Forming and Shaping

(1) Rolling
(2) Forging
(3) Extrusion and Drawing
(4) Sheet-Metal Forming
(5) Powder Metallurgy
(6) Forming and Shaping Plastics and Composite Materials
(7) Forming and Shaping Ceramics and Glass
Flat- and Shape-Rolling Processes

Figure 13.1 Schematic outline of various flat- and shape-rolling processes. Source: American Iron and Steel Institute.
Figure 13.2 (a) Schematic illustration of the flat-rolling process. (b) Friction forces acting on strip surfaces. (c) The roll force, $F$, and the torque acting on the rolls. The width $w$ of the strip usually increases during rolling, as is shown in Fig. 13.5.
Flat Rolling

- (1) Process (fig 13.2)
- (2) Frictional forces
  - draft \((h_0 - h_f) = \mu^2 R\)
  - higher friction and roll radius, greater the max. draft and reduction in thickness
(3) Roll force and power

- Roll force $F = L_w Y_{\text{avg}}$ for low $\mu$

- Power per roll = $\frac{2\pi F L N}{60000}$ KW
Flat Rolling

-roll forces reduced by
(a) reducing friction
(b) smaller diameter rolls
(c) smaller reduction per pass
(d) at elevated temperature
(e) back and front tension
Flat Rolling

- (4) Roll deflections
  - crown: strip thicker at center (fig. 13.4a)
  - camber: strip with uniform thickness (fig. 13.4b)
  - flattening of rolls: increase roll forces
  - roll stand: compensate roll deflections

- (5) Spreading (fig. 13.5)
Bending of straight cylindrical rolls, caused by the roll force. (b) Bending of rolls ground with camber, producing a strip with uniform thickness.
Figure 13.3 Schematic illustration of a four-high rolling-mill stand, showing its various features. The stiffnesses of the housing, the rolls, and the roll bearings are all important in controlling and maintaining the thickness of the rolled strip.
Spreading of a Strip

Figure 13.5  Increase in the width (spreading) of a strip in flat rolling (see also Fig. 13.2a). Similarly, spreading can be observed when dough is rolled with a rolling pin.
Flat-Rolling Practice

- (1) Cast and wrought structure (fig. 13.6)
- (2) Hot rolling
  - Al alloys: 450°C
  - Alloy steels: up to 1250°C
  - Refractory alloys: up to 1650°C
Grain Structure During Hot Rolling

Figure 13.6 Changes in the grain structure of cast or of large-grain wrought metals during hot rolling. Hot rolling is an effective way to reduce grain size in metals, for improved strength and ductility. Cast structures of ingots or continuous casting are converted to a wrought structure by hot working.
Flat-Rolling Practice

(3) Bloom - structural shapes (fig. 13.1)
- Slab - plates, strips
- Billet - bars, rods, wire
  - heavy scale or other defects
  - removed by grinding, blasting, acids
Flat-Rolling Practice

- (4) Pack rolling
  - flat-rolling operation of two or more layers of metal ex. Al foil

- (5) Temper rolling
  - reduce the stretcher strains or Lueder's bands by a light pass of 0.5 ~1.5% reduction
Flat-Rolling Practice

(6) Leveling rolls (fig.13.7)
- improve flattness
Roller Leveling and Defects in Flat Rolling

Figure 13.7  A method of roller leveling to flatten rolled sheets.  See also Fig 15.22.

Figure 13.8  Schematic illustration of typical defects in flat rolling: (a) wavy edges; (b) zipper cracks in the center of the strip; (c) edge cracks; and (d) alligatoring.
Defects

- (1) Internal or structural defects
- (2) Surface defects
  - scale, rust, scratches, gouges, pits, cracks
- (3) Inclusions and impurities
- (4) Wavy edges, zipper cracks, edge crack, alligating (fig. 13.8)
Figure 13.9  (a) Residual stresses developed in rolling with small rolls or at small reductions in thickness per pass. (b) Residual stresses developed in rolling with large rolls or at high reductions per pass. Note the reversal of the residual stress patterns.
Characteristics

(1) Residual stresses (fig. 13.9)

- small rolls or small reduction
  surface: compressive
  middle: tensile

- large rolls or high reduction
  surface: tensile
  middle: compressive
Outline of Forging and Related Operations

Figure 14.2

1. Billet Slug Preform
   - Shearing
   - Sawing
   - Cutting off
   - Machining

2. Furnaces
3. Hot Warm Isothermal
   - Heated dies

4.Forgeability
   - Heading, Coining, Fullering
   - Hubbing, Gathering
   - Piercing, Cogging
   - Roll forging, Skew rolling

