Metal-Forging Processes and Equipment

Text Reference: “Manufacturing Engineering and Technology”, Kalpakjian & Schmid, 6/e, 2010
Chapter 14
Forging

- A process in which the workpiece is shaped by compressive forces applied through various dies and tooling
- Process produces discrete parts

One of oldest and most important metal working processes
4000 BC
First used to make jewelry, coins, implements by hammering metals with stone
Now:
- Large rotors for turbines
- Gears
- Bolts and rivets
- Cutlery
- Hand tools
- Structural components for machinery, aircraft, R/R
- Other transportation equipment

- Compare with Rolling process which generally produces continuous plates, sheets, shapes
FIGURE 14.1 (a) Illustration of the steps involved in forging a knife. (b) Landing-gear components for the CSA and CSB transport aircraft, made by forging. (c) General view of a 445-MN (50,000-ton) hydraulic press.

Source: (a) Courtesy of Mundial, LLC. (b) and (c) Courtesy of Wyman-Gordon Company.
Forged Parts

- Possess good strength and toughness
  - Due to control of metal flow and material’s grain structure
- Reliable for highly stressed applications
- Simple forging with heavy hammer and an anvil
- Most forgings require set of dies and press or powered hammer
FIGURE 14.2  Schematic illustration of a part made by three different processes and showing grain flow.
(a) Casting by the processes described in Chapter 11.  
(b) Machining from a blank, described in Part IV of this book, and (c) forging.  
Each process has its own advantages and limitations regarding external and internal characteristics, material properties, dimensional accuracy, surface finish, and the economics of production.

Source:Courtesy of the Forging Industry Association.
Forging are generally subject to subsequent finishing operations

- Heat treating: To modify properties
- Machining: To obtain accurate final dimensions, & good surface finish

Can minimize finishing operations by Precision Forging (an important example of net-shape or near-net-shape forming processes)

Many forged parts may also be made by alternate processes

  Casting; Powder Metallurgy; Machining

Alternate processes produce parts with different characteristics
- Strength
- Toughness
- Dimensional accuracy
- Surface finish
- Possibility of internal/external defects
### Table 14.1 General 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 and inexpensive dies; wide range of part sizes; good strength characteristics; generally for small quantities</td>
<td>Limited to simple shapes; difficult to hold close tolerances; machining to final shape necessary; low production rate; 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, not economical for small quantities; machining often necessary</td>
</tr>
<tr>
<td>Blocker</td>
<td>Low die costs; high production rates</td>
<td>Machining to final shape necessary; parts with thick webs and large fillets</td>
</tr>
<tr>
<td>Conventional</td>
<td>Requires much less machining than blocker type; high production rates; good utilization of material</td>
<td>Higher die cost than blocker type</td>
</tr>
<tr>
<td>Precision</td>
<td>Close dimensional tolerances; very thin webs and flanges possible; machining generally not necessary; very good material utilization</td>
<td>High forging forces, intricate dies, and provision for removing forging from dies</td>
</tr>
</tbody>
</table>
Open-die Forging

- Simplest form
- Produce very small (nails, pins) to very large (propeller shafts) items; up to 300 tons
- Aka *upsetting; flat-die forging*
- Solid workpiece compressed between two flat dies
- Dies may possess modest cavity for simple forgings
- Can calculate forging force, $F$, by Eq. 14.1
If no friction then have free transverse movement or sliding across die surfaces
If frictionless, then have uniform deformation
In practice have friction: result in *barreling*, aka *pancaking*
Minimize barreling by using an effective lubricant
Also get barreling if have hot workpiece between cold dies
- Material in contact with dies has higher resistance to deformation than the material in the centre
- Central portion expands laterally more than edges
- This ‘thermal barreling’ can be reduced by heated dies
- Can also use thermal barriers (e.g. Glass cloth) at workpiece-die interface
COGGING:

-Aka *Drawing Out*

-An open-die forging operation in which the thickness of a bar is reduced by successive ‘bites’ at specific intervals.
Flash
- Not just undesirable excess metal
- The high pressure and resulting high frictional resistance in the flash presents a severe constraint on any outward flow of the material in the die.
- Principle: In plastic deformation, the material flows in the direction of least resistance (requires less energy).
- Therefore, the material prefers to flow into the die cavity (rather that leave it as flash)
- Therefore die cavity fills first
- Thus, flash process helps ensure complete part formation
Note:

