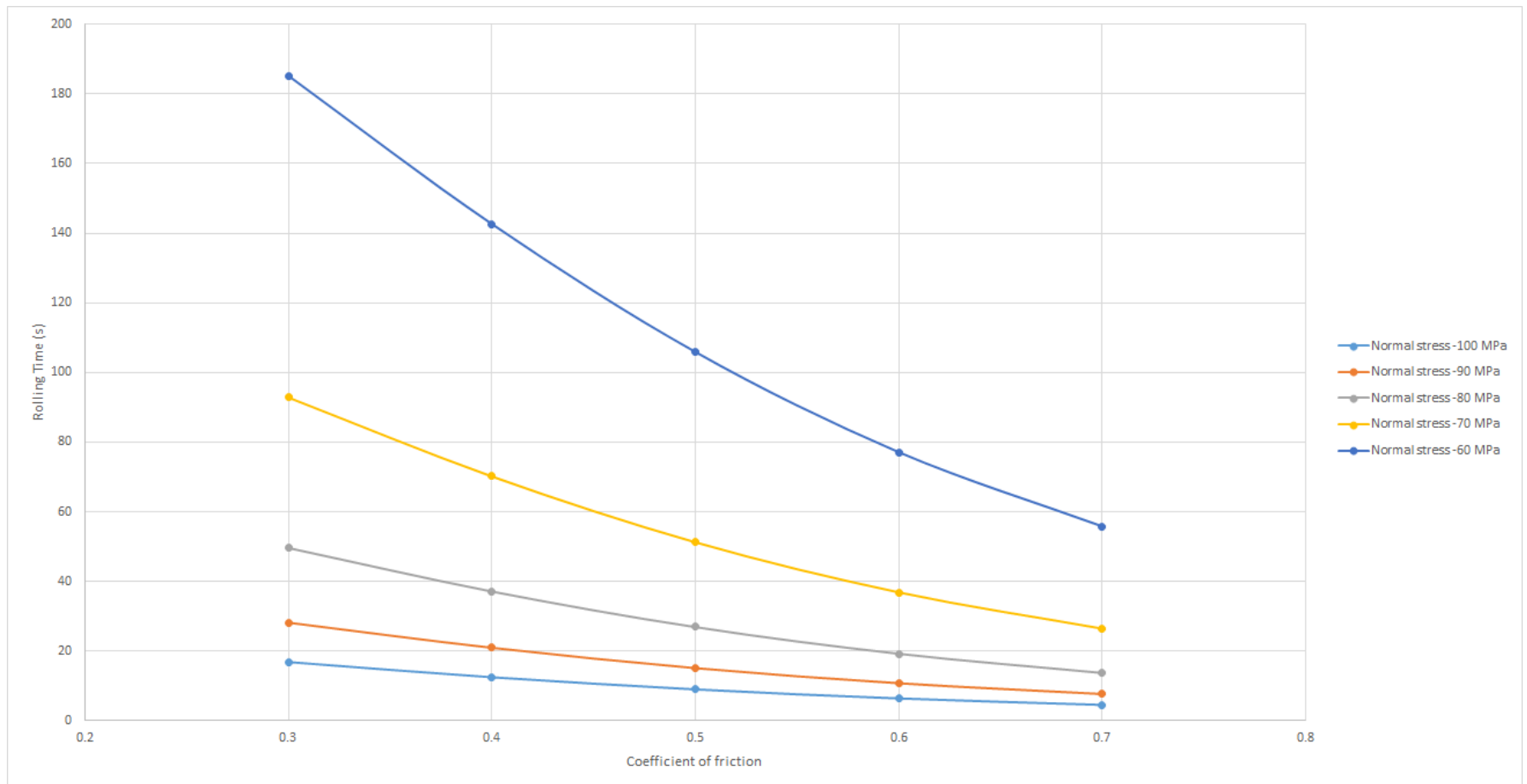
Both contact area and coefficient of friction between the roller and metal affect the applied shear stress



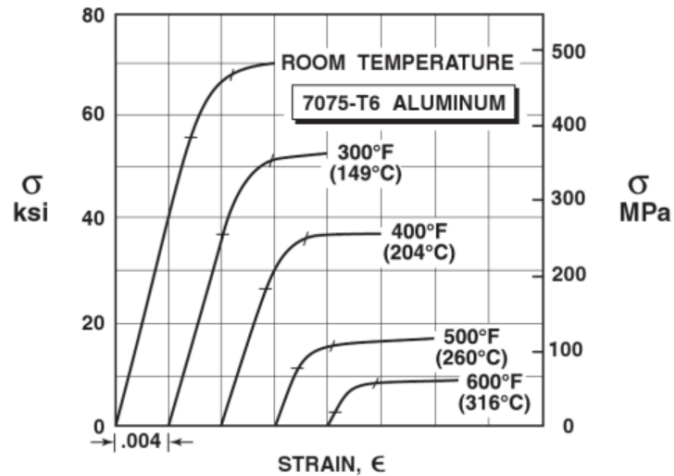
Rolling deforms the metal by shear stress and also moves it in the x direction as a result of the elongation

