Chapter Outline

- Introduction
- Open-die Forging
- Impression-die and Closed-die Forging
- Various Forging Operations
- Forgeability of Metals; Forging Defects
- Die Design, Die Materials, and Lubrication
- Die-manufacturing Methods and Die Failures
- Forging Machines
- Economics of Forging
Forging process is where workpiece is shaped by compressive forces applied through dies and tooling.

Forging operations produce *discrete parts*.

Forged parts have good strength and toughness, and are reliable for highly stressed and critical applications.

Forging can carry out at room temperature (*cold forging*) or at elevated temperatures (*warm or hot forging*) depending on the homologous temperature.
Introduction
Open-die Forging

- **Open-die forging** is the simplest forging operation.

<table>
<thead>
<tr>
<th>General Characteristics of Forging Processes</th>
<th>Process</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open die</td>
<td>Simple and inexpensive dies; wide range of part sizes; good strength</td>
<td>Limited to simple shapes; difficult to hold close tolerances; machining to</td>
</tr>
<tr>
<td></td>
<td></td>
<td>characteristics; generally for small quantities</td>
<td>final shape necessary; low production rate; relatively poor utilization of</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>material; high degree of skill required</td>
</tr>
<tr>
<td></td>
<td>Closed die</td>
<td>Relatively good utilization of material; generally better properties than</td>
<td>High die cost, not economical for small quantities; machining often</td>
</tr>
<tr>
<td></td>
<td></td>
<td>open-die forgings; good dimensional accuracy; high production rates; good</td>
<td>necessary</td>
</tr>
<tr>
<td></td>
<td></td>
<td>reproducibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Blocker</td>
<td>Low die costs; high production rates</td>
<td>Machining to final shape necessary; parts with thick webs and large</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fillets</td>
</tr>
<tr>
<td></td>
<td>Conventional</td>
<td>Requires much less machining than blocker type; high production rates; good</td>
<td>Higher die cost than blocker type</td>
</tr>
<tr>
<td></td>
<td></td>
<td>utilization of material</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Precision</td>
<td>Close dimensional tolerances; very thin webs and flanges possible;</td>
<td>High forging forces, intricate dies, and provision for removing forging</td>
</tr>
<tr>
<td></td>
<td></td>
<td>machining generally not necessary; very good material utilization</td>
<td>from dies</td>
</tr>
</tbody>
</table>
Open-die Forging

- Open-die forging is where a solid workpiece is placed between two flat dies and reduced in height by compressing it.
- Also called **upsetting** or **flat die forging**.
- Workpiece is deformed *uniformly* under *frictionless* conditions.

![Diagram](image_url)
Open-die Forging

- **Barreling** is caused by frictional forces that oppose the outward flow of the workpiece at the die interfaces.
- Minimized by using an effective lubricant.
- **Cogging** is an open-die forging operation where thickness of a bar is reduced by successive forging steps at specific intervals.
Open-die Forging

The forging force, $F$, in an open-die forging operation on a solid cylindrical workpiece can be estimated from

$$F = Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right)$$

$Y_f = \text{flow stress of the material}$
$\mu = \text{coefficient of friction between the workpiece and die}$
$r = \text{the instantaneous radius}$
$h = \text{height of the workpiece}$
EXAMPLE 14.1

Calculation of Forging Force in Upsetting

A solid cylindrical slug made of 304 stainless steel is 150 mm in diameter and 100 mm high. It is reduced in height by 50% at room temperature by open-die forging with flat dies. Assuming that the coefficient of friction is 0.2, calculate the forging force at the end of the stroke.
Open-dieForging

Solution

Calculation of Forging Force in Upsetting

The final radius is \( \pi (75)^2 (100) = \pi (r)^2 \left( \frac{100}{2} \right) \Rightarrow r = 106 \text{ mm} \)

Absolute value of the true strain is \( \epsilon = \ln \left( \frac{100}{50} \right) = 0.69 \)

From Table 2.3, 304 stainless steel has \( K = 1275 \text{ MPa} \) and \( n = 0.45 \). Thus for a true strain of 0.69, the flow stress is 1100 MPa.

The forging force is \( F = (1000)(10^6)\pi (0.106)^2 (1) + \frac{(2)(0.2)(0.106)}{(3)(0.05)} = 45 \text{ MN} \)
Impression-die and Closed-die Forging

- In *impression-die forging*, the workpiece takes the shape of the die cavity while being forged between two shaped dies.
Impression-die and Closed-die Forging

- The blank to be forged is prepared by:
  1. *Cropping* from an extruded or drawn bar stock
  2. Preforming from operations such as *powder metallurgy*
  3. *Casting* or
  4. Using a preformed blank from a prior forging operation
Forging Force

- The forging force, $F$, required to carry out an impression-die forging operation is

$$F = kY_f A$$

- $k$ = multiplying factor obtained
- $Y_f$ = flow stress of the material at the forging temperature

