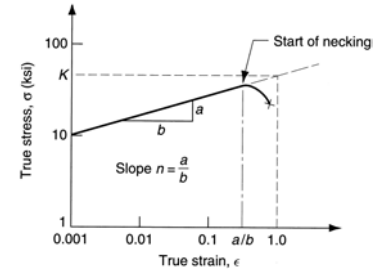
Fundamentals of Metal Forming

Outline

- ✓ Mechanical Properties - *Example*
- ✓ Overview of Metal Forming
- ✓ Cold working - Strain Hardening
- ✓ Annealing - Recrystallization
- ✓ Temperature in Metal Forming
- ✓ Friction and Lubrication in Metal Forming

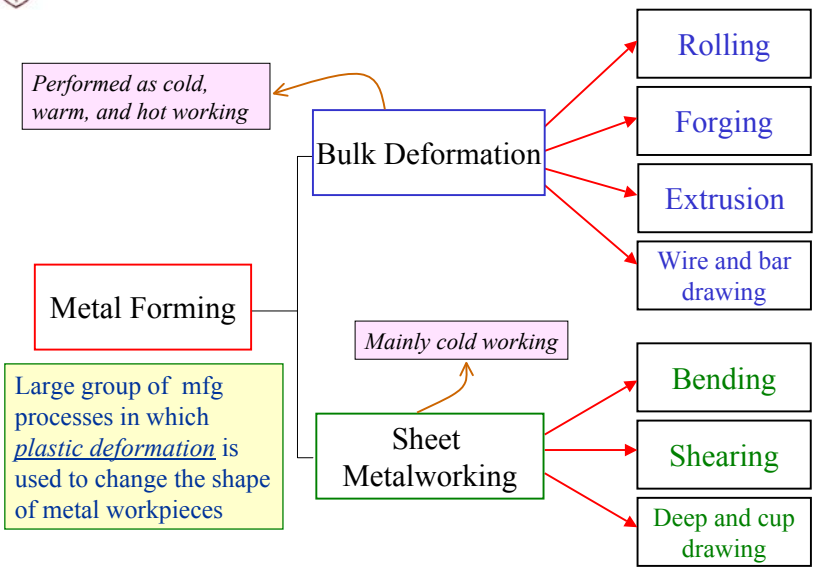
Example

A metal obeys the Hollomon relationship and has a UTS of 300 MPa.
To reach maximum load requires an elongation of 35%. Find K and n.

