1. Introduction
Forging Industry Association has produced this Product Design Guide for Forging to assist those who use forgings, and those who do not yet but could use forgings to advantage. The advantages of forging for engineered products have been realized in a wide range of industries and situations, such as:

?? A steering arm, made from a three piece weldment was creating problems in manufacturing. It was converted to a one piece impression die hot forging at a 13% reduction in weight and reduced manufacturing cost.
?? A cast hub for a large power shovel in a coal field failed, causing an estimated downtime of four to six weeks at a cost of $4000 per hour. The hub was slightly redesigned as an open die forging and produced in two working days.
?? A manufacturer of huge rotary kilns does not want to have to replace the riding tires over the life of the product. The tires are made from rolled rings.
?? A manufacturer of hand tools, which operate under high impact and high fatigue specifies cold forgings made to net shape.

These are just a selected few of the many documented success stories from the purchasers and designers who specify forgings.
The section of primary interest for those who want to specify or purchase forgings is Section 2, Specifying and Purchasing Forgings.
The section of primary interest for those involved in the design and development of products, including selection of the optimum process, is Section 3, The Design and Development of Products Made From Forgings. This section follows the usual sequence of events in a product design program from conception to approval. Sections 4, Characteristics of Forging Alloys, and 5, Manufacturing Processes, provide the necessary background information for those who purchase, specify and design products. The case studies in Section 6 illustrate how several typical forging processes have been used to advantage in a range of product areas.
The Glossary in Section 7 has been tailored to the anticipated needs of product development personnel, to provide concise definitions of terms used in this publication, as well as those that may be encountered in conversations with forging industry personnel.

1.1 Background
Today, systematically designed forging processes are being performed in controlled presses and hammers to produce forged shapes with a high degree of dimensional accuracy and structural integrity. Forgings range in size from very small, weighing only a few grams, such as the parts shown in Figure 1-1, to component products weighed in tons, such as the 450,000 pound generator shaft Figure 1-2.

Figure 1-1 The forging process is capable of economically producing very small parts in large quantities
Figure 1-2 This 450,000 pound generator shaft was produced from an open die forging.

The term forging is applied to several processes in which a piece of metal is shaped to the desired form by plastic deformation of a simple starting form such as bar, billet, bloom or ingot. The energy that causes deformation is applied by a hammer, press, upsetter or ring roller, either alone or in combination. The shape is imparted by the tools that contact the workpiece and by careful control of the applied energy.

1.2 Ongoing Improvements
The forging industry is keeping pace with other metal forming processes through continuous progress in many areas. Five of the most important are:

?? Alloys are being developed and refined to improve their processing characteristics, or “forgeability”.
?? Ongoing manufacturing development in forging processes is increasing the industry’s understanding of the mechanics of the forging process. As a result, production rates are being increased, costs reduced, and many companies are producing shapes and forms that are much closer to net shape than were considered practical a few years ago.
?? Forging companies are utilizing state-of-the-art systems to control critical processes. As process variables are reduced, dimensional precision is improved, and costly chip-making operations are eliminated.
?? CAD/CAM is being used throughout the design and production processes to improve dimensional accuracy of forgings while reducing lead times. The industry is also adopting rapid prototyping techniques to an increasing extent.
?? Modeling and forging simulations, such as flow simulations and thermal simulations, are being used by some forging companies to minimize development time.
?? Fast tool change capability facilitates the preplanned replacement of die inserts in long production runs, and reduces changeover time for shorter runs, such as those required with just-in-time delivery schedules.