- Draft angles (similar to casting but in different application)
- Flash (later removed)
Die Inserts:

- Dies may be made of multiple pieces, especially for complex shapes
- Can replace dies easily in case of wear or damage
- Inserts are usually made of stronger and harder materials
Forging Blanks

- Create forging blank by:
  - Cropping from extruded or drawn bar stock
  - Preforming (such as powder metallurgy)
  - Casting
  - Prior forging operation
- The blank is placed on lower die and changed through successive contact from upper die
**Fullering:** Material is distributed away from an area

**Edging:** Material is gathered into a localized area

**Blocking:** Form part into rough shape, using *blocker dies*

**Finishing** in *impression dies* gives final shape

**Trim** flash
FIGURE 14.8 Trimming flash from a forged part. Note that the thin material at the center is removed by punching.
Forging Force
Impression-die Forging

- In hot forging, usually 550 to 1000 MPa (80 – 140 ksi)

\[ F = kY_f A \]  
\text{Eq. 14.2}

- \( k \): Multiplying factor (Table 14.2)
- \( Y_f \): Flow stress of material
- \( A \): Projected forging area
**TABLE 14.2** 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>
Net Shape Forming

A move to create the final shape with as few operations as possible.

Driven by economic considerations

Aluminum & Manganese are particularly suited; Steels and Titanium can also be precision forged
FIGURE 14.9 Comparison of (a) closed-die forging with flash and (b) precision or flashless forging of a round billet.

1. **Slug:**
   Use processes such as shearing (cropping), sawing, cutting off.
   If necessary, clean surfaces by such means as shot blasting

2. **Descaling** may also occur during initial stages of forging when the (brittle) scale falls off during deformation.

3. **Lubrication:** Does not make sense to attempt to lubricate the very hot slug/preform for hot forging

4. If necessary, remove any excess material (such as flash) by trimming, machining or grinding

5. **Machine & finish** to final dimensions & tolerances

6. **Heat treating** will improve mechanical properties;

7. **Inspect** forging for both external and internal defects

**Inspection:**
The quality, dimensional tolerances & surface finish depend on how well these operations are performed and controlled

In general, for forgings: dimensional tolerances range between ±0.5 & ±1%

In good practice:
   tolerances for hot forging of steel usually less than ±6 mm (0.25”)
   tolerances for precision forging can be as low as ±0.25 mm (0.01”)

Other factors contributing to dimensional inaccuracies:
   Draft angles, radii, fillets, die wear, improper die closure, die mismatching

Surface finish depends on: blank preparation, die surface finish, die wear, effectiveness of lubricant
Lubricants become entrapped in the closed die cavities and (being incompressible) prevent full reproduction of die surface details and surface finish.

A cold forging process in order to produce clear details as forged.
FIGURE 14.10  (a) Schematic illustration of the coining process. The earliest coins were made by open-die forging and lacked precision and sharp details. (b) An example of a modern coining operation, showing the coins and tooling. Note the detail and superior surface finish that can be achieved in this process.

Source: Courtesy of C & W Steel Stamp Co., Inc.
Aka “Upset forging”
Generally performed on end of a round rod or wire in order to increase the cross section
For heads of fasteners such as: Nails, bolts, screws, rivets
May be performed cold, warm, hot
Some parts require multiple stages
Rod/wire may buckle if length-to-diameter ratio is too high; Usual limit is 3:1
Automated headers can produce high volumes of small parts
Production operation can be noisy; requiring ear protection
FIGURE 14.11 (a) Heading operation to form heads on fasteners, such as nails and rivets. (b) Sequence of operations used to produce a typical bolt head by heading.

(a) Diagram showing the steps:
1. Kickout pin
2. Head formed in punch
3. Head formed in die

(b) Measurements for a typical bolt head:
1. 147 mm
2. 38 mm diam
3. 63 mm
4. 114 mm
Piercing

- A process of indenting the surface to produce an impression in workpiece
- Workpiece may be confined or unconstrained
- Ex.: Hexagonal cavity in bolt head
- Piercing Force depends on:
  - Cross-sectional area and punch tip geometry
  - Strength of material (require pressure 3 to 5 times higher)
  - Friction at sliding interfaces
Note the grain structure created as a result of the impact on the head to create the indentation.