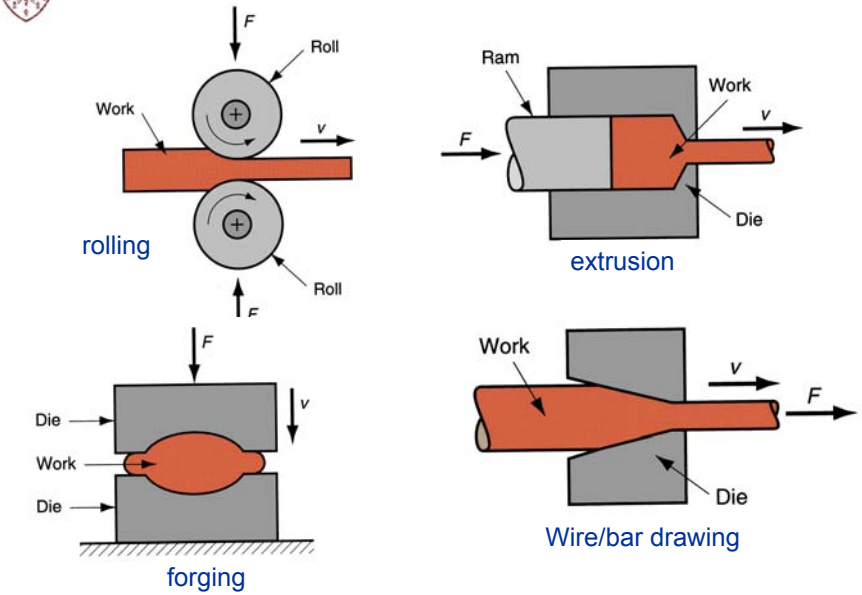


True stress-strain curve plotted on log-log scale

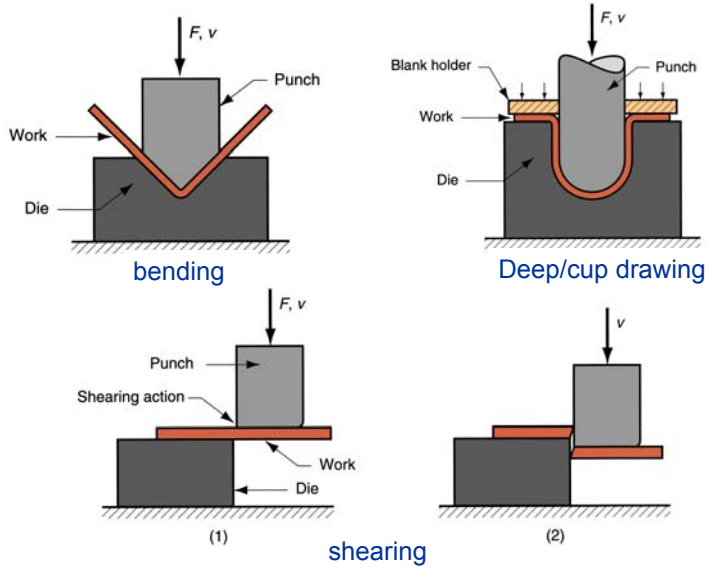
Overview of Metal Forming



Bulk Deformation



Sheet Metalworking



Formability (workability)

Formability of the material depends on:

(1) process variables

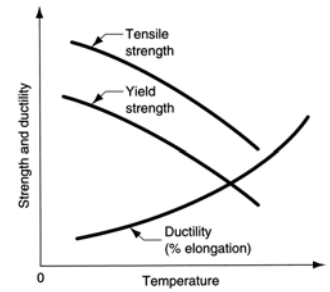
- .....
- .....
- .....

Desirable material properties in metal forming:

– **Low** *yield strength* and **high** *ductility*

(2) Metallurgical changes during deformation

- *formation of voids, composition, inclusions, precipitation, ... etc.*



Ductility increases and yield strength decreases when work temperature is raised

→ Any deformation operation can be accomplished with lower forces and power at elevated temperature

Homologous Temp. Ranges for Various Processes

- T: working temperature
- T_m: melting point of metal (based on absolute temperature scale)

Process	T/T_m
Cold working	< 0.3
Warm working	0.3 to 0.5
Hot working	> 0.6

- e.g. lead
  - T_m = 327 °C
  - Formed at room temperature (20 °C),

  .....

✓ Most metals strain harden at room temperature according to the flow curve ($n > 0$)

✓ But if heated to sufficiently high temperature and deformed, strain hardening does not occur

- *Instead, new grains are formed that are free of strain*
- *The metal behaves as a perfectly plastic material; that is, n = ...*

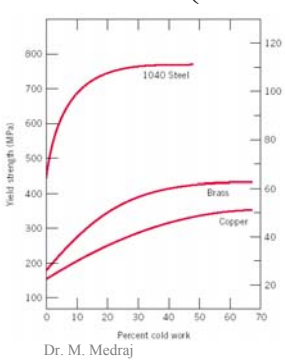
Strain or Work Hardening

- *Strain hardening* (work hardening) is where a material becomes *less ductile, harder* and *stronger* with plastic deformation
- Encountered during *cold working*
- percentage cold work can be expressed as:

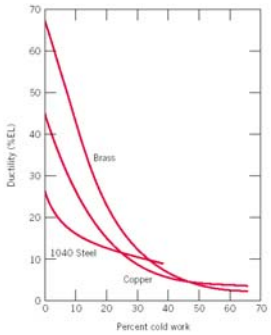
$$\%CW = \left(\frac{A_o - A_d}{A_o}\right) \times 100$$

A_o = original cross-sectional area

A_d = deformed cross-sectional area

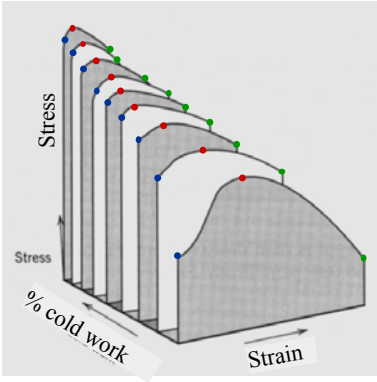


- Ductility ……..…. with cold work
- yield and tensile strength ……



Strain or Work Hardening

- Yield strength (σ_y) increases.
- Tensile strength (UTS) increases.
- Ductility (%EL or %AR) decreases.

