ME 4563

Introduction to Manufacturing Processes

College of Engineering
Arkansas State University

Bulk Deformation

Deformation

What is deformation processing?

- Process to make parts without material removal
- Deformation occurs on parts with L/D approx. equal to 1

Example of products / Typical product dimensions

- Small: coins, surgical wire, etc.
- Large: power plant turbine shafts, aircraft landing gear, etc.

Deformation

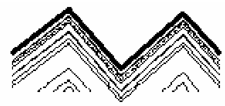
"Cast" Structures are converted to "wrought" structures through some means of deformation

- Normally starts with material that has been cast (ingots, slabs, rods or pipes)
- Several different parts may be formed
- The process involves "heat" (in most cases) and "force" to create the shape

Deformation

Deformation Process characteristics

- Material is deformed
  - – improvement of material properties
    - • grain refinement
    - • grain orientation
    - • work hardening
- Material is conserved
  - – minimal trimming and machining

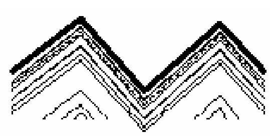


Deformation

Deformation Process characteristics

Effect on grain structure

- Large grains are broken up.
- Grains can be made to flow.



Deformation

Deformation process may be classified according to:

Temperature of deformation

- Hot working
- Cold working
- Warm working

Purpose of Deformation

- Primary Processes
- Secondary Processes

Deformation

Working temperature

- Cold: $T < 0.4\ T_{melting}$
  - strain hardening effect
  - no strain rate effect
- Hot: $T > 0.6\ T_{melting}$
  - no strain hardening effect
  - strain rate effect

Deformation

Strain Rate '$\dot{e}$':

Given by the ratio of the rate at which the specimen is pulled in tension or pushed in compression (v) to the instantaneous deformed length (l)

$$\dot{e} = \frac{v}{l}$$

Units ?

Low strain rates allow more time for atomic or molecular rearrangement, leading to lower stresses and higher ductility. Effected by Temperature

Deformation

Hot working: Temperature of the work piece is high (above "room temperature")

600 –1000 deg. C, depending upon metal/alloy

Advantages: Flow stresses are low (lower forces & power requirements); very large pieces can be worked on; ductility is high – hence large deformations & complex parts

Disadvantages: Energy required to heat the piece; oxidizing can impair surface finish; variations in finishing temperatures lead to wide dimensional tolerances

Deformation

Cold working: Working at "room" temperature

May be raised to 100 – 200 deg. C, depending upon metal/alloy

Advantages: in absence of cooling & oxidation, better tolerances and finishes; high strength; process can be better controlled in terms of material properties that need to be achieved

Disadvantages: Flow stresses high, so are tool pressures and deformation forces – hence higher power requirements too; Ductility of many materials limited – limiting the complexity of shapes that can be achieved

Deformation

Warm working: Working in between temperatures of hot and cold working

Normally to take advantage of the material's behavior at specific temperatures

Example: working of steel between 650 and 700 deg. C
Temperatures are low enough to avoid scaling – leading to good surface finish, yet high enough to reduce stresses and deformation forces

Deformation

Purpose of Deformation – As a Primary Process

- These aim to destroy the cast structure by successive deformation steps
- Results in a semi-fabricated product that will be worked on further – slabs, billets, plates
- Conducted on large scale at specially constructed plants

Deformation

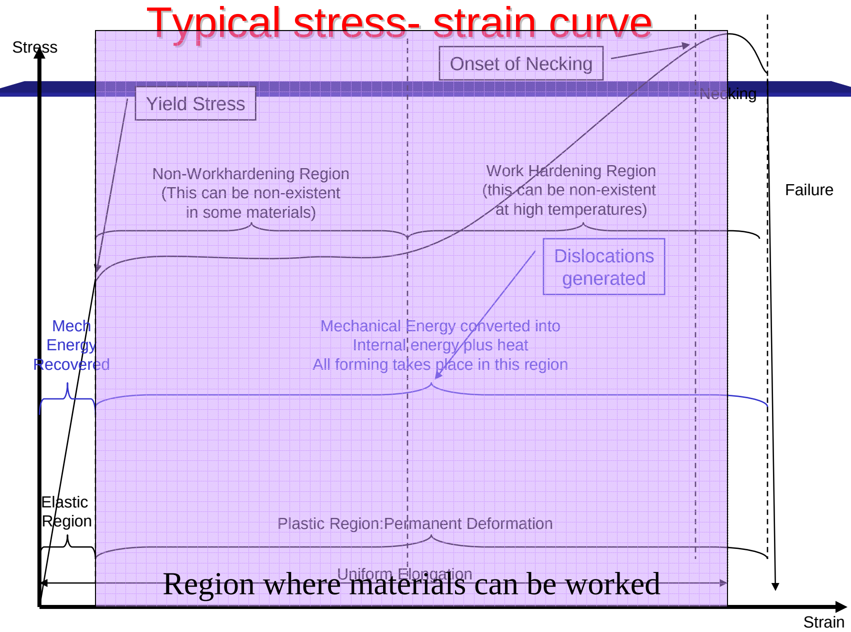
Purpose of Deformation – As a Secondary Process

- Take products of primary process and further transform them into a finished part – bolts, metal parts, wires, rods, etc.
- Focus of all forging as well as other deformation processes

Deformation

- Involves a machine which causes gross or bulk deformation to provide a new shape
- Can only use these processes when the material has a plastic regime in its stress strain behavior.
  - Most metals
  - Most plastics
- Some materials must be formed hot to obtain plastic behavior

Typical stress- strain curve



Bulk Deformation Processes

- Resultant shape is usually further worked or shaped
- Total deformations can be very large:
  - Foil 5000
  - Can stock 1400
  - Typical sheet 400
  - Typical Plate 3
  - Extrusions 8

Deformation = initial dimension / final dimension

Bulk Deformation Processes for Metals

Falls into the following major categories –

- Forging – discrete parts with a set of dies
- Rolling – flat shapes and uniform cross sections; hot and cold
- Extrusion – long lengths of solid or hollow parts with constant cross sections; hot & cold
- Drawing – long rods and wires
- Swaging – radial forging of components

Bulk Deformation Processes

- Forging starts with a sawn off section of a cast or extruded ingot and ends up with a multitude of shapes close to final form
- Least work required to make a useful product

Characteristics of Products

- Forging
  - Produces discrete parts with a variety of unlimited shapes;
  - Typical properties better than extrusions;
  - Surface finish fair to good; High die and equipment costs; Moderate to high labor costs; Moderate to high operator skill

Bulk Deformation Processes

- Rolling typically starts with a rectangular ingot and results in various shapes
  - Plates (t > 6mm)
  - Rolls of thin sheet (t < 6mm)
  - Rods
  - Bars
  - Structural shapes (I-Beams for e.g.)
  - Rails
- Typically, material must be further shaped or formed to be useful

Characteristics of Products

- Flat
  - Produces coils of sheet and foil, rectangular flat plate;
  - Excellent properties; Good surface finish; High capital investment; low labor costs; Skilled labor required to operate mill
- Shape
  - Produces shapes of diverse cross section;
  - Excellent properties along the rolling direction: Good surface finish; Expensive specially shaped rolls; Low labor costs; Relatively low labor skill required to operate mill

Bulk Deformation Processes

- Extrusion starts with typically cylindrical cast ingots and results in a multitude of shapes usually with constant cross section close to final form
- Less subsequent work is required to make products useful then rolled sheet or plate

Characteristics of Products

- Extrusion
  - Produces long lengths of solid and hollow shapes with usually constant cross section;
  - Product may be cut to form discrete products;
  - Excellent surface finish, Excellent properties; Moderate to high equipment cost (dies are expensive); Low to moderate labor costs; Low to moderate operator skill

Characteristics of Products

- Drawing
  - Produces long lengths of solid rod or wires of constant cross section;
  - Smaller cross sections than typical extrusion; Good surface finish; Low to moderate equipment and labor costs; Low to moderate operator Skill

Typical Formed and Shaped Parts in an Automobile

Ceramic Spark Plug

Stamped wheel covers

Springs

Cold-rolled sheet metal body

Stamped plates

Drawn tube for antenna

Metal and plastics

Forged Valves

Molded dashboard

Shaped Windshield

Molded tires

Blow molded plastic tanks for fluids

Tail light lenses

From: Manufacturing Engineering & Technology – Kalpakjian and Schmid, 4th Ed., 2001, Prentice-Hall

Forging

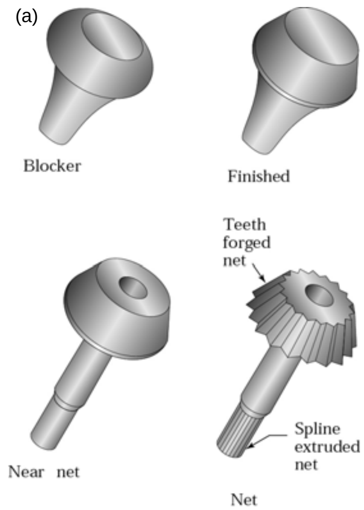
Forging

❖ Forging denotes a family of processes by which plastic deformation of the work-piece is carried out by compressive forces, at room temperature (cold), or at elevated temperatures (hot).

