Product Design Guide for Forging

Introduction

1. Background

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.

2. Ongoing Improvements

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.

3. Forging Processes

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.

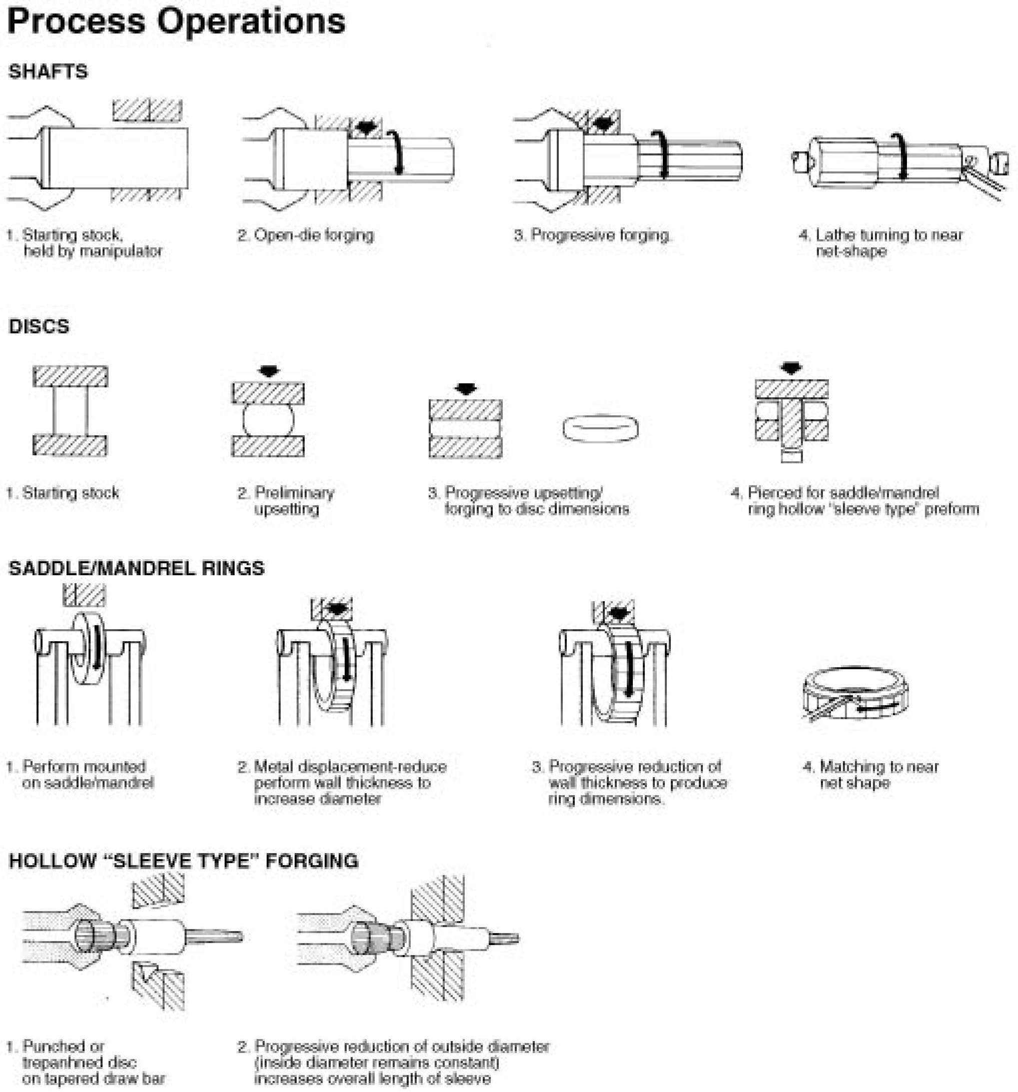
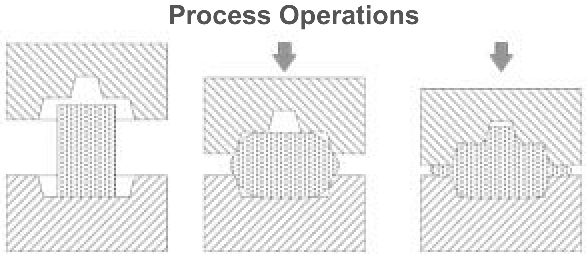
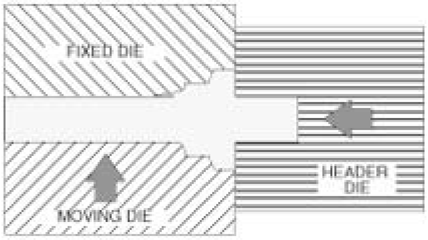


Figure 1-3 The open die forging process





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.

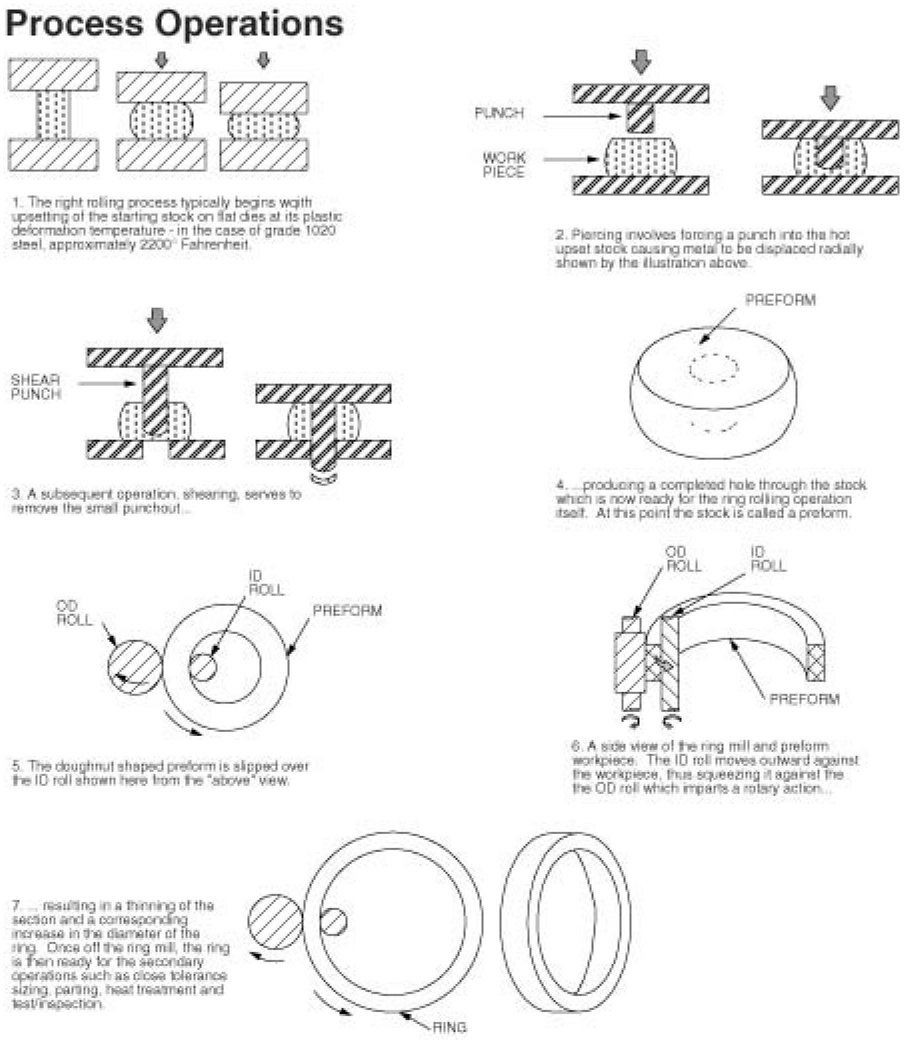
4. Product Advantages

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.



Process Operations

1. The right rolling process typically begins wqith upsetting of the starting stock on flat dies at its plastic deformation temperature - in the case of grade 1020 steel, approximately 2200° Fahrenheit.

2. Piercing involves forcing a punch into the hot upset stock causing metal to be displaced radially shown by the illustration above.

3. A subsequent operation, shearing, serves to remove the small punchout...

4. ...producing a completed hole through the stock which is now ready for the ring rolling operation itself. At this point the stock is called a preform.

5. The doughnut shaped preform is slipped over the ID roll shown here from the "above" view.

6. A side view of the ring mill and preform workpiece. The ID roll moves outward against the workpiece, thus squeezing it against the the OD roll which imparts a rotary action...

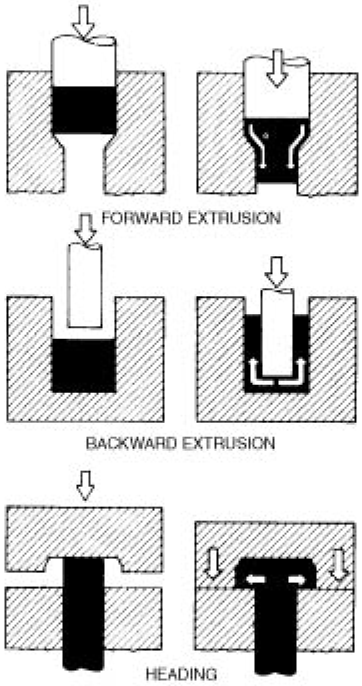
7. ... resulting in a thinning of the section and a corresponding increase in the diameter of the ring. Once off the ring mill, the ring is then ready for the secondary operations such as close tolerance sizing, parting, heat treatment and test/inspection.

Figure 1-5 The ring rolling process

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.

Figure 1-6 Several of the many cross sectioFigure 1-6 Several of the many cross sections that are made by ring rolling

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.



5. Alloys Forged

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 510oC (950oF).
- **Aluminum** forgings are used in applications where temperatures do not exceed 150oC (300oF), 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.

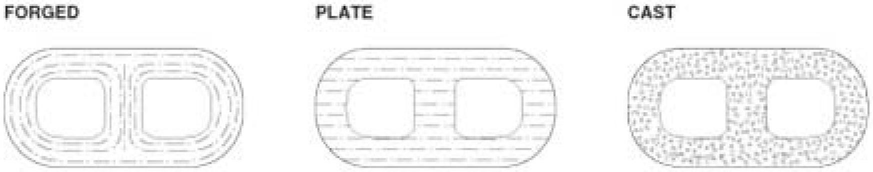


Figure 1-8 A properly engineered forging orients the grain flow to maximize the required mechanical properties. The grain flow in the same part cut from plate is oriented in the direction of rolling; in the casting it is random.

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.

6. Applications of Forging

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-1CommonApplicationsforForgings

- Aerospace
    - Aircraft Engines
    - Airframe and auxiliary equipment
- Guided missiles and space vehicles
- Automotive
    - Passenger cars
    - Trucks, busses and trailers
    - Motorcycles and bicycles
- Bearings, ball and roller
- Electric power generation/transmission
- Industrial and commercial machinery and equipment
- Hand Tools
- Industrial tools
- Internal combustion engines
- Metalworking and special industry machinery
- Mechanical power transmission equipment, incl. bearings
- Off-highway, equipment (construction, mining and materials handling
- Ordinance and accessories
- Oil field machinery and equipment
- Pipeline fittings
- Plumbing fixtures, valves and fittings
- Pumps and compressors
- Railroad equipment and spikes
- Rolling, drawing and extruding equipment and tools for nonferrous metals
- Ship and boat building and repairs
- Special industry machinery
- Steam Engines and turbines
- Steel works, rolling and finishing mills

Specifying and Purchasing Forgings

2. SPECIFYING AND PURCHASING FORGINGS

The purpose of this section is to outline for the purchaser and designer what is specifically required in purchasing a forging, and how the product needs can be met by the forger. Some of the material in it is also presented in Section 3, The Design and Development of Products made from Forgings. The repetition is intentional, making this section a stand-alone, which meets the needs of those who specify and purchase forgings.

The steps in specifying and purchasing forgings are:

1. Select the alloy group that is appropriate to the product requirements.
2. Select a basic forging process for forging an alloy in the selected group.
3. Select a forger with the required capabilities.
4. Form a Concurrent Engineering Team

2.1 Selecting an Alloy Group

The first task in specifying is to identify the optimum alloy group based on broad general guidelines for factors such as mechanical properties, weight, operating temperature and resistance to corrosion. Table 2-1 gives an overview of the seven most commonly forged alloy groups. The selection of the optimum alloy from the group is often addressed by the concurrent engineering team, because the forging engineer may be able to engineer the forging process to enhance critical material properties such as yield strength, fatigue, impact toughness and fracture toughness.

2.2 Selecting a Basic Forging Process

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 often the 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 process.
3. Seamless rings may be made by open die forging over a mandrel, hot 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 diameters are too large for ring rolling, open die forging is the process of choice.

Table 2-1 Overview of Forging Alloys

AlloyGroup	GeneralCharacteristics	TypicalApplications
1. Steels	Most often selected for forgings	
A.. Carbon	Wide range of grades and properties Most grades are readily forged	Nearly all market areas
B. Microalloy	Alternatives to quenched and tempered alloy steels; high strength and toughness without high treatment	Automotive, truck and off-highway
C. Alloy	Improved mechanical properties versus carbon steels	When carbon steels do not have the required properties
2. Stainless Steels	High corrosion resistance; more difficult to forge that carbon or alloy steels	Corrosion resistance and high temperature properties
A. Ferritic	Excellent corrosion resistance; good ductility; can be worked hot or cold	
B. Austenitic	Highly resistance to acids; good toughness at cryogenic temperatures	
C. Martensitic	Can be hardened and tempered; are magnetic	
D. Special grades (e.g. PH, duplex stainless)	Combinations of high strength and corrosion resistance	
3. Aluminum	Most easily forged into precise, intricate shapes; low density; generally heat treated; good corrosion resistance	Aerospace, automotive, truck, military components, sporting wear and accessories

4. Copper base	Excellent, corrosion resistance; excellent forgeability; good dimensional precision; low draft	Leakproof fittings, plumbing fixtures, gears, bearings pumps, valve bodies, non-sparking applications.
5. High Temperature Alloys	Good corrosion and oxidation resistance Good high temperature properties, particularly creep and low cycle fatigue	Gas turbine components
6. Titanium	High strength; low weight; high service temperatures, excellent corrosion resistance	Aerospace, chemical processing, prosthetics
7. Magnesium	Low density; low modulus of elasticity; requires special handling	Where minimum weight is required at relatively low service temperature

When the impression die process is selected, the hot, warm and cold processes may be considered. Table 2-2 gives broad guidelines for choosing among the three. Note that warm and cold forging may be used in combination.

When hot impression die forging is chosen, four options are available: blocker type forgings, finished forgings, near-net forgings, net shape forgings. These are illustrated in Figure 2-1.

Table 2-2 Preselection of Impression Die Forging Process for Steels

FactorsofChoice	TypeofForging		
	Cold	**Warm**	**Hot**
Steel Quality	CWQ/SBQ	SBQ	SBQ
Material costs (grade)	Higher	Medium	Low
Deformation Pressure	High	Medium	Low
Energy Costs	Low	Medium	High
Tolerances	Closest	Close	Generous
Tooling Cost[1]	High	High	Lowest
Size Range	<28 gm (1 oz) to 23kg (50 lb)	110 gm (1/4 lb)[2] to 23 kg (50 lb)	Virtually Unlimited
Shape Restrictions	Limited	Less Limited	Virtually Unlimited

[1] Excluding automation cost

[2] Often in combination with cold formingBlocker 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 difficult to forge heat resistant alloys.

- 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 difficult to forge heat resistant alloys.
- Finished Forgings are suitable for higher 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 3o to 7o.
- Near-Net Forgings are forged as closely as possible to the required dimensions of the finished part so that most surfaces require little or no machining. They are similar to finished forgings except they are closer to final configurations.
- Net Shape Forgings, sometimes called precision forgings, are forged on one or more sides to net shape requiring no further machining on at least one side. For example, tooth forms on 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 or to permit final grinding. The hole and back face are still finish machined in this case.

In some cases, product factors drive the choice of forging processes. For example:

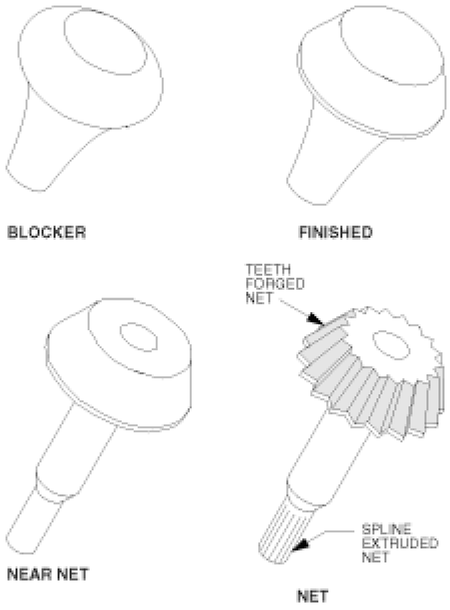


Figure 2-1 Blocker, finished, near-net and net shape forgings

- Increased forging precision tends to drive up the cost of forging operations somewhat, and it usually reduces the cost of finish machining. As production quantities increase, the reduced cost of machining operations becomes a stronger offsetting factor to the higher tooling and processing costs. Appendices A, B, C and D give industry guideline tolerances for several forging processes.

- A very expensive raw material that is difficult to machine will suggest the most chipless process, and small production quantities might best be net shape 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 may be an alternative when quantities are very low; 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 cold, warm or hot forging, depending on complexity and size.

2.3 Selecting a Forging Company

The selection of candidate forging companies is determined by the type of forging process, the alloy used and the size of the component. Information relating these factors to forging companies is readily available in the Custom Forging Capability Guide. This Guide is published every two years by FIA. It lists the forging companies alphabetically for each process and gives the alloy group(s) forged and size capability. It also provides information on types and sizes of forging equipment. Table 2-3 summarizes the process, alloy and size information found in the Guide, and gives typical production quantities. An electronic (and fully searchable) version of the Guide can be accessed through FIA's website at http://www.forging.org.

The custom forge plant is essentially a service organization. One of the most important aspects of the service is assistance in the design and development of a product to be forged. This assistance is best made available by the formation of a concurrent engineering team. The key to the success of a concurrent engineering team is to begin early.

2.4 Forming a Concurrent Engineering Team

A team consisting of the product designer, the purchasing manager and a quality control or manufacturing representative from the purchasing company and a technical representative of the forging company is a good starting point. This team is usually small enough to act quickly and large enough to assure the balanced input. Other team members may be added as the program develops.

The team effort is launched with a series of design conferences. Figure 2-2 is a checklist of information to be exchanged, most of which is originated by the purchaser. As the program proceeds, the forger will contribute in several areas. For example:

1. Engineering Drawings The purchaser supplies engineering drawings of the finished part and sometimes the rough machined envelope; the forger usually submits drawings of the forging for approval.
2. Tolerances The forger will indicate any limitations or improvements on the FIA guideline tolerances.
3. Material and Heat Treatment The forging engineer should be encouraged to suggest alternate alloys and heat treatments to contain costs while maintaining product integrity.

As materials and process technologies advance, it is increasingly important for the product designer and purchaser to involve the forger in decisions that ultimately affect the cost and performance of the product. Close cooperation will yield the greatest benefits from forging industry innovation and can help spur further progress.

