Fundamentals of Metal Forming

Chapter 15
15.1 Introduction

- Deformation processes have been designed to exploit the plasticity of engineering materials
- Plasticity is the ability of a material to flow as a solid without deterioration of properties
- Deformation processes require a large amount of force
- Processes include bulk flow, simple shearing, or compound bending
States of Stress

<table>
<thead>
<tr>
<th>TABLE 15-1</th>
<th>Classification of States of Stress</th>
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</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Simple uniaxial tension</td>
</tr>
<tr>
<td>(2)</td>
<td>Biaxial tension</td>
</tr>
<tr>
<td>(3)</td>
<td>Triaxial tension</td>
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<tr>
<td>(4)</td>
<td>Biaxial tension, compression</td>
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<td>(5)</td>
<td>Biaxial tension and compression</td>
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<td>(6)</td>
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<td>(7)</td>
<td>Biaxial compression</td>
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<tr>
<td>(8)</td>
<td>Biaxial compression, tension</td>
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<tr>
<td>(9)</td>
<td>Triaxial compression</td>
</tr>
<tr>
<td>(10)</td>
<td>Pure shear</td>
</tr>
<tr>
<td>(11)</td>
<td>Simple shear with triaxial compression</td>
</tr>
<tr>
<td>(12)</td>
<td>Biaxial shear with triaxial compression</td>
</tr>
</tbody>
</table>
15.2 Forming Processes: Independent Variables

- Forming processes consist of independent and dependent variables.
- Independent variables are the aspects of the processes that the engineer or operator has direct control:
  - Starting material
  - Starting geometry of the workpiece
  - Tool or die geometry
  - Lubrication
  - Starting temperature
  - Speed of operation
  - Amount of deformation
Forming Operations

<table>
<thead>
<tr>
<th>Process</th>
<th>Schematic Diagram</th>
<th>State of Stress in Main Part During Forming&lt;sup&gt;a&lt;/sup&gt;</th>
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</thead>
<tbody>
<tr>
<td>Rolling</td>
<td>![Rolling Diagram]</td>
<td>7</td>
</tr>
<tr>
<td>Forging</td>
<td>![Forging Diagram]</td>
<td>9</td>
</tr>
<tr>
<td>Extrusion</td>
<td>![Extrusion Diagram]</td>
<td>9</td>
</tr>
<tr>
<td>Shear spinning</td>
<td>![Shear Spinning Diagram]</td>
<td>12</td>
</tr>
</tbody>
</table>
Forming Operations

- Tube spinning
- Swaging or kneading
- Deep drawing
- Wire and tube drawing

In flange of blank, 5
In wall of cup, 1
Forming Operations

- Stretching
- Straight bending
- Contoured flanging (a) Convex
  - At outer flange, 6
  - At bend, 2 and 7
- Contoured flanging (a) Concave
  - At outer flange, 1
  - At bend, 2 and 7

*Numbers correspond to those in parentheses in Table 15-1.*
15.3 Dependent Variables

- Dependent variables are those that are determined by the independent variable selection
  - Force or power requirements
  - Material properties of the product
  - Exit or final temperature
  - Surface finish and precision
  - Nature of the material flow
15.4 Independent-Dependent Relationships

• Independent variables- control is direct and immediate

• Dependent variables- control is entirely indirect
  – Determined by the process
  – If a dependent variable needs to be controlled, the designer must select the proper independent variable that changes the dependent variable
Independent-Dependent Relationships

- Information on the interdependence of independent and dependent variables can be learned in three ways:
  - Experience
  - Experiment
  - Process modeling

**Figure 15-1** Schematic representation of a metalforming system showing independent variables, dependent variables, and the various means of linking the two.
15.5 Process Modeling

• Simulations are created using finite element modeling
• Models can predict how a material will respond to a rolling process, fill a forging die, flow through an extrusion die, or solidify in a casting
• Heat treatments can be simulated
• Costly trial and error development cycles can be eliminated
15.6 General Parameters

• Material being deformed must be characterized
  – Strength or resistance for deformation
  – Conditions at different temperatures
  – Formability limits
  – Reaction to lubricants

• Speed of deformation and its effects

• Speed-sensitive materials- more energy is required to produce the same results
15.7 Friction and Lubrication Under Metalworking Conditions

- High forces and pressures are required to deform a material
- For some processes, 50% of the energy is spent in overcoming friction
- Changes in lubrication can alter material flow, create or eliminate defects, alter surface finish and dimensional precision, and modify product properties
- Production rates, tool design, tool wear, and process optimization depend on the ability to determine and control friction
Friction Conditions

- Metalforming friction differs from the friction encountered in mechanical devices.
- For light, elastic loads, friction is proportional to the applied pressure:
  - \( \mu \) is the coefficient of friction.
- At high pressures, friction is related to the strength of the weaker material.

