Classification of Forging Operations

- Cold vs. hot forging:
  - Hot or warm forging – most common, due to the significant deformation and the need to reduce strength and increase ductility of work metal to produce complex shapes
  - Cold forging – advantage: increased strength that results from strain hardening and minimal machining

- Impact vs. press forging:
  - Forge hammer - applies an impact load
  - Forge press - applies gradual pressure
Types of Forging Dies

- Open-die forging - work is compressed between two flat dies, allowing metal to flow laterally with minimum constraint
  - Low precision but good for small lot size
- Impression-die forging - die contains cavity or impression that is imparted to workpart
  - Metal flow is constrained so that flash is created (preferentially fills “cavity”)
  - Better precision and complexity
- Flashless forging - workpart is completely constrained in die
  - No excess flash is created
Open-Die Forging

Compression of workpart between two flat or simply shaped dies

- Similar to compression test when workpart has cylindrical cross section and is compressed along its axis or its sides
  - Deformation operation reduces height and increases diameter of work
  - Common names include *upsetting* or *cogging*
Cogging

Sequence of steps
Used when rolling is not practical, e.g. low tonnage of material
Reduce size and refine microstructure
Open Die Forging

4000 ton Press

FIG. 11.66 Sequence of operations used to forge a four-throw crankshaft from a 65-t (71.8-ton) ingot. Material: steel (0.21% C, 0.32% Si, 0.76% Mn). (After [11.90].)
If no friction occurs between work and die surfaces, homogeneous deformation occurs, so that deformation is uniform throughout workpart height and:

$$
\varepsilon = \ln \frac{h_o}{h}
$$

where $h_o$ = starting height; and $h$ = height at some point during compression.

- Force, $F = Y_f \times \text{Area}$
Open-Die Forging with Friction

- Friction between work and die surfaces constrains lateral flow of work, resulting in barreling effect.
- In hot open-die forging, effect is more pronounced due to die chilling.

Friction can add 20% or more to the forging load needed.

\[
F = k_f Y_f A = Y_f A \left( 1 + \frac{0.4 \mu D}{h} \right)
\]
Figure 19.14  Sequence in impression-die forging: (1) just prior to initial contact with raw workpiece, (2) partial compression, and (3) final die closure, causing flash to form in gap between die plates.
Impression-Die Forging

Compression of workpart by dies with inverse (negative impression) of desired part shape

- Flash is formed by metal that flows from die cavity into a small gap between die plates – represents a possible flow path, flow inside the cavity represents an alternative
  - Metal will always take the path of least resistance
  - Flash is excess material & must be trimmed, but it serves an important function:
    - As flash forms, friction resists continued metal flow into gap, constraining material to fill die cavity
    - Strain rate sensitivity also resists movement in the flash
    - Chilling also resists flow into the “flash land”
Note non-uniformity of temperature
A Look at the Flash Land

Red indicates cooler metal

Corner to be filled

Gutter

Flash Land

T_{low}

V/h_1

V/h_2

T_{high}

Cooler die
Flash in Impression Die Forging

Part

Flash

1-6

7-8

Forging Load

Forging Stroke

Flash begins to form

1-6

7-8
Trimming operation (shearing process) to remove the flash after impression-die forging.

Cutting/shearing operation to remove flash from workpart in impression-die forging.

- Usually done while work is still hot, so a separate trimming press is included at the forging station.
Impression-Die Forging Practice

- Several forming steps often required, separate die cavities for each step
  - Beginning steps redistribute metal for more uniform deformation and reduced forces/tool stresses
  - Final steps shape the final geometry
- Impression-die forging is often performed manually by skilled operator, difficult to automate

Steps in Impression Die Forging
  - Buster – knock off scale
  - Preform - redistribute metal
  - Blocker - redistribute and partially shape
  - Finisher – complete final shape
Advantages and Limitations

- Advantages of impression-die forging compared to machining from solid stock:
  - Higher production rates
  - Less waste of metal
  - Greater strength
  - Favorable grain orientation in the metal (harder to shear across the grains)

- Limitations:
  - Not capable of close tolerances ($\pm 0.030''$)
  - Machining often required to achieve accuracies and features needed
Figure 19.17 Flashless forging: (1) just before initial contact with workpiece, (2) partial compression, and (3) final punch and die closure.
Flashless Forging

Compression of work in punch and die tooling whose cavity does not allow for flash of excess metal

- Starting workpart volume must equal die cavity volume within very close tolerance
  - Metal acts as incompressible fluid
- Process control more demanding than impression-die forging = Increased $\text{Cost}$
  - Not widely used due to problems in preform volume control which requires precision sawing and is less economical
- Best suited to part geometries that are simple and symmetrical
- Often classified as a *precision forging* process
Load-Stroke Curve Revisited

Forging Load

Forging Energy (Area under curve) for hammers

Cavity fills completely

Flash begins to form

Initial Contact

Forging Complete
Strain energy is the amount of work done (or energy spent) to deform the workpiece.

