Plasticity and Deformation Process

Effect of temperature on

plastic deformation processes

Metal forming operations are limited to stresses that are within the necking region of large plastic deformation so as to avoid fracture of a part during forming

Mild steel, aluminum and other metals with non-linear stress-strain curves are used commonly in metal forming operations

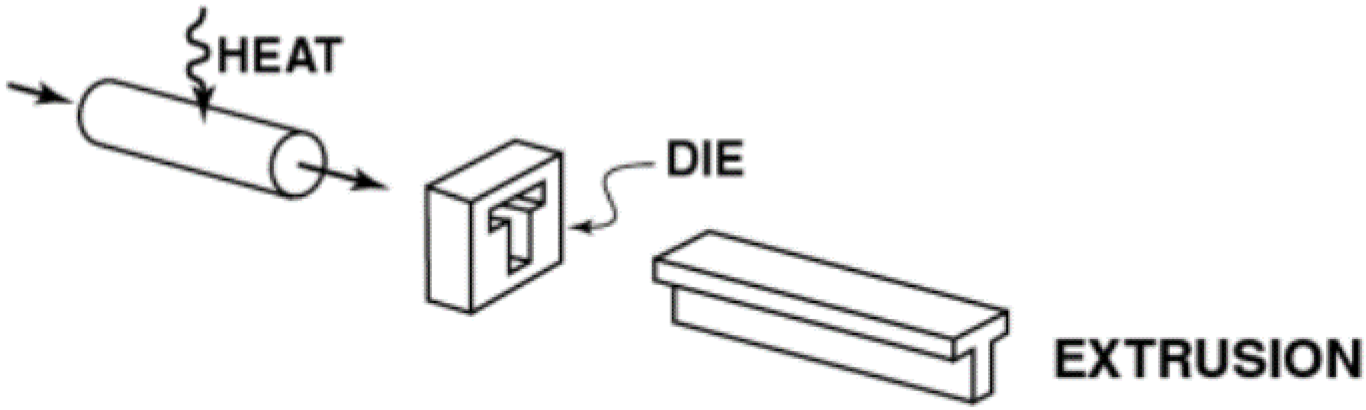
The non-linear stress-strain characteristics of most engineering metals are utilized because of the large deformations in metal forming operations

Heat is often applied to make the material more easily deformed

Heat is also generated during large deformations like bending a strip of aluminum back and forth

Extrusion: Heat is applied to an objet of some size and shape so that it can pass through a die of a different size and shape.

The material is pushed through the die and comes out of the die in the shape of the die.

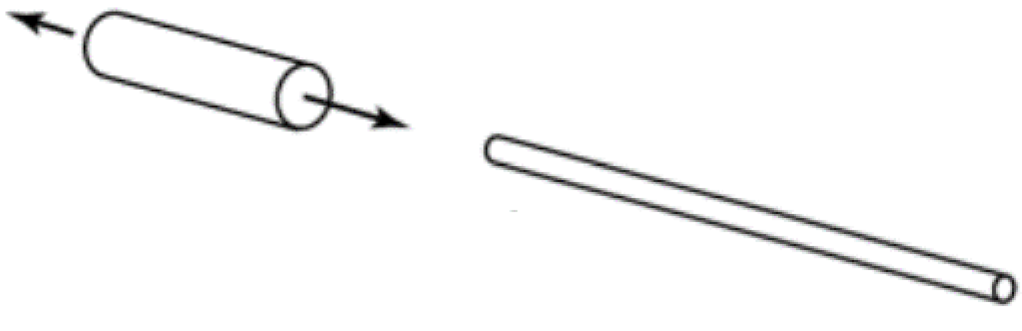


A succession of dies that sequentially approach the desired cross-sectional shape are sometimes used

The process involves a lot of plastic deformation so that the material can drastically change its shape as it goes from one side of the die to the other.

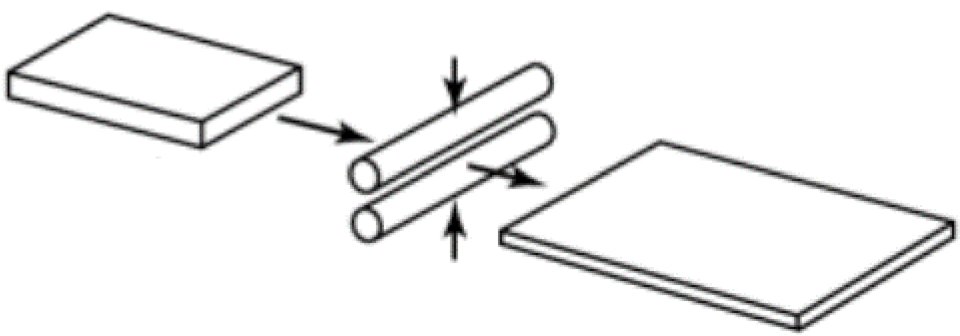
Metal is stretched in wire drawing so that its cross sectional area is reduced to a wire drastically

The main difference between drawing and extrusion is that drawing involves pulling and extrusion ivolves pushing of the material



WIRE DRAWING

A piece of material is passed repeatedly back and forth through rollers in rolling.
The rollers come increasingly closer to one another as time passes until a very wide and long sheet of material is formed
Not only flat sheets but various structural shapes like I-beams and angles channel cross sections are rolled

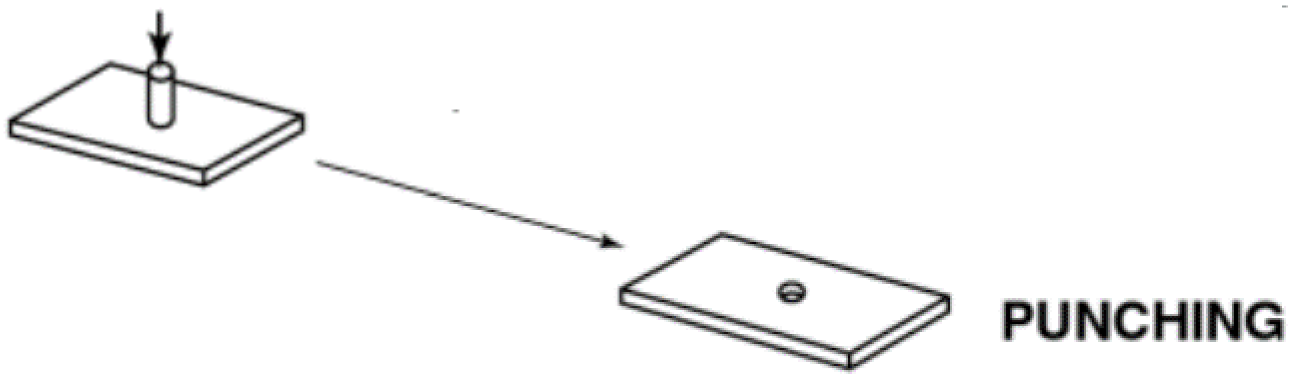


ROLLING

In punching operations, a very hard punch is forced through a softer material to push a piece of the material out the other side

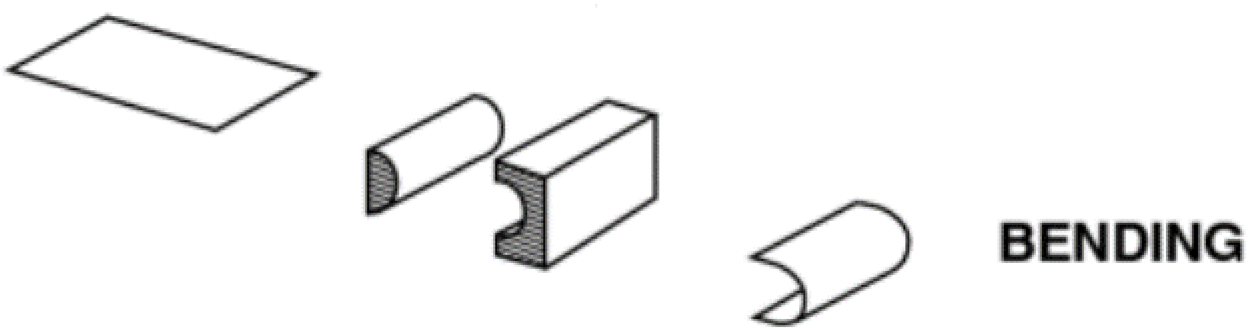
The stresses must go very high on the stress-strain curve locally to cause the material to shear off in the punching direction

In such operations that cause the material to go very far into the plastic region, the elastic deformation may not be considered because it is small compared to the inelastic deformation