❖ Simple forging can be made with a heavy hammer and an anvil using techniques that have been available for centuries.

❖ However, usually a set of dies and a press are required.

Forging



Schematic illustration of the steps involved in forging a bevel gear with a shaft.

Source: Forging Industry Association.

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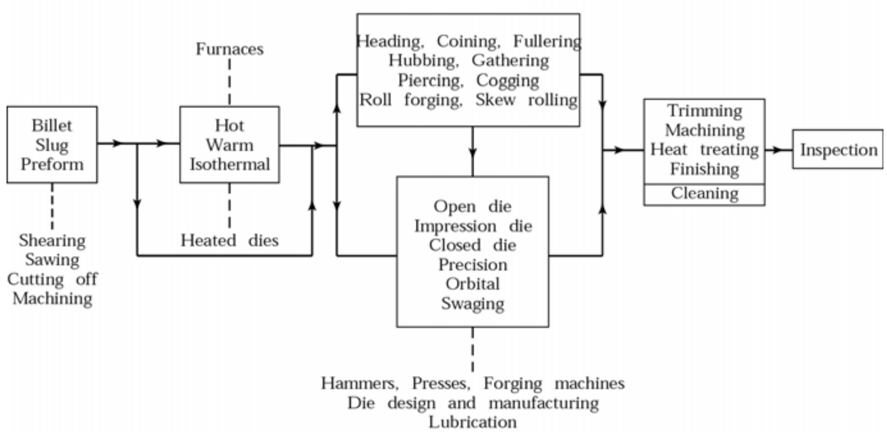
Outline of Forging and Related Operations



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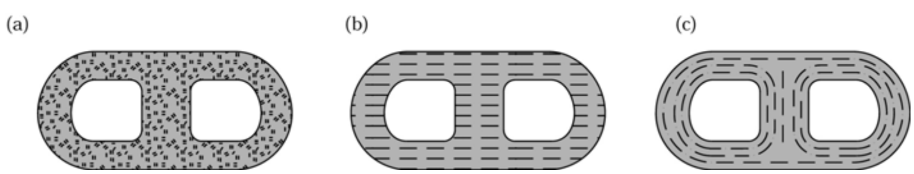
Forging

Advantages:

- The grain flow, i.e., the directional pattern that metal crystals assume during plastic deformation, can be aligned with the directions of the principal stresses that will occur when the work piece is loaded in service.
- Higher strength, ductility, and impact resistance are achieved along the grain flow of the forged material than in the randomly oriented crystals of the cast metal or welded metal
- Structural integrity from piece to piece is better. Good quality forging control makes it easier to avoid internal pockets, voids, inclusions, laps, etc...

Forging

A part made by three different processes, showing grain flow. (a) casting, (b) machining, (c) forging. *Source*: Forging Industry Association.



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Forging

Disadvantages:

- The forged parts often need to be machined before use
- Forging tooling for complicated geometry may be expensive and require multiple passes on the same work piece

Materials used in Forging

- Material must have a good "forgeability"
  - that can be shaped with low forces and without cracking is said to have a good forgeability.
- Forgeability competes with other properties and geometry of the workpiece: such as strength, corrosion resistance, toughness, fatigue resistance, heat resistance, size and section thickness.
- Combined effects of temperature and deformation change the properties of the material.
  - Hence, helpful to know or predict how the process will alter the material properties

Materials used in Forging

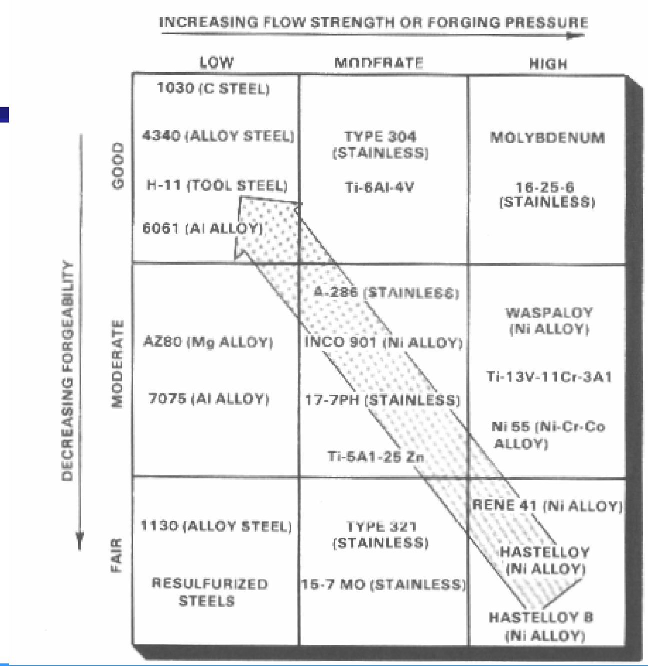
- Most commonly forged materials are steels, copper, forging brass, naval brass, bronze, and copper alloys
- As for steels, their forgeability decreases as their carbon and alloy content increases

Classification of Metals in Decreasing Order of Forgeablilty

TABLE 14.3

Metal or alloy	Approximate range of hot forging temperature (°C)
Aluminum alloys	400–550
Magnesium alloys	250–350
Copper alloys	600–900
Carbon and low–alloy steels	850–1150
Martensitic stainless steels	1100–1250
Austenitic stainless steels	1100–1250
Titanium alloys	700–950
Iron-base superalloys	1050–1180
Cobalt-base superalloys	1180–1250
Tantalum alloys	1050–1350
Molybdenum alloys	1150–1350
Nickel-base superalloys	1050–1200
Tungsten alloys	1200–1300

Forging



Forging Processes

- Open Die
- Impression Die
- Closed Die
  - Upset Forging
  - Precision Forging
- Swaging
- Other Variations

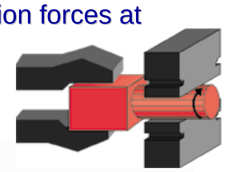
Open Die Forging

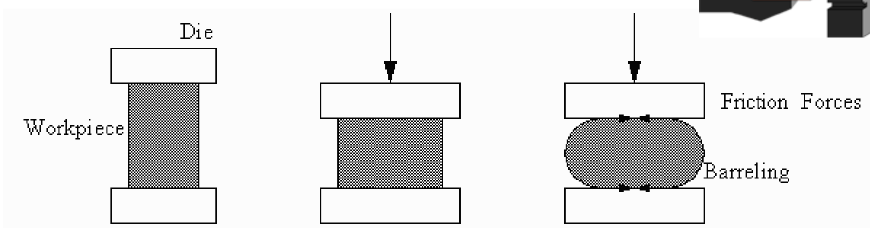
Open Die Forging

- It is the simplest form of forging
- Involves placing a solid cylindrical work piece between two flat dies and reducing its height by compressing it.
- The die surfaces can also be shaped; therefore forming the ends of the cylindrical work piece while compressing it.

Open Die Forging

1. Solid cylindrical billet deformed between two flat dies.
2. Uniform deformation of the billet without friction.
3. Deformation with friction.
   Note barreling of the billet caused by friction forces at the billet-die interface.





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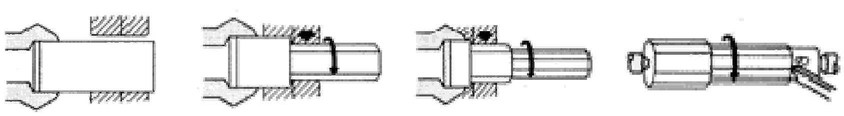
41

Open Die Forging

Forging Shafts:



- Starting stock held by manipulator
- Open die forging
- Progressive forging
- Machining to finish

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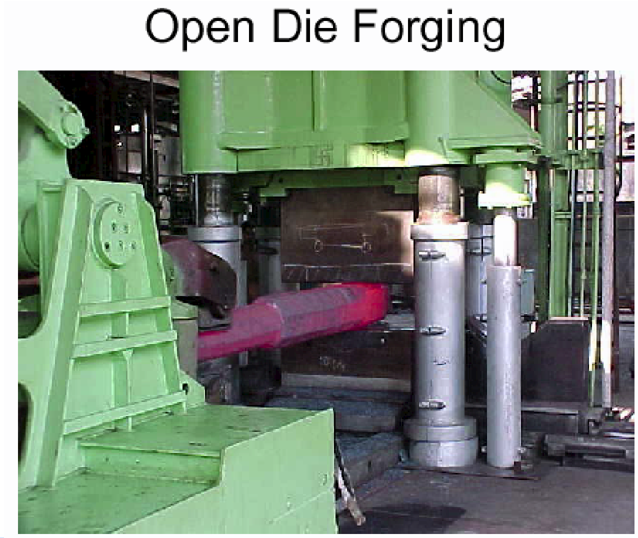
42