For simple upsetting, the strain energy per unit volume is the area under the stress/strain curve during deformation:

\[
\frac{W}{V} = \int \sigma \, d\varepsilon \quad \frac{lbs}{in^2} \cdot \frac{in}{in} = \frac{in - lbs}{in^3}
\]

Some simple math manipulation results in:

\[
V = W \int \sigma \, d\varepsilon
\]
Strain Energy

Low temperature Stress-strain curve:

\[ \sigma = K \varepsilon^n \]

\[ \frac{W}{V} = \frac{K \varepsilon^{n+1}}{n + 1} \]

High temperature Stress-strain curve:

\[ \sigma = \sigma_f \]

\[ \frac{W}{V} \approx \sigma_f \varepsilon \]
Forging Hammers (Drop Hammers)

Apply impact load (falling mass) against workpart
Potential $\rightarrow$ Kinetic $\rightarrow$ Deformation Energy

- Two types:
  - Gravity drop hammers - impact energy from falling weight of a heavy ram
  - Power drop hammers - accelerate the ram by pressurized air or steam

- Disadvantage: impact energy transmitted through anvil into floor of building, Noise

- Commonly used for impression-die forging
Drop Hammer

\[ mgh = \frac{1}{2}mv^2 = \text{Volume} \int k\epsilon^n d\epsilon \]

Cold Forging

\[ mgh = \frac{1}{2}mv^2 \approx \sigma\epsilon \times \text{Volume} \]

Hot Forging
Board Hammers

(Sometimes called drop hammers)
Available energy is solely the potential energy from gravity.

\[ E = mgH = wH \]

Where \( E \) is the hammer energy, \( w \) is the weight of the die and ram, and \( H \) is the drop height, typically less than 6 feet.

Work Units are foot-pounds (US) Newton-meters (SI)
Vertical hammers: Available energy is sum of the potential energy from gravity and the steam or air pressure:

\[ E = (w + PA)H \]

Where \( E \) is the hammer energy, \( w \) is the weight of the die and ram, \( P \) is the air or steam pressure on the downward stroke, \( A \) is the area of the piston, and \( H \) is the drop height.
Hammers

Where does the energy go?

• Noise
• Heat
• Foundation shock
• Workpiece deformation (strain energy)

The blow efficiency, $\eta$, is defined as the fraction of the hammer energy available that goes into deforming the workpiece:

$$\eta = \frac{E_{\text{strain}}}{E_{\text{hammer}}}$$
The efficiency, $\eta$, depends mainly on how much deformation is done during the stroke. In real hammers:

$$0.3 \leq \eta \leq 0.9$$

**Hammer Efficiency**

**“Hard Blow”**
- Force
- Die travel after impact
- Typically in last several blows

**“Soft Blow”**
- Force
- Die travel after impact
- Typically in initial blows
Hammer Calculations

Energy available in the hammer:

\[ E_{\text{hammer}} = (w + PA)H \]

Energy necessary (high temp) to forge the workpiece:

\[ E_{\text{strain}} = \sigma_f \varepsilon V \]

\[
\eta = \frac{E_{\text{strain}}}{E_{\text{hammer}}}
\]

\[ E_{\text{hammer}} = \frac{E_{\text{strain}}}{\eta} = \frac{Y_f \varepsilon V}{\eta} \]
You are trying to upset brass on a small board hammer with a combined die and ram weight of 5,000 lbs. From how high must the die be dropped to do this in 1 step?

70/30 Brass at 1100°F: Constant flow stress of 20 KSI
\[ V = 7.07 \text{ in}^3, \; \varepsilon = 0.69. \] Assume soft blow, \( \eta = 0.8 \).
Upsetting Brass; Hammer Calculation

70/30 Brass at 1100°F: Constant flow stress of 20 KSI

\[ V = 7.07 \text{ in}^3, \, \varepsilon = 0.69. \]  Assume soft blow, \( \eta = 0.8. \)

\[ E_{\text{strain}} = 25000 \ast 7.07 \ast 0.69 = 121958 \text{ in-lbs} \]

\[ E_{\text{hammer}} = \frac{E_{\text{strain}}}{\eta} = \frac{121598}{0.8} = 5000h \]

\[ h = 30.5'' \]  Drop height needed
Forging Presses

- Apply gradual pressure to compress metal (**force-based**)
- Types:
  - Mechanical press - converts rotation of drive motor into linear motion of ram
  - Hydraulic press - hydraulic piston actuates ram
  - Screw press - screw mechanism drives ram
Press Sizing

Need to establish if the force required to form the part is within the press capabilities.

This is complex but a simple estimate can be achieved by:

1. Assuming an average strain rate
2. Calculating the flow stress for the process ($Y_f$) or assuming a constant flow stress
3. Determine the Plan View Area (PVA) of the part including the flash land ($A$)
4. Select a multiplying factor, $k_f$, based on part complexity
5. Force $F = k_f Y_f A$ where $6 \leq k_f \leq 10$

Force can be as high as 60,000 tons
Example Problem: Press Tonnage Calculation

Estimate the forging load necessary for an axisymmetric turbocharger disk blank forged out of Inconel (nickel-base superalloy) on a mechanical press.

Assume Nickel has constant flow stress of 20 ksi at the forging temperature. Simple geometry with flash, $k_f = 7$
Area is forging + flash

PVA = area of forging top view

Use diameter D = 4” here

\[ PVA = \frac{\pi D^2}{4} = \frac{\pi 4^2}{4} = 4\pi \]

\[ F = k_f Y_f A = 7 \times 20,000 \times 4\pi = 879.6 \text{Tons} \]
Forging process used to form heads on nails, bolts, and similar hardware products

- More parts produced by upsetting than any other forging operation
- Performed cold, warm, or hot on machines called *headers* or *formers*
- Wire or bar stock is fed into machine, end is headed, then piece is cut to length
- For bolts and screws, thread rolling is then used to form threads
upset forging operation to form a head on a bolt or similar hardware item. The cycle consists of:
(1) wire stock is fed to the stop
(2) gripping dies close on the stock and the stop is retracted
(3) punch moves forward
(4) bottoms to form the head.
Figure 19.23  Examples of heading (upset forging) operations: (a) heading a nail using open dies, (b) round head formed by punch, (c) and (d) two common head styles for screws formed by die, (e) carriage bolt head head formed by punch and die.