### Range of $k$ Values for Eq. (14.2)

<table>
<thead>
<tr>
<th>Shape</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple shapes, without flash</td>
<td>3–5</td>
</tr>
<tr>
<td>Simple shapes, with flash</td>
<td>5–8</td>
</tr>
<tr>
<td>Complex shapes, with flash</td>
<td>8–12</td>
</tr>
</tbody>
</table>
Impression-die and Closed-die Forging

Closed-die Forging

- In true closed-die forging, flash does not form and the workpiece completely fills the die cavity
- Undersized blanks prevent the complete filling of the die cavity
- It is applied to impression die forging with flash generation

(a) 1. Start of stroke
(b) 1. Start of stroke

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Impression-die and Closed-die Forging

Precision Forging

- In true closed-die forging, flash does not form and the workpiece completely fills the die cavity.
- Undersized blanks prevent the complete filling of the die cavity.
- Precision forging requires:
  1. Special and more complex dies
  2. Precise control of the blank’s volume and shape
  3. Accurate positioning of the blank in the die cavity.
Various Forging Operations

Coining

- A closed-die forging process used in the minting of coins, medallions and jewellery
- **Marking** parts with letters and numbers can be done rapidly through coining
Various Forging Operations

Heading

- Also called **upset forging**
- An upsetting operation performed on the end of a round rod or wire in order to increase the cross section
- Products are nails, bolt heads, screws, rivets, and fasteners
Various Forging Operations

Piercing

- A process of indenting the surface of a workpiece with a punch in order to produce a cavity or an impression

- *Piercing force* depends on:
  1. Cross-sectional area and the tip geometry of the punch
  2. Strength of the material
  3. Magnitude of friction at the sliding interfaces
Various Forging Operations

CASE STUDY 14.1

Manufacture of a Stepped Pin by Heading and Piercing Operations

- A stepped pin is made from SAE 1008 steel
- Cold-forging steps is used to produce this part
Various Forging Operations

Hubbing
- Process consists of pressing a hardened punch with a tip geometry into the surface of a block of metal
- *Hubbing force* can be estimated from $3(UTS)(A)$
- UTS is obtained from Table 2.2 and $A$ is the projected area of the impression

Orbital Forging
- Upper die moves along an orbital path and forms the part *incrementally*
- Operation is quiet, and parts is formed within 10 to 20 cycles of the orbiting die
Various Forging Operations

Incremental Forging

- In this process, a tool forges a blank into a shape in several small steps.
- Similar to cogging where the die penetrates the blank to different depths along the surface.

Diagram:

- Retainer
- Hammer
- Die
- Driven
- Planetary rollers
Various Forging Operations

Isothermal Forging

- Known as **hot-die forging** process where it heats the dies to the same temperature as workpiece
- Complex parts with good dimensional accuracy can be produce

Rotary Swaging

- A solid rod or tube is subjected to radial impact forces by a set of reciprocating dies of the machine
Various Forging Operations

**Tube Swaging**

- The internal diameter and/or the thickness of the tube is reduced with or without the use of *internal mandrels*.
Forgeability of Metals; Forging Defects

- **Forgeability** is defined as the capability of a material to undergo deformation without cracking.

- 2 simple tests:
  1. **Upsetting test**
     - greater the deformation prior to cracking, the greater the forgeability of the metal
  2. **Hot-twist test**
     - maximum number of turns occurs then becomes the forging temperature for maximum forgeability

<table>
<thead>
<tr>
<th>Forgeability of Metals, in Decreasing Order</th>
<th>Approximate range of hot-forging temperatures (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal or alloy</td>
<td></td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>400–550</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>250–350</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>600–900</td>
</tr>
<tr>
<td>Carbon- and low-alloy steels</td>
<td>850–1150</td>
</tr>
<tr>
<td>Martensitic stainless steels</td>
<td>1100–1250</td>
</tr>
<tr>
<td>Austenitic stainless steels</td>
<td>1100–1250</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>700–950</td>
</tr>
<tr>
<td>Iron-based superalloys</td>
<td>1050–1180</td>
</tr>
<tr>
<td>Cobalt-based superalloys</td>
<td>1180–1250</td>
</tr>
<tr>
<td>Tantalum alloys</td>
<td>1050–1350</td>
</tr>
<tr>
<td>Molybdenum alloys</td>
<td>1150–1350</td>
</tr>
<tr>
<td>Nickel-based superalloys</td>
<td>1050–1200</td>
</tr>
<tr>
<td>Tungsten alloys</td>
<td>1200–1300</td>
</tr>
</tbody>
</table>
Forgeability of Metals; Forging Defects

Forging Defects

- When there is an insufficient volume of material, the web will buckle and develop laps.
- If the web is too thick, excess material flows will develop internal cracks.
Forgeability of Metals; Forging Defects

Forging Defects

- Internal defects may develop from:
  1. Nonuniform deformation of the material in the die cavity
  2. Temperature gradients throughout the workpiece during forging
  3. Microstructural changes caused by phase transformations

- Forging defects can cause fatigue failures
Die Design, Die Materials, and Lubrication

- Design of forging dies includes shape and complexity of the workpiece, ductility, strength and sensitivity to deformation rate and temperature, and frictional characteristics.