A sheet of metal is forced between a male and a female die in forging

Die pressing processes like forging and bending cause large plastic deformations



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

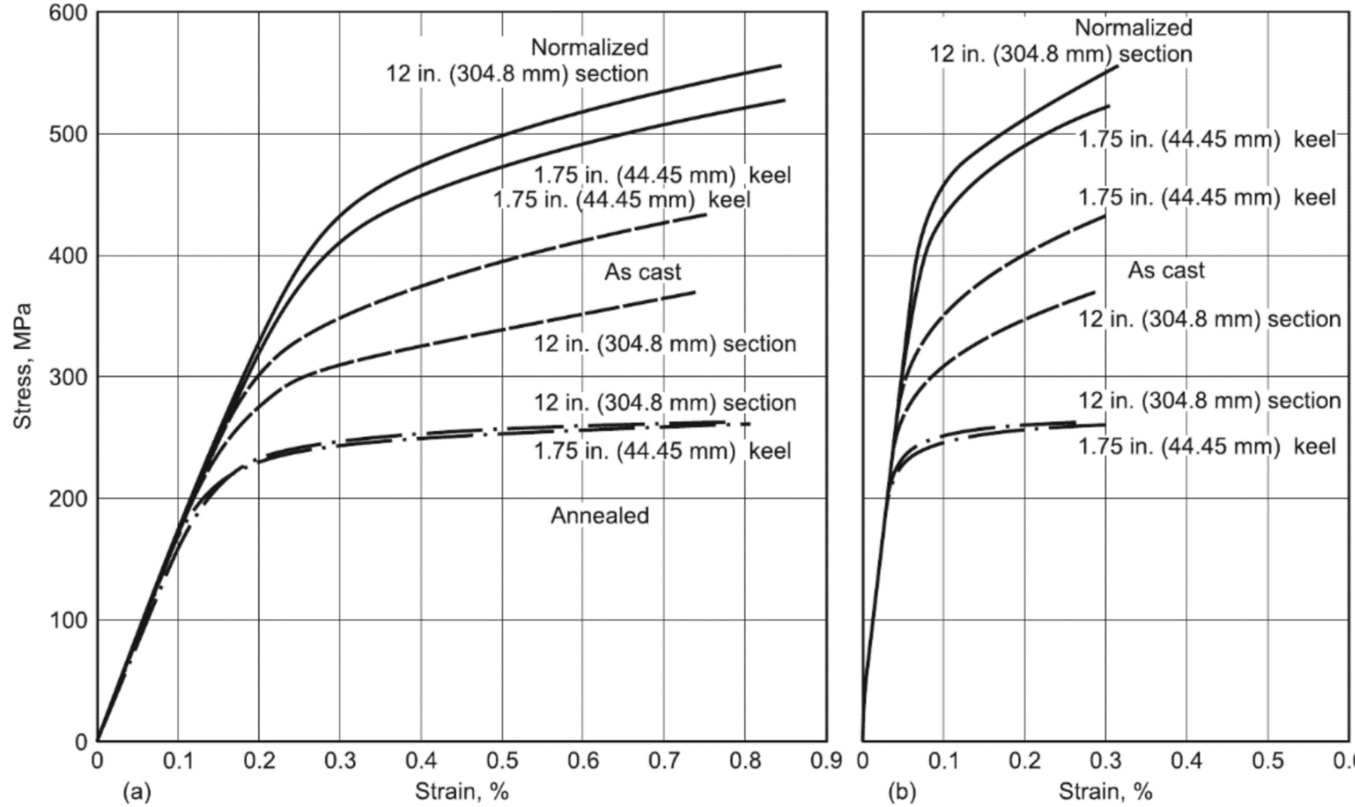
- The elevated temperatures promote diffusion that can remove or reduce chemical inhomogenities, close the pores or reduce their size

- 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

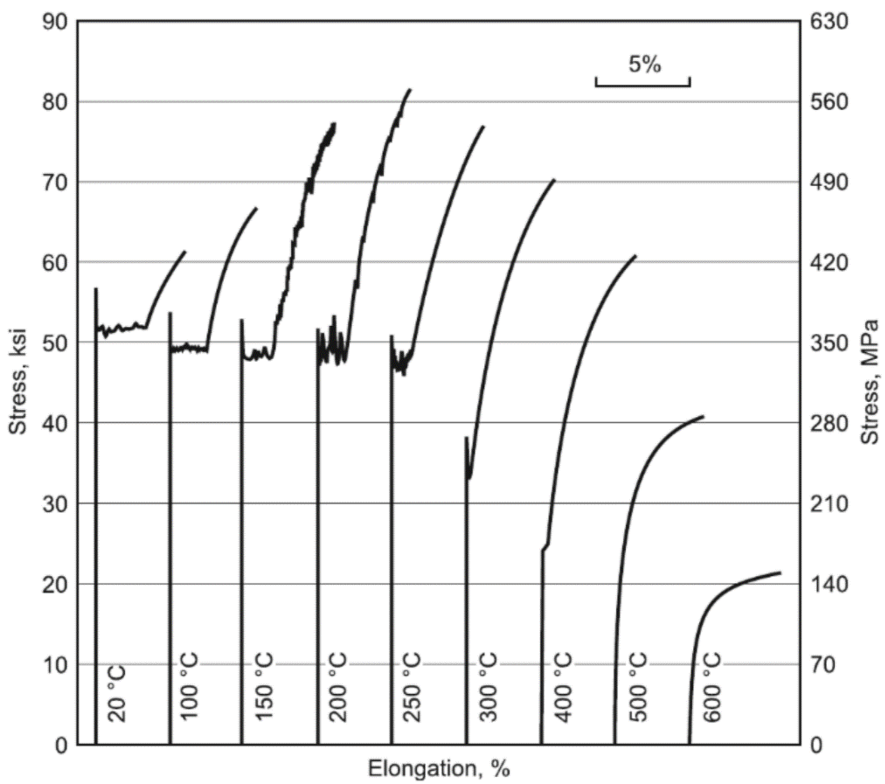
- The metallurgical structure may be nonuniform since the final grain size depends on the amount of deformation, temperature at last deformation, and cooling history after the deformation all of which may vary throughout a workpiece



CI.031 Recarburized steel ductile casting, longitudinal tensile stress-total strain curves (a) with lateral contraction (b)

Comparison is made between 44.45 mm (1.75 in.) keel test blocks and 304.8 mm diam × 50.8 mm (12 in. diam × 2 in.) castings; 50.8 mm (2 in.) square test specimens cut from the latter. As-cast pearlitic nodular iron, normalized pearlitic, and annealed ferritic nodular iron are shown for each size. Composition: Fe-3.52C-1.76Si-0.29Mn-0.026S-0.020P-0.92Ni-0.062Mg

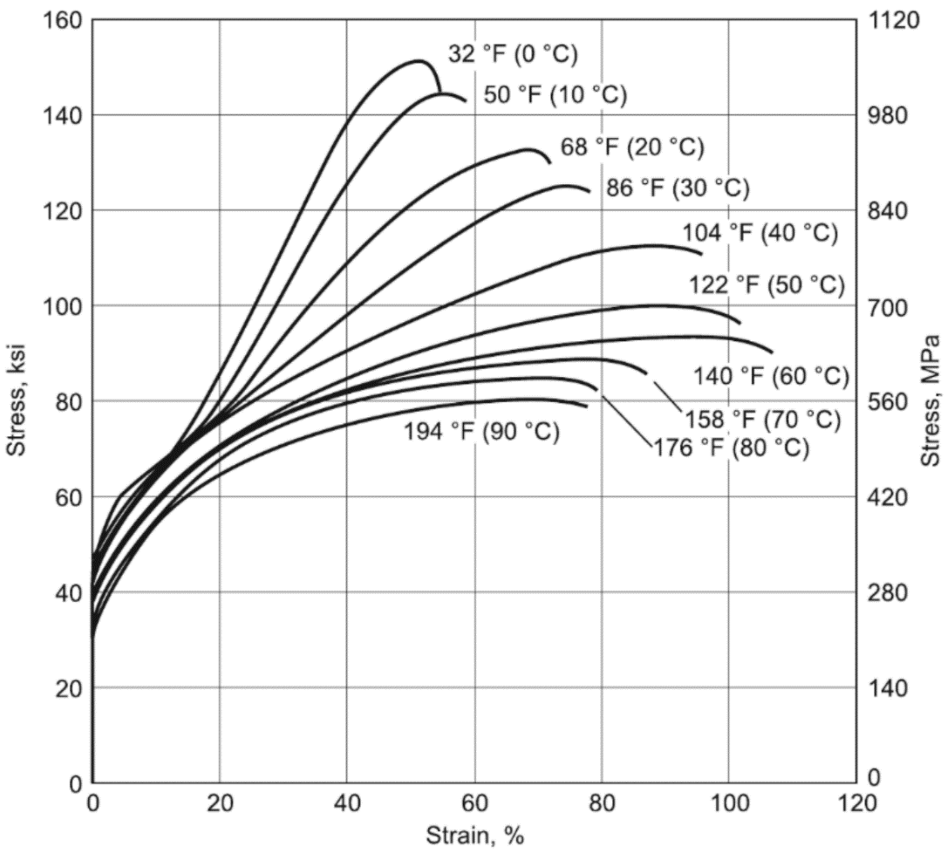
Source: G.N.J. Gilbert, The Effect of Section Size on the Stress-Strain Properties of Nodular Cast Iron, *BCIRA J.,* Vol 12 (No. 6), Nov 1964, p 766