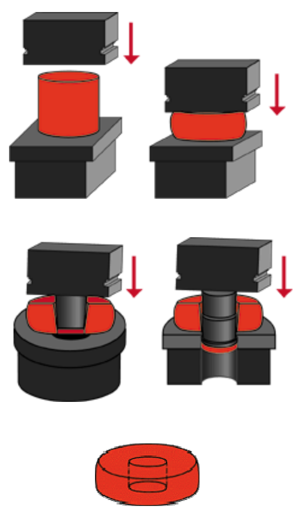
Open Die Forging



Open Die Forging

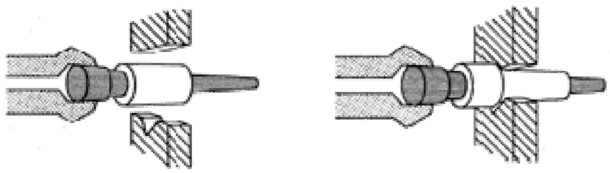
Forging Disks:

- Starting stock
- Preliminary upsetting
- Progressive upsetting/forging to disk dimensions
- Piercing to finish



Open Die Forging

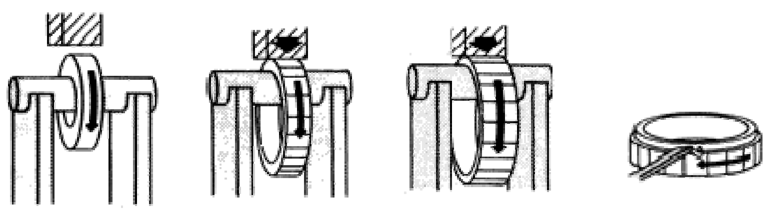
Hollow "Sleeve Type" Forging:



- Starting stock: a punched disk/tube on a tapered draw bar held as shown
- Progressive reduction to required diameter
- Increases overall length of sleeve

Open Die Forging

"Ring Type" Forging:

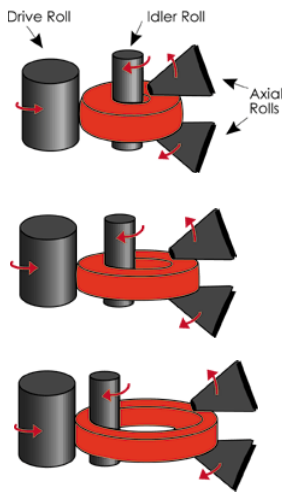


- Starting stock: a preformed disk mounted on a mandrel
- Progressive reduction of wall thickness to required diameter
- Finish to the ring dimensions

Open Die Forging

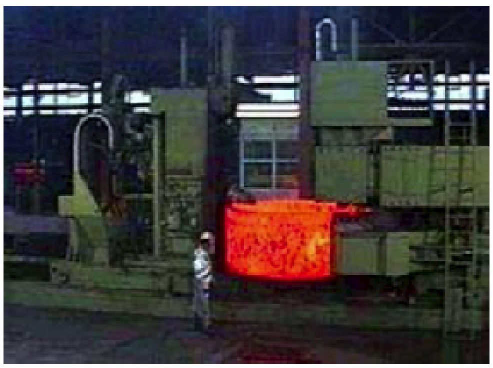
"Rolled Ring" Forging:

- Starting stock: a preformed ring mounted on an idler roll
- Pressure applied by drive roll
- Progressive reduction of wall thickness to required diameter
- Axial rolls control the height
- Finish to the ring dimensions



Open Die Forging

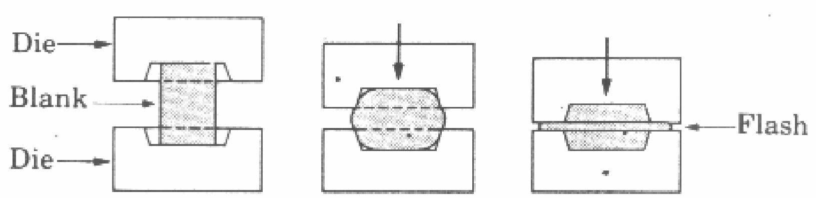
Ring Forging



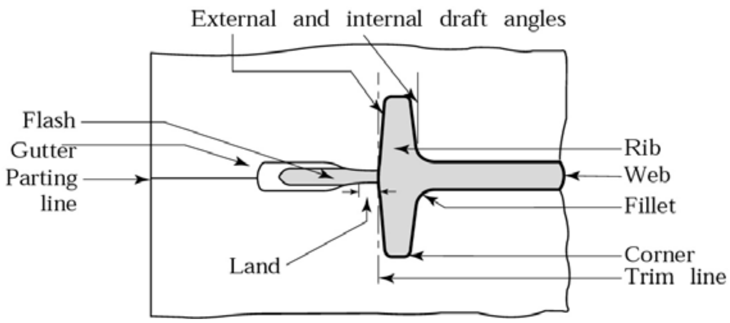
Impression Die Forging

Impression Die Forging

- The work piece is forced to conform to the shape of the die cavity while it is being compressed between the closing dies
- Closing of the die cavities occurs at high striking forces. Some of the material flows radially outward and forms a *flash*.
- Workpiece acquires the shape of the die cavities



Impression-Forging Die



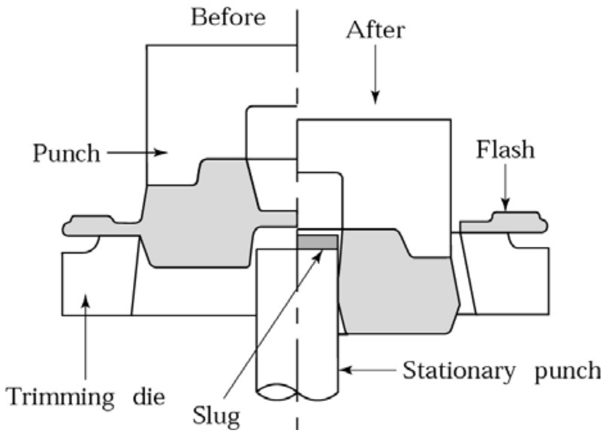
Standard terminology for various features of
a typical impression-forging die.

From: Manufacturing Engineering & Technology – Kalpakjian and Schmid, 4th Ed., 2001, Prentice-Hall

Impression Die Forging - Flash

- Formation of flash prevents further material from flowing in the radial direction in the flash gap
  - length-to-thickness ratio being high
  - results in high frictional resistance to material flow
- In Hot forging
  - flash cools faster than the bulk of the work piece
  - higher resistance to deformation compared to the bulk
  - plays a significant role in helping filling the die cavities

Impression Die Forging



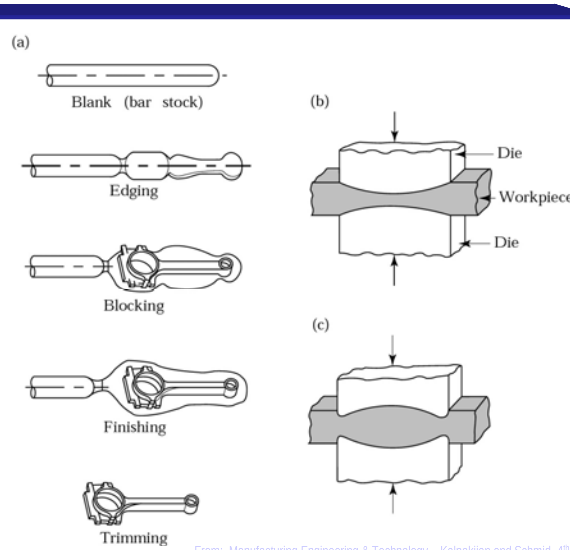
Trimming flash from a forged part.

Note that the thin material at the center is removed by punching.

From: Manufacturing Engineering & Technology – Kalpakjian and Schmid, 4th Ed., 2001, Prentice Hall

Impression Die Forging

(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. (b) Fullering, and (c) edging operations to distribute the material when preshaping the blank for forging.



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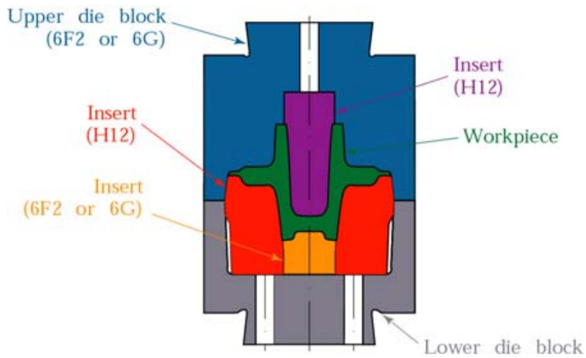
Die Inserts



Die inserts used in dies for forging an automotive axle housing. *Source*: *Metals Handbook, Desk Edition*. ASM International, Metals Park, Ohio, 1985. Used with permission.

