Chapter 15: Fundamentals of Metal Forming

Metal Forming (金屬成型)

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

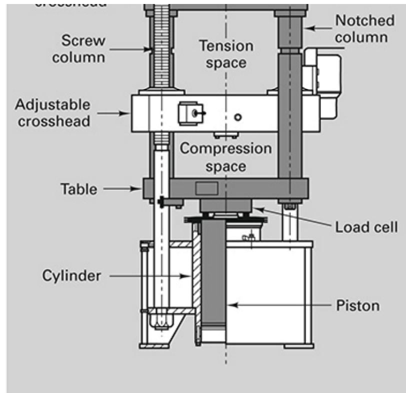
- Die (模具)
- The metal takes a shape of the die
- A force exceeding the yield stress (降伏應力) is applied

Static Properties of Materials

- Constant force on a material is called a static force
- Strength of a material is important
  - Elastic stretching or deflection of a material is related to Young's Modulus
- A number of tests have been developed to determine these static properties of materials

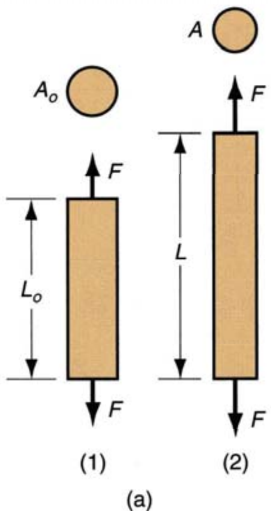
Static Testing

- Tensile test
  - Uniaxial test
  - Generates an engineering stress-strain curve
- Compression test
  - Difficult to test compression
  - Similar results to that of the tensile testing



Tensile Test (拉伸試驗)

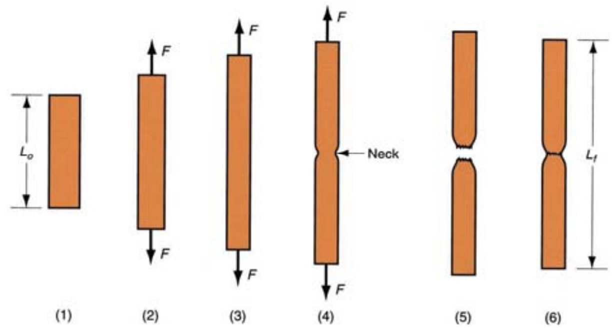
- In the test, a force pulls the material, elongating it and reducing its diameter



Tensile test: (a) tensile force applied in (1) and (2) resulting elongation of material (Source: Groover, 2005)

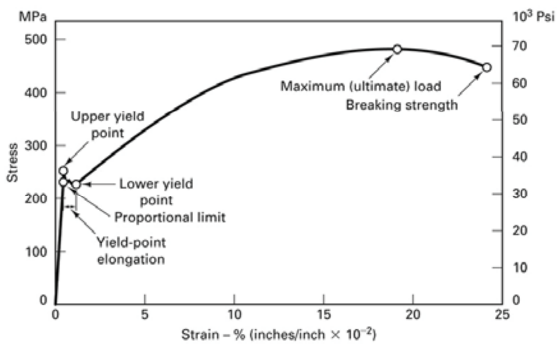
Tensile Test Sequence

- Typical progress of a tensile test: (1) beginning of test, no load; (2) uniform elongation and reduction of cross-sectional area; (3) continued elongation, maximum load reached; (4) necking begins, load begins to decrease; and (5) fracture.