CS.012 1020 carbon steel, tensile stress-elongation curves at room and elevated temperatures

Strain rate = 0.000175/s. Composition: Fe-0.20C. UNS G10200

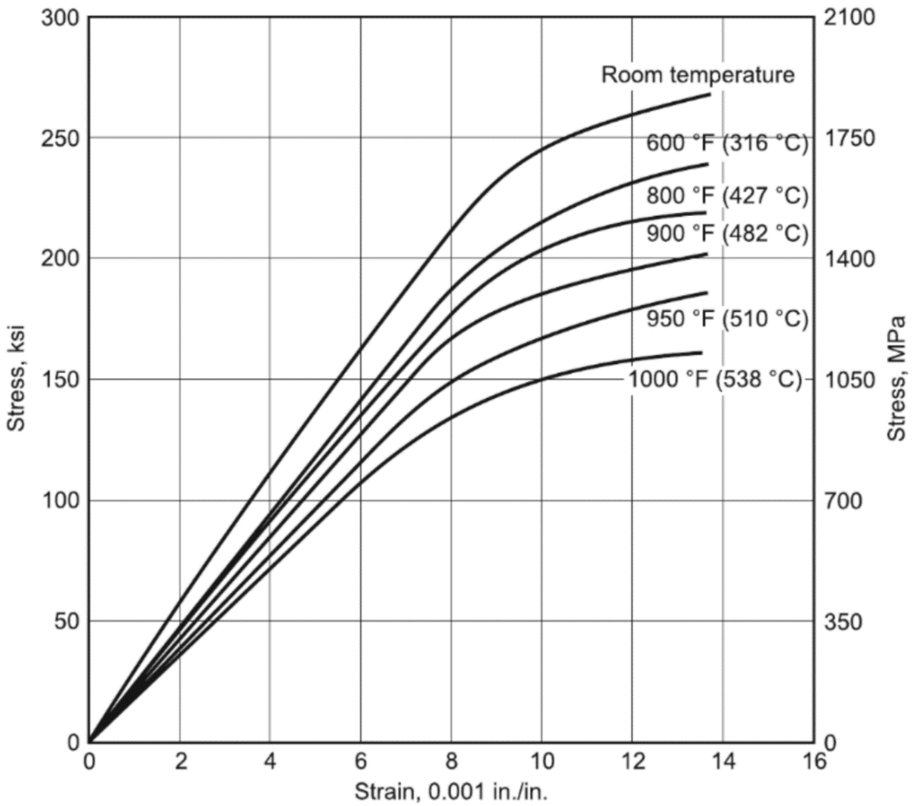
Source: W.C. Leslie, *The Physical Metallurgy of Metals,* McGraw-Hill and Hemisphere Publishing, 1981, p 92



SS.029 301 annealed stainless steel sheet, stress-strain curves at various temperatures

Test direction: transverse. Sheet thickness = 0.508 mm (0.020 in.). Specimen size = 5.08 × 30.48 mm (0.20 × 1.20 in.). Strain rate = 0.062/min. Annealed 600 °C (1112 °F), 30 min, grain size = 34 μm. Composition: Fe-18Cr-8Ni. UNS S30100

Source: A. Rosen, R. Jago, and T. Kjer, Tensile Properties of Metastable Stainless Steels, *J. Mater. Sci.,* Vol 7, 1972, p 870–876. As published in *Aerospace Structural Metals Handbook,* Vol 2, Code 1301, CINDAS/USAF CRDA Handbooks Operation, Purdue University, 1995, p 29



HS.031 18Ni (250) high-strength maraging steel bar, tensile stress-strain curves at room and elevated temperatures

Consumable vacuum arc remelted. Heat treatment: annealed 816 °C (1500 °F), 30 min, air cooled, aged 482 °C (900 °F), 3 h. Composition: Fe-18Ni-7.5Co-5Mo-Ti-Al

Source: "Vascomax 18 Percent Nickel Ultrahigh Strength Maraging Steels," VASCO, Latrobe, PA, 1966. As published in *Aerospace Structural Metals Handbook,* Vol 1, Code 1220, CINDAS/USAF CRDA Handbooks Operation, Purdue University, 1995, p 44

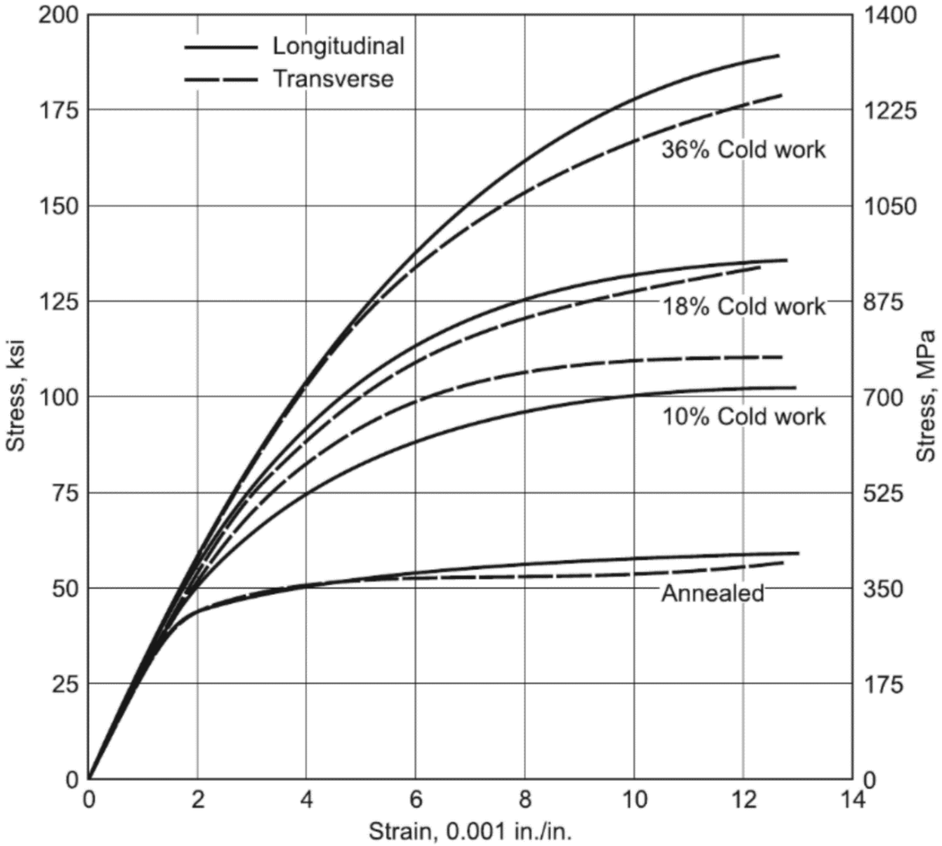
The plastic deformation of metals much below the recrystallization temperature is known as cold working
Cold working has a number of distinct advantages from a manufacturing point of view

- 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



SS.001 201 stainless steel, stress-strain curves showing effect of cold work

Test direction: longitudinal and transverse. Composition: Fe-17Cr-6.5Mn-4.5Ni. UNS S20100

Source: P.D. Harvey, *Engineering Properties of Steel,* American Society for Metals, 1982