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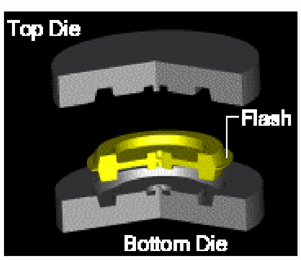
Closed Die Forging

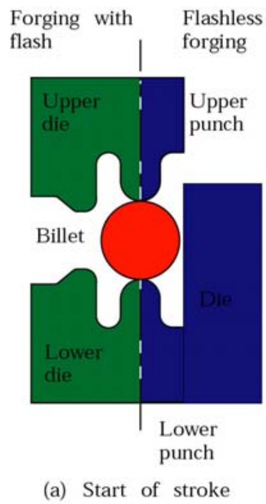
Closed Die Forging

- In closed-die-forging, no flash is formed and the work piece is completely surrounded by the dies.
- Therefore, proper control of the volume of material is essential to obtain a forging of desired dimensions.
- Undersized blanks in closed-die forging prevent the complete filling of the die, while oversized blanks may cause premature die failure or jamming of the dies.

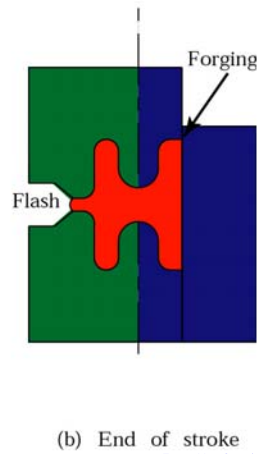
Closed Die Forging



Closed Die Forging



Comparison of Forging With and Without Flash



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

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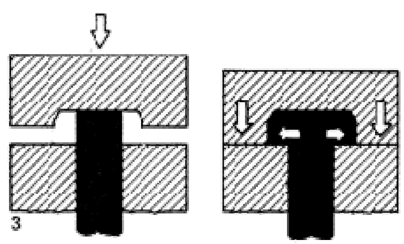
Closed Die Forging

Cold Forging:



Heading, a common technique for making fasteners, gathers steel in the head and other sections along the length of the part

Precision Forging

Precision Forging

- When Forging Demands
  - economical manufacture
  - greater accuracy
  - less post-forging machining operations

then Precision Forging is used

Precision Forging

- Also known as
  - Net shape forging
  - Close tolerance forging
  - No-draft forging
- Machining is minimized
  - exposure of end-grains is less
  - reduction in corrosion & cracking

Precision Forging

- Accurate billet weight is first taken
  - minimizes flash
  - minimizes wastage
- Materials suited for Precision Forging process
  - Magnesium alloys
  - Aluminum

Precision Forging

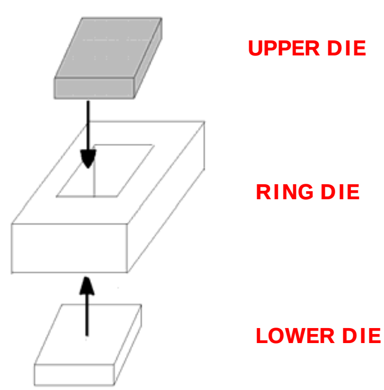
- Compared to conventional forging:
  - Close tolerances
  - Low draft
  - Close control of the process:
    - process temp
    - pressure during forging cycle

Isothermal forging (part & die are at the same temperature)

Precision Forging

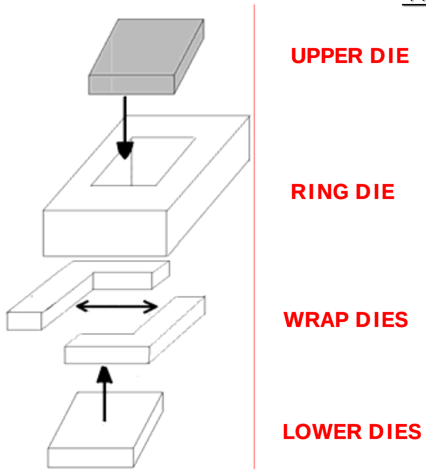
- Die Types
  - Through Die
  - Wrap Die

Through Die



Precision Forging

Wrap Die



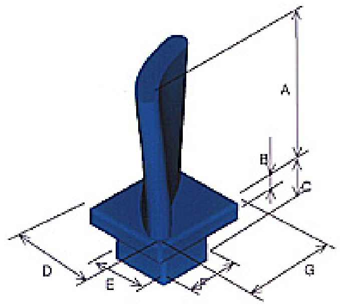
Precision Forging

Advantages of Using Through & Wrap Dies

- Excess material is flashed vertically
  - no external draft angle
  - mismatch allowance
- Small fillets
  - die fills
  - flow-through defects do not occur
- Inner walls
  - 3 degree taper (to vertical)

Precision Forging

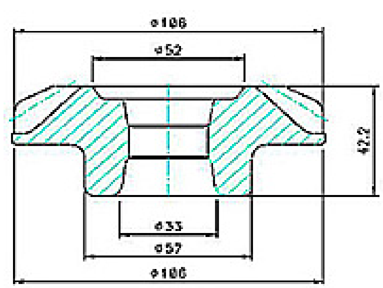
Applications : Turbine Blade



- Benefits
  - better quality control
  - 20% reduction in cost (conventional forging)

Precision Forging

Applications : Gear and Pinion



- Benefits
  - reduced noise (by 30%)
  - improved strength (by up to 30%)
  - 20% reduction in cost (machining)

Precision Forging

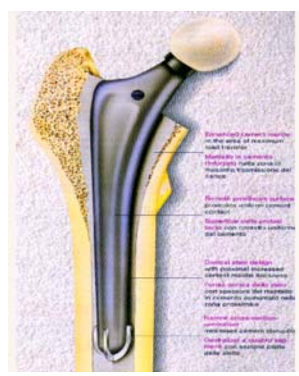
Applications : Pulley Clutch Assembly

- Benefits
  - better durability
  - 20% reduction in cost (conventional forging)

ME 4563 Dr. S. Haran 71

Precision Forging

Applications : Hip Joint



- Benefits
  - Increased durability
  - Reduced corrosion

ME 4563 Dr. S. Haran 72

Upset Forging

Upset Forging

- Upset Forging: a process of

  increasing the diameter of a material by compressing its length

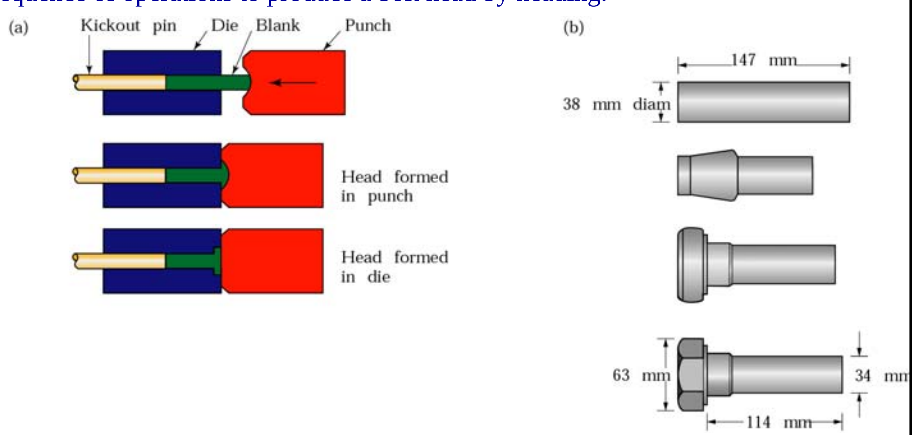
  - Most widely used of all forging processes

Upset Forging

- Parts can be forged both *hot* and *cold*
- Normal starting stock would be
  - wire
  - rod
- Some machines can forge bars up to 250mm in diameter

Upset Forging

(a) Heading operation, to form heads on fasteners such as nails and rivets. (b) Sequence of operations to produce a bolt head by heading.



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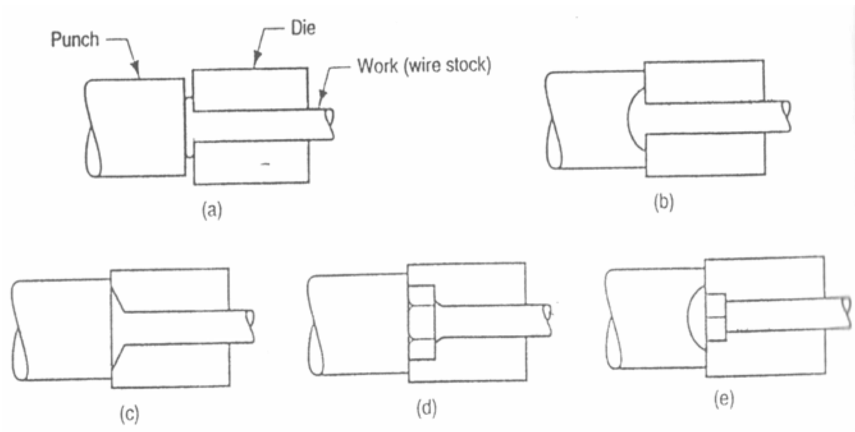
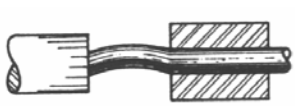
Upset Forging