- Workpiece *intermediate shapes* should be planned so that they properly fill the die cavities.

- Software is available to help predict material flow in forging-die cavities.
Preshaping

- In a properly pre-shaped workpiece:
  1. Material should not flow easily into the flash
  2. Grain flow pattern should be favorable for the products’ strength and reliability
  3. Sliding at the workpiece–die interfaces should be minimized in order to reduce die wear
Die Design Features

- The **parting line** should locate at the largest cross section of the part.
- For simple symmetrical shapes, the parting line is a straight line at the center of the forging.
- For complex shapes, the line may not lie in a single plane.
- **Draft angles** are needed to facilitate removal of the part from the die.
- Selection of the proper radii for corners and fillets is to ensure smooth flow of the metal into the die cavity and improving die life.
Die Design, Die Materials, and Lubrication

Die Materials

- Requirements for die materials are:
  1. Strength and toughness at elevated temperatures
  2. Hardenability and ability to harden uniformly
  3. Resistance to mechanical and thermal shock
  4. Wear resistance

Lubrication

- Greatly influences friction and wear
- Affects the forces required, die life, and material flows into the die cavities

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Die-manufacturing Methods and Die Failures

- Die quality and life are significant aspects of the total manufacturing operation and quality of the parts produced.
- Manufacturing methods that used to make dies are casting, forging, machining, grinding, electrical and electrochemical methods and lasers for small dies.
- Process of producing a die cavity in a die block is called die sinking.
- Hubbing, cold or hot, also used to make small dies with shallow cavities.
- Surface profile and finish are improved by finish grinding and polishing.
Die-manufacturing Methods and Die Failures

- Dies are *machined* from *forged die blocks* by high-speed milling, turning, grinding, and electrical discharge and electrochemical machining.
- Dies are subjected to *finishing operations* such as grinding, polishing, and chemical and electrical processes for surface finish and dimensional accuracy.

**Die Costs**

- Cost of a die depends on its size, shape complexity, application and surface finish required.
- Large number of parts are made from one set of dies.
- *Die cost per piece made* is a small portion of a part’s manufacturing cost.
Die Failures

- Failure of dies results in
  1. Improper die design
  2. Defective die material
  3. Improper finishing operations
  4. Overheating and heat checking
  5. Excessive wear
  6. Overloading
  7. Improper alignment
  8. Misuse
  9. Improper handling of the die
Die Failures

- The proper design of dies and selection of die materials is important
- Large cross sections and clearances of a die is needed to withstand the forces
- Overloading of tools and dies can cause premature failure
Forging Machines

Hydraulic Presses

- Operate at constant speeds and are *load limited*
- Hydraulic presses are slower and involve higher initial costs but require less maintenance

### Typical Speed Ranges of Forging Equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic press</td>
<td>0.06–0.30</td>
</tr>
<tr>
<td>Mechanical press</td>
<td>0.06–1.5</td>
</tr>
<tr>
<td>Screw press</td>
<td>0.6–1.2</td>
</tr>
<tr>
<td>Gravity drop hammer</td>
<td>3.6–4.8</td>
</tr>
<tr>
<td>Power drop hammer</td>
<td>3.0–9.0</td>
</tr>
<tr>
<td>Counterblow hammer</td>
<td>4.5–9.0</td>
</tr>
</tbody>
</table>
Forging Machines

Mechanical Presses

- They are either the crank or the eccentric type
- Mechanical presses are *stroke limited since* speed varies from a maximum to zero
- Due to linkage design, very high forces can be applied in this type of press
- Mechanical presses are preferred for forging parts with high precision
Economics of Forging

- Depending on the complexity of the forging, tool and die, costs range from moderate to high.
- Costs are spread out over the number of parts forged with that particular die set.
- The more expensive the material, the higher the cost of the material relative to the total cost.
- Size of forgings also has some effect on cost.
CASE STUDY 14.2
Suspension Components for the Lotus Elise Automobile

- Lotus group investigated the use of steel forgings to reduce cost and improve reliability and performance.
CASE STUDY 14.2
Suspension Components for the Lotus Elise Automobile

- Used advanced software tools to reduce the number of components and to determine the optimum geometry

<table>
<thead>
<tr>
<th>Fig. 14.20 sketch</th>
<th>Material</th>
<th>Application</th>
<th>Mass (kg)</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b)</td>
<td>Aluminum extrusion, steel bracket, steel bushing, housing</td>
<td>Original design</td>
<td>2.105</td>
<td>85</td>
</tr>
<tr>
<td>(c)</td>
<td>Forged steel</td>
<td>Phase I</td>
<td>2.685 (+28%)</td>
<td>27.7 (-67%)</td>
</tr>
<tr>
<td>(d)</td>
<td>Forged steel</td>
<td>Phase II</td>
<td>2.493 (+18%)</td>
<td>30.8 (-64%)</td>
</tr>
</tbody>
</table>