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

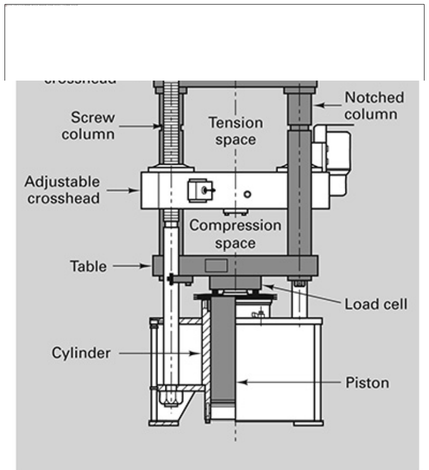
- Die (模具)
- The metal takes a shape of the die
- A force exceeding the yield stress (降伏應力) is applied

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

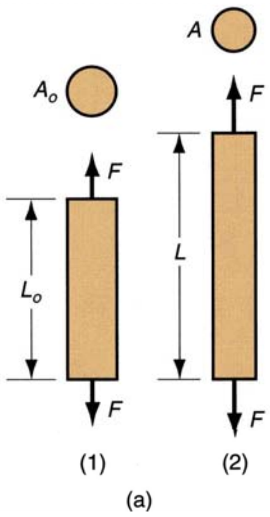
Tensile Test and Compression test

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



Tensile Test (拉伸試驗)

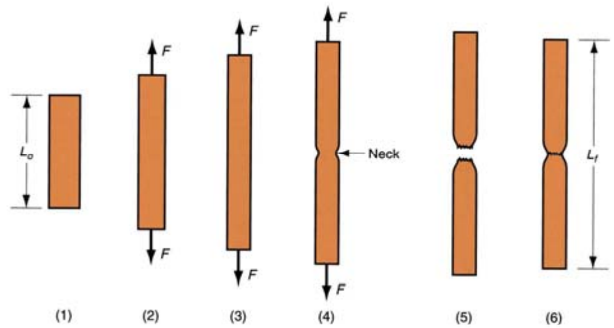
- In the test, a force pulls the material, elongating it and reducing its diameter



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

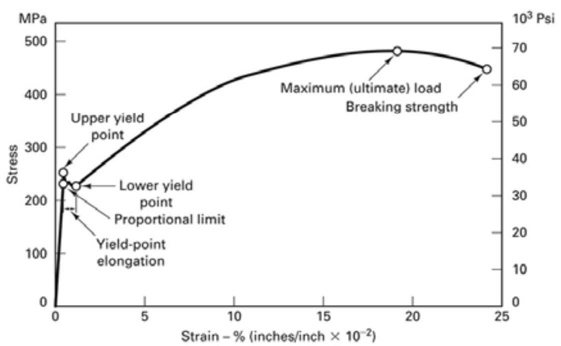
Tensile Test Sequence

- 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



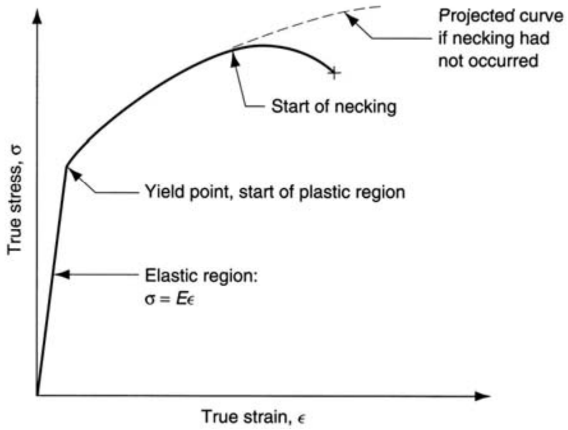
- Key features
  - Proportional limit (比例限) (below this limit, the strain is directly proportional to stress)
  - Ratio of stress to strain is Young's Modulus (楊氏係數)
    - Measures stiffness
  - Ultimate Strength (抗拉強度)
    - Stress at which the load-bearing ability peaks

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

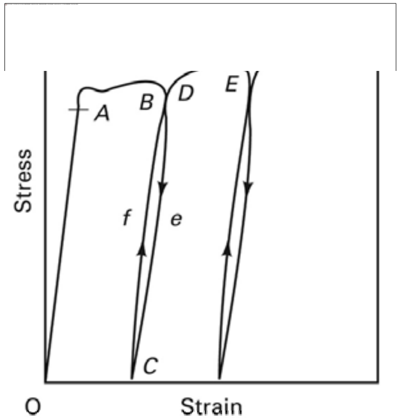
- True stress-strain curve
  - Instantaneous stress versus the summation of the incremental strain



(Source: Groover, 2005)

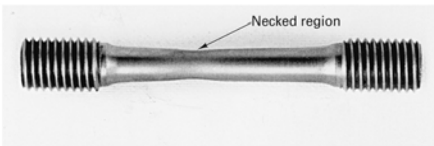
Strain Hardening (應變硬化)