5. Open die Impression die
   - Closed die
   - Precision
   - Orbital
   - Swaging

6. Trimming
   - Machining
   - Heat treating
   - Finishing
   - Cleaning

7. Hammers, Presses, Forging machines
   - Die design and manufacturing
   - Lubrication

8. Inspection
Open-Die Forging (upsetting or flat-die forging)

- (1) Process (fig. 14.3)
- (2) Cogging (drawing out)(fig. 14.5)
  - reduce thickness
- (3) Forging force

\[ F = Y_f \pi r^2 \left( 1 + \frac{2\mu r}{3h} \right) \]
Figure 14.3 A part made by three different processes, showing grain flow. (a) casting, (b) machining, (c) forging. *Source*: Forging Industry Association.
Figure 14.4  (a) Solid cylindrical billet upset between two flat dies.  (b) Uniform deformation of the billet without friction.  (c) Deformation with friction.  Note barreling of the billet caused by friction forces at the billet-die interfaces.
Impression-Die and Closed-Die Forging

- (1) Impression-die forging (fig. 14.6)
  - flash

- (2) Cropped or sheared (fig. 14.7)

- (3) Fullering (fig. 14.8b)
  - material distributed away from an area
Figure 14.6 Stages in impression-die forging of a solid round billet. Note the formation of flash, which is excess metal that is subsequently trimmed off (see Fig. 14.8).
Figure 14.7 (a) Stages in forging a connecting rod for an internal combustion engine. Note the amount of flash required to ensure proper filling of the die cavities. (b) Fullering, and (c) edging operations to distribute the material when preshaping the blank for forging.
Impression-Die and Closed-Die Forging

- (4) Edging (fig. 14.8c)
  - material gathered into a localized area
- (5) Blocking
- (6) Finishing
- (7) Trimming (fig. 14.9)
- (8) Precision forging
  - special and precision die
Trimming Flash from a Forged Part

Figure 14.8 Trimming flash from a forged part. Note that the thin material at the center is removed by punching.
Comparison of Forging With and Without Flash

Figure 14.9 Comparison of closed-die forging to precision or flashless forging of a cylindrical billet. Source: H. Takemasu, V. Vazquez, B. Painter, and T. Altan.
Impression-Die and Closed-Die Forging

- (9) Coining (sizing) (fig. 14.10-11)
- (10) Forging force
  \[ F = k_f Y A \]
- (11) Actual forging pressure range: 550-1000 MPa
Coining

Figure 14.10  (a) Schematic illustration of the coining process. the earliest coins were made by open-die forging and lacked sharp details.  (b) An example of a coining operation to produce an impression of the letter E on a block of metal.
Figure 14.11  (a) Heading operation, to form heads on fasteners such as nails and rivets.  (b) Sequence of operations to produce a bolt head by heading.
Related Forging Operations

- (1) Heading (fig. 14.12)
  - typical parts: head of bolts, screw, rivets, nails
- (2) Pieceing (fig. 14.13)
- (3) Hubbing (fig. 14.14)
- (4) Roll forging (fig. 14.15)
- (5) Skew rolling (fig. 14.16)
  - production of steel ball
Grain Flow Pattern of Pierced Round Billet

Figure 14.12 A pierced round billet, showing grain flow pattern. Source: Courtesy of Ladish Co., Inc.
Roll-Forging

Figure 14.13  Two examples of the roll-forging operation, also known as *cross-rolling*. Tapered leaf springs and knives can be made by this process. *Source:* (a) J. Holub; (b) reprinted with permission of General Motors Corporation.
Production of Bearing Blanks

Figure 14.14 (a) Production of steel balls by the skew-rolling process. (b) Production of steel balls by upsetting a cylindrical blank. Note the formation of flash. The balls made by these processes are subsequently ground and polished for use in ball bearings (see Sections 25.6 and 25.10).
Orbital Forging

Figure 14.15  (a) Various movements of the upper die in orbital forging (also called rotary, swing, or rocking-die forging); the process is similar to the action of a mortar and pestle.  (b) An example of orbital forging. Bevel gears, wheels, and rings for bearings can be made by this process.
Swaging

Figure 14.16  (a) Schematic illustration of the rotary-swaging process. (b) Forming internal profiles on a tubular workpiece by swaging. (c) A die-closing type swaging machine, showing forming of a stepped shaft. (d) Typical parts made by swaging.
Impression-Die and Closed-Die Forging