Table 2-3 Overview of Information Found in FIA's

Custom Forging Capability Guide

Process	AlloyGroup	Size	Quantities
Impression Die	Ferrous Carbon Alloy Stainless Non-Ferrous Aluminum Cooper Base Alloys Magnesium Titanium High Temperature Alloys	Range of sizes by weight (Enables pre-selection of suppliers by product sizes, weights and alloys)	Unlimited (300 or more typical)
Open Die	Ferrous Carbon or Alloy Stainless Non-Ferrous Aluminum Cooper Base Alloys Magnesium Titanium High Temperature Alloys	Shafts - Max Length Discs - Max Diameter Saddle/Mandrel rings - Max. O.D. and Max Length	1 or more (up to 50 typical)
Rolled Rings	Ferrous Carbon or Alloy Stainless Non-Ferrous Aluminum Cooper Base Alloys Magnesium Titanium High Temperature Alloys	Min I.D. and Max O.D^2 Min. and Max. Weights Min. and Max Heights	1 or more (10 or more typical)
Cold Forging	Ferrous Carbon	Range of Sizes by Weight	Usually more than 10,000

	Alloy Stainless Non-Ferrous Aluminum Copper Base Alloys		

[1] Can vary depending on alloy, design and capabilities of the forging company.

[2] The guide also indicates whether or not contours are available for rolled rings

Figure 2-2 Forging Design Conference Checklist

The following information should be exchanged between buyer and forger during conferences held prior to final design and specification of a forged part. This information is the key to identifying ways to improve part performance and reduce cost.

Identification

- Name of component
- Drawing number
- Part number
- Company name and address
- Name and title of person initiating the inquiry or order
- End use

Engineering drawing - forging print and machining prints

- Name of component
- Drawing number
- Position of locating points and/or chucking bosses for subsequent machining operations
- Surfaces to be machined and finish allowance desired
- Type of finishing operation to be used
- Location and nature of part numbers, trademarks and traceability codes (raised or indented numbers and letters)
- Identification of drawing as to issue status or number

Service data

- Maximum design stress
- Description of stress in service (impact, cyclic loading or pressures)
- Nature of wear or abrasion to be encountered
- Operating environment (corrosive agents, maximum service temperatures)

Surface condition

- Surfaces to be machined (marked on drawings)
- Nature of finish (polish, plating, paint, other)
- Whether alternate quotation is desired, with machining and other operations included

Material Composition and Quality[a]

- Metal by name, composition and specification
- Alternate materials permitted

Properties

- Standard specification that applies (additional requirements and/or exceptions)
- Minimum tensile strength
- Hardness (maximum and minimum specified locations
- Other applicable properties

Heat treatment[b]

- Test bar location or prolongation, analysis, and specification number
- Heat treatment (if required)

Part Quantity/Weight

- Total quantity/weight required (in pieces) for initial orders
- Number of pieces/weight per release (if subject to release)
- Estimated annual quantity/weight requirements
- Any limitations on application of FIA quantity tolerances. (Special quantity tolerances are usually quoted separately)

Delivery Schedule

- Initial delivery date and number of pieces
- Subsequent schedule (pieces required per delivery - monthly, daily, weekly, etc.
- Date order is to be completed

Machining and Options

- Specify whether as-forged, forged and blasted, rough machined or finish machined and ready to install
- Specify sub-assembly requirements

- Nature of heat treatment
- Property levels required
- Heat code marking system

Dimensional tolerances

- Tolerance guidelines (FIA)[c]
- Critical dimensions where special tolerances apply

Special inspection requirements

- Inspection methods required (dye penetrant, magnetic particle, ultrasonic)
- Customer's incoming inspection (complete, 100% statistical: average quality level AQL, or other)
- Government agency inspection
- First piece inspection samples required

Shipping

- Special packaging specifications or crating requirements
- Type or name of carrier preferred

Traceability

- Lot code
- Die ID
- Heat code

Testing and inspection[d]

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[a] Express as a simple statement of composition; as a standard AISI, ASTM or SAE classification; or as an industry, company, government or other specification. For additional information see Open Die Forging Technology, p133, Forging Industry Association, 1993.

[b] Heat treatments are specified by the purchaser in general terms, such as annealing, normalizing, or quenching. Specific processing details usually rest with the forging producer.

[c] See Appendices A, B and C for industry guideline tolerances.

[d] The purchaser will normally specify the type of tests and acceptance levels required. Only those tests needed to establish the mechanical properties and quality necessary for reliable service performance should be specified.

2.5 Prints and Specifications

It is important that forging drawings be accurate and complete. The purchaser should indicate his first operation locating points, normally as a part of the drawing, and give prior notice should these points be changed.

It is equally important that the purchaser provide drawings of the finish machined part, or equivalent information. This will assist in the design of forging dies and tools, and in establishing effective inspection procedures.

Unless the purchaser's drawings and specifications direct otherwise, all dimensions are normally assumed to refer to lines intersecting at right angles to each other (commonly referred to as X, Y, and Z axes). Furthermore, unless the purchaser's drawings or specifications direct otherwise, circular shapes are normally assumed to be figures of revolution with a center on an axis, and all circular dimensions are normally shown as diameters.

2.6 Additional Information Services

Although industry standards for forging design, dimensions and tolerances, processing and material composition are available from standards organizations such as ASTM, SAE and ASA, Forging Industry Association serves an important clearing house function for wide ranging supplementary information of value to specifiers and buyers of forgings as well as the forging industry and its suppliers. Following is a partial list of resource material available through FIA, which are shown in Figure 2-3.

Figure 2-3 For additional information on forging processes and capabilities contact Forging Industry Association

- Forging Handbook. This is a basic resource for newcomers to forging as well as forging experts. It contains information on applications, design principles, materials and manufacturing techniques.

- Open Die Forging Technology. This handbook compiles information on manufacturing equipment, methods and design considerations of open die forgings and includes a special section on ring rolling.
- Custom Forging Capability Guide. This comprehensive listing of locations and facilities of FIA member companies is published approximately every two years. An electronic (and fully searchable) version of the Guide can be accessed through FIA's website at http://www.forging.org.
- Forging Solutions Technical Bulletins (Series) This series places emphasis on the benefits of using forgings. Case histories are provided, which highlight cost savings and performance advantages in designing for forgings.
- Making The Most of Forging Benefits (Series) This series of brochures is designed to educate users or potential users of forgings about the benefits of designing with forgings.
- Forging Resources This is a guide to publications, videotapes, handbooks and other resources for and about the forging industry.

For more information on any of these resources, contact Forging Industry Association.

The Design and Development of Products Made from Forgings

4. The Design and Development Made From Forgings

This section presents a step-by-step process for designing a product to be made by forging. Some of the material in it is also presented more briefly in Section 2, Specifying and Purchasing Forgings. The repetition is intentional, making this a stand-alone section, which addresses the needs of those who design and develop products made from forgings.

The product to be designed may be totally new, or it may be redesigned or adapted from an existing application. In either case, the optimum process consists of the following eight steps.

1. Form a concurrent engineering team.
2. This is the best way to get maximum product development input in the critical early stages of design.
3. Establish the design parameters.
4. This step will eliminate materials and processes that are not suitable and focus on the ones that are.
5. Determine the cost drivers.
6. The manufacturer quotes the price, but the designer "designs in" nearly all of the cost.
7. Select the optimum process.
8. Several processes may work; selecting the optimum one requires knowledge of process tradeoffs.
9. Develop the optimum shape for the function and process.
10. The manufacturing process drives the product shape and may have more influence than does product function.
11. Develop the required properties.
12. Properties should be designed into the product — to stay.
13. Specify the correct heat treatment.
14. Heat treatment can significantly increase properties, although heat treatment may not be necessary in some cases, such as microalloy steels.
15. Prove the design.

16. Computer aided engineering and prototype testing are helpful steps in verifying product integrity, before investing in production tooling.

The following sections systematically develop each of the above steps:

Concurrent Engineering (3.1)

Design Parameters for Forgings (3.2)

- Service Loads
- Service Temperatures
- Corrosion Environment
    - Atmospheric
    - Galvanic
    - Stress corrosion cracking
- Interfacing Structural Components

Cost Drivers (3.3)

- Material
- Tooling Cost
- Manufacturing Cost
- Secondary Operations
- Quantities Produced

Process Tradeoffs (3.4)

- Comparison of Open Die, Impression Die, Rolled Ring and Cold Forging Processes
- Forging Processes Compared With Alternate Processes
    - Sheet Metal Stamping
    - Weldments
    - Foundry Casting
    - Investment Casting
    - CNC Machined Bar and Plate
    - Powder Metallurgy Processes
    - Reinforced Plastics and Composites

Designing Products Made From Forgings (3.5)

- Development of a Typical Shape
- Selecting a Forging Company
- Selecting the Optimum Forging Alloy
- Product Design Guidelines

Predicting, Developing and Maintaining Properties in Forgings (3.6)

- Physical Properties
- Mechanical Properties

- Developing and Maintaining Product Performance

Specifying Heat Treating (3.7)

- Steel
    - Annealing Processes
    - Hardening Treatments
- Stainless Steels
- Aluminum Alloys
- Titanium Alloys
- Heat Resistant Alloys

Prototyping (3.8)

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.)

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.

3.2 Design Parameters for Forgings

The design parameters for a forging can best be determined by visualizing the component in its working environment. Five parameters should be considered at the outset.

1. Service loads and peak expected loads
2. Service temperatures
3. Corrosion/oxidation environment
4. Interfacing components
5. Accidental and non-quantifiable conditions

Analysis of these parameters will help to:

- Get all of the factors on the table before design begins
- Identify opportunities for product improvement
- Identify opportunities for cost reduction
- Assist in determining

Whether or not to design for forging

Which forging process to select

Which family of forging alloys will best meet the product needs

- Determine if there are opportunities for consolidating more than one part into a single forging design.

The design decision will also be affected by the anticipated production quantities.

3.2.1 Service Loads

Forgings are most suitable for applications requiring high levels of:

- Tensile strength
- Yield strength
- Fatigue strength
- Shear strength
- Impact toughness
- Fracture toughness
- Ductility

Forgings consistently outperform counterparts made by casting, powder metal processing, weldments, or products machined from plate or bar stock. Alloys suitable for forging in each of the alloy groups exhibit improved mechanical properties and heat treating capabilities that are at least equivalent to their counterparts.

The forging(s) source can help maximize these properties by designing the forging process to develop the optimum grain flow and microstructure in the forging. Grain flow optimization is sometimes called "putting the grain flow against the load". Expected stress concentration points should be resolved at this stage. A good understanding of the processes is essential here.

3.2.2 Service Temperatures

Service temperatures do not generally affect the decision whether to choose forging over an alternate process. However, they are an important driver when deciding which forging alloy to choose. Service temperatures can not always be defined by a single number. For example:

- A temperature may be steady state or cyclic. A familiar example is a forged aluminum piston in an internal combustion engine, which performs satisfactorily when exposed to cyclic flash temperatures that typically reach or exceed 1650°C (3000°F). In contrast, gas turbine engine components, operating at steady state temperatures of 870°C (1600°F), require nickel or cobalt superalloys.
- Metal alloys can withstand occasional short-term temperature excursions, or "spikes", particularly those that occur when loads are at low levels.

- When temperature gradients are present, unusually high temperature excursions may be tolerable if experienced in a localized low-stress area of the forging.

If mechanical properties are affected by low temperatures, such as those below the ductile-brittle transformation range, the forging should be tested at the anticipated low temperature. Ductile-brittle transformation can occur in some alloys at harsh environment test temperatures of -34°C (-30°F), and it is likely to occur in cryogenic applications.

3.2.3 Alloys Forged

Corrosion may appear in any of three forms: atmospheric corrosion, galvanic corrosion or stress corrosion cracking. Atmospheric corrosion describes corrosion that is caused by the chemical action of compounds in the environment on the surface of the material. The most common form is water and water soluble pollutants, or substances encountered in processing equipment. Corrosion is controlled by material selection and surface treatment.

Alloys of magnesium and aluminum are more anodic than most other commonly used metals, and give up metal to less active alloys, such as those in the iron and copper groups. Galvanic corrosion is commonly controlled by three means, either alone or in combination:

- Selecting compatible materials
- Excluding electrolyte from the contact surfaces
- Separating the contact surfaces with a material that is either a non-conductor or is compatible with both.

Stress corrosion cracking occurs in some alloys when they are under continuous load for long periods of time in the presence of a specific chemical substance. The stress levels may be well below the yield point. It can be controlled either by excluding the corrosive environment (protective coatings), by designing the affected area of the forging to acceptable stress levels, or by utilizing stress corrosion resistant thermal or mechanical treatments. (For example, T653 or T23 for aluminum alloys.)

The problem is generally associated with metals that are susceptible to corrosion. For example, magnesium alloys containing more than 1.5% aluminum, in normal atmospheres, are subject to stress corrosion cracking at stress levels of 48 MPa (7 ksi) and higher. Stress corrosion cracking may also occur in corrosion resistant alloys, such as brasses with more than 15% zinc, in the presence of ammonia. Certain aluminum alloys, when aged to peak strength (T6) are susceptible to stress corrosion cracking. Stress corrosion cracking can often be minimized by selecting an alternate material.

3.2.4 Interfacing Structural Components

The components that attach to a forging may present either design problems or opportunities for product improvement. Interfacing components made from different materials may be subject to galvanic corrosion, as noted above. Interfacing components that have significantly different coefficients of thermal expansion, such as aluminum and steel, and are subject to temperature excursions, may require consideration in the attachment methods to tolerate differentials in expansion.

The high ductility usually achieved in forging often permits the design to include features that can be staked, crimped or swaged to reduce or eliminate fasteners. It may also be possible to redesign, reducing parts count and eliminating both fasteners and subassembly operations. This opportunity should be explored when products made by other processes are redesigned as forgings.

3.2.5 Accidental Unanticipated Conditions

High ductility, impact toughness and fracture toughness give forgings a distinct advantage over products made by alternate methods. These properties are essential wherever safety is a concern. Current product liability actions are reinforcing the need to anticipate the unexpected, such as impact loads. They are especially important where failure can threaten the safety of the user. In those cases, the design must be such that any failure is progressive, and not sudden.

For example, wheel spindles for automobiles and trucks are subject to unpredictable damage from impacts. If a brittle fracture occurs, the operator will lose control of the vehicle, potentially resulting in a serious accident. A forged spindle, which has a high level of impact toughness, fracture toughness and high ductility at all anticipated operating temperatures, may undergo plastic deformation, but will remain partially operative to give reasonable insurance against loss of control.

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

A discussion of these five main cost drivers follows.

3.3.1 Material Cost

Material cost is the cost to purchase and process enough material to ship the product. The amount of material purchased must include the amount in the end product plus "engineered" scrap. The raw material for forging is bars, billets, blooms or ingots. Forging alloys purchased in these forms are equivalent in cost to similar alloys used for castings, bar or plate stock.

Purchased raw material must include allowances for punch-outs, flash, other discards and machining allowances. The amount varies with the forging process and part design. The material loss is generally much lower for forging than for "hog-outs" (machined from plate or bar) and stampings, but higher than for powder metallurgy parts making processes. Forging usually produces a higher yield (ratio of product to material consumed) than casting, but the processes do not lend to direct comparison.

There are five primary sources of engineered scrap in forging: punch-outs, flash, other discards, material losses from furnace heating and machining allowance.

- Open die forgings generally have the greatest amount of machining allowance of the forging processes. The process does not produce flash, but there are generally discards from either or both ends of the forging.
- Impression die and upset processes require less finish allowance, but usually generate flash. Net, or near-net impression die forgings eliminate most or all finish allowance, and are sometimes flashless. Near-net forgings also have lower draft angles, and thus embody less material in the end product.
- Ring rolling uses preforms, which are disks with the centers pierced out. The process produces no flash and requires few, if any, finish machining operations.
- Cold forging generally produces no flash and very close dimensional tolerances

3.3.2 Tooling Cost

Tooling preparations cost quoted by forgers generally includes the cost of designing and manufacturing the tools used to produce the forging. It also includes the cost of special gauges and fixtures. Tooling cost varies with a number of factors, the most important being the forging process.

Open Die Open die forgings are made with standard "V", swage or flat dies. Tooling cost is not significant.

Impression Die Tooling cost is usually significant in impression die forgings. It includes one or more impressions (preform, blocker, finisher or other impressions), sometimes preforming rolls, edger or fullering impressions, and usually trim dies. The cost of manufacturing the impression dies is driven by the size and complexity of the forging. Trim die cost is driven by the size of the forging and the complexity of the geometry. Press tooling can differ significantly from hammer tooling due to features such as knockouts, strippers and master tool holders.

Die wear necessitates periodic maintenance, resinks, and ultimately replacement of the dies.

Die wear varies with the alloy being forged with the harder alloys causing faster die wear. This tendency can be reduced by proper adjustments to product design.

Rolled Rings Tooling cost, including manufacturing, maintenance and replacement for rolled rings, is low compared with the impression die process. There is virtually no tooling cost for plain rectangular section rings. However, shaped rollers are required to roll rings that have inside or outside contours. Rolls for forming inside contours (mandrel) cost substantially less than rolls for outside contours (main rolls). Profiled ring rolling also requires dies for the preforming operation. They are less costly than those used for the impression die process, but must be recognized.

Cold Forging Tooling cost for cold forgings is typically five to ten times as much as for equivalent hot impression die forgings when also considering the automation that typically accompanies cold forging processes. But tool life in cold forging is much greater. In many cases, a sequence of operations is used requiring several dies, so that quantities are typically very high. Tool cost can be reduced when similar parts can share common tool details.

3.3.3 Manufacturing Cost

Manufacturing cost includes the cost of labor plus the cost of purchasing, maintaining and operating the required machinery and material handling equipment. A portion of these costs is charged to each forging produced. In most cases it also includes the cost of maintaining and replacing the forging tools. Machinery typically includes saws, shears, furnaces, preforming equipment, the forging press or hammer with its associated controls and trim presses. Material handling equipment typically includes cranes, lift trucks, conveyors, etc.

Manufacturing cost is driven by the number of operations required to produce the forging and the cost of each cost center. Each cost center is assigned an hourly operating cost, which is divided by the number of pieces produced per hour to arrive at the cost charged to the forging. For example, when forging microalloyed steels, which are used to eliminate heat treating, the cost of using special cooling conveyors will be included. The total manufacturing cost is the sum of the costs of the individual operations.

Design simplifications that reduce the number of operations, or reduce the size or complexity of the required forging machines drive toward minimum processing cost. For example, an impression die forging may require several preforming operations, a blocker operation, a finish operation and a trimming operation. The total processing cost is the sum of the costs for each operation. If the design can be modified to reduce the number of operations, processing cost is sometimes reduced significantly.

Processing cost can be reduced by designing the forging to facilitate metal flow in the die and reduce forging pressures. This usually involves modifying sharp details to provide larger radii. In some cases it may be possible to use a smaller forging press with a lower hourly operating cost that produces more parts per hour. Lower forging pressures also tend to reduce tool maintenance and replacement cost, which is usually a part of the quoted piece price.

3.3.4 Secondary Operations

Secondary operations are those required to bring the forging to the required shape, precision, mechanical properties or surface finish. These operations may include:

- heat treatment
- cold coining
- straightening
- machining
- nondestructive testing
- vibratory finishing
- shot blasting
- coatings such as paint and powder coat.

In some cases, special packaging is specified for purposes such as protecting during shipment or positioning uniformly to facilitate assembly. Secondary operations must be factored into the design of the forging so that processing requirements can be recognized in the design.