1.3. Forging Processes
There is a wide variety of processes that can be classified under the above definition of forging. This manual will address five: open die, impression die, ring rolling, warm forging and cold forging. Cold forging is performed at or near room temperature, and work hardening occurs. The other processes are performed at elevated temperatures, where work hardening is diminished or the workpiece is not work hardened at all. Open Die Forging is a hot forming process, which uses standard flat, “V” or swage dies. The hot workpiece temperature improves plastic flow characteristics and reduces the force required to work the metal. The desired shape is systematically formed by a relatively large number of strokes. Open die forging is normally used to produce large parts, which are often well beyond the range of impression die processes. It is sometimes used to produce substantially the same shapes as impression die. In these applications it offers no chargeable tooling cost and very short lead time. However, per-piece
processing costs are higher, dimensional precision is not as good, and more finish machining operations are required compared with impression die forging. The process is shown schematically in Figure 1-3. **Impression Die Forging** utilizes a pair of matched dies with contoured impressions in each die. When the dies close, the impressions form a cavity in the shape of the forging. Often two or more progressive impressions are used, sometimes in conjunction with one or more preforming operations, to form the desired shape. The proper forging temperature improves plastic flow characteristics and reduces the forces on the forging tools. The process is shown schematically in Figure 1-4. **Ring Rolling** forms axisymmetric shapes in a hot forming process. The process begins with a “donut” shaped preform, which is made by upsetting and piercing operations. The preform is placed over the idler or mandrel roll in a ring rolling mill. The idler roll is moved toward a drive roll, which rotates to reduce the wall and increase the diameter, while forming the desired shape. The process is shown schematically in Figure 1-5. Cross sections of typical ring rolled shapes are shown in Figure 1-6.

*Figure 1-3 The open die forging process*
Process Operations

**Upsetting**

*Figure 1-4 The impression die forging process*

**Cold Forging** employs dies that are sometimes similar to impression dies. The temperature of the workpiece is low enough that scale does not form, but the workpiece work hardens. The lower temperature also promotes greater dimensional accuracy. However, the plastic flow characteristics are not as good at the reduced temperatures, and higher applied forces are required. The three basic cold forging processes are shown in *Figure 1-7*.  
Warm forging is a modification of the cold forging process where the workpiece is heated to a temperature significantly below the typical hot forging temperature. 
Forging offers the designer several basic performance advantages to a degree that sets it above alternate processes.

1.4 **Product Advantages of Forging**
Forging offers the designer several basic performance advantages to a degree that sets it above alternate processes.

**Directional Strength** Forging refines the grain structure and develops the optimum grain flow, which imparts desirable directional properties such as tensile strength, ductility, impact toughness, fracture toughness and fatigue strength. *Figure 1-8* illustrates the grain flow of forging compared with machining from bar or plate and casting for the dragline chain link shown in *Figure 1-9*.

**Structural Integrity** Forgings are free from internal voids and porosity. The process achieves very consistent material uniformity, which results in uniform mechanical properties and a uniform, predictable response to heat treatment.
Dynamic Properties  Through proper deformation and grain flow, combined with high material uniformity, the forging process maximizes impact toughness, fracture toughness and fatigue strength. These properties are particularly advantageous in safety related applications, such as aerospace structural components and automotive components, typically suspension, brake and steering systems, which are subject to shock, impact and cyclic loads.
Optimum Material Utilization The features of a forging can be made with varying cross sections and thicknesses to provide the optimum amount of material for the anticipated load. This capability, plus the high mechanical properties of forgings, often allows designers to minimize component part weight, especially when compared with castings and assemblies of sheet metal stampings.

1.5. Alloys Forged
Virtually all metals have alloys that are forgeable, giving the designer the full spectrum of mechanical and physical properties of ferrous and non-ferrous alloys. The most common forging alloys include:

?? Carbon, microalloy and alloy steel forgings account for the greatest volume of forgings for a very wide range of applications.
**Stainless steels** are widely used where resistance to heat and corrosion are required, in applications up to approximately 510°C (950°F).

**Aluminum** forgings are used in applications where temperatures do not exceed 150°C (300°F), and where weight of the component is an issue.

**Copper, brass and bronze** forgings offer excellent corrosion resistance with high thermal and electrical conductivity.

**Iron, nickel and cobalt high temperature alloy** forgings are preeminent for applications of cyclical and sustained loads at high temperatures.

![](image)

**Figure 1-8** A properly engineered forging orients the grain flow to maximize the required mechanical properties. The grain flow in the same part cut from plate is oriented in the direction of rolling; in the casting it is random.

![](image)

**Figure 1-9** The dragline chain link was forged to perform in a demanding environment.

**Titanium** forgings are used where high strength, low weight and excellent corrosion resistance, combined with moderate heat resistance, are required.

**Magnesium** forgings offer the lowest density of any commercial structural metal, at operating temperatures similar to aluminum.