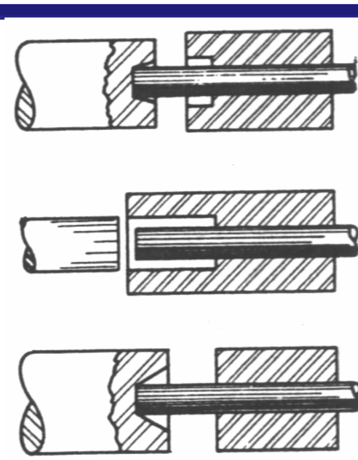


Upset Forging – Design Aspects

- The limiting length of unsupported metal that can be upset in **one** blow without buckling is **3 times** the bar diameter.
- Failure => buckling



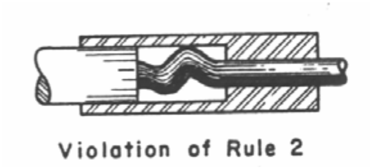
Violation of Rule I

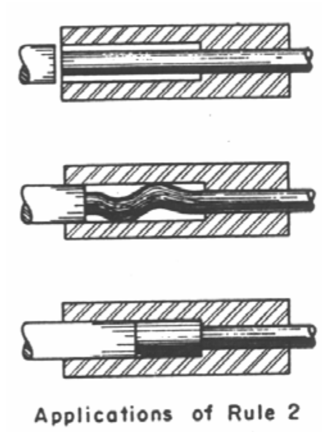


Applications of Rule I

Upset Forging – Design Aspects

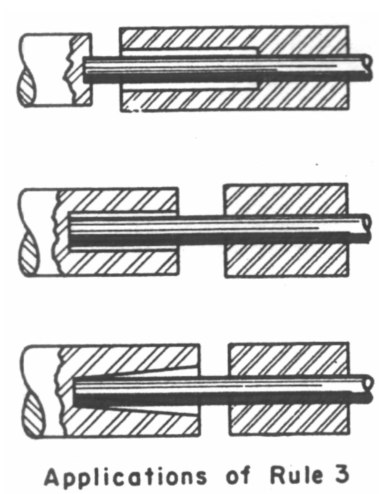
- Lengths of stock greater than **3 times** the diameter may be upset successfully provided that the cavity diameter is not more than 1.5 times the bar diameter



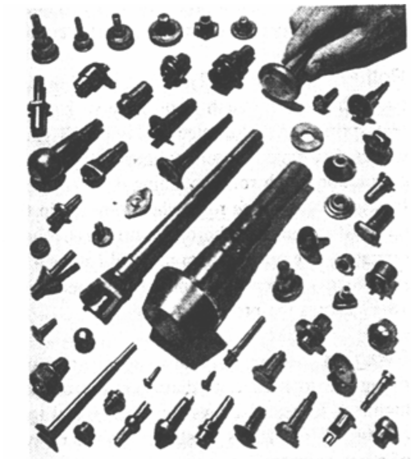


Upset Forging – Design Aspects

- In an upset requiring stock with length more than **3 times** the bar diameter and when the diameter upset is **1.5 times** the bar diameter, the length of unsupported metal beyond the die face must not exceed the bar diameter.



Upset Forging



Variations in Forging

Variations in Forging

The following are miscellaneous forging operations

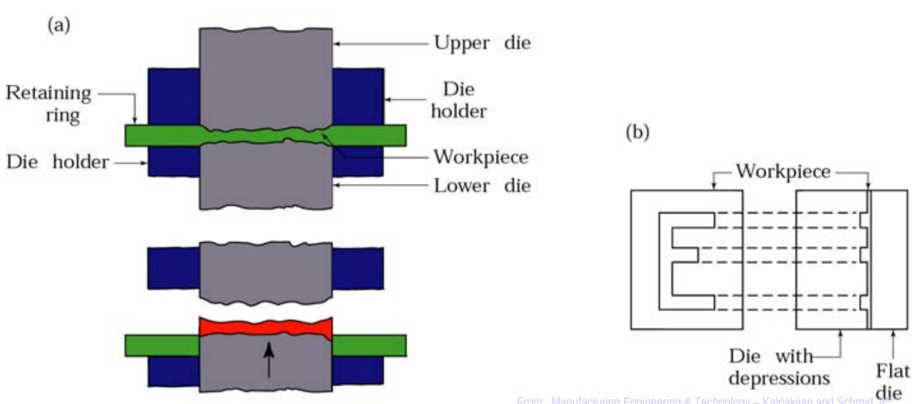
❖ **Coining**

Minting of coins, where the slug is shaped in a completely closed cavity, is an example of closed-die forging.

To produce the fine details of a coin, high pressures, and sometimes several operations are needed, while lubricants are not used because they can prevent reproduction of fine die surface details

Variations in Forging

(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 on a block of metal.



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Variations in Forging

❖ **Heading**

- Heading is an example of open-die forging.
- It transforms a rod, usually of circular cross-section, into a shape with a larger cross-section.
- The heads of bolts, screws, and nails are some examples of heading.
- The work piece has a tendency to buckle if the length-to- diameter ration is too high

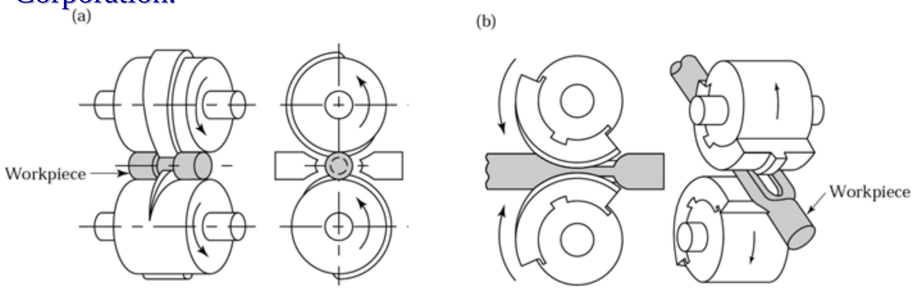
Variations in Forging

❖ **Roll Forging**

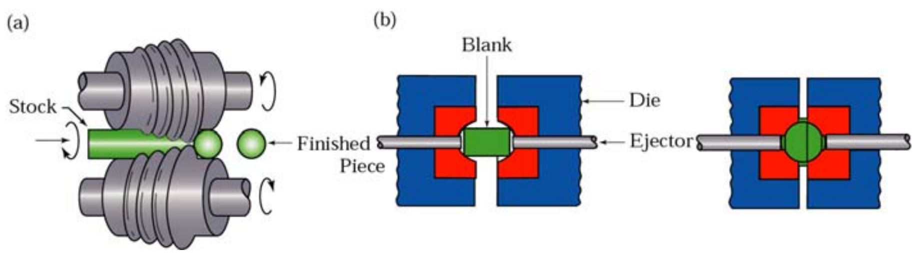
- A bar is passes through a pair of rolls with grooves of various shapes.
- This process reduces the cross-sectional area of the bar while changing its shape.
- This process can be the final forming operation.
- Examples are tapered shafts, tapered leaf springs, table knives, and numerous tools. It can also be a preliminary forming operation, followed by other forging processes. Examples are crankshafts and other automotive components.

Variations in Forging

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) reprinted with permission of General Motors Corporation.



Variations in Forging



(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

Variations in Forging

❖ **Piercing**

The work piece, either confined to a die cavity or unconstrained, is pierced by a punch to produce a cavity or an impression.

The piercing force depends on three factors: the cross-sectional area of the punch and its tip geometry, the flow stress of the material, and the friction at the interface.

❖ **Hubbing**

It is a piercing process where the die cavity produced is used for subsequent forming operations.

To generate a cavity by hubbing, a pressure equal to three times the ultimate tensile strength of the material of the work piece is needed.