(6) Orbital forging (fig. 14.17)
- typical parts: disk shaped parts
- relatively small force

(7) Isothermal forging (fig. 14.18)
- die: Ni or Mo alloys
- intricate forging of Ti or superalloys
Figure 14.17 (a) Swaging of tubes without a mandrel; not the increase in wall thickness in the die gap. (b) Swaging with a mandrel; note that the final wall thickness of the tube depends on the mandrel diameter. (c) Examples of cross-sections of tubes produced by swaging on shaped mandrels. Rifling (spiral grooves) in small gun barrels can be made by this process.
Swaging (radial forging)

- (1) Rotary swaging (fig. 14.19a)
  - rod or tube subjected to radial impact forces by reciprocating dies
- (2) Die-closing swaging (fig. 14.19b)
- (3) Tube swaging (fig. 14.20-21)
Impression-Forging Die and Die Inserts

Figure 14.18 Standard terminology for various features of a typical impression-forging die.

Figure 14.19 Die inserts used in dies for forging an automotive axle housing. (See Tables 5.5 to 5.7 for die materials.) *Source: Metals Handbook, Desk Edition.* ASM International, Metals Park, Ohio, 1985. Used with permission.
Figure 14.20 Examples of defects in forged parts. (a) Laps formed by web buckling during forging; web thickness should be increased to avoid this problem. (b) Internal defects caused by oversized billet; die cavities are filled prematurely, and the material at the center flows past the filled regions as the dies close.
Principles of Various Forging Machines

Figure 14.21 Schematic illustration of the principles of various forging machines. (a) Hydraulic press. (b) Mechanical press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft to give the up-and-down motion to the ram. (continued)
Extrusion and Drawing

(1) Extrusion (fig. 15.1-2)
- Typical products: door, window frames, tubing, structural shapes
- Extruded materials: A1, Cu, steel, Mg, Pb, Ti, refractory metals
Direct Extrusion

Figure 15.1  Schematic illustration of the direct extrusion process.
Figure 15.2 Extrusions, and examples of products made by sectioning off extrusions. *Source:* Kaiser Aluminum.
Extrusion and Drawing

(2) Drawing
- typical products: wire, rod, cable, springs, tubing
Extrusion Process

(1) Methods

- direct or Forward Extrusion (fig. 15.1)
- indirect, Reverse or Backward Extrusion (fig. 15.2a)
- hydrostatic Extrusion (fig. 15.2b)
- lateral Extrusion (fig. 15.2c)
Extrusion Process

(2) Parameters
- extrusion ratio $A_o/A_f$ (fig. 15.4)
- die angle
- friction in the wall and die
- circumscribing-circle diameter (CCD) (fig. 15.5)
- shape factor: perimeter/cross-section area
- temperature
- extrusion speed
- lubrication
Process Variables in Direct Extrusion

Figure 15.4 Process variables in direct extrusion. The die angle, reduction in cross-section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.
Circumscribing-Circle Diameter

Figure 15.5 Method of determining the circumscribing-circle diameter (CCD) of an extruded cross-section.
Extrusion Process

- (3) Extrusion Force

\[ F = A_o k \times \ln \left( \frac{A_o}{A_f} \right) \]

\( k \) : extrusion constant (fig. 15.6)

- (4) Metal Flow Pattern (fig. 15.7)
  - dead-metal zones
Extrusion Constant $k$ for Various Metals

Figure 15.6 Extrusion constant $k$ for various metals at different temperatures. Source: P. Loewenstein.
Types of Metal Flow in Extruding With Square Dies

Figure 15.7 Types of metal flow in extruding with square dies. (a) Flow pattern obtained at low friction, or in indirect extrusion. (b) Pattern obtained with high friction at the billet-chamber interfaces. (c) Pattern obtained at high friction, or with cooling of the outer regions of the billet in the chamber. This type of pattern, observed in metals whose strength increases rapidly with decreasing temperature, leads to a defect known as pipe, or extrusion defect.
Extrusion Practice

(1) Extrusion ratio: 10:1 to 100:1
(2) CCD: Al: 6 mm to 1 m, most 0.25 m
    steel: up to 0.15 m
(3) Ram speed: up to 0.5 m/s
(4) Coaxial extrusion
(5) Stepped extrusion
Hot Extrusion

(1) Die preheated
- reduce cooling of the billet
- prolong die life
Hot Extrusion