- 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

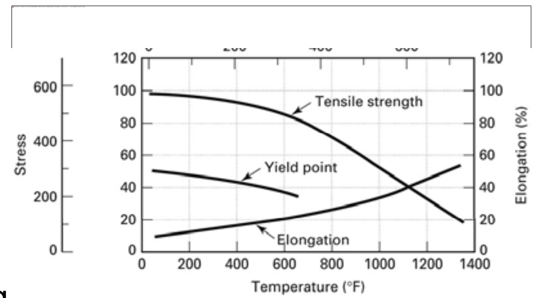


Percent Reduction in Area:

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

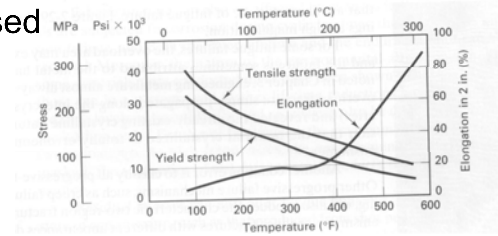
Temperature Effects

- 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



Material Properties in Metal Forming

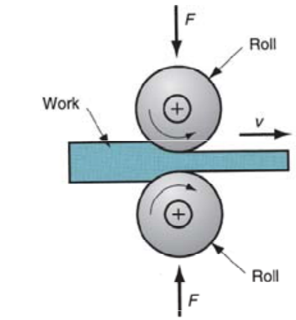
- Desirable material properties:
  - Low yield strength (低降伏強度)
  - High ductility (高延展性)
- These properties are affected by temperature:
  - Ductility increases and yield strength decreases when work temperature is raised
- Other factors:
  - Strain rate and friction



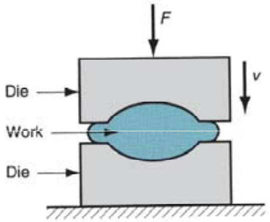
Basic Types of Deformation Processes

- Bulk deformation:
  - Rolling (輥壓): makes sheet metal
  - Forging (鍛造): makes strong solid parts
  - Extrusion (擠製): makes complex cross-sections from soft metals and plastics
  - Wire and bar drawing (拉製): makes strong small dia. wire
- Sheet metalworking
  - Bending (彎曲加工): Bend sheet metal about single axis (2D)
  - Deep drawing: makes "cups" from sheet metal, for mass production (3D)
  - Cutting (切斷): cut or punch sheetmetal
  - Miscellaneous processes

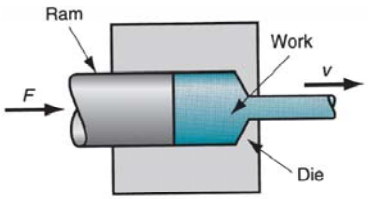
Bulk deformation



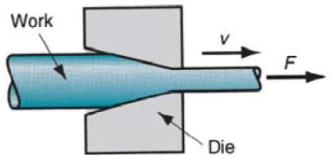
(a) Rolling



(b) Forging



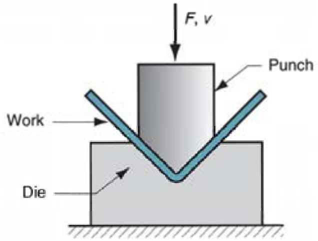
(c) Extrusion



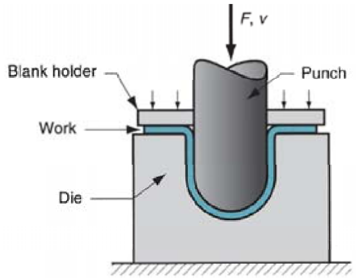
(d) Wire and bar drawing

(Source: Groover, 2005)

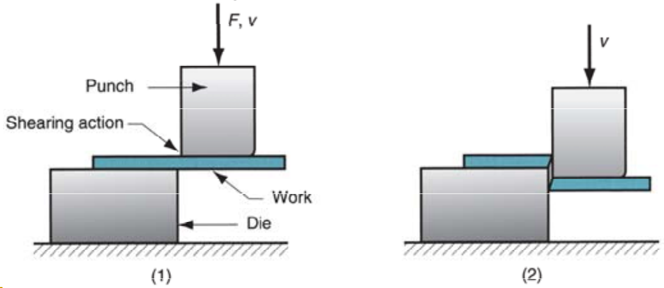
Forming Operations



(a) Bending



(b) Deep drawing



(c) Shearing

(Source: Groover, 2005)

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

Independent variables	Links	Dependent variables
Starting material		Force or power requirements
Starting geometry	-Experience-	Product properties
Tool geometry		Exit temperature
Lubrication	-Experiment-	Surface finish
Starting temperature		Dimensional precision
Speed of deformation	-Modeling-	Material flow details
Amount of deformation		