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

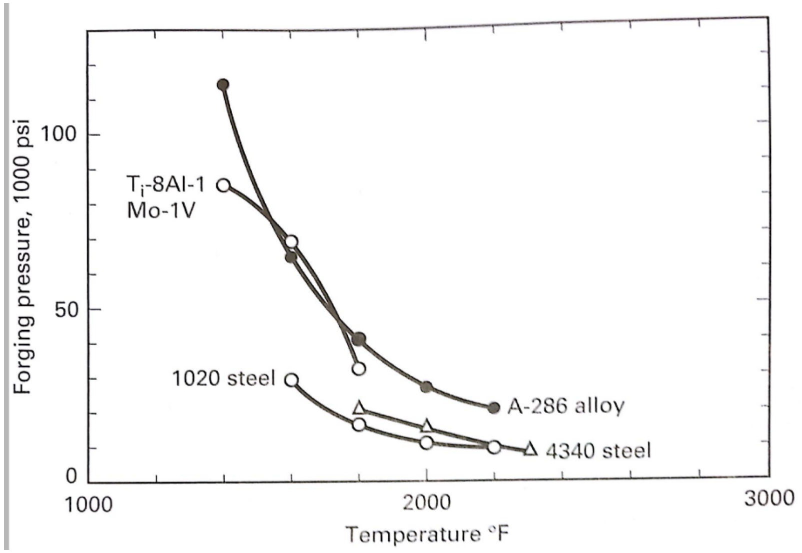
It has the following advantages compared to hot forming:

- 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

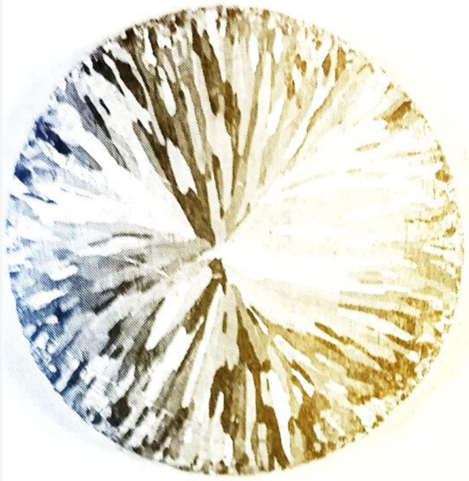
In addition deformation rates are slowed so that the heat generated by deformation is reduced and distributed uniformly over the product at constant temperature

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 structures 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

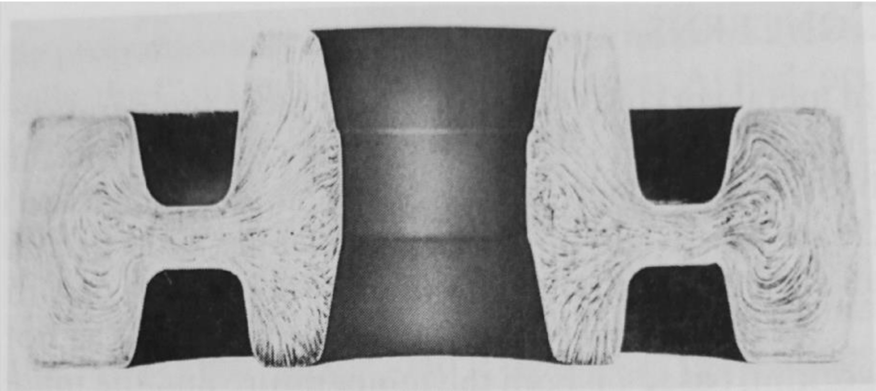
Small gas cavities or shrinkage porosity can form during solidification

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

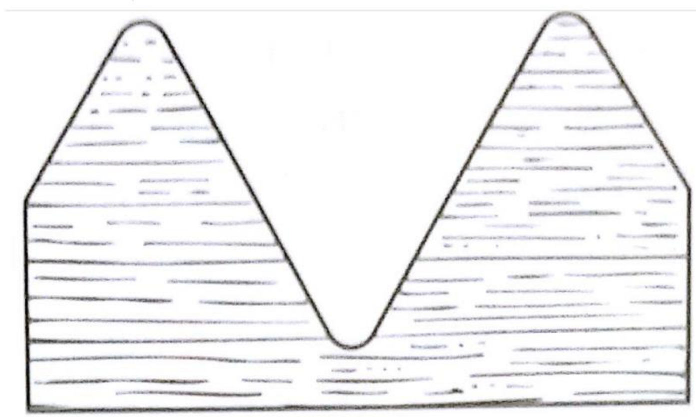
When a metal is plastically deformed, the impurities tend to flow along with the metal, or fracture into rows of fragments that are aligned in the direction of working

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



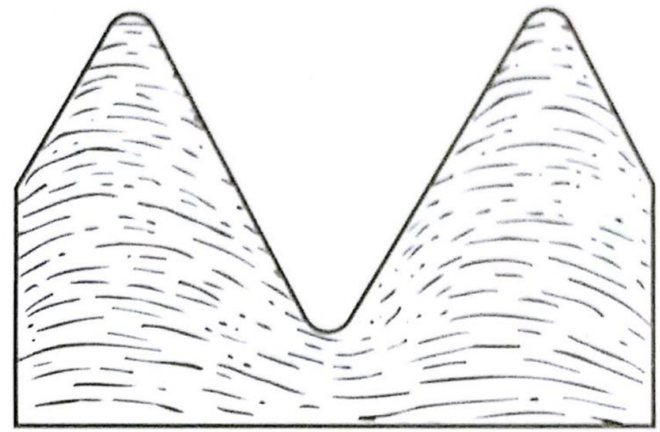
Through proper design of deformation the impurities can often be reoriented into a crack-arresting configuration where they are perpendicular to the direction of crack propagation

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 hot-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

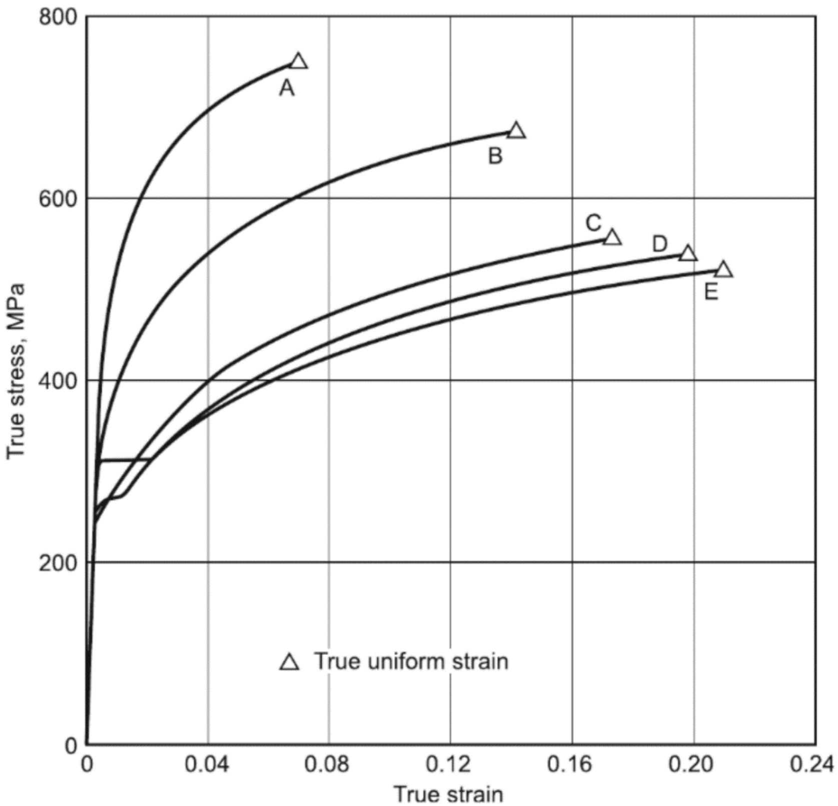
The success of a hot deformation process depends on the ability to control the temperatures within the deformed metal

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



CS.040 Carbon steel, true stress-strain curves showing effect of different cooling rates

Specimens annealed at 810 °C, 10 min. Cooling rate: curve A, 1000 °C/s; curve B, 300 °C/s; curve C, 60 °C/s; curve D, 32 °C/s; curve E, 5 °C/s. Composition: Fe-0.063C-1.29Mn-0.24Si

Source: G. Krauss, Ed., *Deformation, Processing, and Structure,* papers presented at the ASM Materials Science Seminar, 23 Oct 1982 (St. Louis, MO), American Society for Metals, 1984, p 70

