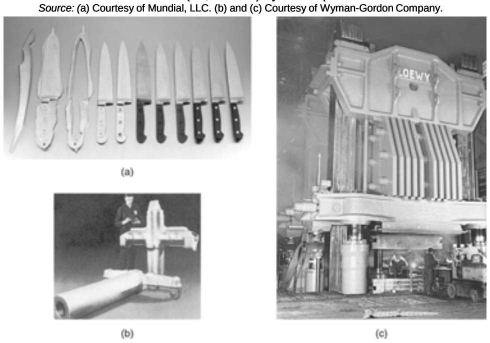
Metal-Forging Processes and Equipment

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*

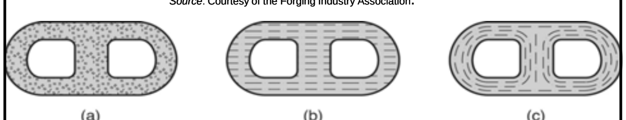
FIGURE 14.1 (a) Illustration of the steps involved in forging a knife. (b) Landing-gear components for the C5A and C5B transport aircraft, made by forging. (c) General view of a 445-MN (50,000-ton) hydraulic press.
Source: (a) Courtesy of Mundial, LLC. (b) and (c) Courtesy of Wyman-Gordon Company.



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.



The Forging Process

- Cold Forging: at room temperature
  - Requires higher forces
  - Need ductile workpiece at working temp.
  - Parts have good surface finish and dimensional accuracy
- Hot Forging: at elevated temperatures
  - Requires lower forces
  - Lower quality surface finish & accuracy

TABLE 14.1 General Characteristics of Forging Processes

TABLE 14.1

General Characteristics of Forging Processes

Process	Advantages	Limitations
Open die	Simple and inexpensive dies; wide range of part sizes; good strength characteristics; generally for small quantities	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
Closed die	Relatively good utilization of material; generally better properties than open-die forgings; good dimensional accuracy; high production rates; good reproducibility	High die cost, not economical for small quantities; machining often necessary
Blocker	Low die costs; high production rates	Machining to final shape necessary; parts with thick webs and large fillets
Conventional	Requires much less machining than blocker type; high production rates; good utilization of material	Higher die cost than blocker type
Precision	Close dimensional tolerances; very thin webs and flanges possible; machining generally not necessary; very good material utilization	High forging forces, intricate dies, and provision for removing forging from dies

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

FIGURE 14.3 (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.

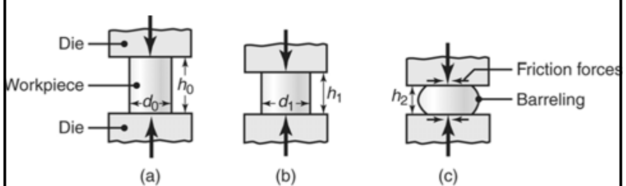
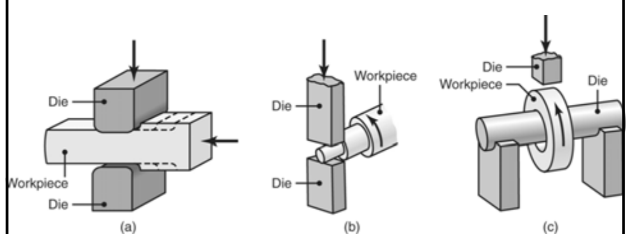


FIGURE 14.4 (a) Schematic illustration of a cogging operation on a rectangular bar. Blacksmiths use this process to reduce the thickness of bars by hammering the part on an anvil. Reduction in thickness is accompanied by barreling, as in Fig. 14.3c.
(b) Reducing the diameter of a bar by open-die forging; note the movements of the dies and the workpiece.
(c) The thickness of a ring being reduced by open-die forging.



Impression-die Forging

- The workpiece takes the shape of the die cavity while being forged between two shaped dies
- Usually hot forge
  - To lower the required forces
  - To attain workpiece ductility
- Creates flash
  - Note that flash ensures cavity fills first

FIGURE 14.5 (a) through (c) Stages in impression-die forging of a solid round billet. Note the formation of flash, which is excess metal that is subsequently trimmed off. (d) Standard terminology for various features of a forging die.