The costs associated with some secondary operations are traded off against tooling and processing costs. For example, it may be possible to produce a forging by developing the rough shape as an open die forging, or in a blocker die, and finish machining to develop the required precision. Or, finish machining cost may be reduced at increased tooling and processing cost by forging to more detail and closer precision using multiple operations. The decision is usually driven by the number of machining operations required, production quantities and raw material cost.

ting cost that produces more parts per hour. Lower forging pressures also tend to reduce tool maintenance and replacement cost, which is usually a part of the quoted piece price.

3.3.5 Quantities Produced

As with other manufacturing processes, there is a setup cost associated with the production of each order of forgings. This includes the cost of installing preforming tools, forging dies, trim dies, and computer programs, as required for the forging. The cost is spread over the quantity produced, so that the effect on piece price decreases as the order quantity increases.

As the total number of forgings anticipated over the life of the product increases, there is a decrease in amortized "per piece" costs such as:

- Design and development of the forging
- Construction of the forging tools
- Installation of automation equipment

- Providing special fixtures and gauges
- Development of the forging processes.

3.4 Process Tradeoffs

When a product that has been traditionally made by some other process is being designed for forging, or when an existing product is being redesigned for forging, the design must focus on the function that is to be performed and avoid the tendency merely to replicate the former shape.

Designing for function, rather than form, will enable the designer to realize the full benefits of forging. It will help, in many cases, to avoid costly overdesign. As noted above, in functional design the various features of the forging are tailored to the mechanical requirements of each feature.

The end product contains the minimum amount of material, minimizing weight and reducing cost. The stamping mentioned below would have a constant thickness while the forging thickness could be varied to develop less weight for essentially the same part.

In most design programs, more than one manufacturing process may be employed, but one process will be optimum. Therefore, identifying the optimum process is a critical step in a the development of a product.

A second factor, often overlooked, is the profound effect of the manufacturing process on the shape of a product. For example:

- The features of a steel stamping are essentially uniform in thickness because the stamping is made from sheet stock of uniform thickness. A forging that performs the same function can have varying thicknesses tailored to the mechanical requirements of each feature.
- A weldment often requires special built-up features at joints, such as flanges and bevels, to develop adequate weld strength. A forging is a monolithic structure, and does not need those features.

In both categories, the finished forgings often weigh less than the part being replaced.

A third factor is the opportunity to combine two or more parts that are being separately manufactured and assembled. Often, substantial cost savings and product improvement can be realized by redesigning into one forging. The tractor drawbar hitch and steering knuckle, shown in Figure 3-2, illustrate successful parts combinations.

The following summaries identify the critical factors for choosing among the available forging processes and for comparing forging with alternate processes. It is worth repeating that these decisions are often best made in concurrent engineering teams.

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.

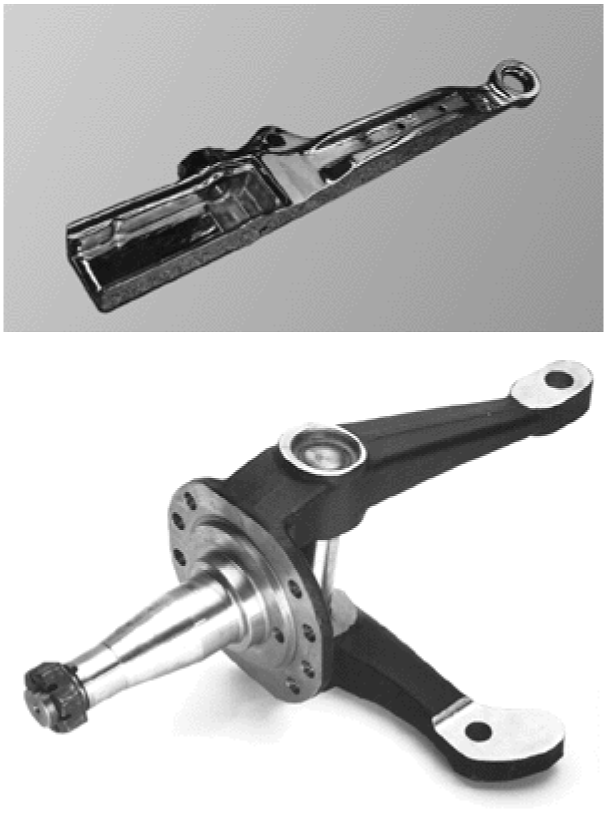


Figure 3-2 The tractor drawbar hitch (top) and truck steering knuckle (bottom) illustrate forging's capability to combine several parts into one.

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 7o to 10o.

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 3o to 7o. (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.

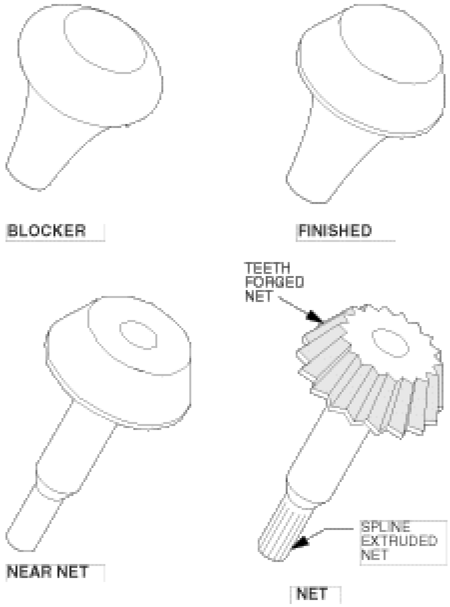


Figure 3-3 Blocker, finished, near-net and net shape forgings.

Following is a summary of several typical areas where product factors drive the choice.

- 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 Forging Processes Compared With Alternate Processes

The choice between forging and alternate processes is driven by five factors.

Material and structural requirements Applications that require high operating temperatures or corrosion resistance require alloys such as stainless steel, titanium or superalloys. Applications that require materials with very high strength, ductility, impact toughness and fatigue strength usually require steel, high strength aluminum or titanium alloys. In these cases, the manufacturing process must be one that can utilize the required materials. Pressure die casting is excluded because it is used almost exclusively for alloys of aluminum, magnesium and zinc, which have low melting points, moderate corrosion resistance, and moderate mechanical properties.

Production quantities Manufacturing processes that are characterized by low tooling cost generally require extensive machining operations to develop the shape and achieve the required precision. For very low production quantities, "hogouts" made by CNC machining or weldments will be economical because the high cost of machining and processing is offset by minimal tooling cost. As volumes increase, impression die forgings become more cost effective.

Shape capability Some processes, such as evaporative pattern and investment casting, offer almost unlimited capabilities to produce complicated shapes. However, they tend to be less controlled and more labor intensive, and may be more costly than an assembly of parts made by a less labor intensive process. Tensile and shear strengths are often lower or more erratic than those for forgings.

Weight reduction In some applications, such as automotive and aerospace, minimum weight is essential. Processes that can produce components as close as possible to the required shape, eliminate material in non-critical areas, and provide superior mechanical properties, offer a distinct advantage over components that may cost less to produce but weigh more.

Product integrity Forgings are free from internal porosity and exhibit a high degree of integrity. Processes that may be characterized by internal flaws, such as inclusions or porosity, are difficult to justify when safety is a concern. They often require extensive, sometimes 100% inspection, which significantly increases the cost. Furthermore, there are few 100% inspection processes that are 100% effective.

3.4.2.1 Sheet Metal Stamping

Sheet metal stamping utilizes sheet products, mostly alloys of steel, stainless steel, aluminum and copper, with steel alloys being predominant. Stampings are suitable at most levels of production, but are most economical where annual production is high. Press productivity and die costs depend on the number of dies and presses required to produce the stamping, which are in turn driven by the complexity of the stamping. The list price of sheet stock is competitive with forging stock, but stamping is not usually as material efficient. Energy consumption is low since the stock is not heated. The range of available alloys is wide, but higher strength materials are often not as formable as lower strength materials. Shape flexibility may therefore be restricted, and process cost increased.

Six factors, usually in combination, give forging advantages over sheet metal stampings.

1. The engineered scrap rate for some types of stampings that are alternatives to forging may be as high as 50% and is occasionally higher. It includes perimeter material in the clamp and binder areas of the die, and openings in the stamping. Engineered scrap is recycled but little of the original purchase price is regained, particularly with sheet steel.
2. Most stampings are made in stages, each requiring a separate die. The die and processing costs are driven by number of dies required.
3. Many applications require that several stampings be separately formed and joined. Manufacturing and tooling costs for the stampings are proportionately increased, and the cost of fixturing and joining is incurred. As parts count increases, forgings become more cost competitive. In some cases forgings have been chosen over one-piece stampings to achieve weight or to gain secondary advantages from shapes that can be forged but cannot be achieved by stamping.
4. Stampings are usually made from stock of uniform thickness, and wall thicknesses can be varied a limited amount throughout the stamping. The capacity to vary thickness depends on the process and cannot always be utilized to optimize the product. The stock thickness of a stamping is therefore usually driven by the mechanical requirements of one critical feature. Alternatives, such as added reinforcements or tailored blanks, require that separate parts be processed and joined. Forging allows more opportunity to tailor feature thicknesses to functional requirements, reducing component weight. This gives forgings an important advantage in applications where minimum weight is critical, such as aerospace applications and automobile suspension members.
5. Assemblies of stampings require features, such as flanges, to facilitate welding or adhesive bonding. These additional features usually increase somewhat the amount of purchased stock and the weight of the end product.
6. Stamping processes work harden the metal to some degree, increasing strength and hardness and decreasing ductility in some areas of the stamping. However, the increases are driven by the process, and usually can not be optimized to the application as is often done in forging. In some cases, work hardening requires intermediate annealing.

3.4.2.2 Weldments

Weldments are generally made from product such as bar, tubing and plate. Part shapes are economically made by burning, laser cutting, shearing or sawing, depending on complexity and thickness. Individual parts in a weldment can be made of different alloys, within the limits dictated by welding parameters. Tooling cost is very low, but the process is labor intensive. Bar and plate stock are rolled, which causes grain orientation with improved mechanical properties in the direction of rolling. Cold rolled stock exhibits a clean, flat surface, which often requires no clean-up.

Weldments may offer an advantage over forgings in low production quantities. The economic advantage of weldments decreases as production quantities increase and the economic advantage shifts to forgings. Applications where production volumes are initially low and growth is anticipated can often be introduced as weldments and converted to forgings with minimal development cost and no compromise in product integrity.

At times, forgings become part of a weldment. For example, when special features are to be added to a forging it is sometimes more economical to weld two forgings together than to forge the entire part. A good example is friction welding a bar of steel to a flange having a stub shaft to form a long axle shaft. Further discussions of this option are beyond the scope of this section.

3.4.2.3 Foundry Casting

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.

3.4.2.4 Investment Casting

Investment casting, sometimes known as the "lost wax" process, is used with a wide range of alloys, including carbon and alloy steels, stainless steels, titanium, nickel, cobalt and aluminum alloys. Tools consist of aluminum molds for injection molding the wax patterns. They are relatively inexpensive and require very little maintenance.

The process is more labor intensive than forging, and is more suited to lower production quantities. Investment casting is most advantageous for small and medium size castings of highly complex shapes, with very good dimensional precision and surface quality. Solidification rates cannot generally be controlled in this process.

Forgings offer essentially the same performance advantages over investment castings as noted above for foundry castings.

3.4.2.5 CNC Machined Bar and Plate

There is virtually no limit to the shapes that can be produced by CNC machines. In most cases, standard cutting tools are used, so that no tooling is purchased. Processing and material costs are generally high, because much of the purchased stock is removed. Forgings generally exhibit superior directional properties and fatigue performance due to grain flow. Hogouts are useful for complex or precision components in very low quantities. They can also be used on a limited basis for prototyping forgings.

3.4.2.6 Powder Metallurgy

Conventional powder metallurgy (P/M), metal injection molding (MIM) and powder forging (P/F) are the three most commonly specified powder metallurgy processes. The processes are used for essentially the same alloys groups as forging. MIM is currently limited to very small components, up to approximately 100 gm (3.5 oz) of complex configuration. It is rarely an alternative to forging. Conventional P/M and powder forging may be alternatives in some applications.

Conventional P/M produces very close dimensional precision, but the process is characterized by porosity, which reduces mechanical properties. Tensile and yield strengths are reduced approximately in proportion to the level of porosity, while ductility and dynamic properties, such as impact toughness, fracture toughness and fatigue strength, are usually much lower than for forgings. Process options such as infiltration and special sintering procedures can improve properties. However, dynamic properties are not equivalent to forgings made from similar alloys.

Dynamic properties in P/M approach those of forgings only when the porosity is reduced to 0.5% or less, and this level is generally achieved only by powder forging. Powder forging is an alternative to impression die forging for small and medium sized components with a high degree of symmetry and high production volumes, such as automotive gears and connecting rods.

3.4.2.7 Reinforced Plastics and Composites

Reinforced plastics and composites generally utilize thermoset plastics, and occasionally thermoplastics, as a matrix. Reinforcing fibers of glass, mineral, carbon and Aramid are added to increase strength and stiffness. These materials are well established in applications where low weight is essential and increased cost can be tolerated, such as aerospace applications.

Regardless of the reinforcing fibers used, the operating temperature range of reinforced plastics and composites is limited by the polymer matrix materials. The effects of temperature within their operating ranges are complex compared with forging alloys.

Forgings offer advantages of lower cost and higher production rates. The mechanical properties of forgings, even in advanced aerospace applications, are better documented so that performance is more predictable. Forging materials outperform composites in almost all physical and mechanical properties, especially impact toughness, fracture toughness and compression strength.

3.5 Designing Products Made from Forgings

As early as possible, preferably in the preliminary design stage, the designer should:

- Select the appropriate forging process
- Select the optimum alloy
- Decide whether heat treatment is required and, if so, select the optimum process.

These decisions will enable the designer to work toward a forgeable shape, and optimize feature sizes based on functional and structural requirements. Often more than one forging process may be selected, and frequently there are several combinations of alloy and heat treatment that may be used, particularly in the ferrous alloy group.

- Factors that drive the process selection are discussed in Section 3.4.2.
- Factors driving the selections of alloys and heat treatment are discussed in Section 4, and summarized in Section 3.5.3 below.

The design of a product to be made by forging typically proceeds as follows:

1. The purchaser designs the finished part, and submits the design to the selected forging company.
2. The forging company generally provides design assistance to the design engineer, based on finished part specifications.
3. The forging company:

- designs the tools
- develops the process
- may recommend an alternate forging alloy or heat treatment.

3.5.1 Development of a Typical Shape

The shape of a forging, as with most other products, is driven by its function, material and manufacturing processes. The sequence of events in determining the shape is similar to the events for products made by any other process.

1. Identify the functional surfaces and features, including those that relate to end use and those that relate to machining or heat treating.
2. Add material to develop the required mechanical properties.
3. Complete the form in a manner that will optimize the product to the selected alloy, forging process and finish machining process.

This sequence of events can best be seen by following a simple forgeable shape through the forging process. The finished drawing for a typical forged part consisting of a disk, hub and rim is shown in cross-section in Figure 3-4. This part can be made in a variety of alloys by several forging processes. In this case, the impression die process has been chosen. Note that the locating surface and chucking surface for the first machining operation are indicated. These notations will enable the forging company to deliver a part that the user can finish machine with minimum difficulty. Figure 3-5 shows the part after forging and trimming operations and prior to machining. Figure 3-6 shows the part in the forging die after it has been forged to shape, prior to ejection and trimming. Note that there is a web of material inside the hub hole, formed by plugs in both the upper and lower die members. There is draft on the walls of the hub to facilitate release of the plugs.

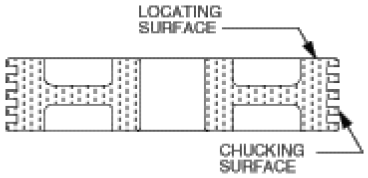
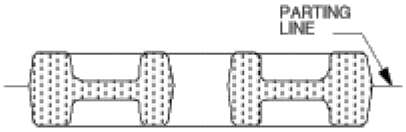
Figure 3-4 Cross Section of a finished part consisting of a disk, hub and rim.	
Figure 3-5 The part in Figure 3-4 after forging and trimming operations and prior to machining.	

Figure 3-7 shows the part in the trim and pierce die at the start of the trim and pierce operation. In Figure 3-8, the part has been pushed down over the lower die, trimming the flash from the perimeter and piercing the hole in the hub. Piercing operations impose high forces on the forging, and may distort the forging somewhat, requiring a subsequent straightening operation. (See Appendix A Tolerances For Impression Die Forgings and Appendix D Specialized Tolerances for Precision Aluminum Forgings.)

3.5.2 Selecting a Forging Company

When the product is developed by concurrent engineering, it is advisable to select a forging company as early as possible, preferably in the preliminary design stage, for reasons set forth in Section 3.1. The selection of candidate forging companies is determined by the type of forging process, the alloy used and the size of the component. For details on forging companies, consult the Forging Industry Association Custom Forging Capability Guide or FIA's website at http://www.forging.org. See also Section 2.3 Selecting a Forging Company.

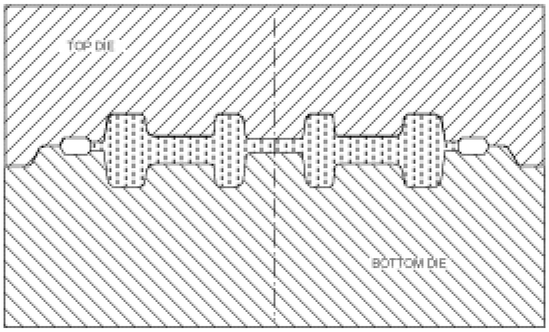


Figure 3-6 The forging show in Figure 3-5 in the die after it has been forged to shape, prior to ejection and trimming.

3.5.3 Selecting the Optimum Forging Alloy

The material specification on a product drawing occupies a very small part of the total space. However, it is a very important part of the specification—in some cases as important as the dimensioned views.

- On the one hand, the alloy must have the ability to be forged; that is, it must be sufficiently forgeable so that the product can be manufactured. Some alloys are relatively easy to forge and may be used to make components with very intricate features. Grades that are more difficult to forge require distinct design approaches.
- On the other hand, the alloy must be able to achieve the required properties so that the product can meet service requirements.

The effects of differences in forgeability on design are described in Section 4 Characteristics of Forging Alloys. Individual forging firms are in the best position to evaluate these factors.

The forging process, particularly development of grain flow, produces significant effects on material properties. In addition, there is a wide range of available heat treatments, particularly for steel alloys. Arriving at the optimum material, processing and heat treatment from the available matrix requires a balance of product design, forging and materials expertise among the purchaser, forging engineer and material supplier.

The design engineer can usually narrow the choice to one or two of the seven groups of forging alloys. Table 3-1 gives a general overview. Additional information can be found by consulting appropriate areas of Section 4 Characteristics of Forging Alloys.