1.6. Applications of Forgings
The wide range of alloys and sizes, combined with excellent mechanical and physical properties has made forgings the design choice for nearly all product areas. The most common are shown in Table 1-1
<table>
<thead>
<tr>
<th>Table-1 Common Applications for Forgings</th>
</tr>
</thead>
<tbody>
<tr>
<td>?? Aerospace</td>
</tr>
<tr>
<td>Aircraft Engines</td>
</tr>
<tr>
<td>Airframe and auxiliary equipment</td>
</tr>
<tr>
<td>?? Guided missiles and space vehicles</td>
</tr>
<tr>
<td>?? Automotive</td>
</tr>
<tr>
<td>Passenger cars</td>
</tr>
<tr>
<td>Trucks, busses and trailers</td>
</tr>
<tr>
<td>Motorcycles and bicycles</td>
</tr>
<tr>
<td>?? Bearings, ball and roller</td>
</tr>
<tr>
<td>?? Electric power generation/transmission</td>
</tr>
<tr>
<td>?? Industrial and commercial machinery and equipment</td>
</tr>
<tr>
<td>?? Hand Tools</td>
</tr>
<tr>
<td>?? Industrial tools</td>
</tr>
<tr>
<td>?? Internal combustion engines</td>
</tr>
<tr>
<td>?? Metalworking and special industry machinery</td>
</tr>
<tr>
<td>?? Mechanical power transmission equipment, incl. bearings</td>
</tr>
<tr>
<td>?? Off-highway, equipment (construction, mining and materials handling</td>
</tr>
<tr>
<td>?? Ordinance and accessories</td>
</tr>
<tr>
<td>?? Oil field machinery and equipment</td>
</tr>
<tr>
<td>?? Pipeline fittings</td>
</tr>
<tr>
<td>?? Plumbing fixtures, valves and fittings</td>
</tr>
<tr>
<td>?? Pumps and compressors</td>
</tr>
<tr>
<td>?? Railroad equipment and spikes</td>
</tr>
<tr>
<td>?? Rolling, drawing and extruding equipment and tools for nonferrous metals</td>
</tr>
<tr>
<td>?? Ship and boat building and repairs</td>
</tr>
<tr>
<td>?? Special industry machinery</td>
</tr>
<tr>
<td>?? Steam Engines and turbines</td>
</tr>
<tr>
<td>?? Steel works, rolling and finishing mills</td>
</tr>
</tbody>
</table>
3.1 Concurrent Engineering

Concurrent engineering is called by various names, such as simultaneous engineering, cooperative engineering, and co-engineering. Regardless of the name, the process encompasses mutual cooperation between the customer, forging supplier and material supplier from the initial stages of product development. In its widest sense, concurrent engineering encompasses all phases of product design and development activities, such as defining the envelope of the product to perform the intended function within a forgeable shape, determining draft angles and tolerances, selection and conservation of material, heat treating, finishing and structural interfaces with mating components. The information that is exchanged between the buyer and forger in a Checklist, at the end of Section 2.

Concurrent engineering should begin at the earliest stages of preliminary design and continue through the life cycle of the product. Consider that:

?? Decisions made during design typically drive 70%, and sometimes more, of the product cost. Input from the forging source and material supplier, beginning at the earliest stages of product design, are essential in controlling the end cost of the product.

?? The cost of design revisions increases approximately ten-fold through each stage of product development. For example, a change made during detailed design may cost ten times as much as it would have cost during preliminary design. A change made during prototyping and testing may cost 100 times as much.

Since the forging source is an important member of the concurrent engineering team, early commitment to the supplier is essential. Information for selecting a forging company is given in Section 2.4

Another, often overlooked advantage of concurrent engineering is the opportunity to identify opportunities for cost and weight reductions that can only be detected with the interchange that occurs when all stakeholders are present. The upper control arm shown in Figure 3-1, which is a conversion from a stamping to a forging, is one example.

Communication among members of the concurrent engineering team is also essential. Current technology, such as CAD and CAM, are facilitating communication as original equipment manufacturers and their forging suppliers share and refine databases. Many forging companies are equipped with electronic data transfer to speed communication, resulting in faster time-to-market. Application protocols are being developed for product data representation and exchange.