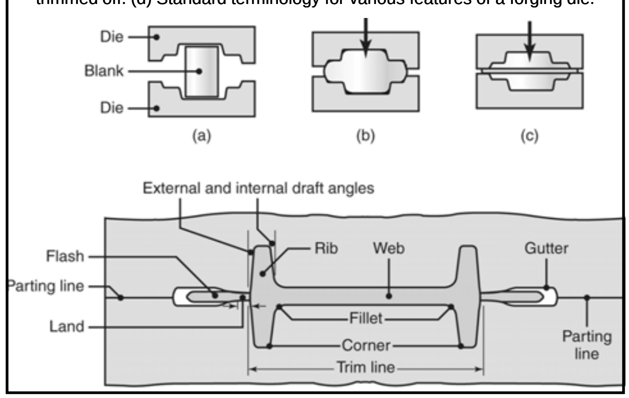
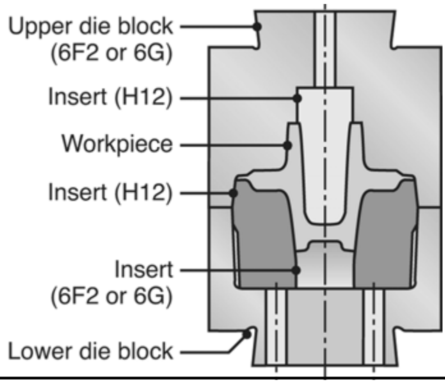


FIGURE 14.6 Die inserts used in forging an automotive axle housing. (See Section 5.7 for die materials.)



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

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

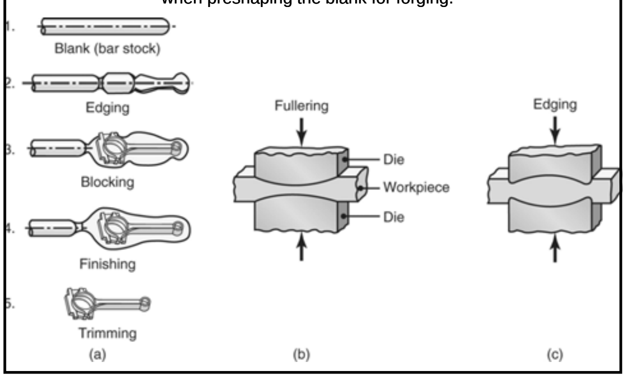
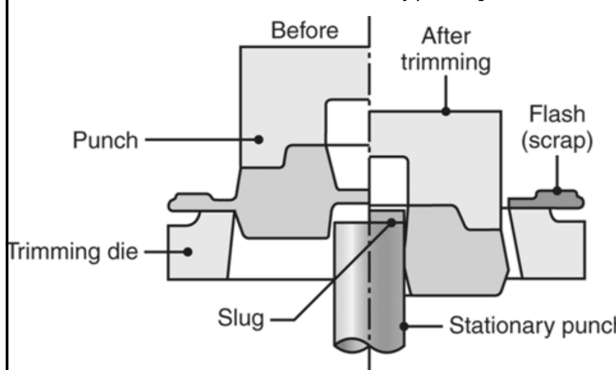


FIGURE 14.8 Trimming flash from a forged part. Note that the thin material at the center is removed by punching.



Forging Force
Impression-die Forging

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

$F = kY_fA$ 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 14.2

Range of *k* Values for Eq. (14.2)

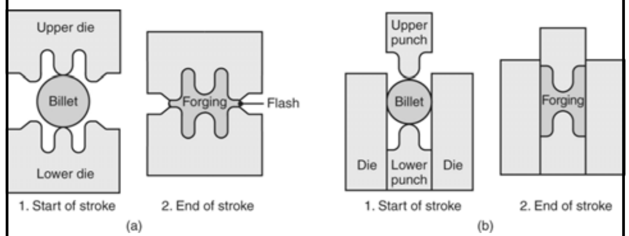
Shape	*k*
Simple shapes, without flash	3–5
Simple shapes, with flash	5–8
Complex shapes, with flash	8–12

Precision Forging

- "Net shape forming" reduces the need for later finishing
- Requires:
  - Special & more complex dies
  - Precise control of blank's volume & shape
  - Accurate positioning of the blank in the cavity
  - Higher capacity equipment
- Al & Mg alloys best for precision forging because they require lower forging loads and temperatures

FIGURE 14.9 Comparison of (a) closed-die forging with flash and (b) precision or flashless forging of a round billet.

Source: After H. Takemasu, V. Vazquez, B. Painter, and T. Altan.



Forging Practice & Product Quality

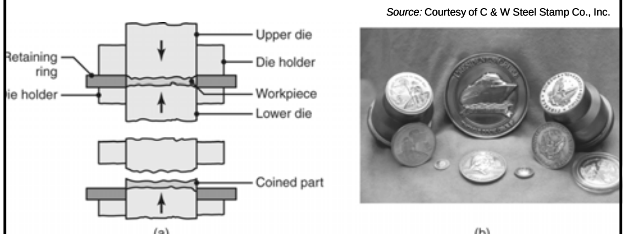
1. Prepare a slug, billet or preform
2. For hot forging: Heat workpiece in a suitable furnace; Descale with wire brush, water jet, steam, scraping.
3. For hot forging: Preheat and lubricate the dies; For cold forging: lubricate the blank
4. Forge the billet in appropriate dies and proper sequence
5. Clean; measure; machine if necessary
6. Perform additional operations if required: straighten, heat treat, grind, machine…..
7. Inspect

Coining

- A closed-die forging process
- Used for coins, medallions & jewelry
- High pressures (up to 6 times material strength) necessary to produce fine details
- May have several coining operations in succession
- No lubricants (get in the way)

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.

