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.

Overview of Metal Forming

Bulk Deformation

Performed as cold, warm, and hot working

Mainly cold working

Large group of mfg processes in which plastic deformation is used to change the shape of metal workpieces

Metal Forming

Rolling
Forging
Extrusion
Wire and bar drawing
Bending
Shearing
Deep and cup drawing

Sheet Metalworking

Bulk Deformation

rolling
extrusion
forging

Wire/bar drawing
Shearing

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<sub>m</sub>: melting point of metal (based on absolute temperature scale)
- e.g. lead
  - T<sub>m</sub> = 327 °C
  - Formed at room temperature (20 °C),

<table>
<thead>
<tr>
<th>Process</th>
<th>T/T&lt;sub&gt;m&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold working</td>
<td>&lt; 0.3</td>
</tr>
<tr>
<td>Warm working</td>
<td>0.3 to 0.5</td>
</tr>
<tr>
<td>Hot working</td>
<td>&gt; 0.6</td>
</tr>
</tbody>
</table>

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

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

- Yield strength ($\sigma_y$) increases.
- Tensile strength (UTS) increases.
- Ductility (\%EL or \%AR) decreases.
- 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).

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

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).

Example: Cold Work Analysis

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

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:
- Heating to an elevated temperature.
- Holding for an extended period.
- Cooling to room temperature.

Involves three steps.
Annealing-Recrystallization in Metals

• 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

• 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
• restoration of mechanical properties → softening

Recovery, Recrystallization and Grain Growth

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

Recovery, Recrystallization and Grain Growth

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**Recrystallization**

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**Recrystallization in Metals**

- 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
  - 0.3\(T_m\) versus ~0.7\(T_m\)
- **hot-working** involves deformation and concurrent recrystallization at high temperature

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

Grain Growth Kinetics

- Variation of grain size ($d$) with time is:
  $$d^n - d_0^n = Kt$$
  where $d_0$ = initial grain size at $t = 0$, and $K$ and $n$ are time-independent constants, $n \geq 2$

- 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?

- 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