(Source: Groover, 2005)

Engineering Stress-Strain Curve



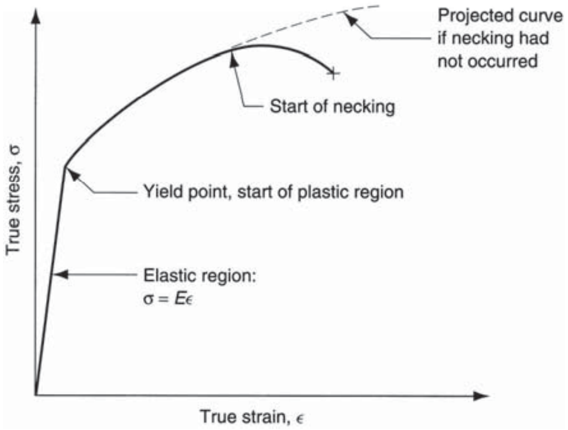
- Key features
  - Proportional limit (彈性限) (below this limit, the strain is directly proportional to stress)
  - Ratio of stress to strain is Young's Modulus (楊氏系數)
    - Measures stiffness
  - Ultimate Strength (抗拉強度)
    - Stress at which the load-bearing ability peaks

Additional Properties from the Stress-Strain Curve

- Plastic deformation- permanent change in shape due to a load that exceeded the elastic limit
- Yield point (降伏點)- stress value where additional strain occurs without an increase in stress
- Offset yield strength- the stress required to produce an allowable amount of permanent strain
- Toughness (韌性)- work per unit volume to fracture a material
  - Total area under the stress-strain curve

True Stress-Strain Curve

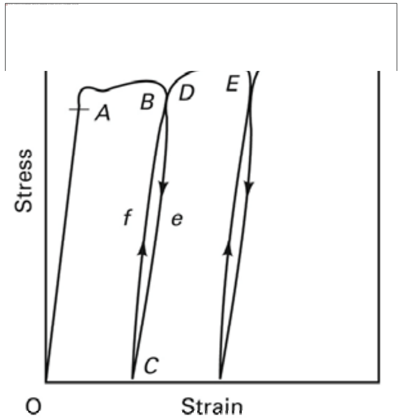
- True stress-strain curve
  - Instantaneous stress versus the summation of the incremental strain



(Source: Groover, 2005)

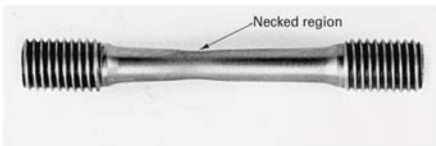
Strain Hardening (應變硬化)

- Loading and unloading within the elastic region will result in cycling up and down the linear portion of the stress strain curve
- When metals are plastically deformed, they become harder and stronger (strain hardening)



Ductility

- Necking is a localized reduction in cross sectional area
- For ductile materials, necking occurs before fracture
- Percent elongation is the percent change of a material at fracture

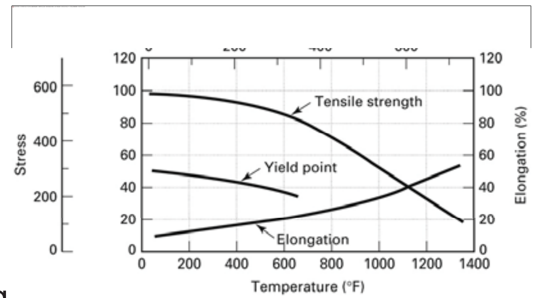


Percent Reduction in Area:

$$R.A. = \frac{A_0 - A_f}{A_0} \times 100\%$$

Temperature Effects

- Ductile-brittle transition temperature is the temperature at which the response of the material goes from high energy absorption to low energy absorption
- Creep (潛變) is failure of a material due to long term exposure to elevated temperature



Introduction to Metal Forming

- 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

Material Properties in Metal Forming

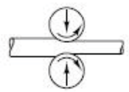
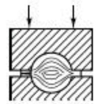
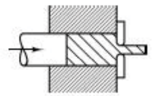
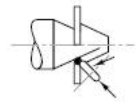
- Desirable material properties:
  - Low yield strength (低降伏強度)
  - High ductility (高延展性)
- These properties are affected by temperature:
  - Ductility increases and yield strength decreases when work temperature is raised
- Other factors:
  - Strain rate and friction