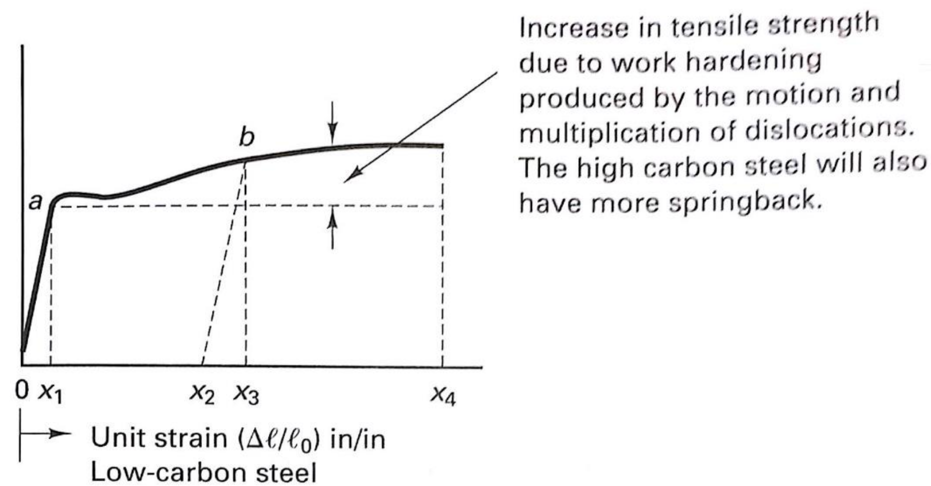
On the other hand the success of a cold working operation depends largely on the quality of the starting metal

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

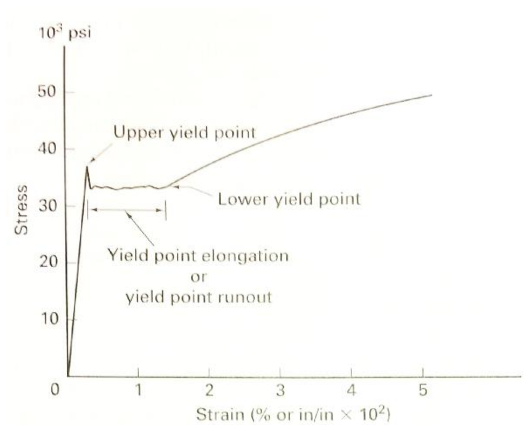
Scale in the starting metal is removed commonly by dipping in acid and washing

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.



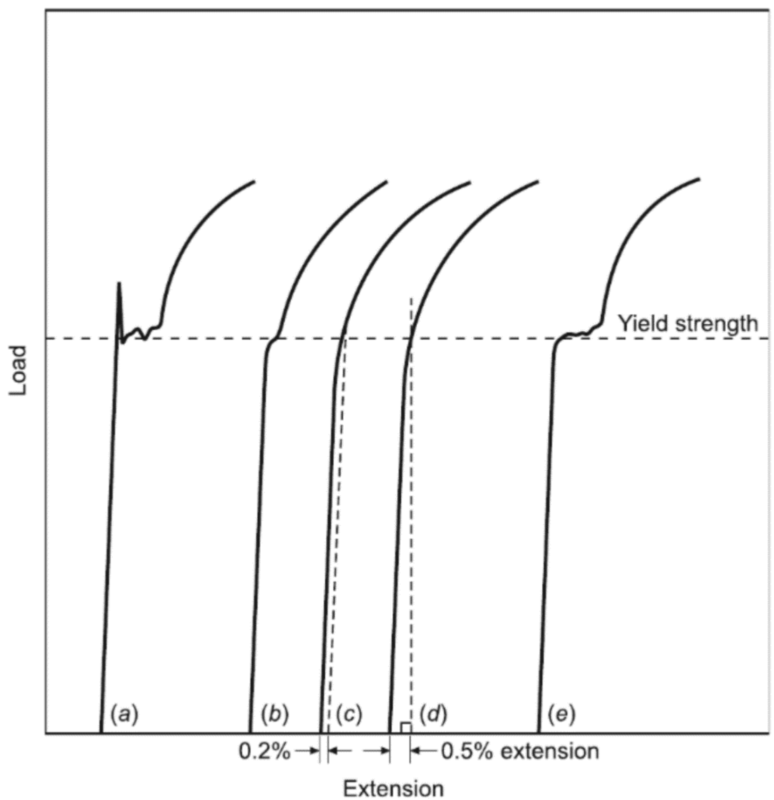
Many low carbon steels exhibit a yield-point runout after loading to the upper yield point
In this case the metal can strain up to several percent with no additional force being required



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

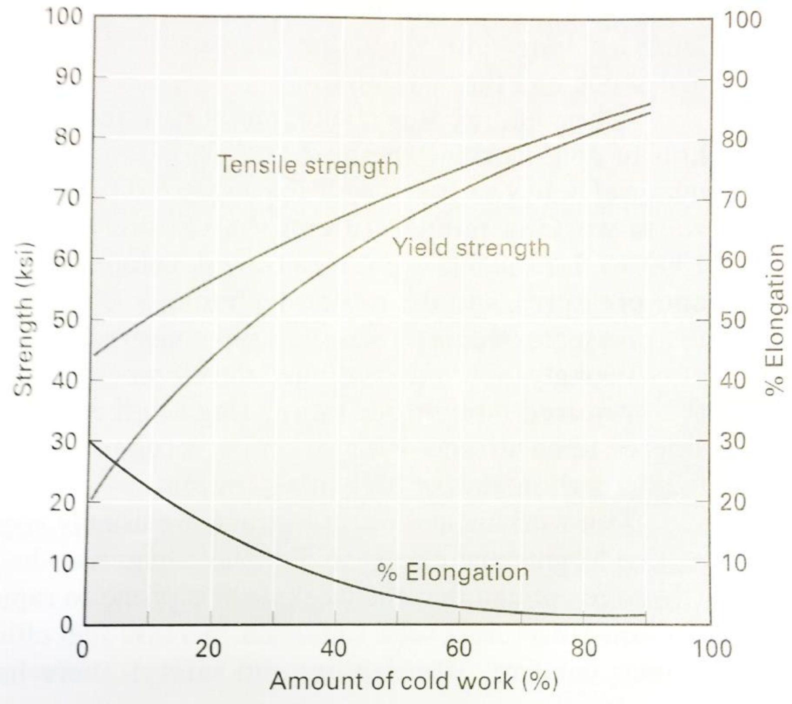


CS.002 Carbon steel, various alloys, load-extension curves showing yield strength

Load-extension curves for steel sheet having the same yield strength (YS) but different characteristic behavior. (a) Annealed dead soft rimmed or aluminum-killed steel. The YS is the average stress measured during yield point elongation. (b) Lightly temper rolled rimmed steel. The stress at the jog in the curve is reported as the YS. (c) and (d) Temper rolled low-carbon steel. May be rimmed, aluminum-killed, or interstitial-free steel with no detectable yield point. The YS is calculated from the load at 0.2% offset (c) or from the load at 0.5% extension (d). (e) Rimmed steel with a yield point elongation due to aging at room temperature for several months. The YS is the average stress measured during yield point elongation.

Source: W.G. Granzow, Sheet Formability of Steels, *Properties and Selection: Irons, Steels, and High-Performance Alloys,* Vol 1, *ASM Handbook,* ASM International, 1990, p 574

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

Microstructural mechanisms of yielding and plasticity

Near defects (especially dislocations) the stress fields and the associated strains are large so that material starts to yield at these sites

Yielding and plastic deformation occurs mainly by slippage of planes which are easier when there are more and faster dislocations on these planes

Peierls-Nabarro stress is the minimum shear stress required to move a dislocation or overcome lattice friction

Critical resolved shear stress is the stress at which slip planes slide

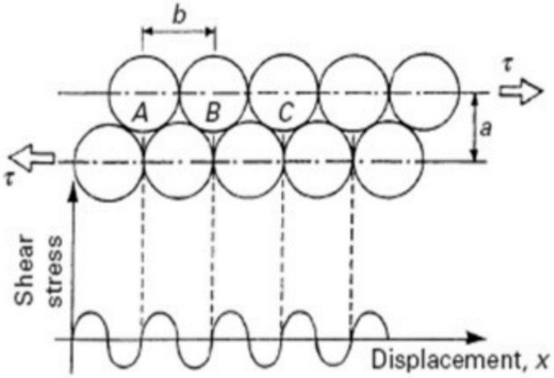
The two are commonly equal because of the dependency of the slippage mechanism to dislocation motion

$$\tau = G\gamma = G\frac{x}{b}$$

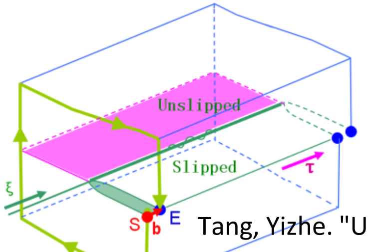
So

$$\tau_{max} = \frac{G}{2\pi}$$ Theoretical CRSS

$$\tau = \tau_{max}\sin\frac{2\pi x}{b} \approx \tau_{max}\frac{2\pi x}{b}$$



Too large stress needed if dislocation moves through all atoms on the slip plane at once



Tang, Yizhe. "Uncovering the inertia of dislocation motion and negative mechanical response in crystals." Scientific reports 8.1 (2018): 140.

