Forging

IME 240/340
Forging

- Shaping discrete workpieces with compressive forces applied through dies and tools
- Dates back to 4000 B.C. or more
- Accomplished with hammers and anvils by blacksmiths
- Typical parts: bolts, rivets, connecting rods, turbine shafts, coins, gears, hand tools, structural components of machinery or aircraft

(a) Schematic illustration of the steps involved in forging a bevel gear with a shaft. 
Source: Forging Industry Association.
Forging

- Room temperature (cold forging) requires greater forces and ductile materials, good dimensional accuracy and surface finish
- Elevated temperatures (warm or hot forging) require smaller forces, but not as good accuracy or surface
- Controllable grain flow, good strength and toughness
- Forged pieces must often have subsequent machining or heat treatment

A part made by three different processes, showing grain flow. (a) casting, (b) machining, (c) forging.  
Source: Forging Industry Association.
Grain Flow in Hot Forging
Open Die Forging

• Hot forging for relatively roughly shaped workpieces
• Use simple processes like upsetting and flattening (cogging) to shape workpieces
• Simple die cavities and shapes
• Multiple blows to workpiece with movement in between
• For large workpieces mechanical manipulators are used to position the part between blows
Upsetting

• Reduction in workpiece height increases diameter
• Pancaking or barrelling can occur due to frictional forces at the die-workpiece interface or thermal differences

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
Cogging

- Successively reducing the thickness of a bar with open die forging
- Also called drawing out
- Reducing the thickness of a long section of a bar without excessive forces or machining

Figure 14.5 Two views of a cogging operation on a rectangular bar. Blacksmiths use this process to reduce the thickness of bars by hammering the part on an anvil. Note the barreling of the workpiece.
Forging Force during Upsetting

- Force for open-die forging on a solid cylindrical piece
- $Y_f$ is flow stress (found by looking up true stress that corresponds to the calculated true strain value, such as on Figure 2.6)
- $r$ and $h$ are radius and height
- Coefficient of friction, $\mu$

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

- Forging between two shaped dies
- Fullering and Edging distribute material into specific regions of the blank
- Blocking creates a rough shape
- Flash is material that is allowed to flow out along the parting lines of the dies
- Flash cools rapidly and increases in frictional resistance, forcing other material to stay within the dies and fill the cavity more completely under pressure; later it is trimmed off

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.
Flash in Forging

- In conventional closed die forging the formation of flash is necessary for die filling

**FIG. 14.2** (a) Forging of a simple axisymmetric part. (b) Load variation during the stroke for forging the part. (From Ref. 1.)
Impression Die Forging Force

- Force for forging a shaped workpiece in closed dies
- $Y_f$ is flow stress
- $k$ is a multiplying factor (3-5 for simple shapes, 5-8 wither flash, and 8-12 for complex shapes)
- $A$ is projected area of the forging, including flash
- Forging pressures for hot forging range from 550-1000 MPa (80-140 ksi)

$$F = kY_f A$$
Precision Forging

- True closed die or flashless forging uses precise volumes of material to completely fill the die cavity.
- Undersize blanks will not fill the cavity, oversize blanks will cause high pressures and may damage the dies.

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

- Reduces the number of additional operations and wasted material.
- Near-net-shape forging (or net-shape)
Coining and Hubbing

- Coining is for minting coins and jewelry
- Completely closed dies and high pressures (5-6 times the strength of the material) to obtain fine details
- Lubricants cannot be used since they are incompressible
  - In hubbing, a pattern is pressed into the die, such as when forging silverware patterns

(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
Cold Heading

- To produce bolts, screws, nails, rivets, and fasteners
- Highly automated, high production rates, but noisy

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.
Roll Forging and Skew Rolling

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) GM

(a)

(b)

(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.
Swaging

- Rotary swaging or radial forging and Tube swaging
- A solid rod or tube is subjected to radial impact forces by reciprocating dies (workpiece is stationary)
- Screwdriver blades made this way

(a) Swaging of tubes without a mandrel; note 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.
Die Design

- Must know workpiece material strength and ductility, deformation rate, temperature sensitivity, frictional characteristics
- Forgeability of materials is capability to undergo deformation without cracking
- Must evaluate shape, size, and complexity of design
- Material flows in the direction of least resistance, which is why intermediate shapes may need to be formed
- Preshaping should prevent material from easily flowing into flash, produce favorable grain flow patterns, and minimize friction and wear at the die-workpiece interface
- Computers can model and predict material flow
Die Design

- Parting lines are usually at the largest cross section
- Flash specifications:
  - Flash clearance should be 3% of maximum forging thickness
  - Land that is 2-5 times flash thickness, then a larger gutter that does not restrict flash flow
- Draft angles are needed (7-10 deg internal, 3-5 external)
- Avoid small radii
- Avoid sharp corners
- Inserts can be used
Die Design