Basic Types of Deformation Processes

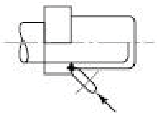
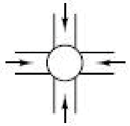
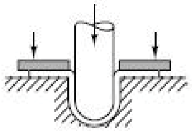
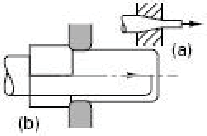
- Bulk deformation
  - Rolling (輥壓)
  - Forging (鍛造)
  - Extrusion (擠製)
  - Wire and bar drawing (拉製)
- Sheet metalworking
  - Bending (彎曲加工)
  - Deep drawing
  - Cutting (切斷)
  - Miscellaneous processes

Forming Operations

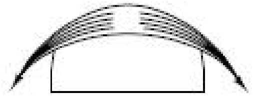
TABLE 15-2 Classification of Some Forming Operations

Process	Schematic Diagram	State of Stress in Main Part During Forming[a]
Rolling		7
Forging		9
Extrusion		9
Shear spinning		12

Forming Operations

Tube spinning		9
Swaging or kneading		7
Deep drawing		In flange of blank, 5 In wall of cup, 1
Wire and tube drawing		8

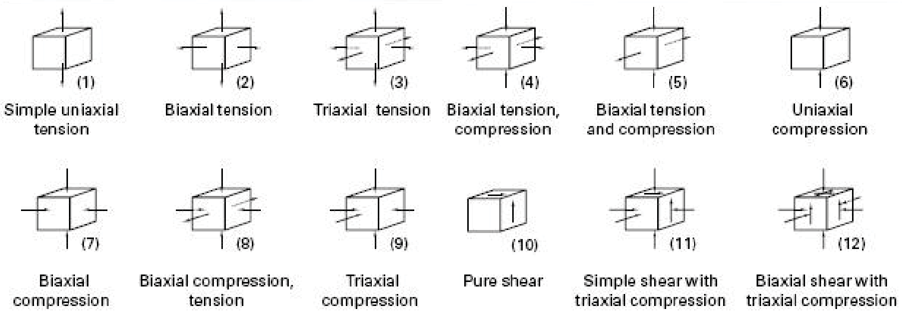
Forming Operations

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

[a] Numbers correspond to those in parentheses in Table 15-1.

States of Stress

TABLE 15-1 Classification of States of Stress



Forming Processes: Independent Variables

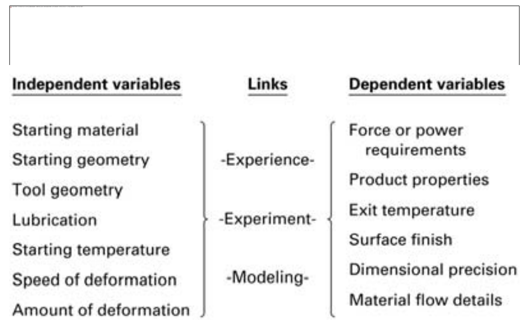
- Forming processes consist of independent and dependent variables
- Independent variables- control is direct and immediate
  - Starting material
  - Starting geometry of the workpiece
  - Tool or die geometry (模具的幾何形狀)
  - Lubrication (潤滑)
  - Starting temperature
  - Speed of operation
  - Amount of deformation

Dependent Variables

- Dependent variables- control is entirely indirect - 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

Independent-Dependent Relationships

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



Process Modeling

- Simulations (模擬) 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
- Heat treatments (熱處理) can be simulation
- Costly trial and error development cycles can be eliminated

General Parameters

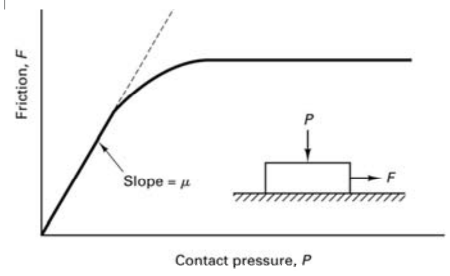
- Material being deformed must be characterized
  - Strength or resistance for deformation
  - Conditions at different temperatures
  - Formability limits
  - Reaction to lubricants
- Speed of deformation and its effects
- Speed-sensitive materials- more energy is required to produce the same results

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 (表面精度) and dimensional precision (尺寸精度), and modify product properties