Note the “End Grain” microstructure at surface at base of indentation. This will be discussed later as a source of defects in forgings. Note also that this appears at bottom the illustration. This likely results if the billet was cut (not formed or cast).
Stepped pin made from SAE 1008 steel
Used as part of a roller assembly to adjust position of car seat
Complex part requiring progressive steps to produce required details and fill the die completely
Cold–forging steps:
-Solid cylindrical blank is extruded in two operations, followed by upsetting operation
-Upsetting operation uses a conical cross section in the die to produce the preform and is oriented such that material is concentrated at the top of the part in order to ensure proper die filling
-After the impression-die forming, a piercing operation is performed to form the bore
-The part is made to net shape on a cold-forming machine at a rate of 240 parts per minute
Some other Forging Processes

- **Hubbing**
  - Press a hardened punch with particular tip geometry into surface of a block of metal
  - Resultant cavity is used as a die (utensils)
- **Orbital Forging**
  - Upper die follows orbital path
  - Part formed gradually, continuously
  - Generally used to form disk and conical shapes
- **Incremental Forging**
  - Tool forms blank into final shape, several small steps
  - Die penetrates to different depths along surface
- **Isothermal Forging (aka ‘hot-die forging’)**
  - Dies are heated to same temperature as hot workpiece
  - Maintains high strength and ductility

Hubbing Force = 3(UTS)(A)  Eq. 14.3

Orbital:
- Incremental, continuous process
- Similar to action of mortar & pestle for crushing
- Bevel gears & gear blanks
- Relatively low forging force because low contact surface at a time
- Relatively quiet
- 10 to 20 cycles

Incremental:
- Similar to cogging
- Forms a small area at a time
- Lower forces
- Simpler and less costly tools

Isothermal
- Low forging load
- Improved material flow through cavity
Rotary Swaging

- Aka Radial Forging, Rotary Forging, Swaging
- A solid rod or tube is subjected to radial impact forces by a set of reciprocating dies of the machine
- In die-closing swaging machines, die movements are obtained through reciprocating motion of wedges
- Swaging can be used to assemble fittings over cables and wire
FIGURE 14.14  (a) Schematic illustration of the rotary-swaging process.  
(b) Forming internal profiles on a tubular workpiece by swaging.  
(c) A die-closing swaging machine, showing forming of a stepped shaft.  
(d) Typical parts made by swaging.
FIGURE 14.15  (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. (c) Examples of cross sections of tubes produced by swaging on shaped mandrels. Riffing (internal spiral grooves) in small gun barrels can be made by this process.
Forgeability of Metals

- **Forgeability**: The capability of a material to undergo deformation without cracking; it is based on ductility, strength, forging temperature, friction, forging quality

**Upsetting Test**
- Solid, cylindrical specimen is upset between flat dies
- Forgeability increases with amount of reduction of height prior to cracking of the barrel surface

**Hot-twist Test**
- Twist a series of round specimens to failure, at different temperatures
- Plot graph (turns vs. temp.) of complete turns to failure
- Optimum forging temperature is the temperature of most turns

Hot twist test particularly suitable for steels (ductility)
<table>
<thead>
<tr>
<th>Metal or alloy</th>
<th>Approximate range of hot forging temperatures (°C)</th>
</tr>
</thead>
<tbody>
<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>
Forging Defects

- Surface cracking
- Web buckling (insufficient material)
- Internal cracks (too much material)
- Internal defects:
  - Nonuniform deformation of material in cavity
  - Temperature gradients during forging
  - Microstructural changes (phase transformations)
- End grains at surface susceptible to preferential attack, raising stress
- Forging defects
  - Lead to fatigue failures
  - May cause corrosion & wear during service
FIGURE 14.16  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 an oversized billet. Die cavities are filled prematurely, and the material at the center flows past the filled regions as the dies close.
Forging Die Design

- Requires knowledge of workpiece
  - Shape, ductility, strength
  - Response to deformation rate, temperature

- Rule: The part will flow in the direction of least resistance
  - Therefore, plan intermediate stages so the part fills the cavities
    - (recall Fig 14.7a connecting rod)

- Use simulation software
Preshaping

In properly shaped workpiece:
- The material should not flow easily into the flash
- The grain flow pattern should be favourable for product’s strength and reliability
- Sliding at workpiece/die interface s/b minimized