![Figure 3-1 This cold/warm forged upper control arm cost more to produce than its stamped counterpart. However, its use allowed the designers to reduce vehicle length and weight, resulting in a significant secondary cost reduction. (See Case Study 5.)](image)

The major perceived disadvantage of concurrent engineering is that it increases the time spent in preliminary design, when the design staff is anxious to finalize details and release drawings. However, experience has shown that additional up-front time sharply reduces changes in subsequent stages of product development, where changes incur substantially more cost and time.
3.3 Cost Drivers
The actual cost of a forging can be determined only by obtaining a cost analysis from a reputable forging producer. The designer should be aware, however, of the factors that drive the cost of a forging. Five categories of cost drivers should be considered.

- Material cost
- Tooling cost
- Manufacturing cost
- Secondary (value added) operations
- Quantities produced

3.4.1 A Comparison of Open Die, Impression Die, Rolled Ring and Cold Forging Processes
The choice among the various forging processes is driven by component size, production quantities, and component shape. The following guidelines usually apply.

1. When forgings are very large, when very few are required, or when delivery times are very short, open die forging is the typical choice.
2. As shapes become more complex, and production quantities increase, impression die forging becomes the process of choice provided that the size does not exceed the capability of the impression die equipment.
3. Shaft-like forgings with details on the ends or along the length are candidates for upset forging.
4. Seamless rings may be made by open die forging over a mandrel, impression die forging or ring rolling. Diameters less than one foot may be candidates for impression die forging. Diameters less than one foot up to 30 feet, in low to high quantities, are candidates for ring rolling. When quantities are very low or face heights are too large for ring rolling, open die forging over a mandrel can be the process of choice.
5. Relatively small components that are rotationally symmetrical or axisymmetric, require high strength and high precision, and are produced in larger quantities are candidates for cold forging.
When impression die forging is chosen, four options are available: blocker type forgings, finished forgings, near-net forgings, and net shape forgings.

**Blocker Type Forgings** are generally forged in a single impression die, with generous finish allowance. This process is suitable for moderate production quantities. A rough rule of thumb for finish stock is at least 5 mm (0.2 inch) of machining envelope for each 300 mm (12 inches) of dimension for blocker type forgings made from steel. The allowance can be less for aluminum, and should be 25% to 50% more for heat resistant alloys. Draft angles are typically 7° to 10°.

**Finished Forgings** are suitable for high production quantities. They are forged with significantly less finish allowance than are blocker type forgings, and typical FIA guideline tolerances apply. Typical finish allowances are 1.25 to 2.5 mm (0.050 to 0.100 inch) plus draft, which varies from 3° to 7°. (See Appendix A *Guideline Tolerances For Hot Forged Impression Die Forgings*, Appendix B *Tolerances for Hot Upset Forgings* and Appendix D *Specialized Tolerances for Precision Aluminum Forgings*.)

**Near-Net Forgings** are forged with some surfaces requiring little or no machining, and some surfaces may be left as forged. They are similar to finished forgings except they are closer to final configurations. Some forging companies, by virtue of their own special forging equipment, may offer specific improvements over the tolerances and finish allowances considered as “normal” by the FIA Tolerance Guidelines.

**Net Shape Forgings** are forged to net and near-net shapes with many functional surfaces forged to required tolerances, requiring no machining. For example, tooth forms on net shape forged gears up to 125 mm (5 inch) diameter are being forged to tolerances of ±0.10 mm (±0.004 inch), which is often close enough to eliminate gear cutting operations. However, back faces or shafts are usually machined. Product features attributable to these four forging processes are illustrated in Figure 3-3.
Increased forging precision tends to drive up the cost of forging operations somewhat, but it usually reduces the cost of finish machining. As production quantities increase, the reduced cost of machining operations becomes a stronger offsetting factor.

A very expensive raw material that is difficult to machine will suggest the most chipless process, and small production quantities might best be net or near-net forged. If the material is inexpensive and readily machined, open die forging in small quantities may be the optimum choice.

Medium size to large rings can be made either by open die forging over a mandrel and finish machining or by a ring rolling process in which finish machining may or may not be required. Production quantities drive the choice. Open die forging is generally more economical in very low quantities; ring rolling becomes more economical as quantities increase.

Components that have features with rotationally symmetrical or axisymmetric shapes, such as splines, may be candidates for either cold forging or hot impression die forging, depending on complexity and size.

3.4.2.3 Foundry Casting (advantages compared to...)

Foundry casting processes include sand mold processes for essentially all alloys, evaporative pattern (lost foam) processes for iron and aluminum, and permanent mold processes for alloys with low melting temperatures such as aluminum and magnesium. The latter two alloy groups are also cast, in limited quantities, in plaster molds.