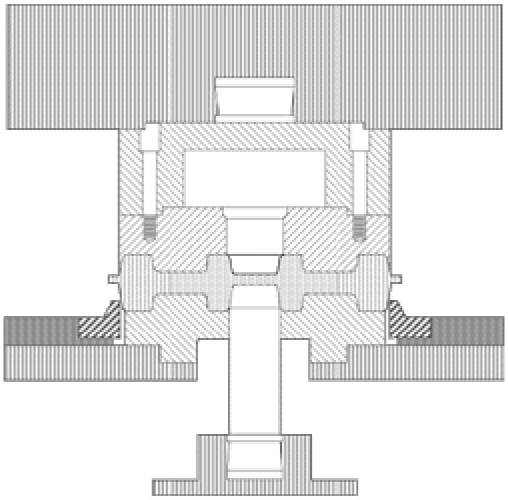
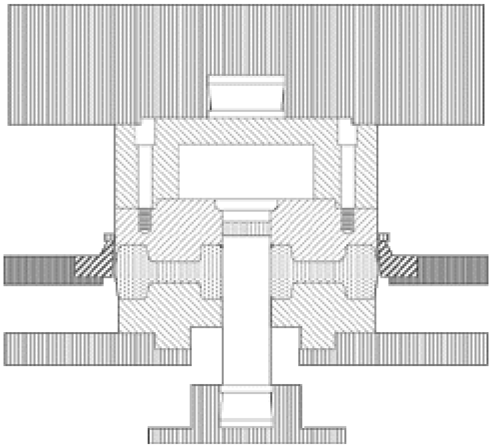
Figure 3-7 Start of the trim and pierce operation.	
Figure 3-8 Completion of the trim and pierce operation.	

Table 3-1 Overview of Forging Alloys

Alloy Group	General Characteristics	Typical Applications

1. Steels	Most often selected for forgings	
A. Carbon	Wide range of grades and properties Most grades are easily forged	Nearly all market areas
B. Microalloy	Alternatives to quenched and tempered carbon steels. High strength and uniform hardness without heat treatment	Automotive, truck and off-highway
C. Alloy	Improved mechanical properties versus carbon steels	When carbon steels do not have the required properties
1. Stainless Steels	High corrosion resistance, more difficult to for than carbon or alloy steels	Where corrosion resistance and high temperature properties are required
A.Ferritic	Excellent corrosion resistance, good ductility, can be worked cold or hot.	
B. Austenitic	Highly resistance to to acids, good toughness at cryogenic temperatures	
C. Martensitic	Can be hardened and tempered, are magnetic	
D. Special grades (e.g. PH and duplex alloys)	Combinations of high strength and corrosion resistance	
3. Aluminum	Most easily forged into precise, intricate shapes, low density, generally heat treated, good corrosion resistance	Aerospace, automotive, truck, military components, sporting wear and accessories
4. Copper Base	Excellent corrosion, resistance, excellent forgeability, good dimensional precision, low draft.	Leakproof fittings, plumbing fixtures, gears, bearings, pumps, value bodies, non-sparking applications
5. High Temperature Alloys	Good corrosion and oxidation resistance Good high temperature properties, particularly creep low cycle fatigue	Gas turbine components
6. Titanium	High strength, low weight, high service temperatures, excellent corrosion resistance	Aerospace, chemical processing, prosthetics
7. Magnesium	Low density, low modulus of elasticity, requires special handling	Where minimum weight is required at relatively low service temperatures

3.5.4 Product design Guidelines

It is essential that the finished part design reflect an understanding of the forging process so that the forging engineer can minimize the cost of producing the forging and facilitate subsequent machining cost.

3.5.4.1 Design Rules for Parts Made From Impression Die Forgings

Sections 3.5.4.1 through 3.5.4.5 give design rules that are specific to the designated forging process. Please refer to Section 2.5 Prints and Specifications for design information which is applicable to all forging processes.

1. All features should be oriented so that they can be formed in impressions moving in opposite directions, such as the part shown in Figure 3-9. Features such as undercuts and holes oriented other than in the direction of forging are not typically forged and must be fully machined. There are, however, a few special presses with side piercing capability, which permit forging of cross-oriented and hollow features.

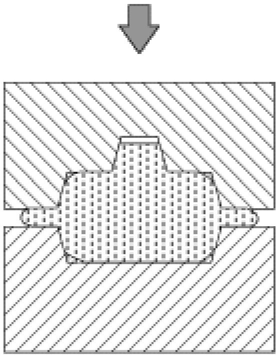


Figure 3-9 The most economical shape to forge is one that can be formed in impression moving in opposite directions.

2. Forging cost is minimized and tolerances reduced when forging loads are balanced, eliminating side loads on the machine members that restrain the dies. Figures 3.10, 3.11 and 3.12 shows an unbalanced condition and two die alternatives.

3. Sharp exterior corners require high forging pressures to fill the corresponding die features. Sharp interior corners (fillets) cause difficulties in metal flow, and may require one or more preform dies to attain, or may require additional machining operations. Therefore, radii should be as large as possible consistent with functional and assembly constraints. Corner and edge radii should also be uniform to minimize die sinking cost.

4. Interior corner (fillet) radii are dependent on forging severity (primarily rib height) and the forgeability of the alloy. Table 3-2 gives preferred and minimum fillet and corner radii for a 25 mm (1.0 in.) rib height, which corresponds to Part 2 in Figure 3-13.

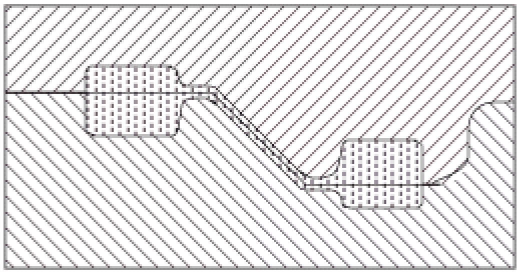


Figure 3-10 The forging as oriented generates a side thrust in the die requiring the counterlock to prevent lateral shift of the die. The counterlock is subject to wear from the side loads.

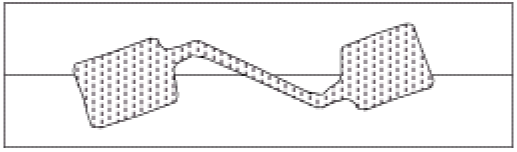


Figure 3-11 The forging can be rotated in the die to balance the lateral loads and eliminate the counterlock. However, the holes in the bosses cannot be forged, and must be fully machined.

5. Draft angles should be the maximum allowable, consistent with functional, assembly and weight constraints. For ferrous forgings, draft angles less than 5° usually prohibit the use of hammers. Dies installed in presses are usually equipped with knock-out pins to eject the forging from the cavity, and can produce forgings with little or no draft.
6. As a general rule, less draft is required on the outside of a feature than on the inside. (See Figure 3-14)

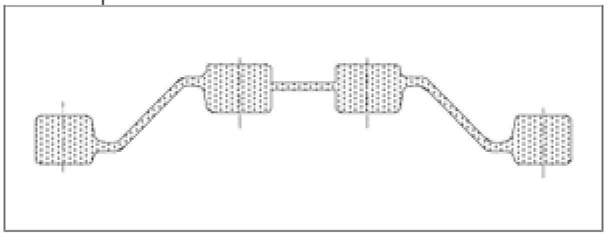


Figure 3-12 Where production quantities justify two sets of impression dies, the forgings can be oriented opposite to balance the side loads. This arrangement permits the holes in the bosses to be forged to reduce the amount of machining required.

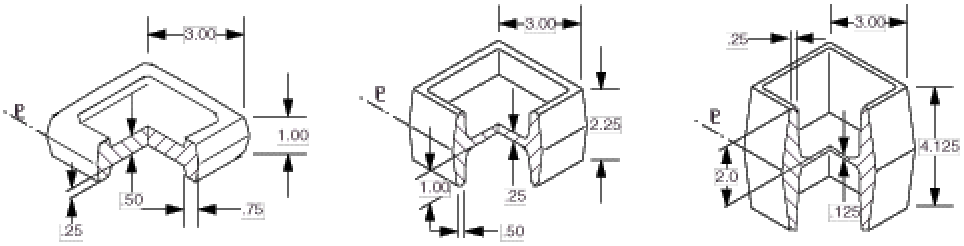


Figure 3-13 This figure represent shapes that are progressively more difficult to forge.

7. Component features that are held to close tolerances should be formed in the same die member to avoid additional cross-die tolerance.

8. All datum targets and tooling points should be located on features made in the same die half, as illustrated in Figure 3-15. The upper die half is preferred since there is less contact between the die and the forging, and consequently less cooling.

9. See Appendix A Tolerances for Impression Die Forgings and Appendix D Specialized Tolerances for Precision Aluminum Forgings.

Table 3-2

Representative Fillet and Corner Radii for Forgings with 25 mm (1.0 in.) High Ribs

Alloy	**Fillet Radius mm (in.)**		**Corner Radius mm (in.)**	
	Preferred	**Minimum**	**Preferred**	**Minimum**
Carbon Steels	10-13 (0.375-0.50)	6 (0.125)	3 (0.19)	1.5 (0.06)
Stainless Steels	6-13 (0.250-0.50)	5 (0.19	5 (0.19)	2.5 (0.09)
Titanium Alloys	13-16 (0.5-0.62)	10 (0.38)	6 (0.25)	3 (0.12)
Iron Base Heat Resistant Alloys	13-19 (0.5-0.75)	6-10 (0.25-0.38)	6 (0.25)	3 (0.12)

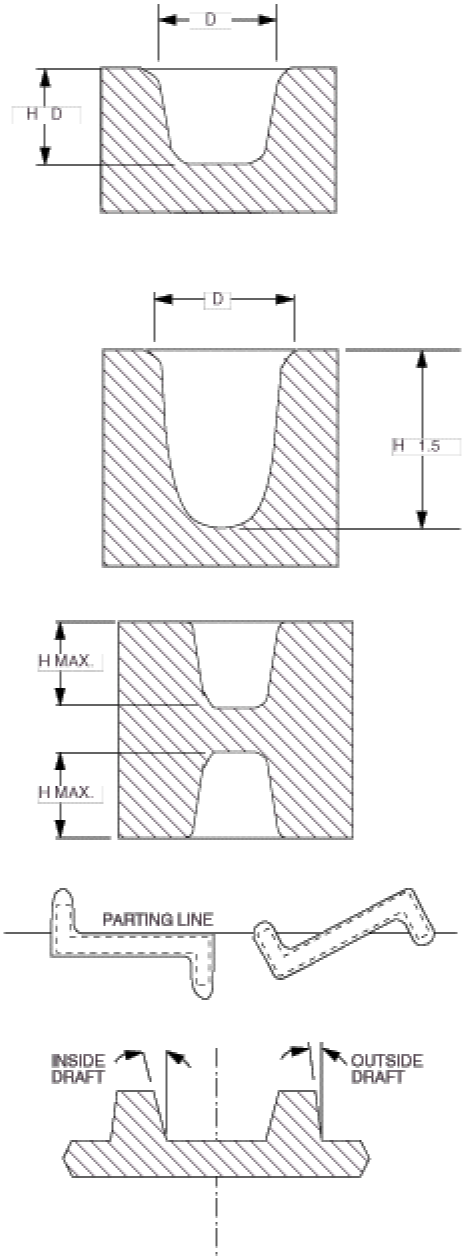


Figure 3-14 As a general rule, less draft is required on the outside of a feature than on the inside.

3.5.4.2 Design Rules For Parts Made From Upset Forgings

1. Parts that are symmetrical about an axis are the most economical for upset forging.
2. Upsetting generally increases the diameter of the beginning stock. Therefore, the stock size will generally correspond to the smallest as-forged diameter. This is the case for the flanged member shown in Figure 3-16. However, there are cases in which a nose can be extruded to achieve a smaller diameter.

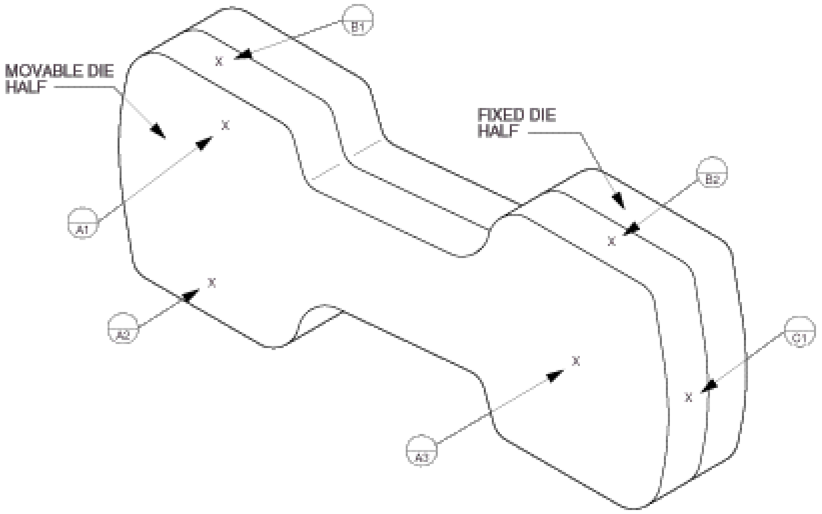
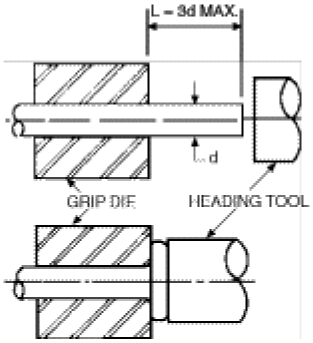


Figure 3-15 Design so that all datum targets and tooling points are in the same die member, preferably the moving member.

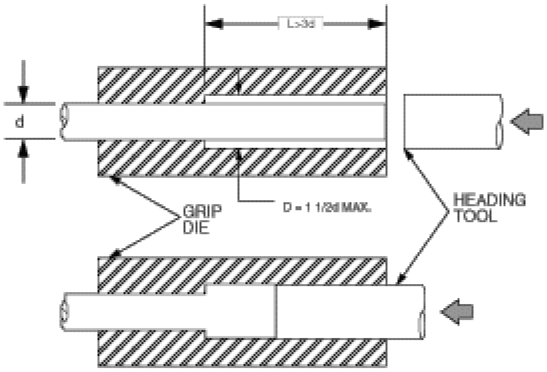
Figure 3-16 The flanged shaft was an ideal candidate for upsetting from bar stock.

3. There are limits to the change in shape that can be achieved in one stroke of an upsetter. There are three rules, which are based on geometric proportions:

Rule 1: The limit of length of unsupported stock that can be gathered in one upset blow without excessive buckling is not more than three times the diameter of the bar as shown in Figure 3-17.



Rule 2: When the length of unsupported bar stock is more than three times its diameter, the bar can be upset in one blow provided that the diameter of the upset is not more than one and one-half times the diameter of the stock as shown in Figure 3-18.



Rule 3: Where the length of unsupported bar stock is more than three times its diameter, and the diameter of the upset is not more than one and one-half times the diameter of the stock, the bar can be upset in one blow provided the amount of unsupported stock beyond the face of the die is not greater than one and one-half times the diameter of the stock, as shown in 4. Upset forgings with very large ratios of maximum to minimum diameter, or with massive features that require gathering sections of bar stock that are long compared with the diameter, will require several forging operations to gather the metal and form it to the desired shape while preventing defects.

Figure 3-19 Rule 3

4. Upset forgings with very large ratios of maximum to minimum diameter, or with massive features that require gathering sections of bar stock that are long compared with the diameter, will require several forging operations to gather the metal and form it to the desired shape while preventing defects.
5. Upset dies are essentially three-piece impression dies. Therefore, maximum radii should be used wherever possible to minimize forging pressure and promote die fill.
6. See Appendix B Tolerances for Hot Upset Forgings.

3.5.4.3 Design Rules for Parts Made From Open Die Forgings

1. Where material properties are critical, it is important to specify the required properties in all directions. This includes tensile strength, yield strength, ductility and impact toughness. The open die forger will design the forging process to develop grain flow that will optimize the properties. Otherwise the forging will be designed so that the grain flow follows the final contour of the forging.

2. In view of the end use of the product, specify the nondestructive testing methods to be employed and acceptable methods for employing them.

3. Open die forging can be employed for a wide range of shapes. For example, non-symmetrical shapes may be forged. Hollow shells can be forged by combinations of operations such as cogging, upsetting trepanning and punching, then mandrel forging. The ball valve housing shown in Figure 3-20 illustrates the shape capability achievable by open die forging.

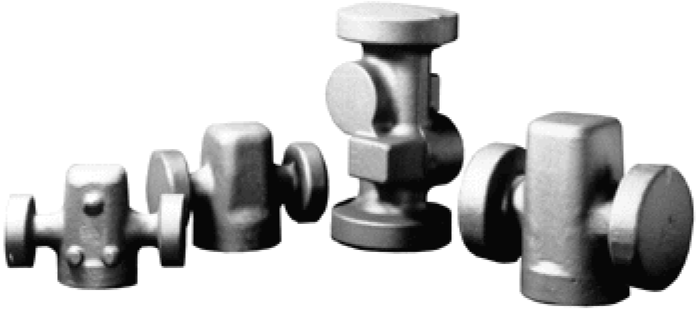


Figure 3-20 This ball valve housing illustrates the shape capability of the open die forging process

4. Be sure to spell out where any prolongations for testing should be located.

3.5.4.4 Design Rules for Parts Made From Rolled Rings

1. To minimize stock allowances, indicate which surfaces may be left as forged.

2. Inside and outside contours are possible where required. See Section 5.2.3 for common contours.

3. Modern ring rolling mills are able to control one of the diameters (either the inside or the outside) more closely than the other. Therefore, indicate the chucking diameter for the first machining operation so that the supplier may produce rings with better consistency in the specified dimension, saving machining setup time.

4. Always specify finish machined dimensions; finish allowances may vary among ring rollers based on individual capabilities. (See Figure 3-21)

5. Supply the drawing, even when purchased quantities are low. Sometimes existing tooling and geometry will fit the requirements.

6. Specify the type and location of required identification, which will be stamped into the ring.

7. Avoid specifying close tolerances and fine surface finish on rough turned rings. Usually a ±1.6 mm (0.062 in.) tolerance and 6.3 micron (250 micro inch) finish are practical.

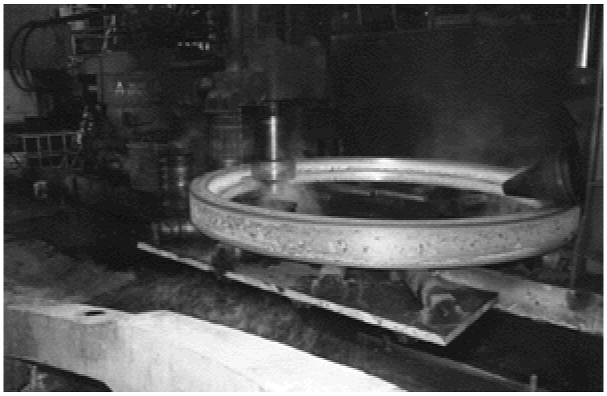


Figure 3-21 specify finish dimensions and allow the ring rolling source to determine the finish allowance.

8. For addition information see Appendix C Tolerances for Rolled Ring Forgings.

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.

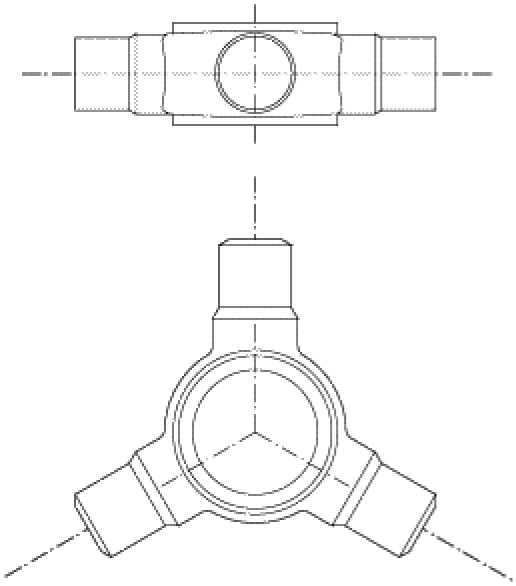


Figure 3-22 Net or near-net shapes, such as tripot inner races or universal joint crosses, can be manufactured using cold or warm lateral extrusions.