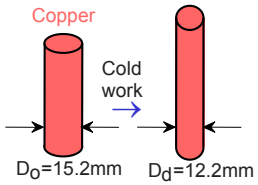


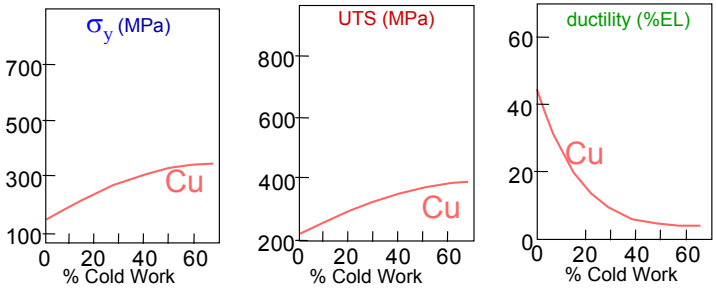
The influence of cold work on the stress–strain behavior for a low-carbon steel.

- dislocation density *increases* with CW
- motion of dislocations is *hindered* as their density increases
- stress required to cause further deformation is increased
- strain hardening is used commercially to improve the yield and tensile properties
  - **cold-rolled low-carbon steel sheet**
  - **aluminum sheet**
- *strain hardening exponent* n indicates the response to cold work (i.e. larger n means greater strain hardening for a given amount of plastic strain)

Example: Cold Work Analysis

- What is the tensile strength & ductility after cold working?





Cold Working

- Performed at room temperature or *slightly* above
- Many cold forming processes are important mass production operations
- Minimum or no machining usually required
  - These operations are *near net shape* or *net shape* processes

Advantages of Cold Forming vs. Hot Working:

- Better accuracy, closer tolerances
- Better surface finish
- Strain hardening increases strength and hardness
- Grain flow during deformation can cause desirable directional properties in product
- No heating of work required (*less total energy*)

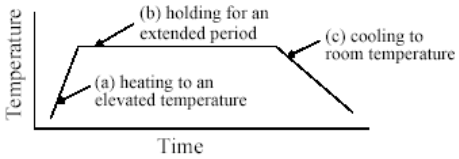
Cold Working

Disadvantages of Cold Forming:

- Equipment of higher forces and power required
- Surfaces of starting workpiece must be free of scale and dirt
- Ductility and strain hardening limit the amount of forming that can be done
  - *In some operations, metal must be annealed to allow further deformation*
  - *In other cases, metal is simply not ductile enough to be cold worked*

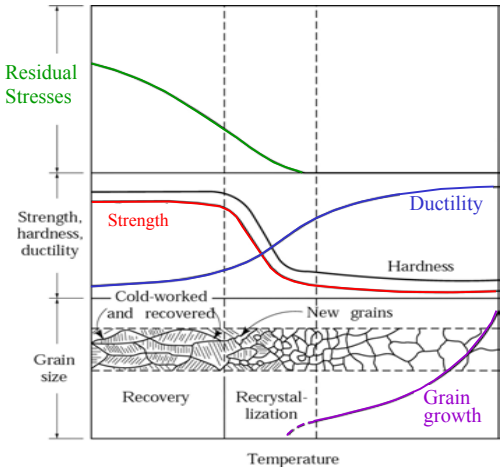
Purposes of annealing:

- ……..
- ……
- ……..



Involves three steps

Annealing-Recrystallization in Metals



Schematic illustration of the effects of recovery, recrystallization, and grain growth on mechanical properties and on the shape and size of grains.

- Formation of new strain-free grains is called *recrystallization*
- Recrystallization takes time - the **recrystallization temperature** is specified as the temperature at which new grains are formed in about ……
- Recrystallization can be exploited in manufacturing
- Heating a metal to its recrystallization temperature prior to deformation allows a greater amount of straining, and lower forces and power are required to perform the process

Recovery, Recrystallization and Grain Growth

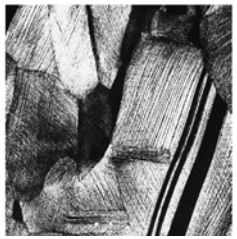
Recovery

- occurs during heating at elevated temperatures below the recrystallization temperature
- dislocations reconfigure due to diffusion and relieve the *lattice strain energy*
- electrical and thermal properties are recovered to their pre-cold worked state

Recrystallization

- recrystallization results in the nucleation and growth of new *strain-free, equiaxed* grains
- contain low dislocation density equivalent to the pre-cold worked condition → *annealed* state
- restoration of mechanical properties → softening

Recrystallization in Metals

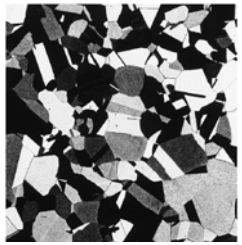


Cold-worked (33%CW)

Initial stage of rec. after heating 3 s at 580°C

Partial replacement of cw grains by rec. ones 4 s.