Forgings offers significant advantages over castings in applications where high reliability, high tensile strength or fatigue strength are required, frequently in combination with high ductility, impact toughness and fracture toughness. Forgings are free from porosity, which is difficult to eliminate in castings. This is particularly true in areas where geometric transitions occur, which are also areas of stress concentration. The superior fracture toughness of forgings often must be considered when designing equivalent castings by applying a “casting factor” to account for casting process and product variations. This “casting factor” imposes a weight penalty that is often enough to make forgings the more economical choice, especially when weight is important.
3.5.4.5 Design Rules for Parts Made by Cold and Warm Forging

1. Commercially made cold forgings typically weigh less than 23 kg (50 lb), although larger forgings have been cold forged.
2. Net shape cold forgings should be considered for products made in high volumes with surfaces that are difficult or expensive to machine due to geometric configurations.
3. Shapes that can be made by upsetting and bending, such as bicycle pedal cranks, are good candidates for cold forging.
4. Net or near-net shapes, such as tripot inner races or universal joint crosses, can be manufactured using cold or warm lateral extrusion. (See Figure 3-22.)
5. Consider replacing heat treatment with cold forging to work harden the product to yield strengths exceeding 550 MPa (80,000 psi).
6. Specify the material with the lowest possible amount of carbon and lowest alloying level.
7. Cold forgings do not require draft angles to release them from the tooling.
8. Solid or tubular shaped products with either through or blind holes, with net formed splines or other axial features, can be made by cold forging.
9. When specifying blind holes, keep in mind:
   • Holes that are deep in proportion to their diameter are difficult to forge.

![Figure 3-22 Net or near-net shapes, such as tripot inner races or universal joint crosses, can be manufactured using cold or warm lateral extrusions.](image)

- Maintain uniform side wall thicknesses.
- The wall at the bottom of the blind hole should be at least as thick as the side walls.  (See Figure 3-23.)

![Figure 3-23 The hole on the left can be forged; the one on the right will require a drilling operation.](image)
10. Consult with the forger to determine the net shape capability, and design net shape surfaces within those capabilities.

11. When designing solid shapes, minimize the difference between the largest and smallest diameters of the part (See Figure 3-24.)

12. Avoid undercut diameters in products to be cold forged. They can be forged in some cases if the undercut is wide as illustrated in Figure 3-25. Consult with the forger.

13. Avoid extremely thin or thick wall sections when designing tubular parts.

![Figure 3-24 Minimize diameter ratios.](image)

Figure 3-25 Undercuts can be forged in some cases if they are wide compared with the diameter of the feature.


### 3.8 Prototyping

Prototypes of forgings fill the gap in the evaluation process between computer simulations and the manufactured end product. There are two general types, which serve a variety of purposes: soft and hard metal. Soft prototypes are made from materials such as wood, foam and plastic, and are not suitable for functional testing. Hard metal prototypes, as the name implies, are made from metal. Their usefulness in functional testing depends on the extent to which their critical properties approximate those of the forged end product.

Ultimately, the only way to produce a prototype that has the same properties as the forging is by forging in production tools. This is not always feasible because the cost and lead time associated with the procurement of forging tools may be prohibitive. Therefore, alternate processes are often employed. The selection of the prototyping process is driven by:

- The selected forging process
- The purpose of the prototype
- The properties of the end product that are to be evaluated

**Open die forgings** are generally made in low quantities with minimal or no cost for special tools. Prototypes are usually forged and machined by the same processes as the production parts.

**Rolled rings** can usually be made from standard tools. Where standard tools are not available, the rings may be rolled to the approximate configuration and machined to the final shape. Grain flow is usually circumferential, so that performance is not affected by machining operations.