Friction Conditions

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



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 (表面磨耗) is related to friction
- 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

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
- Recrystallization temperature = about $0.6T_m$
- Temperature varies greatly with material
- Recrystallization removes the effects of strain hardening
- Hot working may produce undesirable reactions from the metal and its surroundings

Advantages of Hot Working

- Large plastic deformation
- Lower forces and power required
- Reduce fracture in cold working
- Strength properties of product are generally isotropic (等向性)
- No work hardening
  - Advantageous in cases when part is to be subsequently processed by cold forming

Disadvantages of Hot Working

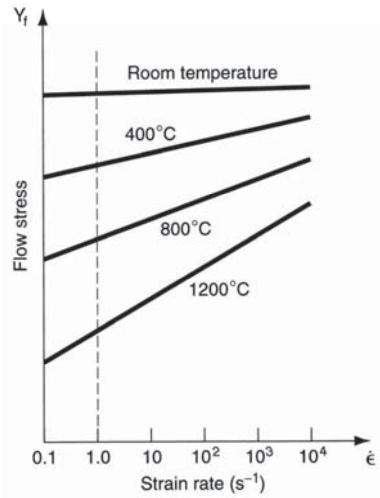
- Lower dimensional accuracy
- Higher total energy required
  - Due to the thermal energy to heat the workpiece
- Work surface oxidation (scale)
  - Poorer surface finish
- Shorter tool life

Effect of Temperature on Flow Stress

- Effect of temperature on flow stress for a typical metal.

$$Y_f = C\dot{\varepsilon}^m$$

where C = strength constant (similar but not equal to strength coefficient in flow curve equation), and m = strain-rate sensitivity exponent



(Source: Groover, 2005)

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

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

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

Cold Working

- Performed at room temperature or slightly above
- 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 (殘留應力) 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 (回彈) should also be considered when selecting a material

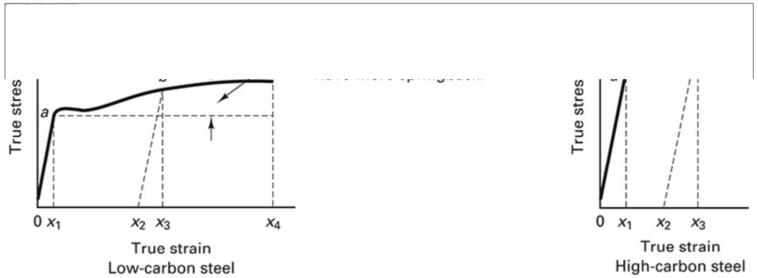
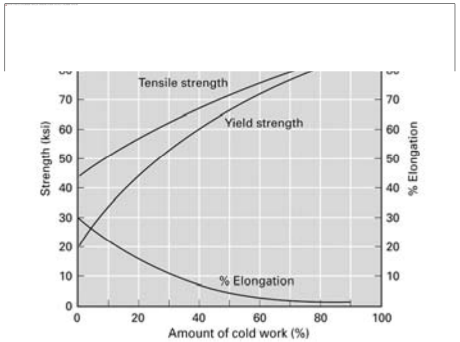


Figure 15-6 Use of true stress-true strain diagram to assess the suitability of two metals for cold working.

Additional Effects of Cold Working

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



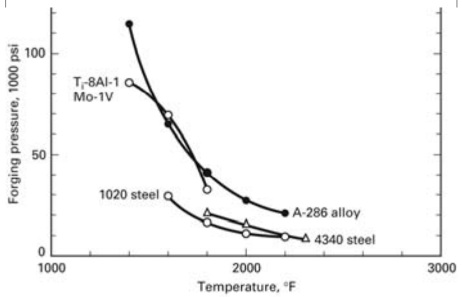
Mechanical properties of pure copper as a function of the amount of cold work (expressed in percent).

Warm Forming

- Deformations produced at temperatures intermediate to cold and hot working ($0.3T_m$ – $0.6T_m$)
- 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 (等溫成型)

- 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



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.*)