Variations in Forging

❖ **Cogging**

Also called drawing out, successive steps are carried to reduce the thickness of a bar. Forces needed to reduce the thickness of a long bar are moderate if the contact area is small

❖ **Fullering and Edging**

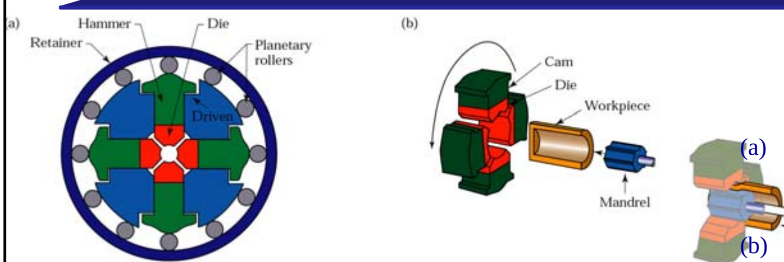
It is an intermediate process to distribute the material in certain regions of the work piece before it undergoes other forging processes that give it its final shape

Variations in Forging - Swaging

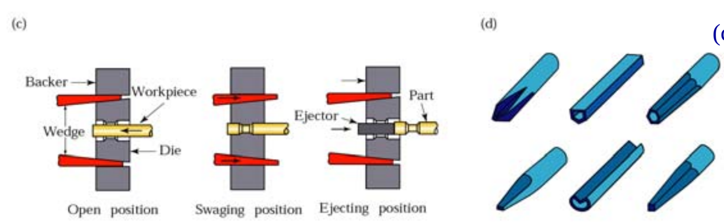
❖ Swaging – Also called Rotary swaging or Radial Forging

- Solid rod or tube is reduced in diameter by the reciprocating radial movement of two or four dies
- Process is carried out at room temperature
- Internal diameter and thickness can be controlled with or without mandrels
- External shapes can also be had on the rod or tube
- Size usually limited to about 50mm dia (2 in.)
- Length is limited by the length of the mandrel (where required)
- Improved mechanical properties and dimensional accuracy

Variations in Forging



Rotary-swaging or Radial Forging



(a) Schematic illustration of the rotary-swaging process. (b) Forming internal profiles on a tubular workpiece by swaging. (c) A die-closing type swaging machine, showing forming of a stepped shaft. (d) Typical parts made by swaging

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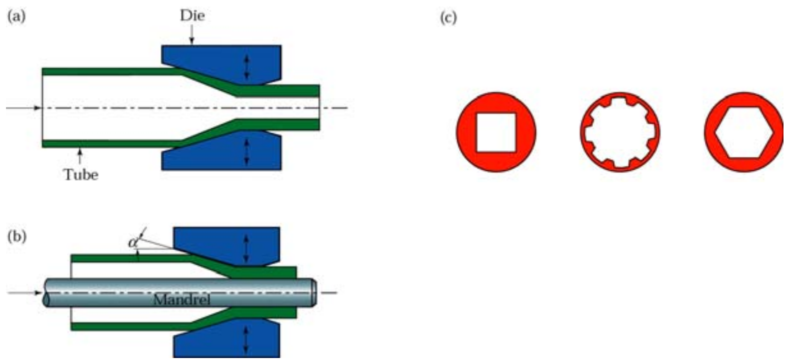
Swaging of Tubes With and Without a Mandrel



(a) Swaging of tubes without a mandrel; not 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. Rifling (spiral grooves) in small gun barrels can be made by this process.

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Forging Machines

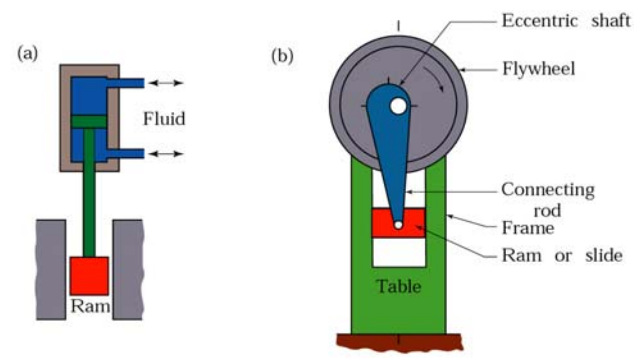
Presses –	Hydraulic
	Mechanical
	Screw
Hammers –	Gravity Drop – drop forging
	Power Drop – steam, air, fluid
	Counter blow – two hammers
	High energy rate (one blow !)

Speed Range of Forging Equipment

TABLE 14.4

Equipment	m/s
Hydraulic press	0.06–0.30
Mechanical press	0.06–1.5
Screw press	0.6–1.2
Gravity drop hammer	3.6–4.8
Power drop hammer	3.0–9.0
Counterblow hammer	4.5–9.0

Principles of Various Forging Machines



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. (continued)

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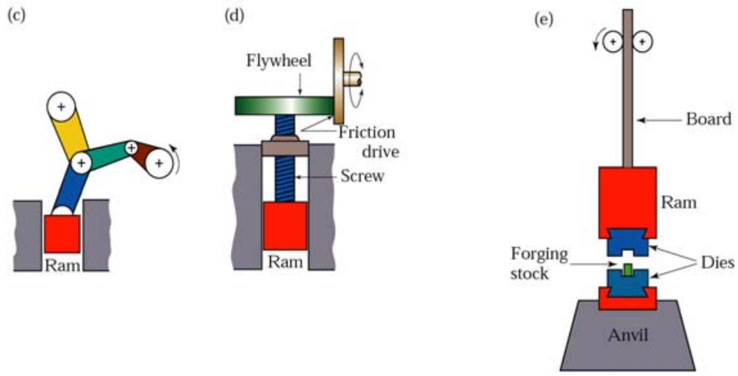
Principles of Various Forging Machines



Schematic illustration of the principles of various forging machines. (c) Knuckle-joint press. (d) Screw press. (e) Gravity drop hammer.

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Open die forging

Hydraulic Press

JSW, Japan

Open die forging

Push down
Hydraulic Press

JSW, Japan

Open die forging

Pull down
Hydraulic Press

JSW, Japan

Open die forging

Rotator for Forging press

JSW, Japan

Forging Dies

Forging Dies

Die design is an integral part of the forging process. Several factors to be considered.

- Final part shape determined by die accuracy
- Multiple parts can be made in one die
- Progressive shaping can be done in one die set
- Need to be stronger than highest forging stress

Forging Dies

Failure of Dies generally results from one or more of the following causes:

- Improper design
- Defective material
- Improper heat treatment and finishing operations
- Excessive wear
- Overloading
- Misuse
- Improper handling

Forging Dies – Important Parameters

- Die materials
- Draft angles
- Flash
- Parting Lines
- Fillet radii

Forging Dies – Die Materials

- Operating conditions of Dies
  - high pressures
  - high temperatures
  - abrasion
- Die qualities required
  - good strength
  - toughness
  - thermal shock resistance
  - hardness

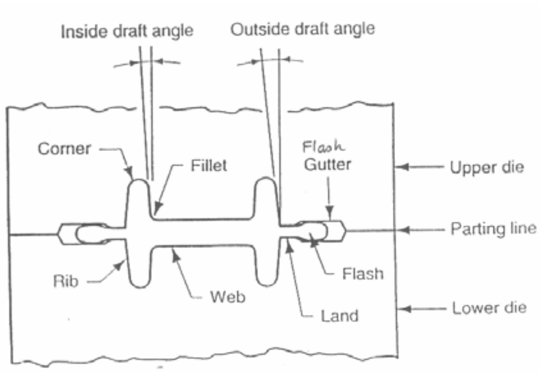
Forging Dies – Die Materials

- Forging steels
  - special alloy steels
  - nickel , chromium, molybdenum
- Forging non-ferrous metals
  - alloy steels
  - chromium, molybdenum, vanadium
- Die steels
  - machined, hardened, and tempered

Forging Dies – Draft Angles

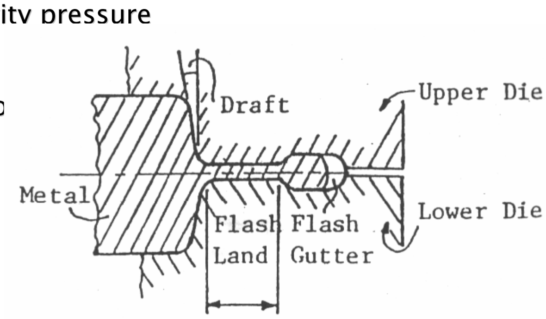
..the taper applied to external and internal sides of a closed die forging.

- Function
  - to facilitate removal of part after forging
  - to aid in metal flow in the die cavity.
- Outside draft angle
  - 3 degrees
    - Al, Mg
  - 7 degrees
    - steel, titanium
- Inside Draft angle > Outside Draft angle



Forging Dies – Flash

- In closed-die forging
  - flash is formed between the die halves
- Frictional resistance in flash land
  - increased die cavity pressure
- Flash gutter
  - provides space fo excess material
  - limits pressure build-up

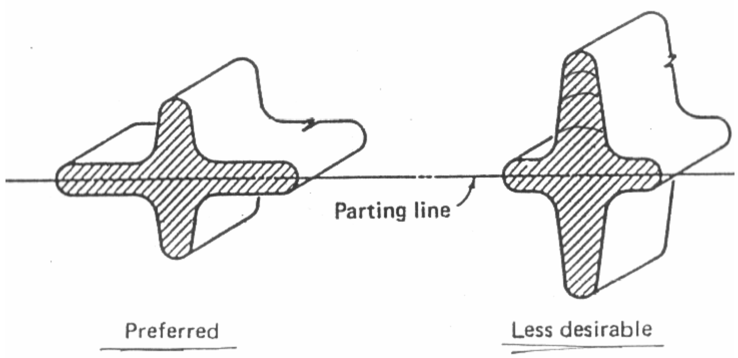


Forging Dies – Parting Lines

- The surface separating the upper and lower halves
  - straight
  - horizontal
  - inclined in one or more planes
- Influences
  - initial cost
  - die wear
  - grain flow
  - mechanical properties
  - post-forging machining/trimming operations