**Impression die forgings** Some of the most common prototyping processes for impression die forgings are listed in Table 3-8:
<table>
<thead>
<tr>
<th>Purpose</th>
<th>Process</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Visual appearance evaluation; clearance, installation and removal studies (mockups).</td>
<td>Nearly any method that produces the required shape, such as hogouts, stereolithography, wood or foam.</td>
<td>Mechanical and physical properties are not important to the evaluation.</td>
</tr>
<tr>
<td>2. Approximate the performance of the end product.</td>
<td>A. Hogout made from a similar material and heat treated as required.</td>
<td>Static properties can be closely approximated; dynamic properties may be difficult to approximate.</td>
</tr>
<tr>
<td></td>
<td>B. Open die forged and finish machined.</td>
<td>Very low tooling cost, good approximation of static properties, better approximation of dynamic properties than hogouts.</td>
</tr>
<tr>
<td></td>
<td>C. Blocker die forging finish machined as necessary.</td>
<td>Somewhat higher tooling cost, better approximation of static and dynamic properties than open die forging.</td>
</tr>
<tr>
<td>3. Certify product performance.</td>
<td>Forge in production tools and finish.</td>
<td>Flash may be removed by hand to negate trim dies.</td>
</tr>
</tbody>
</table>
4.4 Copper, Brass and Bronze Alloys

Forgings made from copper based alloys offer a number of advantages over products made by other processes. Dimensional precision is greater than by casting, working the alloys develops improved strength, and overall cost is modest. Zero draft forgings are possible, though not always practical. However, minimum draft forgings are being produced. Minimum draft capability is independent of alloy composition; alloys that can be forged by conventional means can be forged to minimum draft angles approaching 1°. Cored forgings are common and provide near-net shape parts with minimal waste. Copper based alloys whose major alloying element is zinc are designated brasses. Those whose major alloying element is other than zinc are designated bronzes, such as silicon bronze and aluminum bronze. Those alloys with very high copper content, typically 98% or more, are generally designated "coppers", such as beryllium copper. Copper based alloys are designated by a six-character alpha-numeric system. The first character is C, indicating the copper base. The next five are numeric characters. The first numeric indicates the major group, and the remaining four designate the alloys within the group. Copper based alloy forgings are corrosion resistant and pressure tight, and are commonly specified for high pressure liquid and gas handling applications such as fittings, plumbing hardware, refrigeration components and commercial valves. Strength is enhanced by the deformation that takes place in forging, making high strength brass forgings the choice in certain gears, bearings and hydraulic pumps. The homogeneous, porosity free structure of brass forgings makes them the ideal starting point for highly polished decorative door hardware and plumbing components. Copper based alloys have been rated for forgeability, taking into account factors such as required forging pressure, die wear and hot plasticity. Forging brass, C37700, is the most forgeable and is rated at 100%. Brasses containing 35% to 40% zinc are rated at 90%, and coppers, with 99.9% minimum copper are rated at 65%. Silicon bronze, C65500, is the least forgeable at 40%. Copper based alloys can be easily cleaned after forging and trimming by using a chemical processes or by other more environmentally friendly methods. Typical forging grades include:

<table>
<thead>
<tr>
<th>CDA</th>
<th>AMS</th>
<th>Composition</th>
<th>Common name</th>
</tr>
</thead>
<tbody>
<tr>
<td>C37700</td>
<td>4614</td>
<td>59% Cu, 39% Zn, 2% Pb</td>
<td>Forging brass</td>
</tr>
<tr>
<td>C46400</td>
<td>4611-12</td>
<td>60% Cu, 39% Zn, 0.75% Sn</td>
<td>Naval brass bars and rods</td>
</tr>
<tr>
<td>C63000</td>
<td>4640</td>
<td>81% Cu, 10% Al, 5% Ni, 3% Fe, 1% Mg</td>
<td>Nickel aluminum bronze</td>
</tr>
<tr>
<td>64200</td>
<td>4633</td>
<td>91% Cu, 7.2% Al, 1.8% Si</td>
<td>Aluminum silicon bronze</td>
</tr>
<tr>
<td>C67700</td>
<td>4619</td>
<td>65% Cu, 23% Zn, 4.5% Al, 4% Mn, 3% Fe, 0.5% Sn</td>
<td>Manganese bronze</td>
</tr>
</tbody>
</table>

Additional information about the remaining alloys in this category can be obtained from the Copper Development Association, Inc. 405 Lexington Avenue, New York, NY 10017.
4.8 Summary (forging alloys)
The material that is selected for a forging application must be one that can achieve the required physical
and mechanical properties. Where alloys from several groups meet performance requirements, the most
economical alloy, in terms of material and processing costs, should be chosen. The following summary is
helpful in making a preliminary selection.