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 $60^\circ/s$

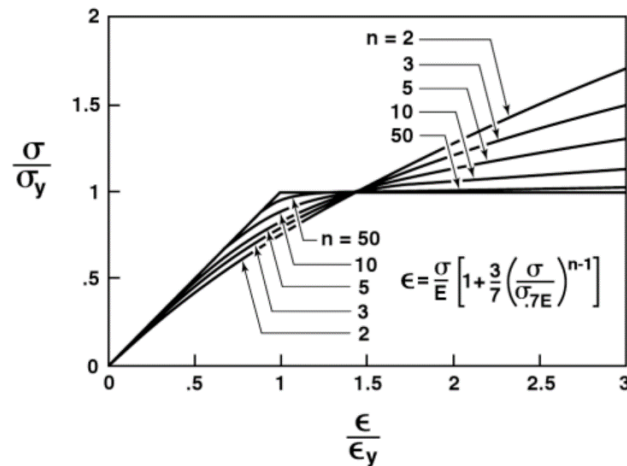


To achieve the desired reduction in thickness by rolling, metal should be heated above their recrystallization temperature to enable flowability and avoid strain hardening

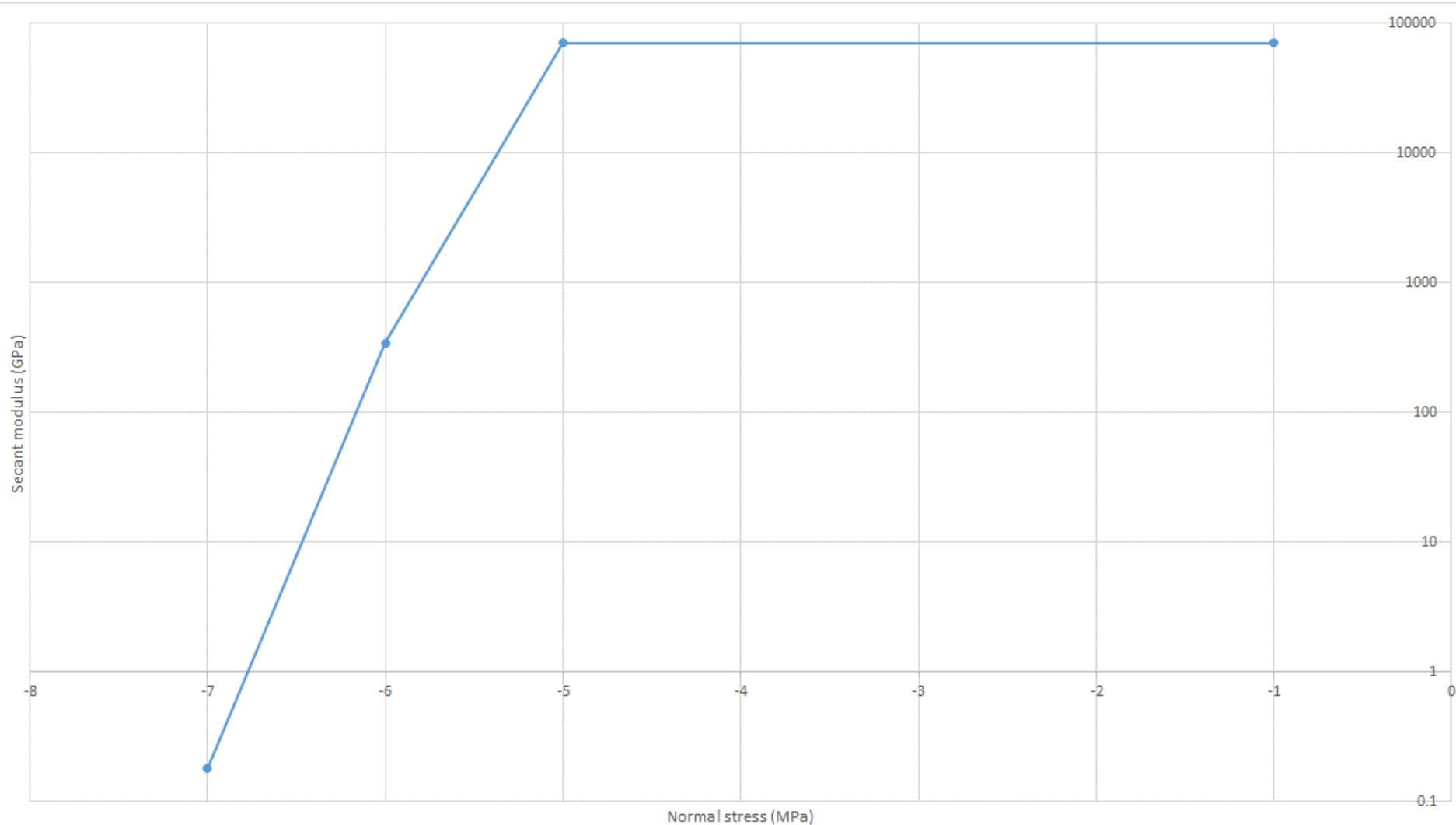


Compressive Stress-Strain Curves for 7075-T6 Aluminum as a Function of Temperature (After Mathauser and Brooks)

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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