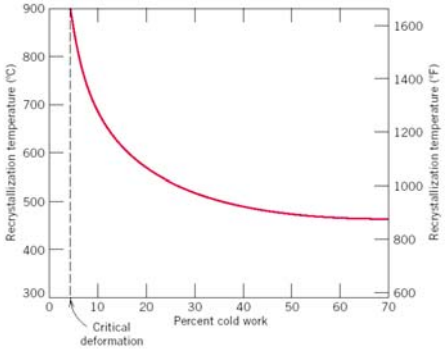
Complete recrystallization (8 s at 580°C).



Grain growth after 15 min at 580°C

Grain growth after 10 min at 700°C

Recrystallization in Metals

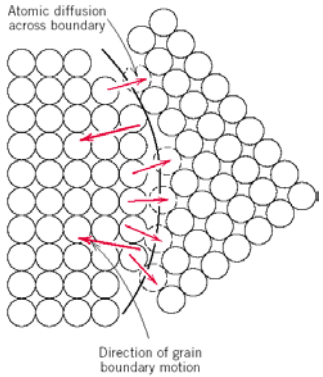


The variation of recrystallization temperature with percent cold work for iron. ***For deformations less than the critical (about 5%CW), recrystallization will not occur.***

- Rate of recrystallization increases with amount of cold work
- require a *critical* amount of cold-work to cause recrystallization (2-20%)
- recrystallization is easier in pure metals than alloys and occurs at lower temperature
  - $0.3T_m$ versus $\sim 0.7T_m$
- *hot-working* involves deformation and concurrent recrystallization at high temperature

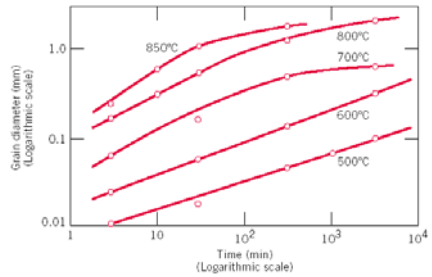
Grain Growth

- Growth of new grains will continue at high temperature
- does not require recovery and recrystallization
- occurs in both metals and ceramics at elevated temperature
- involves the migration of grain boundaries
- large grains grow at expense of small ones
- reduction of grain boundary area (*driving force*)



Schematic representation of grain growth via atomic diffusion.

Grain Growth Kinetics



The logarithm of grain diameter versus the logarithm of time for grain growth in brass at several temperatures.

- Variation of grain size (d) with time is:

$$d^n - d_o^n = Kt$$

where d_o = initial grain size at t = 0, and K and n are time-independent constants, n is ≥ 2

- log d versus log t plots give linearity at low temperatures
- grain size increases with temperature
- *toughness* and *strength* are superior in *fine grained* materials

Warm Working

- Performed at temperatures above room temperature but below recrystallization temperature
- Warm working: T/T_m from 0.3 to 0.5

Advantages of Warm Working:

- Lower forces and power than in cold working
- More intricate work geometries possible
- Need for annealing may be reduced or eliminated

Hot Working

- Deformation at temperatures above *recrystallization temperature*
  - In practice, hot working usually performed somewhat above $0.5T_m$
  - Metal continues to soften as temperature increases above $0.5T_m$, enhancing advantage of hot working above this level

Why Hot Working?

Capability for substantial plastic deformation of the metal - far more than possible with *cold* working or *warm* working

- Why?
  - ***Strength coefficient*** *is substantially less than at room temp.*
  - ***Strain hardening exponent*** *is zero (theoretically)*
  - *Ductility is significantly increased*

Advantages of Hot Working vs. Cold Working

- Workpart shape can be significantly altered
- Lower forces and power required (*equipment*)
- Metals that usually fracture in cold working can be hot formed
- Strength properties of product are generally isotropic
- No strengthening of part occurs from work hardening
  - *Advantageous in cases when part is to be subsequently processed by cold forming*

Disadvantages of Hot Working:

- Lower dimensional accuracy
- Higher total energy required
  - *due to the thermal energy to heat the workpiece*
- Work surface oxidation (scale), …… surface finish
- …… tool life

Friction in Metal Forming

- In most metal forming processes, friction is undesirable:
  - Metal flow is retarded
  - Forces and power are increased
  - Wears tooling faster
- Metalworking lubricants are applied to tool-work interface in many forming operations to reduce harmful effects of friction
- Benefits:
  - *Reduced sticking, forces, power, tool wear*
  - *Better surface finish*
  - *Removes heat from the tooling*
- Considerations in Choosing a Lubricant:
  - Type of forming process *(rolling, forging, sheet metal drawing, etc.)*
  - Hot working or cold working
  - Work material
  - Chemical reactivity with tool and work metals
  - Ease of application
  - Cost

Next time:

Rolling