Critical resolved shear stress is much lower than G/2π in reality for non-perfect crystalline materials
For example for NaCl, G= 23.7GPa, τ_{max}= 2.9GPa!

This is because dislocations move through the slip planes one step (one atom) at a time, breaking one elastic bond at a time

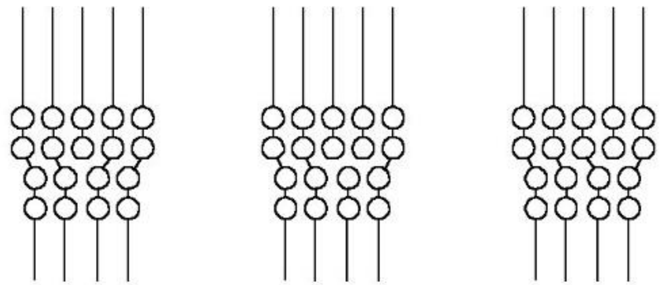
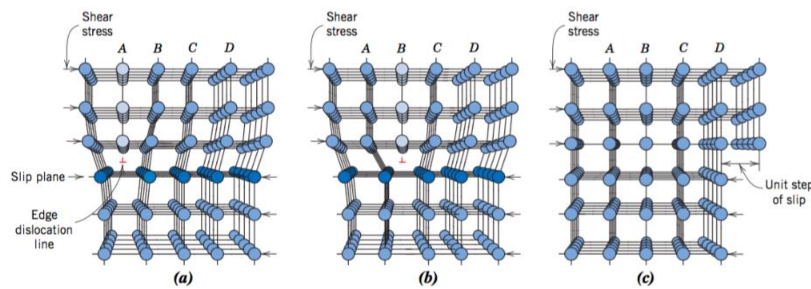
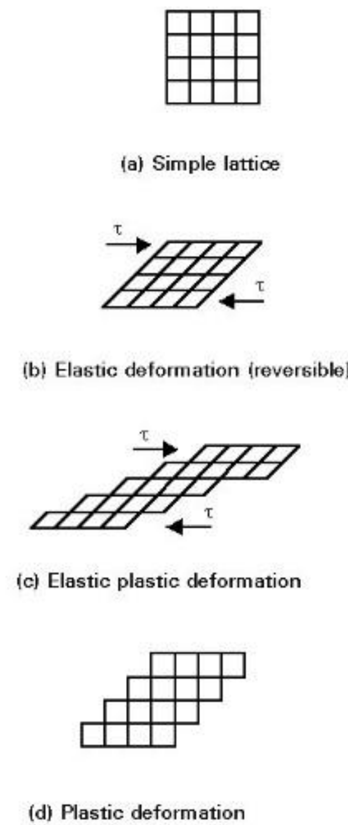
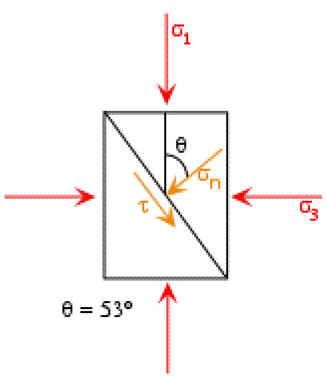


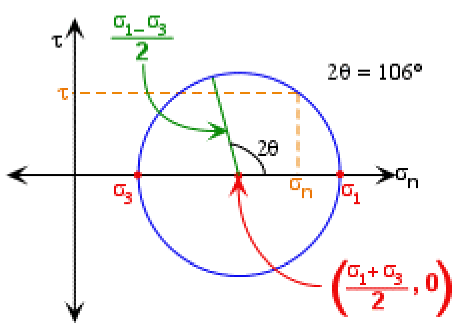
Figure 3 Movement of a dislocation through a crystal lattice





So slip and plastic deformation occurs at moderate stress states within the material





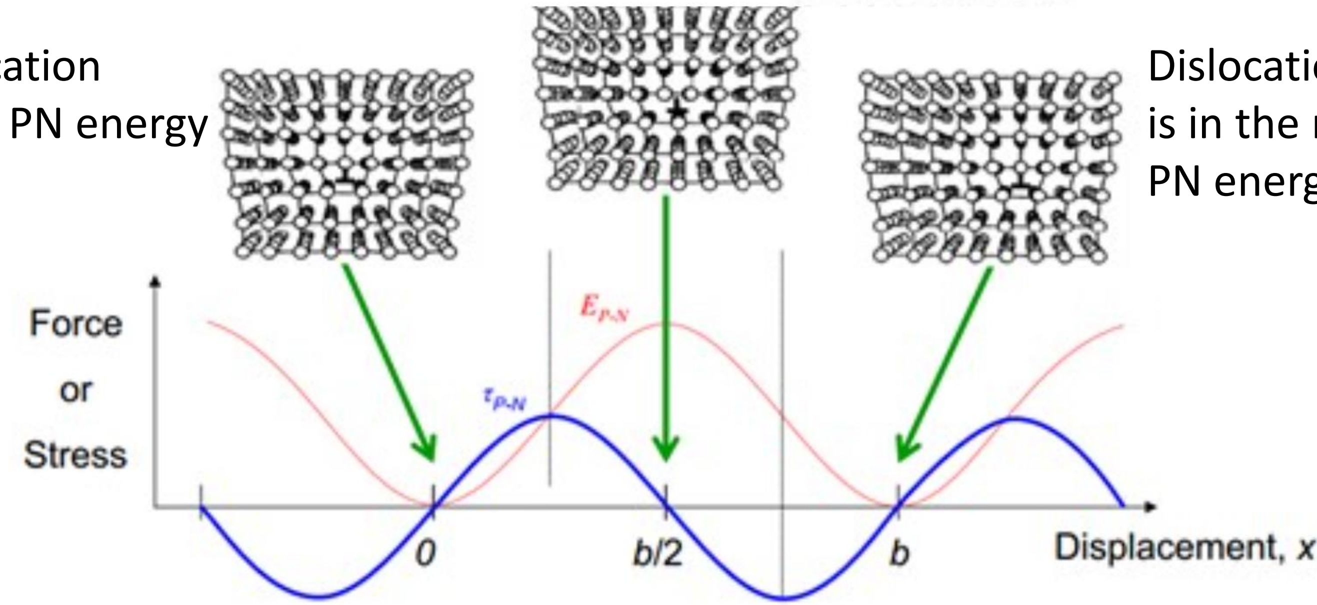
Peierls-Nabarro stress is accepted as the real critical resolved shear stress

It is a sensitive (exponential) function of the structure of the dislocation which is determined by the bonding in the crystal and the crystal structure

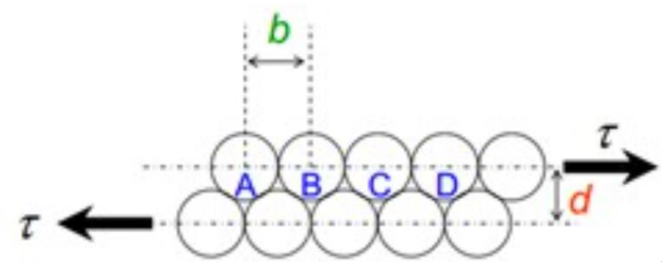
Stress applied to pull it out of the valley

Dislocation is in a PN energy valley

Dislocation is in the next PN energy valley



PN stress is needed for atomic adjustments around the dislocation



$$\tau_{P-N} = \frac{2\pi}{b^2} E_{P-N} = \frac{2G}{(1-\nu)} \exp\left(\frac{-2\pi w}{b}\right)$$

Wider dislocations in small crystals require a lower PN stress

Generally, $\tau_{PN} = G * \exp\left(-\frac{2\pi w}{b}\right)$

Narrow dislocations are more difficult to move than wide ones
Dislocations with larger b are more difficult to move

For example
τ_{PN}= G when w=0,
τ_{PN}= G/400 when w=b,
τ_{PN}= G/10^{14} when w=5b,
τ_{PN}= G/10^{27} when w=10b