- 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.)

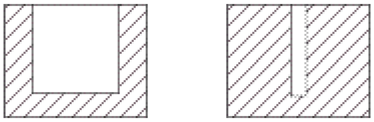


Figure 3-23 The hole on the left can be forged; the one on the right will require a drilling operation.

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.

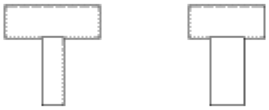


Figure 3-24 Minimize diameter ratios.

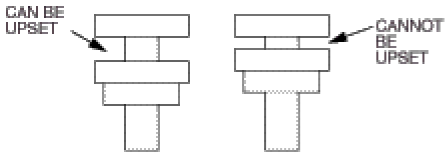


Figure 3-25 Undercuts can be forged in some cases if they are wide compared with the diameter of the feature.

14. Avoid sharp corners: use fillets and radii.

3.6 Predicting, Developing and Maintaining Properties in Forgings

The properties of products made from forgings generally fall into two categories: physical and mechanical. To the extent that these properties can be predicted in advance, the product design engineer can readily optimize the design with conventional design technology. Where the properties depend to some extent on processing variables, the input of the entire concurrent engineering team is required.

3.6.1 Physical Properties

The physical properties of a forging that are most often of interest in product design are:

- Density
- Electrical conductivity (resistivity)
- Thermal conductivity
- Specific heat
- Coefficient of thermal expansion

Since forgings are fully dense, these properties are generally independent of process, and any variations are not usually significant. They are listed in standard reference sources, and can be used with reasonable confidence to predict real world performance.

3.6.2 Mechanical Properties

Mechanical properties for forging alloys, like physical properties, are listed in standard reference sources. In some cases they are not affected by subsequent manufacturing operations, and can be used with reasonable confidence to predict real world performance. In other cases, mechanical properties are altered by subsequent processes, in varying amounts and with varying degrees of predictability in the end product. Variations are caused by factors such as:

- Forging temperature
- Forging reduction (deformation) which, in turn, affects grain size
- Heat treatment.

In some cases an experienced forging engineer can predict properties, such as yield strength, in critical areas of the forging with reasonable accuracy. Predictability is enhanced by two characteristics of forgings.

1. Forgings are fully dense and not subjected to discontinuities, such as porosity in castings.
2. Forging alloys are homogeneous, and not subject to variations in composition, such as orientation of reinforcing fibers in composites.
3. The essential mechanical properties of forging alloys and the effect of processing are summarized in Table 3-3.

Table 3.3 Effects of Processing on Mechanical Properties

Property	A: Hot Forged Without Heat Treatment	B: Hot, Warm or Cold Forged and Heat Treated	C: Warm or Cold Forged Without Heat Treatment
Tensile Strength Yield Strength Hardness Elongation Reduction in Area Modulus of Elasticity Poisson's Ratio Impact Toughness Fracture Toughness Fatigue Strength	Subject to variations due to variations in cooling rates. No variation Will vary with variations in cooling rate and forging temperature. Can be enhanced by control of grain flow.	Varies within the forging with section size, heat treatment and material hardenability.. No variation. Affected by grain flow and controlled by heat treatment.	Warm forging, varies due to variations in cooling rate. No variation Cold forging, will vary with amount of grain flow. Warm forging, will vary with variations in cooling rate.

The variations in properties due to processing have various implications on design, depending on the critical requirements of the application. The implications are of special interest in the preliminary design stage when computerized engineering tools such as finite element analysis or modal analysis are used. Several classes of application are summarized in Table 3-4.

Table 3-4 Performance Predictability for Selected Design Criteria

Design Criteria	Critical Properties for Modeling	Forging Process and Heat Treatment
Deflection or vibration response at stress levels below yield strength	Density, modulus of elasticity and Poisson's Ratio	Performance is predictable for all groups, but yield strength may be difficult to predict for Groups A and C.
Static loads developing stresses below yield strength	Modulus of elasticity, Poisson's Ratio, yield strength	Minimum performance is predictable for Group A. Performance is usually better for groups B and C, but properties are more difficult to predict an may vary within the part.
Static loads developing stresses in the plastic deformation range below fracture	Modulus of elasticity, Poisson’s Ratio, yield strength and plastic stress-strain data.	

Fatigue caused by cyclic loading	Fatigue Strength	
Impact loads causing gross plastic deformation	Impact strength	Difficult to model regardless of forging process and heat treatment unless input loads can be predicted.

The mechanical properties of a forging are best optimized for each application when the product design engineer identifies to the forging engineer those areas of the product where performance is critical, and the properties required. The earlier this occurs in the design process, the better able is the forging engineer to tailor the design and process to achieve optimum performance.

In those cases where performance must be optimized beyond the capabilities of computer aided engineering with available material properties data, particularly where material must be minimized due to weight limitations or material cost, the concurrent engineering team may perform an iterative process of test-and alter by:

- Designing and evaluating the product as closely as possible, with maximum anticipated values for properties, using computer aided engineering techniques
- Producing sample forgings and finishing as required
- Evaluating by test
- Modifying the design and re-testing as necessary

In this type of development program, the fewer the number of iterations, the lower the cost and the shorter the development cycle. It is critical to remember that products made from forgings are formed in hard dies, which are the negative of the finished product. Material is added to the product by removing metal from the die, and removed from the product by adding material to the die. It is therefore more practical to add material to the product than remove it.

The recommended practice, when close optimization is required, is to underdesign slightly on the initial design, and subsequently add metal to critical sections. The alternative, to overdesign and subsequently remove metal from the part requires adding metal to or resinking the die, and should be discouraged.

3.6.3 Developing and Maintaining Product Performance

When the required structural performance has been achieved in pre-production samples, the next concern is the potential variation in product performance over the production life of the product. Any such variation can be maintained within acceptable limits by:

- Evaluating the selected forging alloy for its response to the anticipated processes

- Maintaining close control over manufacturing processes, such as preheat temperature and atmosphere and cooling rates (where hot or warm forging are employed); preforming, forging and trimming operations; and heat treating (where it is employed)
- Establishing test procedures for periodically evaluating the properties or performance of the forgings

The first two factors underscore the need for careful selection of the material, and working with a forger who has the capability of producing the forgings with the required repeatability. It is axiomatic, if the materials and processes are maintained within the proper limits, the properties of the forging will be consistent.

When it is desirable or necessary to verify mechanical properties, standard inspection methods are available. Some of the most commonly employed test methods are briefly described below. A more detailed discussion, including references to relevant ASTM specifications, is available in FIA publications.

1. Chemical Analysis Control of the chemical composition of the forging stock is essential to attaining consistent properties in the forging. The supplier of forging stock routinely furnishes certified reports of the chemical analysis of the melt from which the material was produced. The analysis is verified by the forge plant either by comparative methods or analysis.

2. Hardness Testing is widely used for steel forgings for several reasons.
    - The procedure, including sample preparation, is simple
    - Hardness correlates closely with tensile strength
    - It is nondestructive
    - Portable equipment is available for forgings that are too large to test with stationary equipment

3. Tensile Tests are used to establish:
    - ultimate strength
    - yield strength
    - ductility

They are performed on specimens taken from the forging according to guidelines, mutually agreed between the forger and purchaser, for location and orientation, and usually constitute destructive testing. In some cases, particularly for open die forging and ring rolling, specimens may be taken from a prolongation, which is an area of the forging at an agreed location that is used for test, and is not part of the finished part. When prolongations are used, the tensile test is nondestructive.

4. Notched-Bar Impact Tests are also performed on specimens taken from the forging. The tests are dynamic, and are used to define:
    - impact strength

- notch toughness
- fracture mode (brittle, ductile or combination)

5. Fracture Toughness Testing measures the resistance of a given material in a given condition to catastrophic failure in the presence of a pre-existing crack.

6. Bend Tests are performed on samples taken from the forging to test for ductility by bending the specimen through a specified angle to a specified inside radius of curvature. The criterion for failure is whether cracks form on the tension surface after bending.

7. Ultrasonic Testing is one of the most reliable and widely used methods of nondestructive testing for steel forgings. It provides a means for evaluating the internal quality of forgings using a portable instrument. The process yields information on the size, location and orientation of discontinuities.

8. Eddy Current Testing is a non-destructive test method for detecting surface imperfections in bar and rod stock, cold forgings and fully cooled warm and hot forgings. It can be used for 100% automatic production testing.

9. Magnetic Particle Testing is one of the easiest nondestructive methods for detecting surface and near-surface discontinuities in ferro-magnetic materials.

10. Liquid Penetrant Testing is used to detect discontinuities that are open to the surface. For ferrous parts a permeable red dye is used with a white developer. For non-ferrous parts, a fluorescent die penetrant is most commonly used, viewed under black light. Any discontinuities are outlined and are readily detected.

11. Metallography is the technique of microscopic examination of polished or etched sections of metal specimens. It is employed to evaluate:

- micro cleanliness
- grain size
- microstructure

3.7 Specifying Heat Treating

Heat treating is a sequence of heating and cooling operations applied to a metal to alter the properties. Metals in all of the alloy groups can be heat treated to at least some extent.

3.7.1 Heat Treating Steel

Most heat treatments for steel can be categorized as either annealing or hardening. Both terms encompass a wide range of variations in procedures and end results.

3.7.1.1 Annealing Processes for Steel

Five basic annealing processes for steel are shown in Table 3-5.

Table 3-5 Basic Annealing Processes for Carbon and Alloy Steels

Material	Purpose	Process	Comments
0.30% to 0.60% Carbon	Facilitate machining	Full anneal: heat to 28 to 56˚C (50 to 100˚F) above the upper critical limit and cool slowly at a predetermined rate.	Long cycle time, sometimes many hours.
Up to 0.25% Carbon	Facilitate cold working	Process anneal (sub-critical annealing or stress-relief annealing): heat to a point just below the lower critical point, hold for a prescribed time and cool.	
0.69% or higher Carbon	Facilitate cold working or machining	Spheroidizing: heat to just below the critical point or to just above and slow cool (5.5˚C or 10˚F per hour) through the critical point.	
All		Normalizing:[1] heat to 55 to 85˚C (100 to 150˚F) above the upper critical point and slow cool.	Ensures homogeneous austenitic grain size on reheating for hardening, and improves toughness.
Thin sections or small parts		Isothermal annealing (cycle annealing): heat to above the upper critical point, cool rapidly to predetermined level, hold, then cool to room temperature.	Rapid cycle.

[1] Normalizing is often specified for parts that will be hardened and tempered. This annealing process refines the grain size and improves metal toughness.

3.7.1.2 Hardening Treatments for Steel

Hardening treatments can grouped into three categories, as shown in Table 3-6.

Table 3-6 Hardening Treatments for Steels

Purpose	Process	Process
Increase hardness throughout	Through hardening forging	Heat to the austenitic phase and quench the entire forging
Harden surface only	Localized induction hardening	Control heat so that only the surface is made austenitic and quench
Harden surface only	Case hardening	Spheroidizing: heat to just below the critical point or to just above and slow cool (5.5˚C or 10˚F per hour) through the critical point.

Following are brief descriptions of six commonly employed heat treatment processes for carbon and alloy steels. A qualified heat treatment source should be consulted to identify the appropriate optimum heat treatment process for each application.

- Quenching and Tempering: quenching in a suitable medium from an austenitizing temperature, typically 845 to 925°C (1550 to 1700°F), and reheating to achieve desired hardness. Carburizing: adding carbon to the surface of steel, in a controlled atmosphere furnace, to increase the ultimate hardness, typically to a depth of 0.5 to 1.0 mm (0.020 to 0.040 in.). The process is followed by quenching and tempering.

- Nitriding: adding nitrogen in a controlled atmosphere furnace to form nitrides in the steel, which develops very high hardness and superior wear resistance. The case depth is normally several hundredths of a millimeter (a few thousandths of an inch) thick. The process is followed by quenching and sometimes tempering.
  Carbonitriding: adding both carbon and nitrogen in a controlled atmosphere furnace to optimize properties, to a depth similar to carburizing. The process is followed by quenching and tempering.
- Austenitizing: Heating to an austenitizing temperature and cooling under controlled conditions to develop a combination of ductility and hardness with maximum impact toughness. Generally applied to fairly high alloy steels.
  Marquenching: Heating to an austenitizing temperature and quenching in molten salt. The process results in minimum transformation stress, and is applied only to fairly high alloy steels. The process is followed by tempering.

3.7.2 Heat Treating Stainless Steels

Stainless steels may be divided into four groups to distinguish their response to heat treatments. The ferritic, austenitic and martensitic grades are described in Section 4.2. The precipitation hardening grades, designated with a PH suffix (e.g.15-5 PH) constitute a group which, unlike the other three, achieves both high strength and corrosion resistance. Following is a brief overview of the heat treatment capabilities of the four groups.

Ferritic Stainless Steels — Ferritic stainless steels are not hardened by quenching. The only heat treatment applied to ferritics is annealing because they develop minimum hardness and maximum ductility, impact toughness and corrosion resistance in the annealed and quenched condition. Annealing also relieves stresses developed during welding or cold working and provides a more homogeneous microstructure.

Austenitic Stainless Steels — Conventional austenitic stainless steels will work harden with cold working, but cannot be hardened by heat treatment. Annealing is employed to optimize corrosion resistance, softness and ductility; consequently post-annealing may be specified after welding or thermal processing. This group is usually purchased in the annealed or cold worked condition.

Martensitic Stainless Steels — The maximum hardness achievable in martensitic stainless steels depend primarily on their carbon content. Therefore heat treating this group is essentially the same as for plain carbon or low alloy steels, but process parameters are different because the higher alloy content of the group makes them respond more sluggishly. They exhibit excellent hardenability so that maximum hardness is achieved in the center of sections up to 30 mm (12 in.) thick by air cooling. There are two principal types of heat treatment.

1. Annealing reduces hardness and increases ductility. Full annealing is expensive and time consuming, and should be specified only when required for severe forming.
2. Austenitizing, quenching and tempering are employed to increase strength and hardness. These processes also affect corrosion resistance, sometimes requiring balancing of the heat treatment parameters to optimize product strength and corrosion resistance requirements.

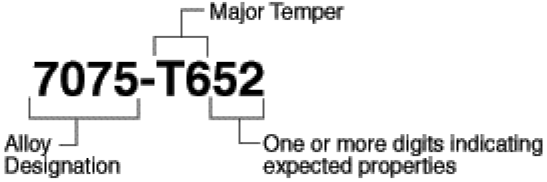
Precipitation Hardening (PH) Stainless Steels — The most commonly forged grades of PH stainless steels are 15-5 PH and 17-7 PH. These grades combine the high corrosion resistance of austenitic grades with the strengths achievable in martensitic grades. Procedures are available for homogenization, austenite conditioning, transformation cooling and precipitation hardening (age-tempering) these grades.

Duplex Stainless Steels — The typical forging grades contain a mixture of austenite and ferrite in their microstructures. They are generally not heat treated other than annealing.

3.7.3 Heat Treating Aluminum Alloys

Aluminum alloys are heat treated for the same purpose as steel: to relieve stresses, improve mechanical properties or facilitate cold working or machining. The processes generally produce nearly uniform properties throughout the forging, and are not used for localized effects such as surface hardening.

The system for designating heat treatment for forgings is the standard temper designation system for cast and wrought alloys. The designation is an alpha-numeric sequence, which follows the alloy designation and is separated from it by a hyphen. For example:



Where necessary, additional digits are used to designate variations in treatment conditions within the major subdivisions. Table 3-7 gives an overview of tempering treatments for aluminum alloys.

Table 3-7 Overview of Temper Designations for Aluminum Alloys

	Designation	Comments

Condition		
No special control over thermal conditions or strain hardening	F: As Fabricated	No property limits for forgings.
Lowest strength temper.	O: Annealed	May be followed by a digit other than zero.
Strengthened by strain hardening, with or without supplementary thermal treatment to produce some strength reduction.	H: Strain Hardened	Always followed by two or more digits.
Unstable temper applicable only to alloys whose strengths change spontaneously at room temperature over time.	W: Solution Heat Treated	Always followed by one or more digits, e.g. T4...solution treated T6...aged
Applicable to alloys whose strength is stable within a few weeks of solution heat treatment.		

3.7.4 Heat Treating Titanium Alloys

Titanium alloys are heat treated to achieve the following:

- Stress relieving, to reduce residual stresses developed during fabrication.
- Annealing, to achieve an optimum combination of ductility, machinability, dimensional stability and structural stability.
- Solution treating and aging, to increase strength.
- Combinations of processes are employed to optimize properties and gain other advantages such as:
    - Fracture toughness
    - Fatigue strength
    - High temperature creep strength
    - Resistance to preferential chemical attack
    - Prevent distortion
    - Condition the forging for subsequent forming and fabricating operations.

There are three principal types of heat treatment.

1. Stress Relieving Titanium alloys can be stress relieved without adversely affecting strength or ductility. The process for forgings takes place at 595 to 705°C (1100 to 1300°F) for a period of one to two hours, followed by air cooling. It decrease undesirable residual stresses that may result during forging processes.
2. Annealing Mill annealing, which is usually applied to forging bar stock, is not a full anneal, and may leave traces of cold or warm working in some products. Duplex and triplex annealing are used to improve creep resistance and fracture toughness.
3. Solution Treatment and Aging This process consists of heating to a specified temperature for the alloy, quenching at a controlled rate in either oil, air or water, and aging. Aging consists of reheating to a temperature between 425 and 650°C (800 to 1200°F) for approximately two hours. This process develops higher strengths than are achievable by the other processes.

3.7.5 Heat Treating Heat Resistant Alloys

Three types of heat resistant alloy groups are commonly forged and heat treated:

- iron based
- nickel based
- cobalt based.

Heat Treating Iron Based Heat Resistant Alloys Iron base heat resistant alloys can be heat treated by one of three principal types, depending on chemical composition, fabrication requirements and anticipated service.

1. Annealing is performed at temperatures between 705 and 980°C (1300 and 1800°F) to soften and stress relieve a work hardened forging.
2. Solution Treating is normally applied to age-hardenable alloys before the aging treatment to put age-hardening constituents and carbides into solid solution.
3. Age Hardening, or precipitation hardening, is performed at temperatures of 425 to 700°C (800 to 1300°F) to develop maximum design strength, sometimes at two different ageing temperatures.

Heat Treating Nickel Based Heat Resistant Alloys Nickel alloys can be heat treated by one of six principal process types, depending on chemical composition, fabrication requirements and anticipated service. Selection of the optimum heat treatment depends on the desired objective and the capability of the alloy to respond.

1. Annealing is used to produce a recrystallized grain structure and soften work-hardened alloys. It usually requires temperatures between 705 and 1205°C (1300 and 2200°F), depending on alloy composition and degree of work hardening.
2. Solution annealing is a high-temperature anneal, performed at temperatures between 1150 and 1315°C (2100 and 2400°F) of certain nickel alloys to put carbides into solid solution and produce a coarse grain size for enhanced stress-rupture properties.
3. Stress relieving is used to remove or reduce stresses in work-hardened, non-age-hardenable alloys without producing a recrystallized grain structure. It is performed at temperatures between 425 and 870°C (800 and 1600°F) depending on alloy composition and the degree of work hardening.
4. Stress equalizing is a low temperature heat treatment used to balance stresses in cold-worked forgings without an appreciable decrease in the mechanical properties produced by cold working.
5. Solution treating is a high-temperature heat treatment used to put age-hardening constituents into solid solution. It is normally applied to age-hardenable materials before the aging treatment.
6. Age hardening, or precipitation hardening, is a heat treatment performed at intermediate temperatures of 425 to 870°C (800 to 1600°F) on certain alloys to develop maximum strength by precipitation of a dispersed phase throughout the matrix.

