FUNDAMENTALS OF METAL FORMING

- Overview of Metal Forming
- Material Behavior in Metal Forming
- Temperature in Metal Forming
- Strain Rate Sensitivity
- Friction and Lubrication in Metal Forming
Metal Forming

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

• The tool, usually called a *die*, applies stresses that exceed yield strength of metal
• The metal takes a shape determined by the geometry of the die
Stresses in Metal Forming

• Stresses to plastically deform the metal are usually \textit{compressive}
  – Examples: rolling, forging, extrusion

• However, some forming processes
  – Stretch the metal (\textit{tensile} stresses)
  – Others bend the metal (\textit{tensile} and \textit{compressive})
  – Still others apply \textit{shear} stresses
Material Properties in Metal Forming

• Desirable material properties:
  – Low yield strength and high ductility
• These properties are affected by temperature:
  – Ductility increases and yield strength decreases when work temperature is raised
• Other factors:
  – Strain rate and friction
Bulk Deformation Processes

- Characterized by significant deformations and massive shape changes
- "Bulk" refers to workparts with relatively low surface area-to-volume ratios
- Starting work shapes include cylindrical billets and rectangular bars
Figure 18.2 – Basic bulk deformation processes: (a) rolling
Figure 18.2 – Basic bulk deformation processes: (b) forging
Figure 18.2 – Basic bulk deformation processes: (c) extrusion
Figure 18.2 – Basic bulk deformation processes: (d) drawing
Sheet Metalworking

• Forming and related operations performed on metal sheets, strips, and coils
• High surface area-to-volume ratio of starting metal, which distinguishes these from bulk deformation
• Often called *pressworking* because presses perform these operations
  – Parts are called *stampings*
  – Usual tooling: *punch* and *die*
Figure 18.3 - Basic sheet metalworking operations: (a) bending
Figure 18.3 - Basic sheet metalworking operations: (b) drawing
Figure 18.3 - Basic sheet metalworking operations: (c) shearing
Material Behavior in Metal Forming

- Plastic region of stress-strain curve is primary interest because material is plastically deformed
- In plastic region, metal's behavior is expressed by the flow curve:
  \[ \sigma = K \varepsilon^n \]
  where \( K \) = strength coefficient; and \( n \) = strain hardening exponent
- Stress and strain in flow curve are true stress and true strain
Flow Stress

• For most metals at room temperature, strength increases when deformed due to strain hardening
• \textit{Flow stress} = instantaneous value of stress required to continue deforming the material

\[ Y_f = K \varepsilon^n \]

where \( Y_f \) = flow stress, that is, the yield strength as a function of strain
Average Flow Stress

Determined by integrating the flow curve equation between zero and the final strain value defining the range of interest

\[
\bar{Y}_f = \frac{K \varepsilon^n}{1 + n}
\]

where \( \bar{Y}_f \) = average flow stress; and \( \varepsilon \) = maximum strain during deformation process
Temperature in Metal Forming

- For any metal, $K$ and $n$ in the flow curve depend on temperature
  - Both strength and strain hardening are reduced at higher temperatures
  - In addition, ductility is increased at higher temperatures
Temperature in Metal Forming

• Any deformation operation can be accomplished with lower forces and power at elevated temperature
• Three temperature ranges in metal forming:
  – Cold working
  – Warm working
  – Hot 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
Disadvantages of Cold Forming

- 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

Warm Working

• Performed at temperatures above room temperature but below recrystallization temperature
• Dividing line between cold working and warm working often expressed in terms of melting point:
  – $0.3T_m$, where $T_m =$ melting point (absolute temperature) for metal
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
- Recrystallization temperature = about one-half of melting point on absolute scale
  - In practice, hot working usually performed somewhat above 0.5 $T_m$
  - Metal continues to soften as temperature increases above 0.5 $T_m$, 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 temperature
  – 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
• 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), poorer surface finish
- Shorter tool life
Strain Rate Sensitivity

- Theoretically, a metal in hot working behaves like a perfectly plastic material, with strain hardening exponent $n = 0$
  - The metal should continue to flow at the same flow stress, once that stress is reached
  - However, an additional phenomenon occurs during deformation, especially at elevated temperatures: *Strain rate sensitivity*
What is Strain Rate?

- Strain rate in forming is directly related to speed of deformation $\nu$
- Deformation speed $\nu = \text{velocity of the ram or other movement of the equipment}$

*Strain rate* is defined:

\[ \dot{\varepsilon} = \frac{v}{h} \]

where $\varepsilon = \text{true strain rate}$; and $h = \text{instantaneous height of workpiece being deformed}$
Evaluation of Strain Rate

- In most practical operations, valuation of strain rate is complicated by
  - Workpart geometry
  - Variations in strain rate in different regions of the part
- Strain rate can reach $1000 \text{ s}^{-1}$ or more for some metal forming operations
Effect of Strain Rate on Flow Stress

- Flow stress is a function of temperature.
- At hot working temperatures, flow stress also depends on strain rate.
  - As strain rate increases, resistance to deformation increases.
  - This effect is known as *strain-rate sensitivity*.
Figure 18.5 - (a) Effect of strain rate on flow stress at an elevated work temperature. (b) Same relationship plotted on log-log coordinates.
Strain Rate Sensitivity Equation

\[ Y_f = C \dot{\varepsilon}^m \]

where \( C \) = strength constant (similar but not equal to strength coefficient in flow curve equation), and \( m \) = strain-rate sensitivity exponent
Figure 18.6 - Effect of temperature on flow stress for a typical metal. The constant $C$ in Eq. (18.4), indicated by the intersection of each plot with the vertical dashed line at strain rate = 1.0, decreases, and $m$ (slope of each plot) increases with increasing temperature.
Observations about Strain Rate Sensitivity

- Increasing temperature decreases $C$, increases $m$
  - At room temperature, effect of strain rate is almost negligible
    - Flow curve is a good representation of material behavior
  - As temperature increases, strain rate becomes increasingly important in determining flow stress
Friction in Metal Forming

• In most metal forming processes, friction is undesirable:
  – Metal flow is retarded
  – Forces and power are increased
  – Wears tooling faster
• Friction and tool wear are more severe in hot working
Lubrication in Metal Forming

• 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