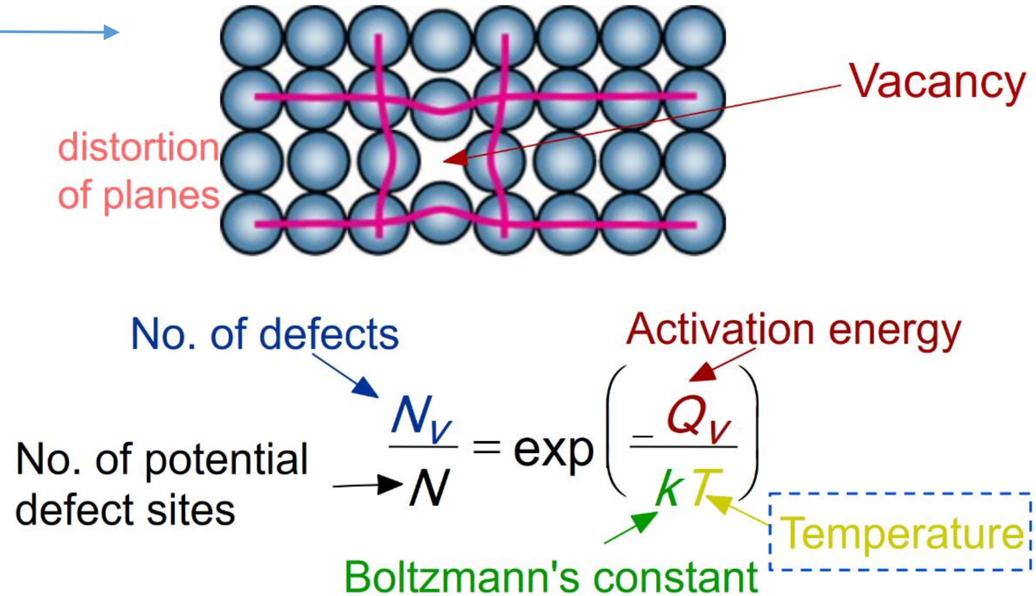
Nature of atomic bonding in the crystal determines the width of the dislocation

Covalent crystals fail by brittle fracture before $\boldsymbol{\tau_{PN}}$ is reached because of their strong and directional bonds (low w)
Metallic crystals can be cold worked to large strains because of their weaker, non-directional bonds (high w)

PN stress is theoretical and based on elastic material properties at absolute zero K

The dislocation motion can also be induced by thermal fluctuation in a thermal activation process similar to the creation of vacancies in a crystal by heat energy

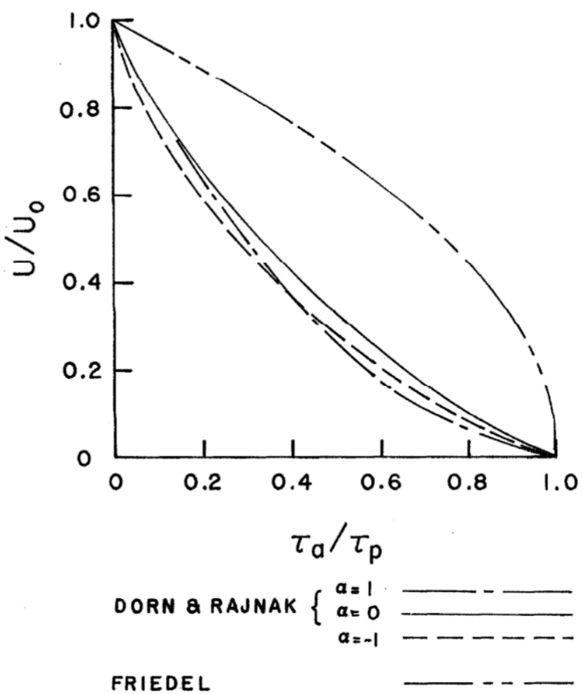
Vacancy formation as a function of T



Similar thermal activation occurs during dislocation motion

$$v = v_0 * \exp\left(-\frac{U(\tau_a)}{kT}\right)$$

where v is the dislocation velocity
U is the activation energy which is a function of applied stress, τ_a
(inverse relationship)



Application of both heat and mechanical energy moves dislocations easier

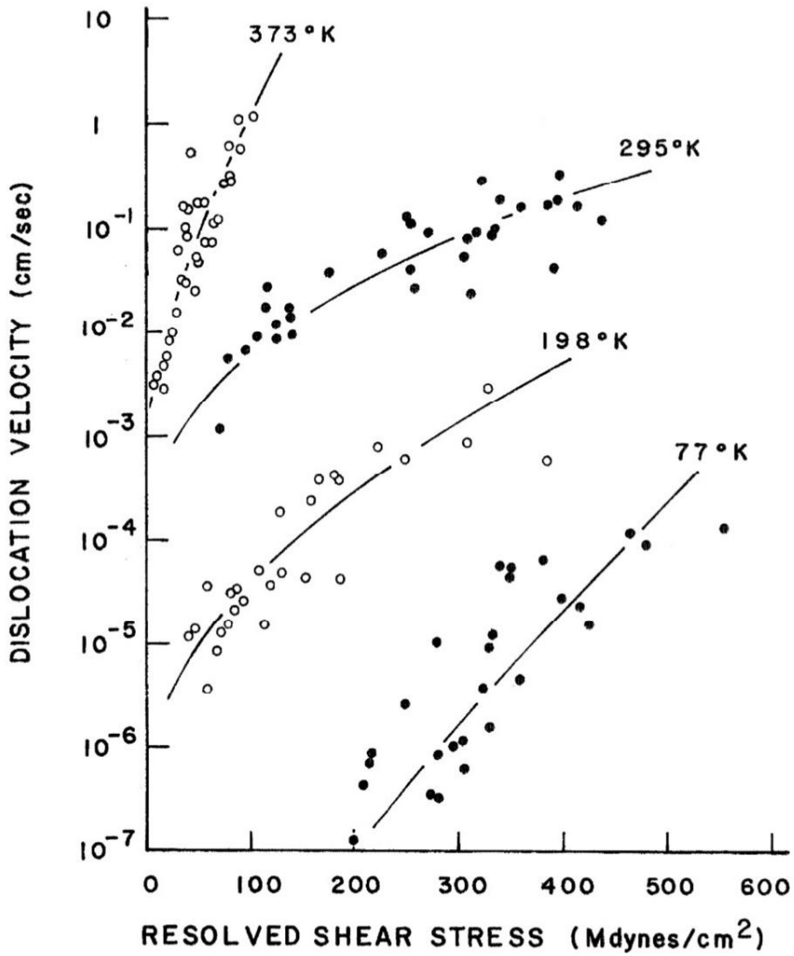


Figure 17. Dislocation Velocity in Iron Single Crystals as Function of Resolved Shear Stress for Several Temperatures.