(2) Die Design and Materials (fig.15.8)
- square die (shear die): nonferrous metals, Al
- spider die, porthole die, bridges die (fig.15.9) hollow cross-section
- guidelines for die design (fig.15.10)
- die materials: hot-work die steels with Zr (partially stabilized Zr) coating
Extrusion-Die Configurations

Figure 15.8  Typical extrusion-die configurations: (a) die for nonferrous metals; (b) die for ferrous metals; (c) die for T-shaped extrusion, made of hot-work die steel and used with molten glass as a lubricant. Source for (c): Courtesy of LTV Steel Company.
Components for Extruding Hollow Shapes

Figure 15.9  (a) An extruded 6063-T6 aluminum ladder lock for aluminum extension ladders. This part is 8 mm (5/16 in.) thick and is sawed from the extrusion (see Fig. 15.2).  (b)-(d) Components of various dies for extruding intricate hollow shapes.  Source: for (b)-(d): K. Laue and H. Stenger, Extrusion--Processes, Machinery, Tooling.  American Society for Metals, Metals Park, Ohio, 1981.  Used with permission.
Hot Extrusion

(3) Lubrication (table I3.1)
- glass for steel, stainless steel, high temp. metals

(4) Jacketing (canning)
- use Cu or mild steel container to avoid metals stucked to the container
# Extrusion Temperature Ranges for Various Metals

<table>
<thead>
<tr>
<th>Metal</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>200–250</td>
</tr>
<tr>
<td>Aluminum and its alloys</td>
<td>375–475</td>
</tr>
<tr>
<td>Copper and its alloys</td>
<td>650–975</td>
</tr>
<tr>
<td>Steels</td>
<td>875–1300</td>
</tr>
<tr>
<td>Refractory alloys</td>
<td>975–2200</td>
</tr>
</tbody>
</table>
Cold Extrusion

(1) Advantages
- improve mechanical properties
- good tolerance
- improve surface finish
- high production rates
Examples of Cold Extrusion

Figure 15.11 Two examples of cold extrusion. Thin arrows indicate the direction of metal flow during extrusion.
Cold Extrusion

- (2) Punch hardness: HRC 60-65
- (3) Die hardness: HRC 58-62
- (4) Tool materials: table 5.9
- (5) Example: part and bevel-gear shaft
Cold Extruded Spark Plug

Figure 15.12 Production steps for a cold extruded spark plug. *Source:* National Machinery Company.

Figure 15.13 A cross-section of the metal part in Fig. 15.12, showing the grain flow pattern. *Source:* National Machinery Company.
Impact Extrusion

(1) Similar to indirect extrusion
Figure 15.14  Schematic illustration of the impact-extrusion process. The extruded parts are stripped by the use of a stripper plate, because they tend to stick to the punch.
Examples of Impact Extrusion

Figure 15.15  (a) Two examples of products made by impact extrusion. These parts may also be made by casting, by forging, or by machining; the choice of process depends on the dimensions and the materials involved and on the properties desired. Economic considerations are also important in final process selection.  (b) and (c) Impact extrusion of a collapsible tube by the Hooker process.
Hydrostatic Extrusion

1. Pressure: 1400 MPa
2. Characters
   - Improve ductility
   - Typical products: solid shapes, tubes, hollow shapes honeycomb, clad profiles
3. Fluid
   - Vegetable oils at room temp.
   - Waxes, polymers, glass at elevated temp.
Extrusion Defects

- (1) Surface cracking or tearing (hot shortness)
  - due to high temp., friction, and speed
  - occur in Al, Mg, Zn, high temp. alloys

- (2) Pipe (tailpipe or fishtailing) (fig. 15.16)
  - due to improper metal flow pattern (fig. 15.7c)
  - reduce by controlling friction, temp. gradient, flow pattern
Figure 15.16  (a) Chevron cracking (central burst) in extruded round steel bars. Unless the products are inspected, such internal defects may remain undetected, and later cause failure of the part in service. This defect can also develop in the drawing of rod, of wire, and of tubes. (b) Schematic illustration of rigid and plastic zones in extrusion. The tendency toward chevron cracking increases if the two plastic zones do not meet. Note that the plastic zone can be made larger either by decreasing the die angle or by increasing the reduction in cross-section (or both). Source: B. Avitzur.
Extrusion Defects

(3) Internal cracking (center or chevron cracking) (fig. 15.17)
- due to a state of hydrostatic tensile stress at the centerline
- increase with increasing die angle and amount of impurities and decreasing extrusion ratio and friction
Hydraulic-Extrusion Press