Heat Treating Cobalt Based Heat Resistant Alloys Cobalt based alloys are generally supplied in the solution (annealed) condition only. They are generally not hardenable by aging. Solutioning after forging minimizes residual stresses. Strength and hardness can be increased only by working at typical forging temperatures.

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 3-8 Prototyping Processes for Impression Die Forgings

Purpose	Process	Remarks
1. Visual appearance evaluation; clearance, installation and removal studies (mockups).	Nearly any method that produces the required shape, such as hogouts, stereolithography, wood or foam.	Mechanical and physical properties are not important to the evaluation.
2. Approximate the performance of the end product.	A. Hogout made from a similar material and heat treated as required.	Static properties can be closely approximated; dynamic properties may be difficult to approximate.
	B. Open die forged and finish machined.	Very low tooling cost, good approximation of static

		properties, better approximation of dynamic properties than hogouts.
	C. Blocker die forging finish machined as necessary.	Somewhat higher tooling cost, better approximation of static and dynamic properties than open die forging.
3. Certify product performance.	Forge in production tools and finish.	Flash may be removed by hand to negate trim dies.

Characteristics of Forging Alloys

The material specification on a product drawing occupies a very small part of the total space. However it is a very important part of the specification, in some cases as important as the dimensioned views.

The product designer has a wide variety of alloys from which to choose. Most forging grades of ferrous or non-ferrous alloys are selected based on their inherent property levels as bar or billet materials, usually after heat treatments are performed. The forging process tends to improve some of the mechanical properties, such as impact toughness, fatigue strength, and tensile ductility, which are dependant on the grainflow patterns developed during forging. For example:

- Forgings are usually selected for applications requiring high ductility, impact toughness, fracture toughness and fatigue strength; therefore, forging alloys with inherently high ductility and tensile strength are generally selected.
- Alloys that cannot withstand very high rates of deformation are restricted to slower speed presses, and can not be forged readily on equipment such as hammers and high-speed presses.
- Alloys selected for cold forging must be able to undergo the required deformations at room temperature without excessive work hardening.

Another factor in alloy selection is the ability of the alloy to be forged; that is its forgeability. Some alloys are relatively easy to forge and may be used to make components with very intricate features. Grades that are more difficult to forge require distinct design approaches. The effects of differences in forgeability on design are described in this and other sections. Individual forging firms are in the best position to describe how such designs are affected.

The majority of forging alloys are in one of seven primary alloy groups:

- Carbon, microalloy and alloy steels
- Stainless steels
- Aluminum
- Copper
- Iron, nickel, or cobalt based heat resistant alloys

- Titanium
- Magnesium

Some refractory alloys such as tungsten, molybdenum, tantalum and columbium (niobium), and some light reactive alloys such as zirconium, beryllium, hafnium have been forged on a limited basis. These materials are considered outside the scope of this design guide.

4.1 Carbon, Microalloy and Alloy Steels

There are hundreds of steels that range in carbon content from approximately 0.06% to 1.5%. Many contain metallic alloying elements, such as manganese, chromium and molybdenum, ranging from trace amounts to approximately 9%. Virtually all can be readily forged. There are three groups within the general classification of "steels": carbon steels, microalloyed (MA) steels and alloy steels. Stainless steels have distinctly different properties, and are generally recognized as a separate group. Forging grades use the AISI or SAE grade designation systems. Tool steels also fit into the alloy steel family.

4.1.1 Carbon Steels

Carbon steels are most often specified. The broad range of grades gives the designer wide latitude in selecting one with the optimum combination of mechanical properties, forgeability and minimum cost.

By definition, carbon steel is iron combined with carbon varying from 0.06% to 1.5%. Carbon steels may also contain maximum amounts of manganese of 1.65% and/or silicon of 0.60%. The more common grades are between 1006 and 1095 with nominal 0.06% to 0.95% carbon respectively. There are some maximum limits to the residual elements, typically less than a total 0.80% for such elements as Cr, Mo, V, Cu, and Ni.

Free-machining grades of carbon steels that contain sulphur (1100 series), lead (12Lxx series) or sulphur/phosphorous (1200 series) are not as readily forged as the carbon steel counterparts. The additions produce controlled amounts of inclusions in the steel that assist chip breakage during machining, but the inclusions can also cause the steel to crack during forging, particularly during hot or cold upsetting.

4.1.2 Microalloy (MA) Steels

The new microalloy steels are becoming increasingly recognized as offering both cost savings and high performance for use in hot forged products. They find wide application in automotive, off-highway and similar original equipment industries. The yield strengths exhibited with these materials range from 415 to 825 Mpa (60,000 to 120,000 psi) without heat treatment. These strength capabilities make MA steels an economical alternative to quenched-and-tempered alloy steels.

MA steels provide for uniform hardness across cross sections up to 100 mm (4 in.) thick. Cost savings with MA steel forgings are realized through the elimination of heat treatments such as quench and temper (Q&T), when a straightening heat treatment is required. However, some processes require the use of special equipment such as cooling fans, water spray cabinets and conveyors, which can add to manufacturing costs. Therefore, theoretical cost reductions based purely on eliminated processes can be misleading.

The elimination of heat treating and often straightening operations facilitates just-in-time delivery schedules. One company reports shipping components in the afternoon that were forged in the morning.

The rapidly growing use of microalloy forging has been encouraged by recently developed microalloy grades and by the introduction of a comprehensive, new ASTM specification A-909 Standard Specification for Steel Forgings, Microalloy, for General Industrial Use. This specification includes compositions for achieving at least four (4) strength and hardness levels. It is intended to make it easier for designers to select the proper combination of steel composition, processing and properties for MA forgings.

MA steels and forgings have been in widespread use internationally. Nationally accepted specifications for microalloy steels and forgings, such as the new ASTM specification and other ASTM specifications for MA forging steels, will encourage the selection of microalloy forgings for safety critical parts as well as for more generic forgings.

Microalloy steels usually have carbon contents in the range of 0.15 to 0.55%, manganese in the range of 0.60 to 1.65%, silicon in the range of 0.15 to 0.65% and either small amounts of vanadium, columbium (niobium), titanium or nickel and molybdenum in various combinations. Vanadium, columbium and titanium form carbides and/or nitrides that remain in solid solution at most forging temperatures, but precipitate during the subsequent cooling at controlled rates. The precipitation phenomenon assists in enhancing the strength of these steels after forging and controlled cooling.

MA steels can be categorized into two types based on their microstructural characteristics. The first are of ferritic-pearlitic microstructure and the second are of a bainitic structure. Both the ferritic-pearlitic and bainitic MA steels exhibit good yield strengths while the bainitic MA steels generally show higher impact toughness.

4.1.3 Alloy Steels

Alloy steels have manganese or silicon contents at levels similar to those of carbon steels, and additions such as chromium, nickel, molybdenum or vanadium, or, less often, additions of boron, cobalt, columbium, titanium or tungsten.

Alloying elements are added for their effects on processing during manufacture and on performance during service. Alloying elements are used primarily to:

1. Improve selected mechanical properties, through control of the metallurgical structure. For example:
   - Increased hardenability by the addition of elements such as chromium, molybdenum vanadium or boron.
   - Increased impact toughness by the additions of elements such as manganese and nickel.
2. Improve retention of strength and ductility at relatively high service temperatures by the additions of chromium, nickel and cobalt.
3. Improve retention of mechanical properties, particularly ductility and impact toughness, at relatively low service temperatures by the additions of nickel and silicon.
4. Achieve increased resistance to atmospheric and chemical corrosion and elevated temperature oxidation by the additions of chromium and nickel.

Sulphur, which is often added to some bar steel grades for improving machinability, can adversely affect both the forgeability and the property performance of forgings, especially those heat treated to strengths above about 550 MPa (80,000 psi) tensile. If machinability is desirable in the forging steel, it is preferable to use "special order partially resulphurized" grades, with about half the sulphur content of normal resulphurized steels. Furthermore, some mills can use special sulphide shape controlled treatments, which include calcium, tellurium and some rare earth materials that tend to modify manganese sulphide inclusions to a more forgeable condition.

The standard alloy steel grades are found in the AISI and SAE 1300 through 9800 series. They are listed in many AISI publications and in the ASM and SAE Handbooks. Modifications of these types are also used in special applications. As a rule, these standard grades are specified when more strength, ductility and impact toughness are required than can be attained in carbon steels. They are also specified when specific properties such as wear resistance, corrosion resistance, heat resistance and special low temperature impact properties are required. Some alloy steels are formulated for special treatments such as carburizing or carbo-nitriding. Detailed discussions of steel grades is beyond the scope of this publication.

4.2 Stainless Steels

Stainless steels are usually defined as alloy steels containing at least 10% chromium, either alone or with other alloying elements. In the United States, steels with as low as 8% chromium are included in this classification. Stainless steels are specified when special properties, such as corrosion resistance and resistance to scaling are required. Some grades, such as Type 422, have strength and impact toughness up to 650°C (1200°F).

Stainless steels are considered more difficult to forge than carbon or alloy steels in that they require higher forging pressures at normal forging temperatures. Three groups within the general classification of stainless steel are of interest in forging: ferritic, austenitic and martensitic. There are many special grades of stainless steels not classified in any of these groups. For example, a whole series of forging alloys is included in what might be termed special stainless or heat resistant grades.

4.2.1 Ferritic Grades

Ferritic stainless steels are low carbon grades containing 10% to 30% chromium. Some grades additionally contain molybdenum, silicon, aluminum or titanium to develop special properties. The microstructures are basically ferrite with some scattering of finely distributed carbides. They exhibit excellent corrosion resistance and considerable ductility, can be worked hot or cold, and are relatively inexpensive. They cannot be hardened by heat treating, but strength can be increased moderately by cold working.

Ferritic stainless steels containing 16% to 18% chromium are generally the most useful alloys in this group. Chromium contents in the range of 15% to 30% are used to resist oxidizing at progressively higher elevated temperatures. Typical ferritic forging grades include:

SAE No.	**ASTM**	**Composition**
405	A-473	12%Cr, 0.2%Al
409	A-473	11%Cr, 0.5%Ti
429	A-473	15%Cr,
430	A-473	17%Cr
446	A-473	25%Cr

While most other ferritic stainless grades are forgeable, they are not considered common forging grades.

4.2.2 Austenitic Grades

Austenitic grades contain 8% to 18% of nickel in addition to typically 18% to 20% chromium. They cannot be hardened by heat treatment, but can be hardened by cold working, and excellent properties are developed in the grades with lower nickel content. This class is highly resistant to many acids, and alloys in this family exhibit excellent impact toughness at cryogenic temperatures, as low as liquid nitrogen (-200°C or -325°F). Alloys with higher (25%) chromium can be used at temperatures up to 1095°C (2000°F) without excessive scaling. Two types, 304L and 316L have carbon contents below 0.03%, and are specified where welding is required and postannealing is impractical.

Commonly used austenitic forging grades include:

SAE No	**AMS No**	Percent Composition						
		Cb	Cr	Mo	Ni	Ta	Ti	

302	A473[2]			18			8	
304	A473[2]			18			9	
310	5651			25			20	
316	5648			18	2.5		12	
321	5645			18			9	[1]
347	5653			18			10	[1]

[1] Indicates minor amounts, depending on carbon content

[2] ASTM specification

SAE standards list several other grades that have special purposes and, while not as commonly forged, are just as forgeable as these listed grades. 303 is not a common forging alloy because its sulphur causes problems.

4.2.3 Martensitic Grades

Martensitic stainless steels usually contain a maximum of 14% chromium, except types 440A and 440B, which contain 16% to 18% chromium. Carbon is added in sufficient amounts to promote hardening. Other elements, when present, are usually restricted to 2% or 3%. They exhibit excellent strength, and, unlike most other stainless grades, they are magnetic. Martensitic stainless steels are hardened and tempered using processes similar to those used for as alloy steels. Typical tempering temperatures range from 540 to 620°C (1000 to 1150°F).

Commonly used martensitic forging grades include:

SAE No	**AMS No**	**Percent Composition**					
		C	**Cr**	**Mo**	**Ni**	**S[1]**	**Si**
403	A473[2]	0.2	12				
410	5613	0.12	12				1
416	5610		13	0.6		0.15	
420	5621	0.2	13				
431	A473[2]	0.2	16		2		

440A	5631	0.7	17	0.7			
440C	5630	1.1	17	0.7			

[1] Sulphur reduces forgeability

[2] ASTM specification

SAE grades include several others that have special purposes and, while not commonly forged, are just as forgeable as these listed grades.

4.2.4 Special Stainless Grades

There are many special grades of stainless steels that are not classified exclusive to any one of the above three families. For example, there is a series of forging alloys that include grades such as 17-4PH, 15-5PH and PH13-8Mo, which are precipitation hardenable (PH) grades. These grades include Cr-Ni additions similar to the austenitic grades but with additions of copper, titanium, columbium and/or aluminum. These additions permit a solution treatment, followed by a suitable aging cycle, to promote a compound strengthening effect.

The alloys are usually "soft martensitic" in the annealed condition and are then transformed to a hard martensitic condition either by an aging cycle or by a sub-zero cooling cycle. Subsequent intermediate temperature treatments or aging cycles then produce the final properties. These alloys are typically capable of achieving tensile and yield strengths higher than the martensitic grades of stainless, yet exhibit resistance to corrosion similar to the 18-8 family of austenitic steels.

There are also a few special purpose stainless grades that are approximately twice as strong as the 304-type austenitic grades and are as corrosion resistant. These are called "duplex" stainless grades. The most common applications are nuclear components. They have higher chromium contents than the PH grades, similar nickel and lower carbon. Other elements are used to enhance strength. The resulting microstructure is a mixture of austenite and ferrite with very little carbide; hence the term "duplex". UNS designatons for the more common grades are S32550, S31803 and S32304.

Major alloy contents for some commonly forged special stainless grades are:

Alloy	**AMS**	**Percent Composition**

		AL	Cb	Cr	Cu	Mo	Ni
17-4PH	5643		0.3	17	4		4
17-7PH	A705[1]		0.3	15	3.5		5
15-7PH	A705[1]	1		15		3	7
15-5PH	5659	1		15	3		5
PH13-8Mo	5629	1		13		2	8
2205[2]	S31803[3]			22		3	5.5

[1] ASTM specification

[2] Also contains 0.2% N

[3] UNS specification (duplex-stainless)

There is a grade in this family called AM-355; it contains 16% Cr, 5% Ni, 3% Mo, and is heat treated with slightly different cycles from the PH grades. This grade has continued to be offered as a forging grade. SAE and AISI guides and UNS designations list several other grades that have special purposes and, while not commonly forged, are just as forgeable as these grades.

4.3 Aluminum Alloys

Of the various groups of alloys, the aluminum alloys are most readily forged into precise, intricate shapes. The five most significant reasons are:

- They are very ductile at normal forging temperatures
- They can be forged in steel dies that are heated to the same temperature as the workpiece
- They do not develop scale during heating
- They require low forging pressures
- They may be forged at high or low strain rates

Aluminum alloys are designated by the four-digit numerical system that is an industry standard for wrought alloys. The numbers are systematically assigned, but do not have any quantitative significance. The first digit indicates the major alloying element, and the last three distinguish the various alloys in the group. For example, the major alloying element in the 2xxx series is copper, in the 6xxx series magnesium and in the 7xxx series zinc.

The major factors influencing the forgeability of aluminum alloys are the solidus temperature and deformation rate. Most of the alloys are forged at approximately 55°C (100°F) below the corresponding solidus temperature.

Most aluminum alloys can be forged in any type of equipment that is used for other metals. However, some grades, such as the 7xxx series, are more deformation rate sensitive and tend to have reduced forgeability when deformation rates are high. Therefore these grades require special care when forged on hammers and high speed presses. Good, continuous lubrication is required because the alloys do not form scale and will seize, gall or cause pressure welding to the die steel if they come in direct contact with it.

Some grades of the 5xxx series may be used in the as-forged condition. All other alloys are generally strengthened slightly in the hot-working range, then subjected to solution heat treating, quenching (usually in water or water-based synthetic quenchants) and subsequently aging at temperatures between 120 and 175°C (250 and 350°F). The aging processes vary from the as-quenched condition to normal aging (T6), or to overaging (T7x), which is done to enhance the stress-corrosion and impact toughness properties with some loss of strength.

Another series of supplemental temper designations denotes when small compressive or tensile deformations are imparted to the forgings after solution treatment. In this case, the supplemental designations are often of a three digit variety (e.g. T-652, T-651). This practice, while adding operations, and hence cost, improves resistance to stress corrosion cracking while not reducing the strength of the forgings.

The strength properties of aluminum alloys are affected by alloy composition, forging process variables and the final heat treatment. Corrosion resistance is affected primarily by alloy composition and the final aging cycle. For example, the 2xxx series, with significant amounts of copper, are generally more prone to atmospheric corrosion, pitting, stress corrosion and galvanic reactions than are zinc-magnesium 7xxx alloys with very low levels of copper.

Aluminum forging alloys 2xxx and 7xxx are used extensively in aerospace applications and airframe structures, due to their favorable high fatigue strength and low density. The 2xxx and 6xxx grades are selected for automotive applications, with the 6xxx grades specified where superior resistance to corrosion is required.

Some of the most commonly forged aluminum alloys are:

Alloy	AMS	Major Alloys	Product Applications
2024-T6	4133	Al-Cu-Mn-Si	Mostly commercial, some aerospace
2219-T6	4243	Al-Cu-Mn	Mostly aerospace
6061-T6	4127	Al-Mg-Si	Mostly commercial
7049-T73	4320	Cu-Mg-Zn	Mostly commercial
7050-T74	4107	Al-Zn-Mg-Cu-Zr	Mostly aerospace
7050-T752	4333	Cu-Mg-Zn	Mostly aerospace
7075-T6	4126	Al-Zn-Mg-Cu-Cr	Mostly commercial, some aerospace
7075-T651-T652	4310	Al-Zn-Mg-Cu-Cr	Mostly aerospace
7075-T73	4141	Al-Zn-Mg-Cu-Cr	Mostly aerospace

Additional information about the remaining alloys in this category can be obtained from the Aluminum Association, 900 19th Street N.W., Washington, D.C., 20006.

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:

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

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.

4.5 Iron, Nickel and Cobalt Heat Resistant Alloys

Heat resistant alloys of iron, nickel and cobalt are used where high temperature performance, particularly creep resistance, is required. These alloys have been typically selected for gas turbine components such as blades, turbine wheels and latter stage compressor disks, which are subjected to long term rotational stresses and high temperatures. Increased understanding of the alloy systems has permitted the upgrading of forgings by mechanical and thermal treatment to satisfy requirements for high strength in applications other than creep resistance, such as low and high cycle fatigue and crack growth resistance.

Such alloys are designed to offer high strength at elevated temperatures. These characteristics, which are desirable in the end product, make forging very difficult. Furthermore, any additive that improves service temperature performance tends to decrease workability. Alloy cleanliness also has a significant effect on hot forgeability.

Alloy selection is generally directed at optimizing one or more of seven properties:

- Creep strength
- Tensile strength
- Low-cycle fatigue response
- High-cycle fatigue response
- Fracture toughness
- Creep rupture behavior
- Cyclic rupture (creep-fatigue interaction) behavior.