- Die materials must have strength and toughness at elevated temperatures, hardenability, resistance to mechanical and thermal shock, wear resistance
- Die selection based on size, required properties, forging temperature, operation type, cost, and production quantities
- Common die materials are tool and die steels with chromium, nickel, molybdenum, and vanadium
- Dies are forged from castings, and then machined and finished as needed, often with heat treatment to increase hardness and wear resistance
- Lubricants act as thermal barriers for hot workpiece and cooler dies, improve metal flow, and are parting agents
Die Failure Causes

- Improper design
- Defective material
- Improper heat treatment and finishing operations
- Overheating and cracks caused by temperature cycling – usually preheat dies to 1500-2500 degrees Celsius
- Excessive wear – chipping or cracking from impact forces (can be repaired by welding or laser metal deposition)
- Overloading
- Misuse or improper handling – failure to remove a forged part before inserting a new blank
- Die failures are often catastrophic at high speeds and therefore, dangerous to employees (use safety shields!)
Types of Forging Machine

- **Work Restricted Machines (Energy or Load Limited)**
  - Hammers
    - Gravity drop hammers
    - Power hammers
    - Counterblow hammers
  - Friction Screw Presses
  - Hydraulic Presses

- **Stroke Limited (Restricted) Machines**
  - Mechanical presses
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.  (c) Knuckle-joint press.  (d) Screw press.  (e) Gravity drop hammer.
Forging Hammers

• Gravity Drop Hammers – drop forging with a free falling ram; energy based on product of ram’s weight and drop height
  • Ram weights of 180-4500 kg (400-10000 lbs)
• Power Drop Hammers – downstroke is accelerated by steam, air, or hydraulic pressure
  • Ram weights of 225-22500 kg
• Counterblow Hammers – two rams that approach each other horizontally or vertically (part may be rotated between successive blows); operate at high speeds with less vibrations transmitted – very large capacity possible
• High Energy Rate Machines – ram accelerated by an inert gas at high pressure; very high speeds but problems with maintenance, die breakage, and safety
Forging Hammers
Mechanical Presses

• Mechanical Presses – crank or eccentric shaft driven, or knuckle-joint for very high forces; stroke limited
  • 2.7-107 MN (300-14000 tons)

Higher production rates than hammers – less blows

More precise than hammers – moving die plate guided by slide ways or columns
Hydraulic Presses

- Hydraulic Presses – constant speeds, load limited, longer processing times, higher initial cost than mechanical presses but require less maintenance
  - 125 MN (14000 tons) open die, 450 MN (50000 tons) closed die
Friction Screw Presses

- Screw Presses – flywheel driven, energy limited (if dies do not completely close, cycle repeats)
  - Small production runs, high precision
  - 1.4-280 MN (160-31500 tons)
### 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>