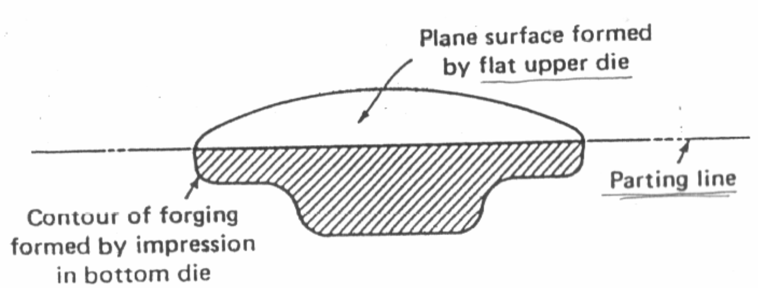
Forging Dies – Parting Lines

- It should pass through the maximum periphery of the forging



Forging Dies – Parting Lines

- Simplify die construction
  - reduce costs
  - eliminate possible mismatch

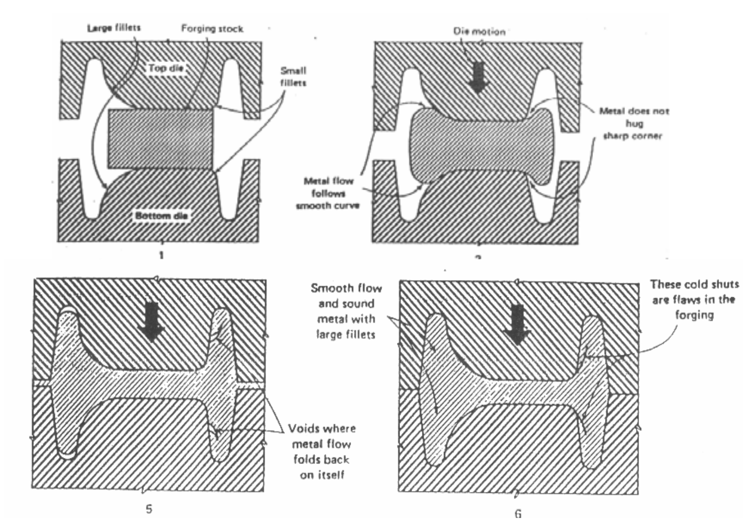


Forging Dies – Fillet Radii

Practice is to:

- Provide generous radii
  - abrupt change in metal flow direction => defects
- Die Fillets
  - min radius : 3mm
  - too small => stress concentrations

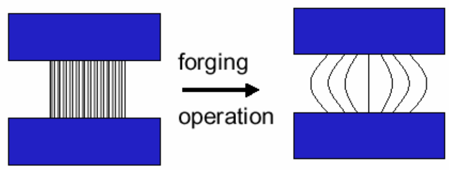
Forging Dies – Effects of Fillet Radii



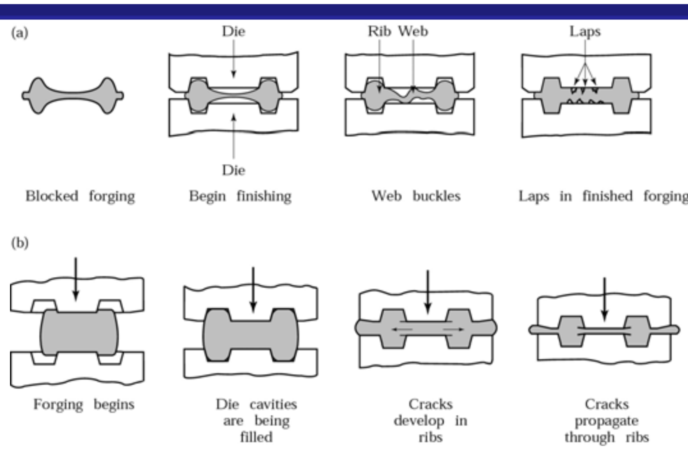
Defects in Forged Parts

Main forging defect

- Surface cracks
  - due to sticking and barreling, leading to tensile forces on the surface.



Defects in Forged Parts



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 oversized billet; die cavities are filled prematurely, and the material at the center flows past the filled regions as the dies close.

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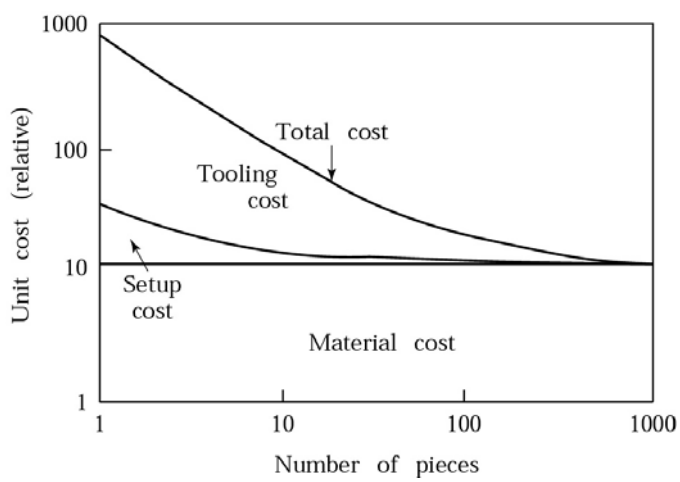
Forging Economics

Factors in the cost of Forgings

- Tool & Die costs – moderate to high depending upon the complexity of the job. Spread over number of jobs.
- Cost of dies relative to material cost (that is to be forged) - high for small parts
- Setup and tooling costs decrease as number of jobs increase
- Labor costs are generally seen to be moderate
- Die design and die manufacturing is being done by CAD/CAM operations leading to more economical forgings

Unit Cost in Forging



Typical unit cost (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.

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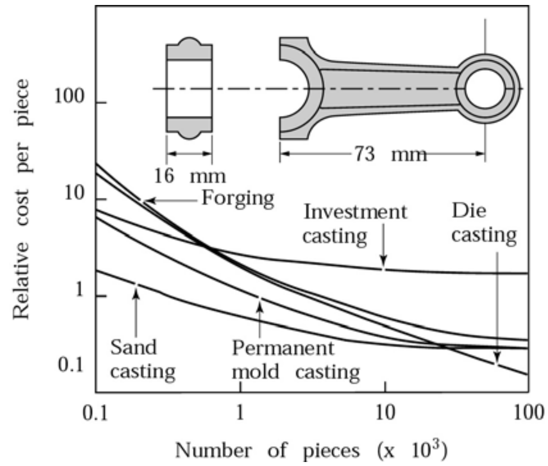
Relative Unit Costs of a Small Connecting Rod

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.



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Forging vs. Casting

- **Forgings are stronger**

Casting cannot obtain the strengthening effects of hot and cold working. Forging surpasses casting in predictable strength properties - producing superior strength that is assured, part to part.

- **Forging refines defects from cast ingots or continuous cast bar**

A casting has neither grain flow nor directional strength and the process cannot prevent formation of certain metallurgical defects. Pre-working forge stock produces a grain flow oriented in directions requiring maximum strength.

Forging vs. Casting

- **Forgings are more reliable, less costly**

Casting defects occur in a variety of forms. Because hot working refines grain pattern and imparts high strength, ductility and resistance properties, forged products are more reliable. And they are manufactured without the added costs for tighter process controls and inspection that are required for casting.

Forging vs. Casting

- **Forgings offer better response to heat treatment**

Castings require close control of melting and cooling processes because alloy segregation may occur. This results in non-uniform heat treatment response that can affect straightness of finished parts. Forgings respond more predictably to heat treatment and offer better dimensional stability.

- **Forgings' flexible, cost-effective production adapts to demand**

Some castings, such as special performance castings, require expensive materials and process controls, and longer lead times. Open-die and ring rolling are examples of forging processes that adapt to various production run lengths and enable shortened lead times.

Forging - Applications

AUTOMOTIVE & TRUCK

The characteristics of forged parts strength, reliability and economy are what makes them ideal for vital automotive and truck applications. Forged components are commonly found at points of shock and stress such as wheel spindles, kingpins, axle beams and shafts, torsion bars, ball studs, idler arms, pitman arms and steering arms.

AGRICULTURAL MACHINERY & EQUIPMENT

VALVES, FITTINGS, OIL FIELD APPLICATIONS

Because of their superior mechanical properties and freedom from porosity, forgings are often associated with the high pressure applications of the valve and fitting industry. Corrosion and heat-resistant materials are used for flanges, valve bodies and stems, tees, elbow reducers, saddles and other fittings. Oil field applications include rock cutter bits, drilling hardware, and high-pressure valves and fittings.

HAND TOOLS & HARDWARE

Pliers, hammers, sledges, wrenches and garden tools, as well as wire-rope clips, sockets, hooks, turnbuckles and eye bolts are common examples. Surgical and dental instruments are also often forged. Special hardware for electrical transmission and distribution lines such as pedestal caps, suspension clamps, sockets and brackets are commonly forged for strength, dependability and resistance to corrosion.

Forging - Applications

OFF-HIGHWAY EQUIPMENT/RAILROAD

Strength, toughness, machinability and economy account for the many uses of forgings in off-highway and heavy construction equipment, mining equipment, and material handling applications.