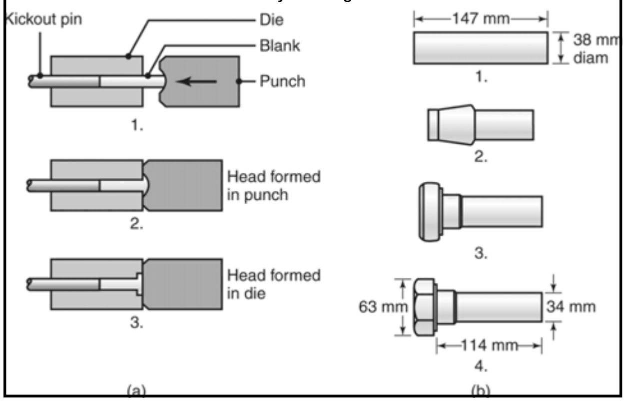
Source: Courtesy of C & W Steel Stamp Co., Inc.



Heading

- 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.



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

FIGURE 14.12 A pierced round billet showing grain-flow pattern. (See also Fig. 14.2c). *Source:* Courtesy of Ladish Co., Inc.

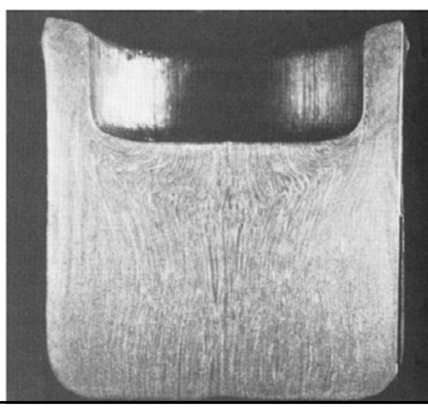


FIGURE 14.13 (a) The stepped pin used in Case Study 14.1. (b) Illustration of the manufacturing steps used to produce the stepped pin. *Source:* Courtesy of National Machinery, LLC.

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

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.

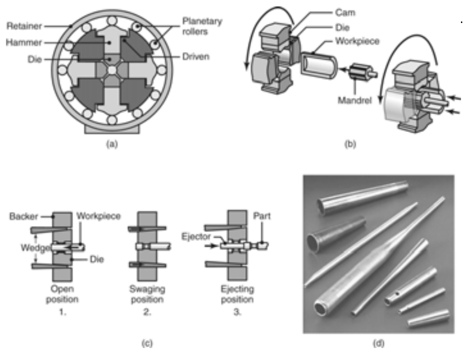
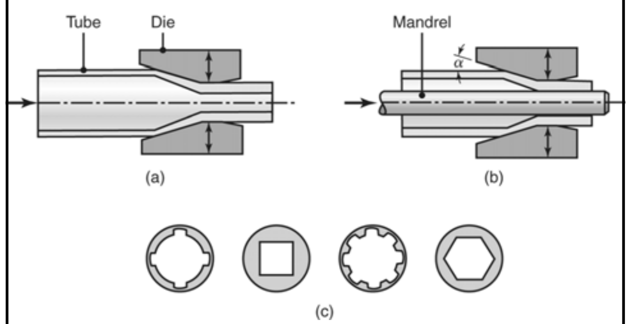


FIGURE 14.15 (a) Swaging of tubes without a mandrel; note the increase in wall thickness in the die gap. (b) Swaging with a mandrel; note that the final wall thickness of the tube depends on the mandrel diameter. (c) Examples of cross sections of tubes produced by swaging on shaped mandrels. Rifling (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

TABLE 14.3 Forgeability of Metals, in Decreasing Order

TABLE 14.3

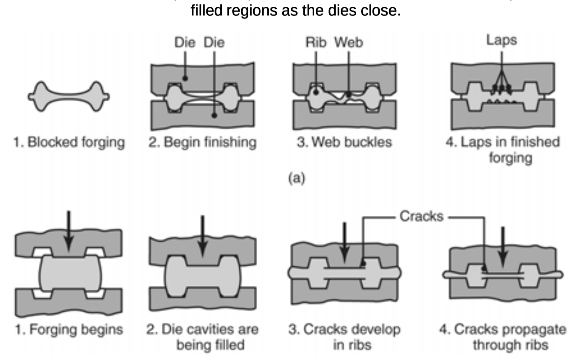
Forgeability of Metals, in Decreasing Order