An example of a forged iron-based heat resistance alloy is A286 (AMS 5737). This and similar alloys are forged with practices similar in many respects to those used for 18-8 austenitic stainless grades. Because they are alloyed with reactive elements such as titanium, aluminum, boron, or columbium, they respond to solution and aging cycles similar to the specialty stainless grades.

Cobalt based forging alloys such as L605, Alloy 188 and N-155 continue to be used. S-816 alloys are still used for exhaust valves on gasoline and diesel engines.

The most widely forged true heat resistant alloys are Ni-Cr-Fe-based, such as alloys 718, 706 and 625. More highly alloyed Ni-Cr-Co based materials like Waspaloy, alloy 41 and alloy 500, which are very high strength and very difficult to forge, are less widely used. Forging process for heat resistant alloys are highly refined to control temperatures, strain rate, strain and alloy condition. These controls are necessary to achieve uniform critical properties, such as grain size, and other characteristics after heat treatment.

Some "super-superalloys" such as Rene 95, IN 100, Merl 76 and low-carbon Astroloy are best forged with a more complex process that includes the initial consolidation of compacted billets of powder, followed by sintering, canning, and then hot extrusion to develop the starting billets for forging. This P/M (powder metallurgy) route precedes the use of isothermal or hot die forging process to near-net shapes. These alloys contain less cobalt and more reactive metals like titanium, aluminum, columbium, or tungsten. They tend to form stable carbides that improve creep resistance at higher service temperatures.

Heat resistant alloy forgings and processes are often computer modeled using various commercial codes. Modeling reduces costly tryout and costly inputs, such as material and die preparations, prior to tooling and process development. This practice has led to some remarkable refinements in the forgings processes and quality improvements.

Typical forging grades and nominal compositions are:

IronBasedHeatResistantAlloy	
A286	AM5737
Nickel-IronBasedHeatResistantAlloy	
Alloy 901	AMS 5660
CobaltBasedHeatResistantAlloys	
L605	AMS 5758
188	AMS 5772
N-155	AMS 5769
NickelBasedHeatResistantAlloys	
Ni-600	AMS 5665
Ni-625	AMS 5666
Ni-706	AMS 570
Ni-718	AMS 5663
Ni-X750	AMS 5667
Waspaloy	AMS 5708

Alloy 41	AMS 5712

Following are nominal compositions for several heat resistant alloys.

AlloyDesignation	**PrincipalElement**	**Percentcomposition**								
		AL	**Cb**	**Co**	**Cr**	**Fe**	**Mo**	**Ni**	**Ti**	**W**
A286	Iron	0.2			15	54	1	26	2	
Stellite	Cobalt			Bal	30	3	1	23		4
L605	Cobalt			53	20			0		15
S-816	Cobalt			Bal.	20	3	4	20		
IN 901	Nickel	0.2	4		12	36	6	43	3	
Astroloy	Nickel	4		17	15		5	55	4	
IN 718	Nickel	1	5		19	18	3	52	3	
Rene 41	Nickel	2		11	19		1	55	3	
Rene 95	Nickel	4	4	8	14		3	61	3	4
Udimet 700	Nickel	4		17	15		5	55	3	
Waspaloy	Nickel	1		13	19		4	58	3	
MERL 76	Nickel	5		18	12		3	59	4	v

A comprehensive listing of these alloys and corresponding compositions is given in the ASM Metals Handbook. Forging suppliers should be contacted for their experiences in forging and heat treating these classes of heat resistant alloys.

4.6 Titanium Alloys

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.

The designation system indicates the type and amount of the major alloying constituents. For example Ti-6Al-4V contains 6% aluminum and 4% vanadium.

As with other forging alloys, the mechanical properties of titanium alloys are affected by forging and thermal processes as well as alloy content. However, when die filling is optimized, there is only a moderate change in tensile properties with grain direction, and comparable strengths and ductilities are obtainable in both thick and thin sections. The processing of titanium alloys through the forging and subsequent thermal processes is a highly developed technology.

Titanium alloys are more difficult to forge than most steels. The metallurgical behavior of the alloys imposes some limitations and controls on forging operations, and influences all of the steps in the manufacturing operation. Special care is exercised throughout all processing steps to minimize surface contamination by oxygen, carbon or nitrogen. These contaminants can severely impair ductility, impact toughness, and the overall quality of a titanium forging if left on the surfaces.

Hydrogen can also be absorbed by titanium alloys and can cause problems if levels exceed specified amounts. Hydrogen absorption, unlike that of oxygen, is not always confined to the surface.

Titanium alloys can be forged to precision tolerances. However, excessive die wear, the need for expensive tooling, and problems with microstructure control and contamination may make the cost of close tolerance (not machined) forging prohibitive except for simple shapes like compressor fan blades for turbo-fan engines.

Close tolerance forgings in moderately large sizes are currently being developed using hot die and isothermal forging techniques. Hot die and conventional forging of the Ti-10V-2Fe-3Al alloy, which has a relatively low forging temperature, has been demonstrated to be very successful with dies made from heat resistant alloys and heat treated to over 650°C (1200°F).

Glass coatings are commonly used to protect the titanium forgings from excessive oxidation and to provide some lubrication as well as serving as a release compound to prevent die galling (pressure welding).

There are three basic types of titanium forging alloys: alpha alloys, alpha-beta alloys, and beta alloys. The alpha alloys are designed for resistance to creep at elevated temperatures, exceeding 535°C (1000°F) in some cases. They are not heat treatable in the conventional sense but they are annealed after forging to relieve stresses. The microstructure of alpha is essentially all alpha phase.

The alpha-beta alloys are those that include a mixture of alpha and transformed beta microstructures at room temperatures. They are heat treatable to very high strengths with a solution treatment and an age cycle. The widely used Ti-6Al-4V alloy is also the most common forging alloy.

The beta alloys are those containing sufficient alloy content to retain the beta phase to room temperature. Alloys include the more common Ti-10V2Fe3Al as well as some more highly alloyed grades such as Ti-13V-11Cr-3Al. These alloys are treatable to high strengths exceeding those achievable with Ti-6Al-4V. Ti-13V-11Cr-3Al has been largely superseded by the 10-2-3 grade for forgings.

In all three groups, the forging practices have a profound influence on the resulting properties. Forging suppliers should be contacted for their experiences in forging and heat treating these families of titanium alloys. Commonly forged titanium alloys are:

UnalloyedGrades		
	ASTM Grade	ASTM-B-381
	ASTM Grade 2	ASTM-B-381
	ASTM Grade 3	ASTM-B-381
	ASTM Grade 4	ASTM-B-381
	ASTM Grade 7	ASTM-B-381
AlphaandNear-AlphaAlloys		
	Ti-5Al-2.5Sn	AMS 4966
	Ti-8Al-1Mo-1V	AMS 4973
	Ti-6Al-2Sn-4Zr-2Mo	AMS 4976
	Ti-5Al-3Sn-3Zr-1Nb	(IMI 829)
	Ti-5Al-4Sn-4Zr-1Nb	(IMI 834)
	Ti-6Al-3Sn-4Zr-0.5Si	(Ti-1100)
Alpha-BetaAlloys		
	Ti-6Al-4V	AMS 4928
	Ti-6Al-4V ELI	AMS 4930
	Ti-6Al-6V-2Sn	AMS 4971
	Ti-6Al-2Sn-4Zr-6Mo	AMS 4981
BetaandNear-BetaAlloys		

	Ti-10V2Fe3Al	AMS 4983
	Ti-5Al-2Sn-2Zr-4Mo-4Cr	(Ti-17)

The specifications listed are one of many such that might be applied to each grade. Details of properties obtainable from these and many other titanium alloys are presented in ASM Metals Handbook.

4.7 Magnesium Alloys

Magnesium alloys are best known for their low density, which results in forgings with very low weight. They are sometimes alternatives to aluminum when low weight is essential. Tensile and yield strengths are generally lower than for aluminum, particularly at elevated temperatures; material and processing costs are generally higher. The modulus of elasticity, 45 GPa (6.5 x 10^6 psi), is the lowest of the forging alloys. Both the density and modulus of elasticity are approximately two-thirds that of aluminum alloys, so that the specific stiffness is nearly equal.

The Magnesium grades most commonly forged are:

- AZ31B - 3% Al, 1% Zn
- AZ80A - 8% Al, <1% Z
- ZK60A - 6% Al, <1% Th (thorium)
- HM31A - 3% Th, 1% Al

The first three alloys are most commonly used mainly at room or slightly elevated temperatures; the HM31A is one of several designed for use at elevated temperatures.

Magnesium alloys require special handling procedures that are not required with other alloy groups.

4.8 Summary

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.

Manufacturing Processes

The term forging is applied to processes in which a piece of metal is worked in a machine to the desired shape by plastic deformation of the starting stock. The energy that promotes 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 deformation process.

A forging is produced in three distinct phases: stock preparation in the form of blooms, billets, bar or ingots; plastic deformation of the metal component to rough, close tolerance or net shape in one of the forging processes; and appropriate secondary operations.

5.1 Forging Machinery

There are several types of forging machines that may be used for the open die, impression die and cold forging processes. They vary in factors such as the rate at which energy is applied to the workpiece, and the capability to control the energy. Each type has distinct advantages and disadvantages, depending on the number of forgings to be produced, dimensional precision, and the alloy being forged.

5.1.1 Hammers

Hammers have been continuously used for both open die and impression die forging, and are generally considered the most flexible in the variety of forging operations they can perform. They are characterized by a heavy ram, which contains the upper die. The ram is raised and allowed to fall or is driven onto the workpiece, which is placed on the bottom die. A large, heavy anvil supports the structure and holds the lower or stationary die. Hammers apply energy and cause deformation at very high rates. They are therefore suitable for alloys that can be deformed rapidly without forming cracks and splits in the workpiece. Aluminum 7xxx alloys and most magnesium alloys are not forged in hammers for this reason.

Hammers are classified according to the way in which the ram is raised and whether it falls freely or is driven.

Board Hammers Board hammers, or board drop hammers, which gave rise to the term "drop forging", operate by gravity only. The ram is raised mechanically to a predetermined height, which cannot be varied between blows, but can be reset between jobs. Cycle rates are high, as many as seventy per minute, and the energy imparted to the workpiece is the same on each blow. The workpiece is typically struck several times in impression die forging.

Board hammers are rated by their falling weight. They range in size from 100 to 7500 pounds, but nearly all are between 500 and 6500 pounds. The anvil serves as an inertia block and usually weighs 20 times as much as the hammer.

Air-lift hammers Air-lift hammers are similar to board hammers except that the ram is raised by action of air cylinders. On some hammers, the height can be varied on each stroke, either by the operator or by pre-programmed blow control. Air-lift hammers range in size from 500 to 10,000 pounds falling weight. Many air operated hammers are conversions from steam hammers and operate with power down as well as power up operation.

Steam or Air-Powered Hammers Steam or air-powered hammers are similar to air-lift hammers except that the hammer is raised either by steam or air, and is powered down onto the workpiece by pressurized steam or air, adding controlled energy and speed beyond gravity. Striking force can be varied on each stroke over the entire range from a light tap to full power. The complete control of each work stroke places higher requirements on operator skills than for other types of hammer. In a growing number of cases, they are being controlled by programmable systems.

Steam and air hammers are the largest and most powerful of conventional forging hammers, and typically range in weight from 1000 to 50,000 pounds. Double-frame hammers for open die forging have been built to 220,000 pounds, but 24,000 pounds is the usual maximum size. Anvils weigh 10 to 25 times as much as the hammer ram, and require massive underground installations.

Impacters A modification of air-driven hammers is the impacter, where two rams of equal weight are propelled horizontally toward each other and impact in a central location. Impacters can be automated to forge several hundred parts per hour, and generally are not designed for manual operation as are vertical air-powered hammers.

Other Types Other types of hammers, such as vertical counterblow, helve, trip and impacters are used less extensively. Largest hammers are often counterblow machines where both top and bottom die move simultaneously. Information on various hammers is available in Forging Industry Association literature.

5.1.2 Presses

Forging presses are the second group of forging machines regularly used in impression die and large open die forging. They are commonly classified as mechanical or hydraulic, based on the means used to deliver energy. Presses deliver energy more slowly than do hammers. They are used for all alloy groups, and are used in preference to hammers for alloys that require slow deformation rates, such as 7xxx series aluminum alloys and most of the magnesium alloys. As with hammers, they usually operate vertically. The upper die is attached to the ram, and the downward stroke of the ram exerts force on the workpiece.

Mechanical Presses Mechanical presses typically store energy in a rotating flywheel, which is driven by an electric motor. The flywheel is engaged and disengaged to a mechanical drive such as a crankshaft, eccentric shaft, eccentric gear or knuckle levers, which convert flywheel rotation to vertical motion. The stroke is of set speed, length and duration. Mechanical presses therefore develop consistent forging results, offer high productivity and accuracy, and do not require as high a degree of operator skill as do other types of forging machines. In impression die forging, the workpiece is usually struck once in each impression. Mechanical presses are not suitable for open die forging, where the length of stroke must be varied between strokes.

The applied force is maximum at the bottom of the work stroke, and the estimated load at a position just above this point is the basis for press rating capacity. Ratings typically range from 100 to 10,000 tons. A few special design large capacity presses with ratings up to 16,000 tons are in operation.

Recent developments in mechanical presses are focusing on increased stiffness of the press structure to improve forging accuracy, automation, and high speed (in terms of die-to-workpiece contact time). They are increasingly replacing hammers because of greater environmental compatibility, ease of automation and lower operating costs.

Screw Presses Screw presses are not as widely used in North America as mechanical presses, but unique screw press characteristics are driving an increase in their use. As the name suggests, this type of press uses a mechanical screw to translate rotational motion into vertical. Briefly, the ram acts as the nut on a rotating screw shaft moving up or down depending on screw rotation. Energy is either delivered from a flywheel, which is usually coupled with a torque-limiting (slipping) clutch, or by a direct drive reversing electric motor. The main advantage of screw presses over offset or crank-type mechanical presses is in the final thickness control when the dies impact each other.

Hydraulic Presses Hydraulic presses are operated by large pistons driven by high-pressure hydraulic or hydro-pneumatic systems. They are slow moving compared with mechanical and screw presses, and squeeze rather than impact the workpiece. In operation, hydraulic pressure is applied to the top of the piston, moving the ram downward. When the stroke is complete, pressure is applied to the opposite side of the piston to raise the ram.

Speeds and pressures can be closely controlled. In many presses, circuits provide for a compensation control or sequential control, e.g. rapid advance, followed by sequences with two or more pressing speeds. The press can also be regulated to dwell at the bottom of the stroke for a predetermined time, raised at a slow release speed, and accelerated until it reaches original position. When needed, hydraulic press speed can be increased considerably. In many cases, hydraulic presses used for open and some closed die forging presses use microprocessors or computers to control the press operation, for parameters such as ram speeds and positions.

Hydraulic forging presses are rated according to the maximum force they develop. Presses in use in North America for impression die forging currently range up to 50,000 tons; presses of 72,000 tons and 82,000 tons are in operation in France and Russia. Presses used for open die forging range from 200 tons to 10,000 tons.

Forging Machines (Upsetters) Forging machines are also called upsetters. They were originally developed to upset metal for bolt heads and similar shapes, and are sometimes referred to as "headers". They are currently used to gather or upset (laterally displace) material, either at the end of the feedstock, between the ends, or in several places. They may be used to gather metal prior to forging operations on other equipment, or to produce complex, finished configurations with precision such as gear blanks, bearing races and spindles.

Forging machines are basically double-acting mechanical presses operating in a horizontal plane. They employ a flywheel, air clutch and eccentric shaft to operate the slide (or heading ram). In operation, bar stock, either heated or room temperature, is placed against the stationary die. The grip die moves laterally against the stationary die, gripping the stock tightly. The heading die with its attached heading tool (die) then moves forward against the end of the workpiece and displaces stock into the die impressions. As the ram recedes, the grip die retracts and releases the workpiece, which is ready for subsequent forging operations. In some cases, the forging is punched or sheared off of the bar stock in the final step.

Forging machines are rated for size according to the maximum bar size for which they can provide an upset head. For example, a two-inch upsetter could theoretically head bolts or form features in sizes up to two inches stem diameter.

When a large volume of products are to be produced, such as automotive and bearing manufacturing, automatic, multiple-stage hot forging machines are increasingly being used. These machines are based on a combination of features familiar to cold headers and hot nut formers, and operate at very high production rates approaching 160 parts per minute. They can produce products with complex configurations at high production rates.

5.2 Forging Processes

There is a wide variety of processes that can be classified as forging under the definition at the beginning of this section. Five will be addressed here: open die, impression die, ring rolling, cold forging and warm forging. Cold forging is performed at or near room temperature, and the workpiece work hardens (increases in strength with increasing deformation). The other processes are performed at elevated temperatures, and the workpiece does not work harden significantly.

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 show 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 show 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 Trepanning 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. Trepanning 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.

5.2.2 The Impression Die Process

Impression die forgings range in size from a few ounces to over 10,000 pounds, and vary in length from a fraction of an inch to over twenty-six feet. The process accounts for the vast majority of all commercial forging production. Impression die forging is sometimes called "closed die forging". However, although the terms are sometimes used interchangeably, this design guideline identifies closed die forging as a special form of impression die forging described below under the heading "flashless forging".

Impression die forging provides three-dimensional control of the workpiece, which provides much closer dimensional control than does open die forging. The control is achieved by a pair of matched dies with specially fabricated impressions, which form an impression, or cavity in the shape of the forging. The term "impression die" forging derives from the impressions.

5.2.2.1 Conventional Impression Die Forging

A simple example of conventional impression die forging is illustrated in Figure 5-11. As the two dies approach, the workpiece undergoes plastic deformation, flowing laterally until it touches the side walls of the impression. A small amount of metal continues to flow outside of the impression, forming flash. As the dies continue to approach, the flash is thinned causing it to cool rapidly and offer increasing resistance to further deformation. The flash, in a sense, becomes part of the tool and helps to build up pressure inside of the cavity. The increased pressure promotes flow of metal into features of the impression previously unfilled.

Dimensional control of the forging in lateral directions is controlled by the walls of the die, and is ensured by complete die fill. Dimensional control in the axial direction is achieved by bringing the die faces to a predetermined position.

While flash can promote complete fill of the cavity, it does so at the cost of extremely high die pressures in the flash area. High pressures are undesirable because they reduce die life and require additional power. A flash gutter is often formed in the dies to receive the flash and allow the dies to reach the predetermined position at lower pressures. A typical flash gutter is shown in Figure 5-12.

Quality and production economy are optimized by using a sequence of forging operations, which are generally classified as "preforming" and "finishing". Most of the work of deformation is accomplished in the preforming operations at relatively low pressures. The finishing operation(s) bring the forging to its final contour and precision. The additional cost of the tooling and production operations is more than offset by higher productivity, increased die life and improved product quality. These factors increase in importance as production quantities increase. Forging in only a final die may be practical for very small runs if the shape is simple enough not to form defects.

Preforming operations may include one or more bending or rolling operations, and one or more preforming, or blocker die operations. Blocker dies are characterized by features such as large radii and generous draft angles, which minimize forging pressures. Usually only the final operation is designated as a finish operation. The types of operation and number of each are determined by the forging source, who is also responsible for design of the tools.

In some cases, the blocker die is the final step, and the forgings are known as "blocker forgings". In addition to the features enumerated above, blocker forgings include generous finishing allowances. They are suitable for moderate quantities of parts.