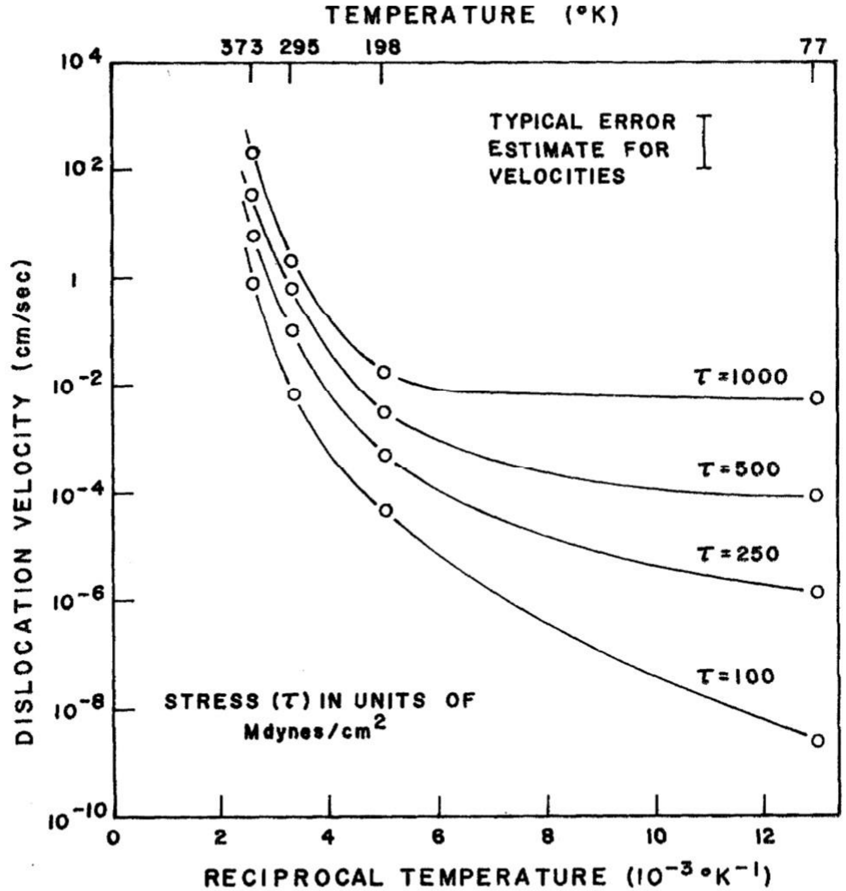
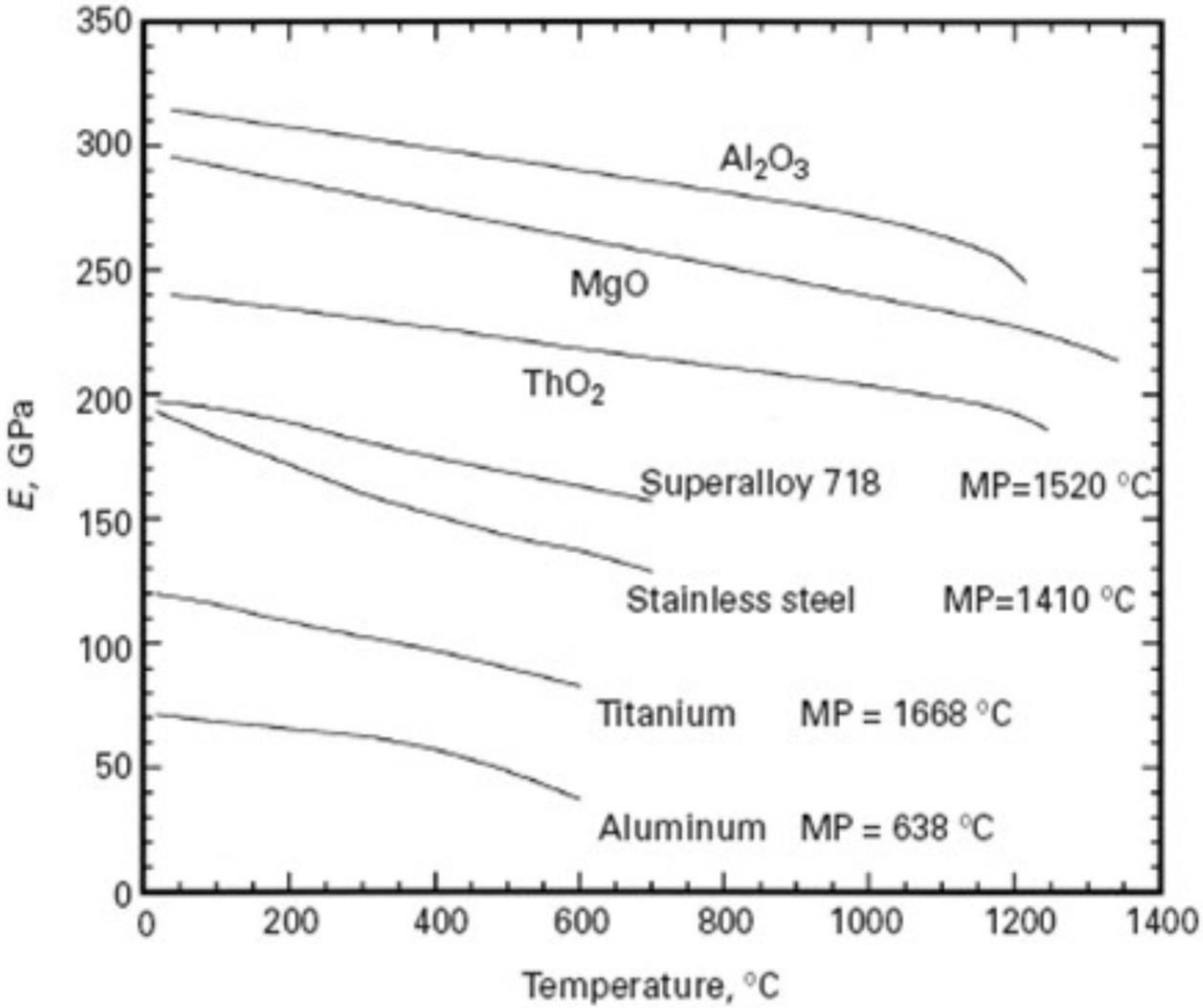


Figure 18. Dislocation Velocity in Iron Single Crystals at Constant Stress as Function of Reciprocal of Temperature.

A.P. L. Turner, 'The effect of stress and temperature on the velocity of dislocations in pure iron monocrystals', 1969

Hence, high T strengthens the effect of applied stress by increasing the entropy of the crystals



Effect of temperature on Young's modulus. (Adapted from J. B. Wachtman Jr.,W. E. Tefft, D. G. Lam Jr., and C. S. Apstein, *J. Res. Natl. Bur. Stand.*, 64A (1960)213 ; and J. Lemartre and J. L. Chaboche, *Mechanics of Solid Materials*, Cambridge: Cambridge University Press, 1990, p. 143.)

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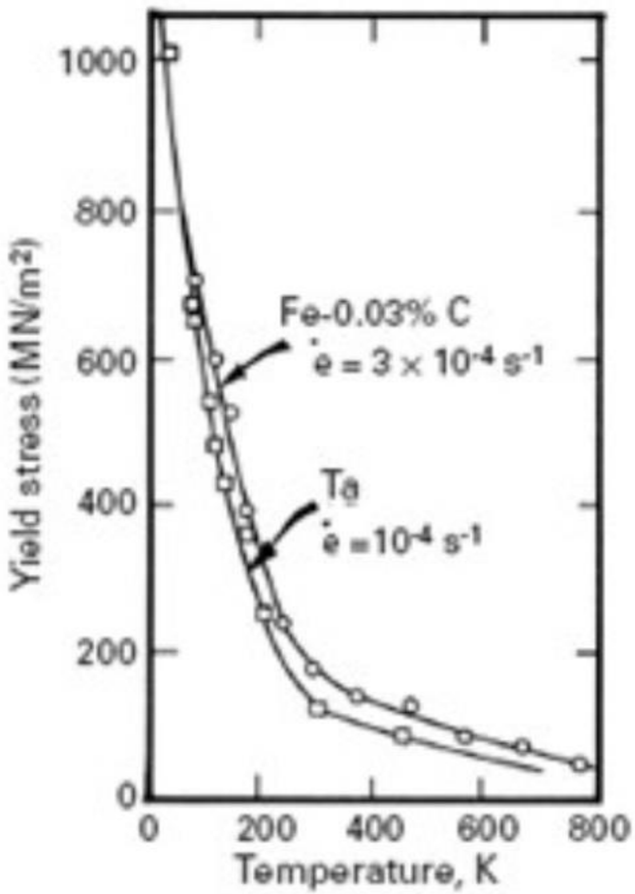
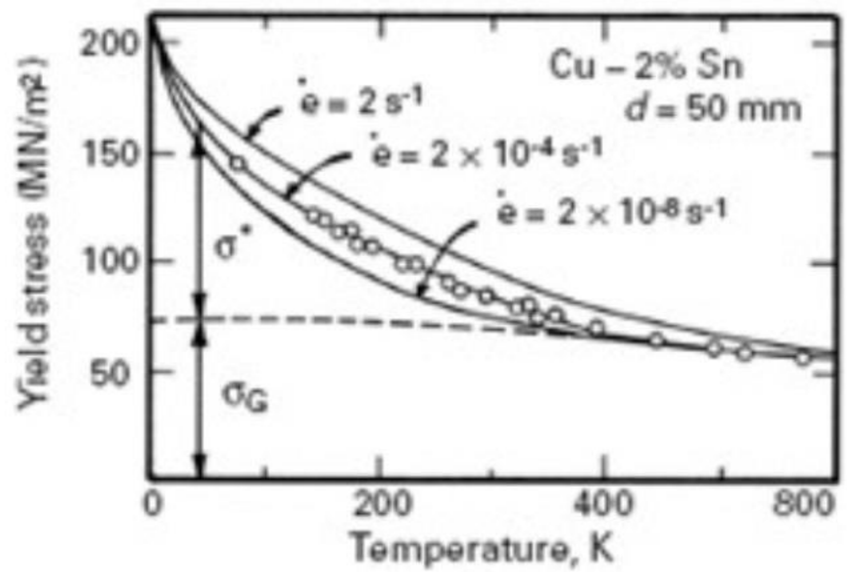


BCC metals



FCC metals