Chapter 14
Forging of Metals

Alexandra Schönning, Ph.D.
Mechanical Engineering
University of North Florida

Figures by
Manufacturing Engineering and Technology
Kalpakjian and Schmid

Introduction

What is forging?
- A process in which the workpiece is shaped by compressive forces applied through dies and tools
- Was initially used by hammering metals with tools in shaping jewelry and coins
- Can be performed using a hammer and an anvil

Forging results in discrete parts
- Bolts, rivets, connecting rods, shafts for turbines, gears, hand tools

Temperature
- Room or elevated

Cold forging
- Requires greater force
- Good dimensional accuracy and surface finish

Hot forging
- Requires less force
- Dimensional accuracy and surface finish not as good

Forging results in discrete parts
- Bolts, rivets, connecting rods, shafts for turbines, gears, hand tools

Temperature
- Room or elevated

Cold forging
- Requires greater force
- Good dimensional accuracy and surface finish

Hot forging
- Requires less force
- Dimensional accuracy and surface finish not as good

Finishing operations are generally required
- Heat treating
- Precision forging
- New trend

Grain structure in forging can be controlled
- Results in good strength and toughness

Characteristics of Forging Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open die</td>
<td>Simple, inexpensive dies; useful for small quantities; wide range of sizes available; good strength characteristics</td>
<td>Limited to simple shapes; difficult to hold close tolerances; machining to final shape necessary; low production rates; relatively poor utilization of material; high degree of skill required</td>
</tr>
<tr>
<td>Closed die</td>
<td>Relatively good utilization of material; generally better properties than open-die forgings; good dimensional accuracy; high production rates; good reproducibility</td>
<td>High die cost for small quantities; machining often necessary</td>
</tr>
<tr>
<td>Blocker type</td>
<td>Less die cost; high production rates</td>
<td>Machining or final shape necessary; thick webs and large fillets necessary; some wear; higher die cost than blocker type</td>
</tr>
<tr>
<td>Continuous type</td>
<td>Requires low stress machining than blocker type; high production rates; good utilization of material;</td>
<td>Requires high forces, intricate dies, and provision for removing forging from dies</td>
</tr>
<tr>
<td>Precision type</td>
<td>Close tolerances; machining often easy; consistent very good material utilization; very thin webs and flanges possible</td>
<td></td>
</tr>
</tbody>
</table>

Impression-Die Forging

The workpiece acquires the shape of the die cavities (impressions are made)

The process:
- The blank is created by:
  - Cutting from an extruded or drawn bar stock
  - Powder metallurgy
  - Casting
- Precision blank in a prior forging operation

Blank is placed in the lower die
The upper die descends
The workplace deforms due to the compressive forces applied.

Fullerling (Figure b)
- Material is distributed away from an area

Edging (Figure c)
- Material is forced into an area
Impression-Die Forging (cont.)

- Blocking
  - Uses blocking dies. Results in almost the proper shape
- Finishing
  - In impression dies.
  - This gives the final details of the forging
- Removal of flash
  - Flash. Material the flows out through the parting line
- Closed Die forging
  - No flash is formed. The material completely fills the cavity.
  - Undersized blanks: don’t fill the cavity completely
  - Oversized blanks: flash is created. Excessive pressure is needed; dies may fail prematurely.

Comparison of Forging With and Without Flash

- The right side of the sphere experiences flashless forging
- The left side experiences forging with flash

Precision Forging

- Trend of today:
- Near-net shape, near-net-forging
- Formed part is close to the final dimensions
- Special dies with higher accuracy
- Greater forces are required
  - Material used: those requiring low forging loads
    - Aluminum alloys, magnesium alloys
- Final part requires less machining
- Good surface finish
- Cost: Tradeoff
  - Higher investment
  - More expensive dies
  - Higher loads
  - Higher accuracy in positioning of the workpiece
  - Financial advantage
    - Less material is wasted
    - Less machining is required