GENERAL INDUSTRIAL EQUIPMENT

Forgings of great size are often found in industrial equipment and machinery used by the steel, textile, paper, power generation and transmission, chemical and refinery industries to name just a few. Typical forged configurations include bars, blanks, blocks, connecting rods, cylinders, discs, elbows, rings, T's, shafts and sleeves.

ORDNANCE/SHIPBUILDING

Forged components are found in virtually every implement of defense, from rifle triggers to nuclear submarine drive shafts. Heavy tanks, missiles, armored personnel carriers, shells and other heavy artillery are common defense-related applications of forged components.

Forging - Applications

AEROSPACE

High strength-to-weight ratio and structural reliability can favorably influence performance, range, and payload capabilities of aircraft.

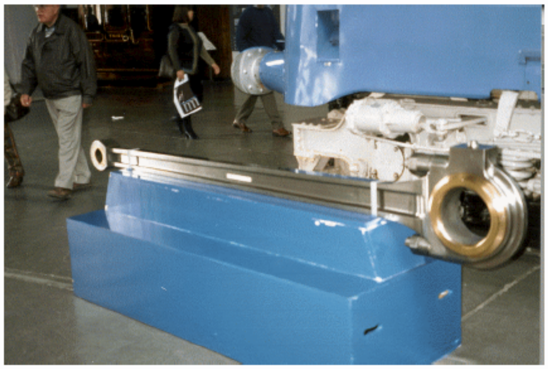
Made of various ferrous, non-ferrous and special alloy materials, forgings are widely used in commercial jets, helicopters, piston-engine planes, military aircraft and spacecraft.

Some examples of where a forging's versatility of size, shape and properties make it an ideal component include bulkheads, wing roots and spars, hinges, engine mounts, brackets, beams, shafts, landing gear cylinders and struts, wheels, brake carriers and discs and arresting hooks. In jet turbine engines, iron-base, nickel-base and cobalt-base superalloys are forged into components such as discs, blades, buckets, couplings, manifolds, rings, chambers and shafts.

Forging - Applications

This aft dome is used in Titan IV space launch vehicles

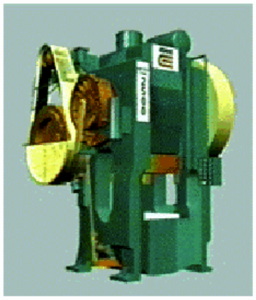
Railroad engine connecting rod



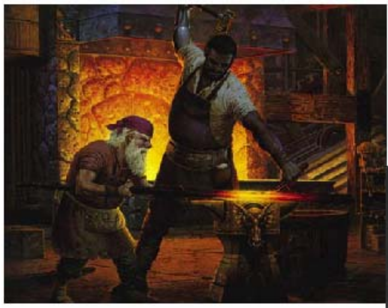
Forging - Applications

The forging process can produce a variety of automotive parts including (from left): connecting rods and caps, transmission shift forks and u-joint steering yokes

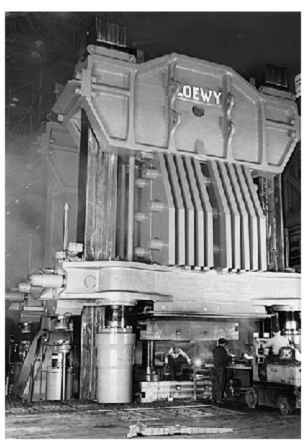
Forging



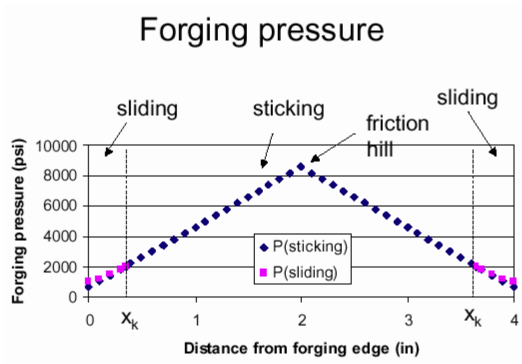
Forging

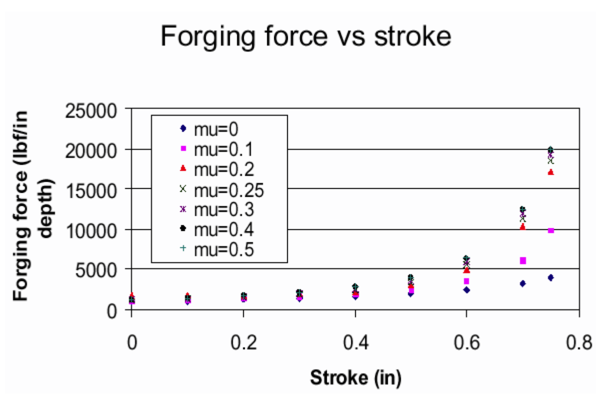


Aircraft landing gear



50,000 ton press


Forging pressure
sliding
sticking
friction hill
sliding
Forging pressure (psi)
10000
8000
6000
4000
2000
0
0
x_k
1
2
3
x_k
4
Distance from forging edge (in)
P(sticking)
P(sliding)

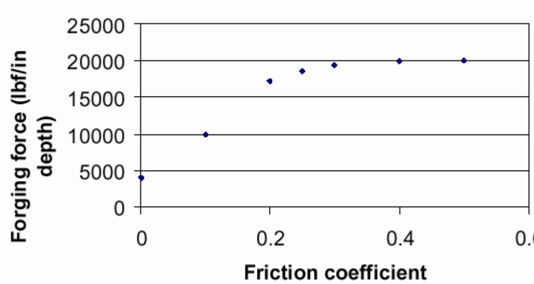

Forging force vs stroke
Forging force (lbf/in depth)
25000
20000
15000
10000
5000
0
0
0.2
0.4
0.6
0.8
Stroke (in)
mu=0
mu=0.1
mu=0.2
mu=0.25
mu=0.3
mu=0.4
mu=0.5

Effect of friction coefficient (μ)

Friction coefficient	Fmax (lbf/in depth)	xk	Stick/slide
0	4000	2	slide
0.1	9883	2	slide
0.2	17161	0.573	both
0.25	18549	0.347	both
0.3	19288	0.213	both
0.4	19886	0.070	both
0.5	20000	0	stick

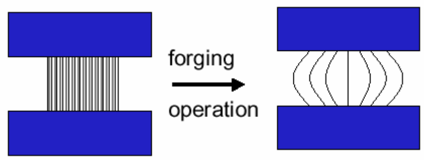
- Friction is very important

Forging force vs. friction coefficient (μ)

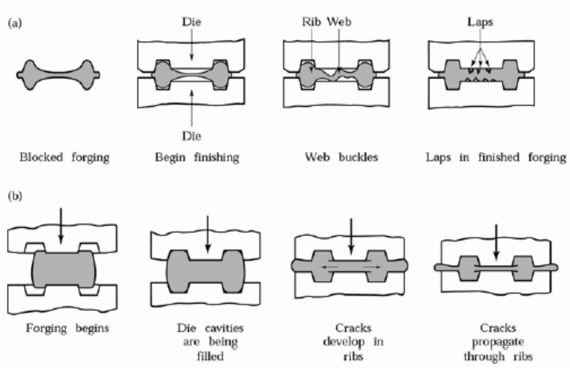


Main forging defect

- Surface cracks
  - due to sticking and barreling, leading to tensile forces on the surface.

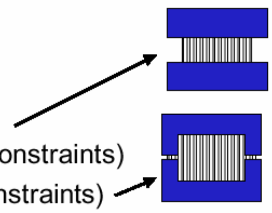


Forging Defects



Forging

- Part formation by pressing between dies
  - Dies are hard metal shapes
- Temperature
  - Hot (usually)
  - Cold
- Dies
  - Open (no lateral constraints)
  - Closed (lateral constraints)



Forging hammer capabilities

	Moving mass (kg)	Energy at strike (J)
Gravity drop hammers	500 - 5,000	6,000 - 75,000
Power drop hammers	500 - 18,000	18,000 - 600,000
High energy rate forming		500,000 - 5,000,000

Forging press parameters

	Load capacity	Strokes per minute	Power (kW)
Mechanical presses			
Open-back, inclinable	150 - 1,250 kN	200 - 100	3 - 15
High-speed, straight side	300 - 2,000 KN	2000 - 200	
Larger straight side	1 - 6 MN	100 - 20	10 - 60
Transfer presses	2 - 40 MN	50 - 10	
Forging presses	3 - 80 MN	100 - 30	20 - 500
Hydraulic presses			
Universal	4 - 25 MN		
Forging presses	2 - 500 MN		150 - 1000

Hot upsetting machine parameters

Rate size (mm) (upset diameter)	Forging force (MN)	Strokes/min	Power (kW)
25	0.5	90	5
38	1	65	10
50	2	60	15
75	4	45	25
100	6	35	40
125	8	30	50
150	10	27	60
175	13	25	90
200	16	23	110
225	20	20	150