### TABLE 14.6  
Equivalent Capacities of Presses and Hammers

<table>
<thead>
<tr>
<th>Maximum energy</th>
<th>Hydraulic presses, rating (tons)</th>
<th>Counterblow hammers, rating (kg-m)</th>
<th>Power hammers, rating (lb)</th>
<th>Mechanical presses, rating (tons)</th>
<th>Gravity drop hammers, rating (lb)</th>
<th>Friction screw presses, rating (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ft-lb</td>
<td>kg-m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3,850</td>
<td>533</td>
<td>170</td>
<td>450</td>
<td>455</td>
<td>210</td>
<td>1,000</td>
</tr>
<tr>
<td>5,870</td>
<td>812</td>
<td>260</td>
<td>650</td>
<td>680</td>
<td>320</td>
<td>1,500</td>
</tr>
<tr>
<td>8,830</td>
<td>1,200</td>
<td>400</td>
<td>1,000</td>
<td>910</td>
<td>475</td>
<td>2,000</td>
</tr>
<tr>
<td>11,000</td>
<td>1,540</td>
<td>400</td>
<td>1,000</td>
<td>1,000</td>
<td>600</td>
<td>2,200</td>
</tr>
<tr>
<td>11,320</td>
<td>1,570</td>
<td>550</td>
<td>1,130</td>
<td>1,360</td>
<td>820</td>
<td>2,500</td>
</tr>
<tr>
<td>14,200</td>
<td>1,960</td>
<td>680</td>
<td>1,360</td>
<td></td>
<td></td>
<td>3,000</td>
</tr>
<tr>
<td>16,700</td>
<td>2,310</td>
<td>750</td>
<td>2,000</td>
<td>1,500</td>
<td>900</td>
<td>3,300</td>
</tr>
<tr>
<td>19,400</td>
<td>2,690</td>
<td>900</td>
<td>2,000</td>
<td>1,800</td>
<td>1,080</td>
<td>4,000</td>
</tr>
<tr>
<td>21,700</td>
<td>3,000</td>
<td>935</td>
<td>2,500</td>
<td>1,870</td>
<td>1,120</td>
<td>4,100</td>
</tr>
<tr>
<td>22,500</td>
<td>3,120</td>
<td>1,090</td>
<td>2,000</td>
<td>2,000</td>
<td>1,200</td>
<td>4,400</td>
</tr>
<tr>
<td>24,700</td>
<td>3,420</td>
<td>1,125</td>
<td>2,250</td>
<td>2,250</td>
<td>1,350</td>
<td>5,000</td>
</tr>
<tr>
<td>26,200</td>
<td>3,630</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5,050</td>
</tr>
<tr>
<td>28,500</td>
<td>3,950</td>
<td>1,250</td>
<td>2,500</td>
<td>1,500</td>
<td>5,550</td>
<td>1,250</td>
</tr>
<tr>
<td>30,000</td>
<td>4,160</td>
<td>1,350</td>
<td>3,000</td>
<td>2,700</td>
<td>1,620</td>
<td>6,000</td>
</tr>
<tr>
<td>34,400</td>
<td>4,770</td>
<td>1,500</td>
<td>4,000</td>
<td>3,000</td>
<td>1,800</td>
<td>6,600</td>
</tr>
<tr>
<td>41,600</td>
<td>5,770</td>
<td>1,800</td>
<td>3,600</td>
<td>2,160</td>
<td>1,830</td>
<td>8,000</td>
</tr>
<tr>
<td>46,000</td>
<td>6,370</td>
<td>2,000</td>
<td>5,500</td>
<td>4,000</td>
<td>2,400</td>
<td>8,800</td>
</tr>
<tr>
<td>52,000</td>
<td>7,200</td>
<td>2,250</td>
<td>6,000</td>
<td>4,500</td>
<td>2,700</td>
<td>10,000</td>
</tr>
<tr>
<td>58,000</td>
<td>8,030</td>
<td>2,500</td>
<td>5,000</td>
<td>5,000</td>
<td>3,000</td>
<td>2,500</td>
</tr>
<tr>
<td>70,000</td>
<td>9,700</td>
<td>3,000</td>
<td>8,000</td>
<td>6,000</td>
<td>3,600</td>
<td>3,080</td>
</tr>
<tr>
<td>86,800</td>
<td>12,000</td>
<td>3,700</td>
<td>10,000</td>
<td>7,400</td>
<td>4,400</td>
<td>3,800</td>
</tr>
<tr>
<td>94,000</td>
<td>13,000</td>
<td>4,000</td>
<td>8,000</td>
<td>4,800</td>
<td></td>
<td>4,180</td>
</tr>
<tr>
<td>118,000</td>
<td>16,000</td>
<td>5,000</td>
<td>13,000</td>
<td>10,000</td>
<td>6,000</td>
<td>5,000</td>
</tr>
<tr>
<td>138,000</td>
<td>19,100</td>
<td>5,850</td>
<td>16,000</td>
<td>11,700</td>
<td>7,900</td>
<td>6,060</td>
</tr>
<tr>
<td>142,000</td>
<td>19,600</td>
<td>6,000</td>
<td>12,000</td>
<td>7,200</td>
<td></td>
<td>6,220</td>
</tr>
<tr>
<td>173,000</td>
<td>23,900</td>
<td>7,300</td>
<td>20,000</td>
<td>14,600</td>
<td>8,700</td>
<td>7,590</td>
</tr>
<tr>
<td>220,000</td>
<td>27,120</td>
<td>8,300</td>
<td>25,000</td>
<td>16,600</td>
<td>10,000</td>
<td>9,650</td>
</tr>
<tr>
<td>240,000</td>
<td>32,200</td>
<td>10,000</td>
<td>32,000</td>
<td>29,000</td>
<td>10,600</td>
<td>10,220</td>
</tr>
<tr>
<td>300,000</td>
<td>41,500</td>
<td>12,500</td>
<td>13,650</td>
<td>25,000</td>
<td>13,650</td>
<td></td>
</tr>
<tr>
<td>361,500</td>
<td>50,070</td>
<td>15,000</td>
<td>40,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>425,000</td>
<td>59,000</td>
<td>17,500</td>
<td>35,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60,000</td>
<td>18,000</td>
<td>36,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>484,000</td>
<td>67,036</td>
<td>20,000</td>
<td>50,000</td>
<td>40,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>546,800</td>
<td>75,500</td>
<td></td>
<td>63,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>610,000</td>
<td>84,500</td>
<td>25,000</td>
<td></td>
<td>50,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>694,400</td>
<td>95,800</td>
<td></td>
<td>80,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>738,800</td>
<td>102,000</td>
<td>30,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>868,000</td>
<td>120,200</td>
<td>35,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,280,000</td>
<td>172,000</td>
<td>50,000</td>
<td>144,000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Forging Economics

- A set of dies for automotive body panels can be $2M
- Small dies can be $100+
- Dies are used for many parts though, so per unit part costs are low
- Moderate labor costs
  - Reduce by automation

Figure 14.23 Relative unit costs of a small connecting rod made by various forging and casting processes. Note that, for large quantities, forging is more economical. Sand casting is the more economical process for fewer than about 20,000 pieces.