Forging Force

- What force is required for impression-die forging?
  - \( F = kY_fA \)
  - \( F \) = required force
  - \( k \) = multiplying factor (Table 4.2)
  - \( Y_f \) = flow stress of the material at the forging temperature
  - \( A \) = projected area of the forging (including flash)

<table>
<thead>
<tr>
<th>Shape</th>
<th>Range of k Values for Equation ( F = kY_fA )</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>

Coining

- Completely closed-die forging process
- Used in:
  - Minting coins, medallions, and jewelry
- Lubricants can’t be used
  - Can become entrapped in the cavity, hindering full closure of the die
  - Some surface details may not be imprinted

Related Forging Operations

- Heading
  - Upsetting operation (flat-die forging)
  - Perfomed at the end of a round bar/wire
  - Example: heads of bolts
  - Buckling may occur
    - Unsupported length-to-diameter ratio
- Piercing
  - Indenting but not breaking through
  - May be followed by punching
  - Used to produce a cavity in the workpiece
- Hubbing
  - Pressing a hardened punch into the block of metal
  - Typically has a specific tip
  - Used to make dies for forging operations
Related Forging Operations (cont.)

- **Roll Forging**
  - Cross section of the bar is reduced or shaped by passing it through a pair of rolls with shaped grooves.
- **Skew rolling**
  - Used for making ball bearings.
  - Spherical blanks are formed.
  - Spherical balls can also be formed by upsetting (flat-die forging) pieces sheared from a round bar.
- **Isothermal Forging or Hot-die forging**
  - Dies are heated to the same temperature as the hot workpiece.
  - Expensive and low production.
  - Complex parts with good dimensional accuracy.

Forging Die Design

- **The material will flow in the direction of least resistance.**
  - Shape the workpiece accordingly.
- **Pre-shape**
  - Material should not easily flow into the flash.
  - Minimize sliding at the workpiece-die interface.
  - CAE software can be used to aid in understanding the flow of material: mold-flow software.

- **Die design features**
  - Flash
  - Gutter
  - Land
  - Parting line
  - External and internal draft angles:
    - Internal: 5-10°
    - External: 5-10°
  - Radii: small are not good.

Forging Die Design (cont.)

- **Die inserts**
  - Higher accuracy
  - Better material
  - Easier to replace
  - Reduces the cost.

Die Materials and Lubrication

- **Requirements for die materials**
  - Strength and toughness at elevated temperatures.
  - Hardenability and ability to harden uniformly.
  - Resistance to mechanical and thermal shock.
  - Wear resistance.
  - Common materials are tool and die steels.
- **Lubrication**
  - Reduces friction and wear.
  - Effect on the forces required and the flow of metal in the cavities.
  - Can act as a thermal barrier between the die and workpiece (slows the rate of cooling).
  - Acts as a parting agent.
  - Used: graphite, glass, molybdenum disulfide.

Forgeability

- **Ability of material to undergo deformation without cracking**
- **No test is universally accepted**
- **Common tests**
  - Upset a solid cylindrical specimen and observe cracking.
    - The greater the deformation prior to cracking, the higher the forgeability.
  - Hot-twist test
    - A round specimen is twisted continuously until it fails.

Table 14.3: Metal and alloy range of hot forging temperature (°C)

<table>
<thead>
<tr>
<th>Metal or alloy</th>
<th>Approximate range of hot forging temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloys</td>
<td>400–500</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 steel</td>
<td>850–1150</td>
</tr>
<tr>
<td>Martensitic stainless steel</td>
<td>1100–1250</td>
</tr>
<tr>
<td>Austenitic stainless steel</td>
<td>1100–1250</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>1100–1250</td>
</tr>
<tr>
<td>Nickel-base superalloys</td>
<td>1000–1100</td>
</tr>
<tr>
<td>Titanium superalloys</td>
<td>1000–1100</td>
</tr>
<tr>
<td>Stainless alloys</td>
<td>1100–1200</td>
</tr>
<tr>
<td>Molybdenum alloys</td>
<td>1050–1200</td>
</tr>
<tr>
<td>Nickel-base superalloys</td>
<td>1100–1200</td>
</tr>
<tr>
<td>Tungsten alloys</td>
<td>1050–1200</td>
</tr>
</tbody>
</table>

Forgeability of metals are in descending order.