Carbon, microalloyed and alloy steels are low to moderate in cost. The main cost drivers are processing
and machining. The alloys are readily hot forged and some shapes are cold forgeable in selected alloys.
When precision or near-net forgings are anticipated, the designer should be aware that eventual purchased
quantities of forgings should be large enough to justify the typical added tooling preparation charge. There
are times when the added tooling costs are well justified to eliminate a difficult to machine shape regardless
of purchase quantities.

Alloy formulation may also be governed by product dimensions. As section sizes become progressively
heavier, higher alloy levels are required to achieve hardenability.

Stainless steels are higher in cost than carbon, microalloy and alloy steels. They are hot forgeable into
simple shapes and low profile structural shapes, but the high forging pressures restricts net shape forging
to simpler shapes. The hot die forging process should be reviewed when more complex shapes are
encountered or when the more difficult to forge alloys are specified. The 300 series alloys require 20 to
40% higher forging pressures than the 400 series, due mainly to the higher nickel content.

Aluminum alloys are moderate in cost, comparatively low in weight, and readily hot forged because most
tool materials maintain adequate properties at the forging temperatures of aluminum alloys. Net shape
forgings are being made in sizes up to 400 square inches projected area in the plan view. Net shape
forging processes are well developed. Guidelines for design of forgings are available, and are being
upgraded.

Copper based alloys are chosen when a combination of properties is required, such as corrosion
resistance, bearing capability, and moderate cost. Strength is moderate compared with other forging alloys,
but generally superior to castings made from equivalent alloys. The alloys can be forged to close
tolerances, and smooth surfaces can be maintained. Freedom from porosity, which is found in castings,
aids in developing a cosmetic finish.

Heat Resistant Alloys of iron, nickel and cobalt are among the highest cost forging alloys, and often the
most difficult to forge. They are generally selected only when the required elevated temperature properties
cannot be achieved by other alloy systems. When the most heat resistant alloys cannot be forged by
conventional processes, superplastic forging may be a process in which the alloy is forged at temperatures
very near the melting range. In the case of “super-super” alloys, such as IN100, MERL 76 and Rene 95, the
isothermal process under vacuum is the primary way of forging high quality parts.

Titanium Alloys are selected for applications requiring high strength, low weight, high operating
temperature or high corrosion resistance. Specific strength is high compared with steel. Densities are
approximately 55% those of steel and 60% greater than aluminum alloys. The properties and cost of
titanium alloys make them the choice in applications where a premium can be justified for high performance,
such as aerospace, chemical processing and prosthetic devices.

Magnesium alloys are sometimes considered as alternatives to aluminum alloys, and are used when
minimum product weight is essential. They offer a weight advantage of about 30% versus aluminum.
However, the magnesium alloys are more prone to corrosion than aluminum alloys and require more
attention to coatings. Mechanical properties, such as modulus of elasticity and tensile and yield strengths,
are not as high as for aluminum alloys, particularly at elevated temperatures. Thus, the strength to weight
ratio is not as favorable. Magnesium is the one metal system that seems to have been replaced by
reinforced plastics.
5.2.1 The Open Die Process
Open die forging is a hot forming process that uses standard flat, "V", concave or convex dies in presses. The process is used to form a virtually limitless range of component sizes from a few pounds to over 300 tons. The workpiece is heated to improve its plastic flow characteristics and reduce the force required to work the metal. The workpiece is systematically deformed by a series of strokes from the upper die while being supported on the lower die. The position is changed between strokes by a means such as the manipulator shown in Figure 5-1.

Open die forging processes allow the workpiece freedom to move in one or two directions. The workpiece is typically compressed in the axial direction (direction of movement of the upper die) with no lateral constraint. Lateral dimensions are developed by controlling the amount of axial deflection, or by rotating the workpiece. Some of the most commonly performed operations are upsetting; cogging; drawing; piercing, punching, saddening and hot trepanning; hollow forging; closing in; and ring forging. Following is a brief description of the most common operations.

Some of the latest in programmable press controls are being applied to open die processes. Programmable controls generate greater accuracy, better utilization of stock, and repeatability.

**Upsetting**
Upsetting is working with the axis of the stock in the vertical position under the forging press or hammer. The operation decreases the axial length of the stock and increases its cross section. Upsetting is usually accomplished with flat dies, as shown in Figure 5-2. Flat dies are larger than the cross section of the workpiece. Friction between the dies and workpiece is inevitable, and causes the barreling effect shown in the figure.