**Figure 15-2** The effect of contact pressure on the frictional resistance between two surfaces.
Friction

- Friction is resistance to sliding along an interface
- Resistance can be attributed to:
  - Abrasion
  - Adhesion
- Resistance is proportional to the strength of the weaker material and the contact area
Surface Deterioration

- Surface wear is related to friction
- Wear on the workpiece is not objectionable, but wear on the tooling is
- Tooling wear is economically costly and can impact dimensional precision
- Tolerance control can be lost
- Tool wear can impact the surface finish
Lubrication

- Key to success in many metalforming operations
- Primarily selected to reduce friction and tool wear, but may be used as a thermal barrier, coolant, or corrosion retardant
- Other factors
  - Ease of removal, lack of toxicity, odor, flammability, reactivity, temperature, velocity, wetting characteristics
15.8 Temperature Concerns

- Workpiece temperature can be one of the most important process variables
- In general, an increase in temperature is related to a decrease in strength, increase in ductility, and decrease in the rate of strain hardening
- Hot working
- Cold working
- Warm working
Hot Working

- Plastic deformation of metals at a temperature above the recrystallization temperature
- Temperature varies greatly with material
- Recrystallization removes the effects of strain hardening
- Hot working may produce undesirable reactions from the metal and its surroundings
Structure and Property Modification by Hot Working

• The size of grains upon cooling is not typically uniform

• Undesirable grain shapes can be common (such as columnar grains)

• Recrystallization is followed by:
  – grain growth
  – additional deformation and recrystallization
  – drop in temperature that will terminate diffusion and freeze the recrystallized structure
Hot Working

- Engineering properties can be improved through reorienting inclusion or impurities.
- During plastic deformation, impurities tend to flow along with the base metal or fraction into rows of fragments.

Figure 15-3 Cross section of a 4-in.-diameter case copper bar polished and etched to show the as-cast grain structure.

Figure 15-4 Flow structure of a hot-forged gear blank. Note how flow is parallel to all critical surfaces. (Courtesy of Bethlehem Steel Corporation, Bethlehem, PA.)
Temperature Variations in Hot Working

- Success or failure of a hot deformation process often depends on the ability to control temperatures.
- Over 90% of the energy imparted to a deforming workpiece is converted to heat.
- Nonuniform temperatures may be produced and may result in cracking.
- Thin sections cool faster than thick sections.

*Figure 15-5* Schematic comparison of the grain flow in a machined thread (a) and a rolled thread (b). The rolling operation further deforms the axial structure produced by the previous wire- or rod-forming operations, while machining simply cuts through it.
Cold Working

- Plastic deformation below the recrystallization temperature
- Advantages as compared to hot working
  - No heating required
  - Better surface finish
  - Superior dimensional control
  - Better reproducibility
  - Strength, fatigue, and wear are improved
  - Directional properties can be imparted
  - Contamination is minimized
Disadvantages of Cold 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
• Imparted directional properties can be detrimental
• Undesirable residual stresses may be produced
Metal Properties and Cold Working

- Two features that are significant in selecting a material for cold working are
  - Magnitude of the yield-point stress
  - Extent of the strain region from yield stress to fracture
- Springback should also be considered when selecting a material

**Figure 15-6** Use of true stress-true strain diagram to assess the suitability of two metals for cold working.
Initial and Final Properties in a Cold-Working Process

• Quality of the starting material is important to the success or failure of the cold-working process

• The starting material should be clean and free of oxide or scale that might cause abrasion to the dies or rolls

Figure 15-7 (Below) Stress-strain curve for a low-carbon steel showing the commonly observed yield-point runout; (Right) Luders bands or stretcher strains that form when this material is stretched to an amount less than the yield-point runout.
Additional Effects of Cold Working

- Annealing heat treatments may be performed prior or at intermediate intervals to cold working.
- Heat treatments allow additional cold working and deformation processes.
- Cold working produces a structure where properties vary with direction, anisotropy.

Figure 15-8 Mechanical properties of pure copper as a function of the amount of cold work (expressed in percent).
Warm Forming

- Deformations produced at temperatures intermediate to cold and hot working
- Advantages
  - Reduced loads on the tooling and equipment
  - Increased material ductility
  - Possible reduction in the number of anneals
  - Less scaling and decarburization
  - Better dimensional precision and smoother surfaces than hot working
  - Used for processes such as forging and extrusion
Isothermal Forming

- Deformation that occurs under constant temperature
- Dies and tooling are heated to the same temperature as the workpiece
- Eliminates cracking from nonuniform surface temperatures
- Inert atmospheres may be used

Figure 15-10: Yield strength of various materials (as indicated by pressure required to forge a standard specimen) as a function of temperature. Materials with steep curves may require isothermal forming. (From “A Study of Forging Variables,” ML-TDR-64-95, March 1964; courtesy of Battelle Columbus Laboratories, Columbus, OH.)