Forging Defects

- **Surface cracking**
- **Insufficient volume to fill the cavity**
- **Grain flow pattern is important**
  - Flow lines may reach a surface perpendicularly: end grains.
  - Act as stress raisers.
  - Be attacked by the environment.
- **Forging defects can cause fatigue failures**
Defects in Forged Parts

Figure 14.20 Examples of defects in forged parts. (a) Labors 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.

Forging Machines: Presses

- **Hydraulic press**
  - Operate at a constant speed
  - They are load limited (press stops if the load required exceeds its capacity)
  - Takes longer than other types of forging machines
  - Workpiece may cool
  - Capacity
    - 125 MN for open forging
    - 450 MN – 730 MN (differs in different countries) closed-die forging
  - Compared to mechanical presses:
    - Higher initial cost, slower
    - Require less maintenance

- **Mechanical press**
  - High production rates
  - Require less operating skills than other forging processes
  - 2.7 MN – 107 MN
  - Knuckle-joint mechanical press
  - Very high forces can be applied with this design

- **Screw Press**
  - Forging load is transmitted through a vertical screw
  - Used for both open- and closed-die forging operations

Forging Machines: Hammers

- Derive their energy from potential energy of the ram
  \[ V = mgh \]
- High speeds
- **Types**
  - Gravity drop hammers
  - Power drop hammers
  - Counterblow hammers
  - Two rams approach each other simultaneously
  - Vertical or horizontal

Forging Practice and Process Capabilities

- Prepare slug, billet, or preform by shearing, sawing, cutting off
- For hot forging
  - Heat the workpiece
  - Preheat and lubricate the dies
  - For cold forging
  - Lubricate the blank
  - Forge in appropriate dies
  - Remove flash by trimming, machining, grinding
  - Clean forging, check dimensions
  - Machine if necessary
  - Additional operations
    - Heat treating
    - Inspect the forging
    - Tolerance: +/- 0.5% to +/- 1% of the dimensions
    - Automation in forging
      - Loading and unloading into the furnace
      - Mechanical manipulators are used to move the billets in the dies
      - Important in the manufacture of high-quantity parts
      - Gest, axles, nuts, bolts

Table 14.4

<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>
Die Manufacturing Methods

- Dies are made by:
  - Casting, forging, machining, grinding, and electrical or electrochemical methods of die sinking.
  - Most common: machines dies from forged die blocks
  - Hubbing
    - Pressing a hardened punch into the block of metal
    - Typically has a specific tip geometry
    - Used to make dies for forging operations

Die Failures

- Improper design
  - Sharp corners
  - Abrupt changes in cross sections
  - Small radii

- Defective materials
- Improper heat treatment and finishing operations

- Overheating
- Excessive wear
- Overloading
- Misuse
- Improper handling

Residual stresses can cause serious injury
- Dies resting may suddenly disintegrate
- Pieces will fly away at high speeds → injury and death
- Metal shielding should be used around dies

The Economics of Forging

- Tool and die costs range from moderate to high
- Tool and die costs are spread over the parts manufactured
- Labor costs in forging are moderate
  - Reduced by automation

Unit Cost in Forging

Figure 14.22 Typical unit costs (cost per piece) in forging, note how the setup and tooling costs per piece decrease as the number of pieces forged increases for the same die.

Example of Forging: Wrench

- High alloy steel
  - Alloy → chrome vanadium
  - High strength
- Strain hardened
- Mass produced
- Drop-forged