**Cogging**
Cogging is the systematic reduction of an ingot to billets or blooms by narrow dies. Narrow dies, shown in Figure 5-3 exceed the width of the workpiece, but not the length. Narrow dies may be flat, as shown, V, concave or convex. The ingot is reduced and elongated by repeated strokes as it is systematically advanced and sometimes rotated. The process changes the grain structure of the metal as shown in Figure 5-4 and consolidates internal ingot defects such as porosity and blow holes.

**Drawing or Solid Forging**
Drawing or solid forging is used to produce a shape with length much greater than its cross section by reducing the section and simultaneously elongating the ingot or bloom, as shown in Figure 5-4. It is used to produce stock for further forging operations or end products, such as bars or shafts.

**Piercing, Punching and Trepnaning**
In these operations, a punch is forced into a piece of hot steel to form a cavity. Piercing generally implies a blind cavity made by displacement with no removal of metal. Punching implies the use of a solid punch to form a through hole by displacing and removing metal in the form of a slug. Trepnaning also forms a through hole, using a hollow punch to remove the central metal as a core. Two piercing sequences are shown in Figure 5-5.

**Hollow Forging**
Hollow forging is used to produce hollow forms by expanding or lengthening on a mandrel. The process, shown in Figure 5-6, begins with a pierced or cupped forging. Wall thicknesses are reduced and length increased by a drawing operation. Long hollow forms use a mandrel, in an operation similar to ring forging, which is shown in Figure 5-7.

**Closing-in**
Closing-in is used to reduce the section on a portion or portions of a hollow forging. The area or areas to be reduced are reheated to forging temperature and reduced using V-tapered, curved or formed dies. A variant is shown in Figure 5-7. The forging was provided with a step on the outer diameter, which is reduced so that only the bore is reduced at the site.

**Ring Forging**
Ring forging produces rings from pierced blanks by open die forging over a mandrel. The process is shown in Figure 5-8. Slight rotation of the ring on each press stroke reduces the ring wall uniformly and increases both the inside and outside diameters. The height of the ring remains nearly constant, but may require edging.

**Combined Processes**
The above operations are usually combined to produce shapes ranging from simple to complex in a wide range of sizes. The process is specially suited for very large, and sometimes very complex forgings, which are well beyond the range of impression die processes, such as the 60,000 pound as-forged crankshaft shaft shown in Figure 5-9 and the large valve body shown in Figure 5-10.
6.1 Case Study No. 1 Flanged Ball Valve Adaptor

Component name: Flanged Ball Valve Adaptor
Forging Process: Rolled ring (profiled) from hot press forged blank
Size, finished, mm (in.): 1015 (40.0) O.D. x 205 (8.0) high
Estimated weight, kg (lb): 650 (1430)
Alloy: Carbon steel
Tensile strength, MPa (psi): 480 (70,000)
Yield strength, MPa (psi): 250 (36,000)
Hardness, BHN: 197
Elongation: 22%
Impact Toughness, J (ft-lb): 16.3-20.3 (12-15) @ -45°C (-50°F)
Secondary Operations: Machining, hydrostatic testing
Heat treatment: Normalizing
Alternate process: Fabrication from open die (mandrel) forging, casting
Annual Production: 450

The flanged adaptor for a 610 mm (24 in.) ball valve, shown in Figure 6-1A, is used in lines that transmit commodities such as oil, gas, chemicals and food. It connects the valve body to the flange line. The forged design offered the possibility of reduced weight compared with a casting by the use of thinner walls. The integrity of the thinner walls was gained by developing circumferential grain flow and uniform grain size, and by eliminating porosity. The reduced wall design was verified by hydrostatic testing. Machining operations were improved by the elimination of hard spots. The weight reduction was approximately 20%, which is important in offshore applications. Forging engineers contributed to the design with the suggestion to increase the body flange O.D. to the same size as the line flange to produce a symmetrical section, reducing tooling set-up. Two-piece construction from straight forged rings, shown in Figure 6-1B, was considered. The one-piece construction was more economical due to a substantial reduction in machining operations and elimination of welding.

Figure 6-1A

Figure 6-1B