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

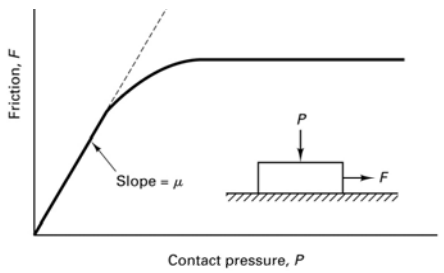
- Material being deformed must be characterized
  - Strength or resistance for deformation
  - Conditions at different temperatures
  - Formability limits
  - Reaction to lubricants
- Speed of deformation and its effects
- Speed-sensitive materials- more energy is required to produce the same results

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

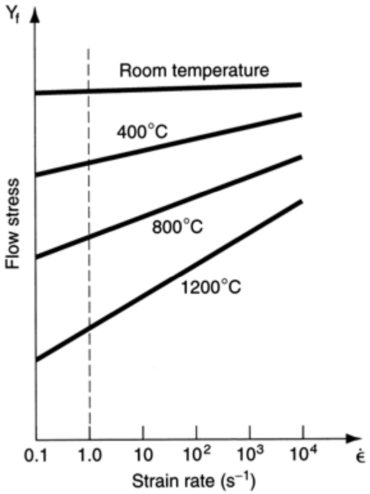
- Lower dimensional accuracy
- Higher total energy required
  - Due to the thermal energy to heat the workpiece
- Work surface oxidation (scale)
  - Poorer surface finish
- Shorter tool life

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

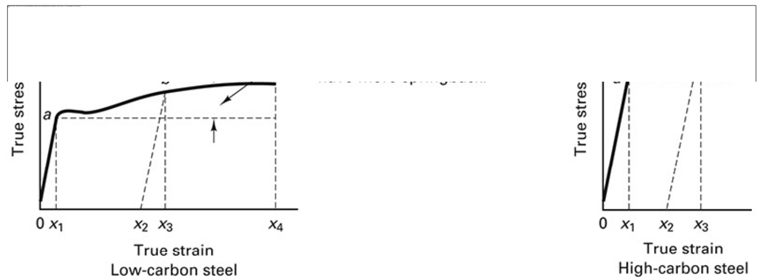
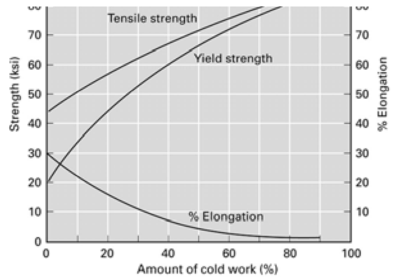


Figure 15-6 Use of true stress-true strain diagram to assess the suitability of two metals for cold working.

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).

1 UNS No.	2 SAE and/or AISI No.	3 Processing	4 Tensile Strength, MPa (kpsi)	5 Yield Strength, MPa (kpsi)	6 Elongation in 2 in, %	7 Reduction in Area, %	8 Brinell Hardness
G10060	1006	HR	300 (43)	170 (24)	30	55	86
		CD	330 (48)	280 (41)	20	45	95
G10100	1010	HR	320 (47)	180 (26)	28	50	95
		CD	370 (53)	300 (44)	20	40	105
G10150	1015	HR	340 (50)	190 (27.5)	28	50	101
		CD	390 (56)	320 (47)	18	40	111
G10180	1018	HR	400 (58)	220 (32)	25	50	116
		CD	440 (64)	370 (54)	15	40	126
G10200	1020	HR	380 (55)	210 (30)	25	50	111
		CD	470 (68)	390 (57)	15	40	131
G10300	1030	HR	470 (68)	260 (37.5)	20	42	137
		CD	520 (76)	440 (64)	12	35	149
G10350	1035	HR	500 (72)	270 (39.5)	18	40	143
		CD	550 (80)	460 (67)	12	35	163
G10400	1040	HR	520 (76)	290 (42)	18	40	149
		CD	590 (85)	490 (71)	12	35	170
G10450	1045	HR	570 (82)	310 (45)	16	40	163
		CD	630 (91)	530 (77)	12	35	179
G10500	1050	HR	620 (90)	340 (49.5)	15	35	179
		CD	690 (100)	580 (84)	10	30	197
G10600	1060	HR	680 (98)	370 (54)	12	30	201
G10800	1080	HR	770 (112)	420 (61.5)	10	25	229
G10950	1095	HR	830 (120)	460 (66)	10	25	248

HR = Hot Rolled;
CD = Cold Drawn

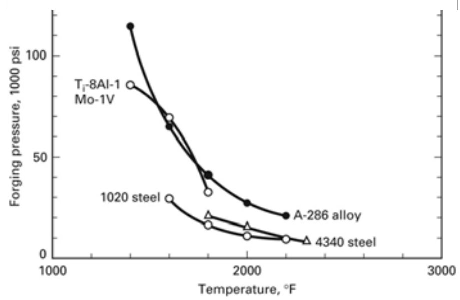
(Source: Budynas and Nisbett, 2008)

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.)*