- Selection of preshapes requires calculations for cross-sectional areas at each location in forging
  - Computer models and simulation are useful tools
Extra flash allowed to flow into gutter to avoid unnecessary forging load
Forging shrinks upon cooling both radially and longitudinally
Therefore internal draft angles higher than external draft angles
Allow extra metal for machining at flanges, holes & mating surfaces
Die Materials

- **Requirements:**
  - Strength and toughness at elevated temperatures
  - Hardenability and ability to harden uniformly
  - Resistance to mechanical and thermal shock
  - Wear resistance, especially to abrasion caused by mill scale on hot forging surface
- **Usually made from tool and die steels containing Cr, Ni, Mo, Va**

Dies made from tool and die steels containing Chromium, Nickel, Molybdenum, Vanadium
  - To provide strength and wear resistance
Lubrication

- Lubricants affect:
  - Friction & wear
  - Forces required
  - Die life
  - Flow process

- Lubricants can act as thermal barrier between hot workpiece and cool dies
  - This slows cooling, causing improved metal flow

- Lubricants act as a parting agent
  - This eases later separation
Die-manufacturing Methods

- Forging dies made many ways:
  - Casting, Forging, Machining, Grinding, Electrical, Electrochemical, Rapid tooling

- Method choice depends on:
  - Size & shape
  - How die is used:
    - Casting, forging, extrusion, powder metallurgy, plastics molding
Die Failures

- Improper die design
- Defective or improper selection of die material
- Improper manufacturing, including heat-treating and finishing
- Overheating and heat checking (cracking caused by temperature cycling)
- Excessive wear
- Overloading (excessive force on die)
- Improper alignment of die components wrt their movements
- Misuse
- Improper handling of the die
<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>
FIGURE 14.17  Schematic illustration of the principles of various forging machines.
(a) Mechanical press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft to give up-and-down motion to the ram.
(b) Knuckle-joint press. (c) Screw press. (d) Hydraulic press.
Forging Machines

- **Hydraulic Press**
  - Operate at constant speeds
  - Load limited
  - High initial costs, relatively slow, low maintenance

- **Mechanical Press**
  - Crank or eccentric
  - Stroke limited
  - High force at end of stroke
  - High production rates, easier to automate, require lower operator skill

Load limit: press stops if the load required exceeds capacity

Stroke limit: speed maximum at centre of stroke and zero at bottom of stroke
Screw Press is energy limited because they draw their energy from a flywheel.

Hammers are energy limited because they draw their energy from the potential energy of the ram which is converted to kinetic energy.

For hammers, the low cooling rates make them attractive for forging of complex shapes.
Forging Machines

- **Power Drop Hammers**
  - Ram's downstroke is accelerated by steam, air or hydraulic pressure

- **Gravity Drop Hammers**
  - Energy derived from free-falling ram

- **Counterblow Hammers**
  - Two simultaneous H & V rams

- **High-Energy-Rate**
  - Ram is accelerated rapidly by inert gas at high pressure
FIGURE 14.18 Typical cost per piece in forging; note how the setup and the tooling costs per piece decrease as the number of pieces forged increases if all pieces use the same die.
FIGURE 14.19 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 most economical process for fewer than about 20,000 pieces.
FIGURE 14.20  (a) The Lotus Elise Series 2 automobile.  
(b) Illustration of the original design for the vertical suspension uprights, using an aluminum extrusion.  
(c) Retrofit design, using a steel forging.  
(d) Optimized steel forging design for new car models.  
Source: (a) Courtesy of Fox Valley Motorcars. (b) through (d) Courtesy of Lotus Engineering and the American Iron and Steel Institute.
### TABLE 14.5  Comparison of Suspension Upright Designs for the Lotus Elise Automobile

<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>
Summary: Metal-Forging Processes & Equipment

- Forging
  - Family of processes
  - Deformation through compressive forces
  - Applied through a set of dies
  - Performed cold, warm, hot

- Workpiece in die cavity considerations:
  - Behaviour during deformation
  - Friction
  - Heat transfer
  - Material-flow characteristics

- Other considerations:
  - Selection of die materials
  - Lubricants
  - Temperatures (workpiece & die)
  - Forging speeds
  - Equipment
Summary: Metal-Forging Processes & Equipment

- Defects
  - Result from improper design & control of forging process
  - Appear in preform shape, workpiece quality, die geometry
  - Can be predicted by software
- Variety of forging equipment
- Die failure can be expensive
  - Therefore die design, material selection, production methods are important