Figure 15.17  General view of a 9-MN (1000-ton) hydraulic-extrusion press. 
Source: Courtesy of Jones & Laughlin Steel Corporation.
Chap. 16
Sheet-Metal Forming
(1) Typical products: metal desks, file cabinets, appliances, car bodies, aircraft fuselages, beverage cans

(2) Typical materials: low-carbon steels

(3) Outline of sheet-metal forming processes (fig.16-1).
Outline of Sheet-Metal Forming Processes

Figure 16.1
Shearing (blanking/piercing)

(1) Process - three steps (fig. 16.2)
- Plastic deformation
  penetration depth = 0.3 thickness of sheet-metal
- Shear
  smooth and shiny burnished surfaces burnish depth
- Fracture
  rough fracture surfaces
  fracture depth
  fracture angle
Figure 16.2 (a) Schematic illustration of shearing with a punch and die, indicating some of the process variables. Characteristic features of (b) a punched hole and (c) the slug. Note that the scales of the two figures are different.
Shearing (blanking/piercing)

(2) Major parameters
- shape and materials for punch and die
- punch speed
- lubrication
- clearance
Shearing (blanking/piercing)

- (3) Increasing clearance
  - rougher sheared edge and zone
  - larger deformation zone (fig. 16.3)
  - decrease the ratio of the burnished to rough areas
Figure 16.3 (a) Effect of the clearance, $c$, between punch and die on the deformation zone in shearing. As the clearance increases, the material tends to be pulled into the die rather than be sheared. In practice, clearances usually range between 2% and 10% of the thickness of the sheet. (b) Microhardness (HV) contours for a 6.4-mm (0.25-in) thick AISI 1020 hot-rolled steel in the sheared region. Source: H. P. Weaver and K. J. Weinmann.
Shearing (blanking/piercing)

- (4) Increasing punch speed
  - smaller deformation zone
  - narrower and smoother sheared surface
- (5) Burr
- (6) Punch force
  \[ F = 0.7 \text{ TL (UTS)} \]
Shearing (blanking/piercing)

(7) Shearing operations
- die cutting (fig. 16.4b)
  perforating
  parting
  notching
  lancing
- fine blanking (fig. 16.5)
Figure 16.4  (a) Punching (piercing) and blanking.  (b) Examples of various shearing operations on sheet metal.
Figure 16.5  (a) Comparison of sheared edges produced by conventional (left) and by fine-blanking (right) techniques.  (b) Schematic illustration of one setup for fine blanking.  *Source:* Feintool U.S. Operations.
Shearing (blanking/piercing)

- slitting (fig. 16.6)
- steel rules
  - soft metals paper, leather rubber
- nibbling
- scrap in shearing
Figure 16.6 Slitting with rotary knives. This process is similar to opening cans.
Shearing (blanking/piercing)

- (8) Shearing dies
  - shaving (fig. 16.7)
  - shear angle (fig. 16.8)
    reduce shear force
  - compound dies (fig. 16.9)
  - progressive dies (fig. 16.10)
  - transfer dies
Figure 16.7 Production of an outer side panel of a car body, by laser butt-welding and stamping. Source: After M. Geiger and T. Nakagawa.

Legend

- g 60/60 (45/45) Hot galvanized alloy steel sheet. Zinc amount: 60/60 (45/45) g/m².
- m20/20 Double-layered iron-zinc alloy electroplated steel sheet. Zinc amount 20/20 g/m².
Examples of Laser Welded Parts

Figure 16.8 Examples of laser butt-welded and stamped automotive body components. Source: After M. Geiger and T. Nakagawa.
Figure 16.9  Schematic illustrations of the shaving of a sheared edge. (a) Shaving a sheared edge. (b) Shearing and shaving, combined in one stroke.

Figure 16.10  Examples of the use of shear angles on punches and dies.
Shearing (blanking/piercing)

- (9) Die materials and heat treatment
  - tool steel, HSS, carbides
- (10) Lubrication
Sheet-Metal Characteristics

- (1) Elongation
- (2) Yield-point elongation
  - lueder's band
  - temper rolling by 0.5-1.5% cold rolling
- (3) Anisotropy
- (4) Grain size
  - orange peel
Test Methods for Formability of Sheet Metals

- (1) Cupping tests (fig. 16.13)
- (2) Bulge test (fig. 16.14)
  - biaxial stretching
  - forming-limit diagram (FLD) (fig. 16.15)