Metal or alloy	Approximate range of hot-forging temperatures (°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-based superalloys	1050–1180
Cobalt-based superalloys	1180–1250
Tantalum alloys	1050–1350
Molybdenum alloys	1150–1350
Nickel-based superalloys	1050–1200
Tungsten alloys	1200–1300

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

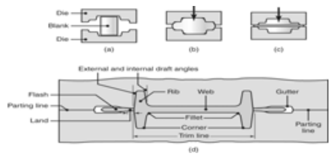
Preshaping

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

Die Design Features



- Locate parting line at largest cross-section of the part
- Allow extra flash to flow into gutter
- Flash thickness about 3% of max. thickness
- Length of *land* usually 2 – 5 times flash thickness
- Internal draft angles: 7º-10º; external draft angles: 3º-5º
- Provide maximum size radii (to facilitate metal flow)
- Provide metal allowances for machining

Die Materials

- <u>Requirements:</u>
  - 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, Mb, Va

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

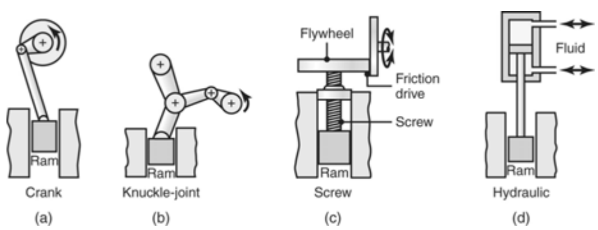
TABLE 14.4 Typical Speed Ranges of Forging Equipment

TABLE 14.4

Typical Speed Ranges of Forging Equipment

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

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

Forging Machines

- Screw Press
  - Energy limited
  - Suited for small production quantities, especially thin parts with high precision
- Hammers
  - Energy limited
  - High speed – low forming time minimizes cooling
  - Versatile and low cost

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.

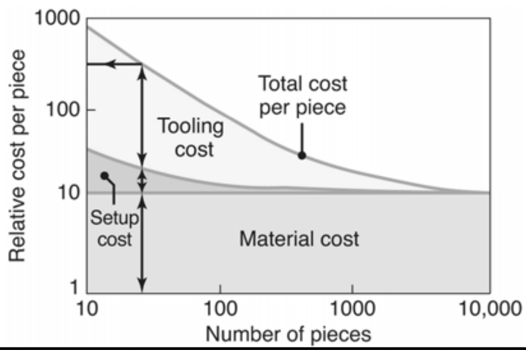


FIGURE 14.19 Relative unit costs of a small connecting rod made by various forging and casting processes.
Note that, for large quantities, forging is more economical. Sand casting is the most economical process for fewer than about 20,000 pieces.

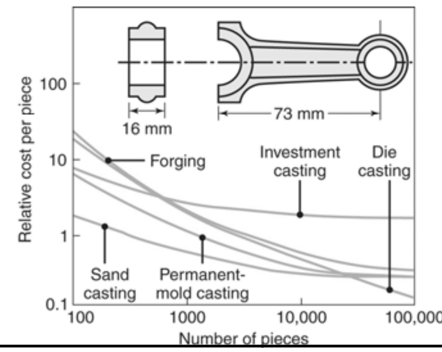


FIGURE 14.20 (a) The Lotus Elise Series 2 automobile.
(b) illustration of the original design for the vertical suspension uprights, using an aluminum extrusion.
(c) retrofit design, using a steel forging.
(d) optimized steel forging design for new car models.
Source: (a) Courtesy of Fox Valley Motorcars. (b) through (d) Courtesy of Lotus Engineering and the American Iron and Steel Institute.

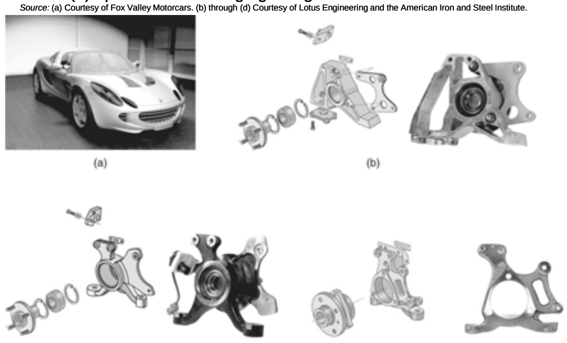


TABLE 14.5 Comparison of Suspension Upright Designs for the Lotus Elise Automobile

TABLE 14.5

Comparison of Suspension Upright Designs for the Lotus Elise Automobile

Fig. 14.20 sketch	Material	Application	Mass (kg)	Cost ($)
(b)	Aluminum extrusion, steel bracket, steel bushing, housing	Original design	2.105	85
(c)	Forged steel	Phase I	2.685 (+28%)	27.7 (−67%)
(d)	Forged steel	Phase II	2.493 (+18%)	30.8 (−64%)

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 continued

- 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