The complexity of impression die forgings drives the cost.

Forging Industry Association recognizes three impression die shape classes, with one to three shape groups in each, and four to six sub-groups for each shape group. Each shape is systematically identified with a three-digit number. The classification system is shown in Figure 5-13.

5.2.2.2 Flashless (Enclosed Impression Die) Forging

Impression die forging is sometimes performed in totally enclosed impressions. The process is used to produce a near-net or net shape forging. The dies make no provision for flash because the process does not depend on the formation of flash to achieve complete filling. Actually, a thin fin or ring of flash may form in the clearance between the upper punch and die, but it is easily removed by blasting or tumbling operations, and does not require a trim die. The process is therefore called "flashless forging", and is sometimes called "enclosed die forging".

Enclosed dies are illustrated in Figure 5-14. In some cases the lower die may be split, allowing as-forged undercuts. Split die arrangements are illustrated in Figure 5-15.

The absence of flash is an obvious advantage for flashless forging over the conventional impression die process, but the process imposes additional requirements. For example, flashless forging is usually accomplished in one operation, and does not allow for progressive development of difficult-to-forge features through several stages of metal flow. In addition, the volume of metal in the workpiece must be controlled within very narrow limits to achieve complete filling of the cavity without developing extreme pressures. It takes some very well controlled preforming steps to accomplish this precise weight control in the final die.

5.2.2.3 Net and Shape Forging

Net and near net shape forging represents some relatively recent developments of the conventional impression die forging process. Net and near net shape forgings are distinguished by geometric features that are thinner and more detailed, varying parting line locations, virtual elimination of draft, closer dimensional tolerances and with many as-forged surfaces. The resulting product benefits are much fewer machining operations, reduced weight and lower costs for raw materials and energy. In many cases, the only machining operations required are drilling of attachment holes.

Net and near net shape forgings in the as-forged and heat treated condition usually reflect a higher production cost than do their conventionally forged counterparts. They are often but not necessarily flashless. The cost advantage shifts to net shape forging as post-forging machining operations are eliminated.

A cost study for an aircraft aluminum forging made by four processes identifies the cost drivers and illustrates the trade-offs for this application. The four processes are hand forging, blocker type (forging to approximate shape and machining), conventional forging and net shape forging.

The cost drivers are charted and the effects calculated for various production quantities in Table 5-1. The cost is given in relative terms, rather than dollars, with the piece price of a conventional forging taken as

1. The advantage for net shape forging over hand forging begins at 110 units; at 140 or more units, net shape forging is the most economical of the four processes. Other applications will have different cost ratios. Actual values can be determined only by consultation with the forging company representative.

Table 5-1: Cost Comparison of Wide-Body Jet Forging.
Courtesy of FIA member company.

Forging Process	**Hand**	**Blocker Type**	**Conventional Finished**	**Net Shape**
Forging costs	---			
Tooling	---	308	615	1000
Set-up	1.48	30.8	18.5	23
Piece cost		1.23	1.0	1.9
Machining costs				
Tooling	1.46	123	92	31
Set-up	21	15.4	11.5	2.3
Piece cost	8.5	5.4	3.5	0.23

5.2.2.4 Hot Die and Isothermal Forging

Heat transfer from the workpiece to the die surfaces causes thermal gradients in the workpiece. The cooler areas at the die surfaces undergo less plastic flow than in the hotter core areas, so that plastic flow is not uniform. This is termed die chilling. In conventional forging practice, dies for steel forgings are typically heated to a maximum temperature range of 400 to 500°F (205 to 260°C), depending on equipment, to reduce chilling. The effects of chilling can also be reduced by using fast-acting forging machines, such as hammers, screw presses and mechanical presses, to reduce the contact time. The use of glass lubricants assists by forming a thermal barrier between the workpiece and die surfaces and reduce the die chilling effect.

Die chilling can be reduced by heating the dies nearer to the actual forging temperature. Die chilling can be eliminated entirely by heating the dies to essentially the same temperature as the workpiece. The former is called hot die forging; the latter isothermal forging.

Aluminum alloys are usually hydraulic press forged under isothermal or near isothermal conditions at around 800°F (425°C). In this range, conventional die materials do not undergo any significant loss of strength or hardness.

However, steels and alloys of titanium and nickel are forged in the range of 1700 to 2300°F (925 to 1260°C). Isothermal forging of these alloys requires special tooling materials, such as nickel-based superalloys and molybdenum alloys for dies, and lubricants that can perform adequately at these temperatures. Special attention to the surrounding atmosphere is also important, such as the use of an inert gas or vacuum to protect both the dies and the workpiece from oxidation.

Hot die and isothermal forging offer advantages and disadvantages. The primary advantages are closer forging tolerances resulting in reduced machining and material costs, a reduction in the number of preforming and blocking operations resulting in reduced processing and tooling costs, and the use of slow ram speeds resulting in lower forging pressures and the use of smaller machines.

The primary disadvantages are the requirements for more expensive die materials, uniform and controllable die heating systems, and an inert atmosphere or vacuum around the dies and workpiece to avoid oxidation of the dies. The typical production rates are very low to permit proper die filling at the low forging pressures.

5.2.3 The Ring Rolling Process

Ring rolling is a hot forming process that produces seamless rings varying in size from a few inches in diameter, and weighing less than one pound, to over 25 feet in diameter and face heights approaching 10 feet. The process and equipment are similar in principle to rolling mills used for plate. In both processes, the metal is rolled between two rolls, which move toward each other to form a continuously reducing gap. In ring rolling, the rolls are of different diameters.

The process is shown schematically in Figure 1-5, Section 1. It begins with a hollow circular preform that has been upset and pierced, similar to preforms used for ring forging, illustrated in Figure 5-8. The preform is placed over the idler or mandrel roll, which is forced toward the drive roll. The drive roll rotates continuously, reducing the wall thickness, imparting the desired shape to the cross section, and increasing the diameter. Contours may be rolled on either the inside surface, outside surface or both as shown in Figure 1-6, Section 1.

For larger rings, the mill may also have radial oriented or "pinch" rolls, illustrated in Figure 5-16, which control the height of the ring. They also help to maintain squareness and alignment with virtually no axial growth. In some cases, such rolls can reduce the height as much as required. They are not, however, generally used to roll contours on either top or bottom surfaces.

Thickness-to-height ratios normally range from 16:1 to 1:16, and special equipment can extend these ranges. Cross sections of typical ring rolled shapes are shown in Figure 1-6, Section 1.

Ring rolling produces seamless rings with forged properties, which results in optimum mechanical properties, and predictable and efficient machinability. Tooling cost is low, set-up time is fast, rolled sections require little or no machining. The process is also highly material efficient. The preform typically utilizes up to 95% of the starting billet. Material losses come from the hole punched in the preform, oxidation in medium to large size rings, and any required machining.

Ring rolling can also be used in conjunction with other forging processes. In the example illustrated in Figure 5-17, a blank is formed by upsetting and piercing. The blank is then forged in impression dies to develop the hub, web and rim. The flange is then formed on the rim by ring rolling. In the final step, the wheel is dished to offset the hub from the rim.

It is important to the designer that the power of the rolling mill determines the deformation at the center of the wall during rolling. Excessively light reductions for each pass can cause dimensional problems. In rolling, the compressive deformation may be confined to the surface, and the mid-wall centers of the workpiece are stretched in tension. Experienced mill operators are familiar with the techniques required to roll to size.

In some cases the ring rolling sources have expanding mandrel or sizing machines, which expand the ring a few percent to improve dimensional control and roundness. Sizing may be performed either before or after normalizing. For rings rolled from aluminum alloys, these expanders are used to actually relieve quenching stresses introduced during solution heat treatment.

5.2.4 The Cold Forging Process

Cold forging is one of the most widely used chipless forming processes, often requiring no machining other than drilling. The commonly accepted definition is the forming or forging of a bulk material at room temperature with no heating of the initial slug or inter-stages. The term "no heating" does not include in-process annealing, which may be performed at intermediate stages to relieve the effects of work hardening. The process produces greater dimensional accuracy than hot forming, and does not produce scale. However, the plastic flow characteristics of the workpiece are not as good, so that higher forging pressures are required. Component size is generally limited to 50 pounds or less. The majority of cold forgings weigh less than 10 pounds.

Cold forging is being used in a wide variety of industries including fastener, automotive, pole-line hardware, truck-trailers, outboard engine controls, bicycle pedal cranks, constant velocity joints, universal joint crosses, and military projectile hardware. Shapes generally have been limited to rotationally symmetrical and axisymmetric, including long shafts and struts. Shape capability is being expanded by developments in technology. Some of the most common shapes and combinations of shapes are illustrated below in Section 5.2.4.2.

5.2.4.1 Alloys Used for Cold Forging

In every major alloy group that is used for hot forging, there are alloys suitable for cold forging. The degree of formability varies widely among material groups and among alloys in each group. In general, alloys having a tensile elongation of at least 10% or reduction in area of at least 30% can be cold worked with a reasonable level of success. The best formability is achieved when elongation is above 20% and reduction in area above 45% after cold drawing. As alloy content increases, the amount of deformation possible in a single stage is usually reduced. Some of the alloys that are currently cold forged are listed in Section 4.

5.2.4.2 Cold Forging Processes

There is a variety of cold forging processes currently in -use, either alone or in combination. Following is an overview of those used most often.

Forward Extrusion In the most common forward extrusion process, a billet is pushed through a container or die by means of a punch. The material flows in the same direction as the punch to provide various types of exit sections. The process is also used on hollow slugs to reduce wall thickness, and to manufacture cans with either cylindrical cavities or cavities with varying cross sections. It is used to produce solid shapes such as rounds, thread blanks, squares, rectangles, triangles, polygons and splines. Hollow shapes, including rounds, polygons and splines are also forward extruded. Figure 5-18 shows three types of forward extrusion.

Backward Extrusion In this process, the material flows in the opposite direction to the upper punch. The workpiece is formed either in the cavity formed between the punch and die, or in the cavity of the punch. Backward extrusion is used to produce circular inside and outside diameters, squares with rounded corners, multiple outside diameters and multiple inside diameters. Figure 5-19 shows three types of backward extrusion.

Side Extrusion In this process, the material flows lateral to the direction of the punch, generally in one direction. Two types of lateral extrusion are shown in Figure 5-20.

Upsetting In this process, material flows lateral to the direction of the punch in all directions, increasing the cross section of the stock. The term "heading" is often used interchangeably with upsetting. Sometimes a distinction is drawn, and "heading" (or "flanging") is used to describe upsetting at the end of the workpiece, and "gathering" to describe upsetting at locations other than the end. Headed shapes include T- and L-heads, ball heads, square heads and socket heads. Three types of upsetting operations are shown in Figure 5-21.

Ironing In this process, the wall thickness of hollow cans or tubes is reduced, as shown in Figure 5-22. The force is applied to the bottom of the preform by a relatively long punch. The process differs from forward extrusion in that the workpiece is in tension, whereas forward extrusion places the workpiece in compression.

Nosing Nosing is used to reduce the end of a backward extrusion, or its radius. The process is shown in Figure 5-23.

Radial Forging In this process, tools moving radially forge the workpiece to the desired shape, as shown in Figure 5-24. Radial forging can also be used to make solid parts, such as axles. Hollow parts, such as gun barrels, can be axially forged using a mandrel.

Bending Bending operations are often used to generate non-symmetrical shapes. The process is used to produce rod and bar shapes with and without heads, including J-, S, U-, W-, and Z-bends.

Combined Processes Many of the above processes can be combined to advantage in a single operation. For example, forward and backward extrusion are combined to produce shaft gears with either solid or cup heads, splined shafts and threaded shafts. Seven common process combinations are shown in Figure 5-25.

Process Sequence In almost all cases, cold forgings are made in several forming strokes. The number of strokes is determined by the formability of the alloy, die loading, press loading, press characteristics, and the opportunity to combine processes. If the formability limit is reached, the workpiece must be annealed in an intermediate stage before proceeding with the next operation. The application of surface coatings between processes may be necessary for some materials. The design of process sequence is therefore based on many years of experience by the process design engineer.

Process sequences for two cold forgings are shown in Figures 5-26 and 5-27. The process sequence for the bevel gear in the figure shows the progress in cold forming technology in recent years to produce very intricate shapes.

5.2.4.3 Product Advantages of Cold Forging

The major advantages of cold forging are close dimensional tolerances, good surface finish quality, and the use of lower cost materials to obtain the required strength by work hardening without requiring heat treatment.

The normal value of surface roughness, Ra, is in the range 1.6 to 25 microns (64 to 1000 micro inches). The lower values require additional attention in processing, particularly the maintenance of tool surface finish.

Table 5-2 compares two processes for manufacturing a wheel hub, based on hot and cold forging. The cold forging develops approximately 8% lower yield strength from less expensive material and is not heat treated. It requires one-third as much machining time, and weighs 24% less. A comparative cost analysis would also include processing cost as well as the costs of manufacturing and maintaining the tools, which are not included in this comparison.

Table 5-2 Comparison of Hot Forging and Cold Extrusion for Manufacturing a Wheel Hub*

Steel Alloy	**8620**	**1010**
Weight kg (lb)	2.85 (6.3)	2.3 (4.8)
Finish machining time, min.	4.5	1.5
Finish treatment	Hardening and tempering	None
Yield strength MPa (ksi)	600 (87)	550 (80)

*Ref Forging Handbook, Table 4-3 p 182

5.2.5 The Warm Forging Process

Warm forging is performed with the workpiece heated to a range that is generally above the work hardening temperature and below the temperature at which scale forms. The process fills the niche between the closer tolerance, but sometimes expensive cold forging process and the somewhat lower precision hot forging process. It is being used to produce close tolerance components in steel alloys that were not feasible or impossible by cold forging. It is also being used to produce components very close to final shape that were formerly made by hot forging with generous finishing allowances. Shafts, gears and automotive front wheel drive tulips are currently being warm forged.

Warm forging will also allow conversion of some components from other processes, which may not be candidates for hot or cold forging. Table 2-2 in section 2 lists some guidelines for selecting between the cold, warm and hot forging processes.

5.3 Secondary Operations

Secondary operations are performed to achieve desired mechanical properties, bring the forging to final form or dimensional tolerance, provide corrosion resistance, and improve appearance. In many cases, the forging source has the capability in-house to perform the required secondary operations, giving the designer the advantage of one-source capability.

5.3.1 Heat Treating

Heat treating is often employed to develop properties in the forging that could not otherwise be realized with the selected alloy. Although it is most often associated with ferrous alloys, forging alloys in all of the seven major alloy groups can be heat treated to advantage. Forgings are generally heat treated in the same processes that are used for castings and weldments.

The need for heat treating is sometimes eliminated by using an alloy that develops the required properties in the as-forged condition. For example, microalloyed steels are sometimes used to reduce or eliminate heat treating operations that would be required for carbon steels. However, the purchased price of forging stock is higher, and some additional cost may be incurred due to the requirements for additional air cooling equipment. The optimum combination of alloy and heat treatment is best developed in discussions between the forger and purchaser.

For information on specifying heat treatment, see Section 3.7.

5.3.2 Machining

Machining, or chip-making operations are used to bring the forging to its final form and dimensional tolerance. Forgings are generally machined with essentially the same machinery and cutting tools as equivalent castings and weldments.

The amount of machining varies with the required dimensional precision and forging process. Forgings made by the open die process and those made from blocker dies generally require a significant amount of finish machining, whereas net shape forgings typically require few or no finish machining operations. The cost of machining may be affected by the following factors, which should be identified and discussed between the purchaser and forger:

1. Some alloy additions that enhance machinability and reduce machining costs may also reduce forgeability, and thereby increase processing costs.

2. The cost of machining must often be traded off against the potential additional processing and tooling costs associated with forging to closer tolerances. Purchased quantities will usually affect the tradeoffs.
3. The cost of machining may be minimized by optimizing the allocation of machining responsibility between the forger and the purchaser.

5.3.3 Finishing Operations

There are two categories of finishing operations: those that produce minor dimensional corrections, and surface treatment processes.

Coining, sizing and straightening are commonly used to improve the dimensional accuracy of forgings. When tolerances closer than those that can be economically produced in the forging die are specified, coining and sizing operations are often employed. These processes cause plastic deformation of the forging, either by striking or squeezing a defined area. Coining may be performed either hot or cold, and can be accomplished either before, during or after heat treatment. Cold coining is preferred

because material shrinkage is not a factor and the process can produce excellent surface finishes. Special dies can be used to coin irregular surfaces, but flat surfaces, such as bosses, are most suitable and can be sized to very close tolerances.

Forgings may become slightly warped, twisted or bent during trimming, heat treating, cleaning or handling. They can usually be straightened either manually or by using a special purpose fixture and combining the straightening operation with a sizing operation in a coin press. Cylindrical parts such as tubes, axles and various types of shafts are ordinarily straightened in machine rolls when sufficient quantities are involved.

Surface treatment operations may be performed on forgings to remove scale formed during forging and heat treatment, improve corrosion resistance, enhance appearance and improve surface properties. Surface treatment requirements are based on the alloy and forging process employed. For example:

- Cold and warm forging operations are performed on steel alloys below the temperature range at which scale forms and do not require the removal of scale.
- Scale formation of stainless steel alloys is not generally a problem.
- Aluminum alloys can be given a hard anodized surface to improve abrasion and corrosion resistance.

- Forgings made from copper based alloys generally exhibit good surface quality and high corrosion resistance that eliminates the need for most surface treatment operations.

Forgings generally employ essentially the same finishing operations for corrosion protection and enhanced appearance as castings and weldments made from equivalent alloys. When subsequent machining, painting or other coating operations are anticipated, the forgings are usually cleaned by blasting, tumbling, pickling or, (as with aluminum) caustic-nitric etch. Blast or shot cleaning is the most common cleaning method.

Case Studies

The following case studies represent a variety of products made by forging. They have been chosen to illustrate most of the forging processes, a variety of the alloys, and many of the principles set forth in the preceding chapters. Some of the products were readily formed using only industry standard technology; others required special capabilities. Some of the products are of recent origin, while some were developed more than a decade ago. All are current in the sense that they illustrate the capability of the forging industry to supply products with improved performance, reduced cost or reduced manufacturing and assembly problems compared with alternate processes.

Summary of Case Studies

No	Title	Process	Alloy	Approximate Weight kg (lb)
1	Flanged Ball Valve Adaptor	Rolled Ring	Carbon Steel	650 (1430)
2	Socket Plate	Hot Impression Die	Aluminum	0.14 (0.31)
3	Countershaft	Upsetter	Alloy steel	16 (35)
4	Door Hinge Assembly	Hot Impression Die	Die Aluminum	0.8 (1.75)
5	Upper control Arm for Light Duty Truck	Warm and Cold	Carbon Steel	3.7 (8.2)
6	Cylinder Cap for Agricultural System	Hot Impression Die	Carbon Steel	1.1 (2.2)
7	Crankshaft for High Performance V-6 Engine	Hot Impression Die	Microalloy Steel	26 (58)
8	Hub for Mining Shovel	Open die	Steel	1760 (3875)
9	High Performance Gears	Hot closed impression Die	Alloy Steel	Various

10	Flashless Forged Connecting Rod	Hot closed impression Die	Alloy Steel	2.9 (6.3)
11	Swing Ring Gear	Rolled Ring	Alloy Steel	17,600 (38,800)
12	Lower Control Arm	Hot Impression Die	Microalloy Steel	13 (28)

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.

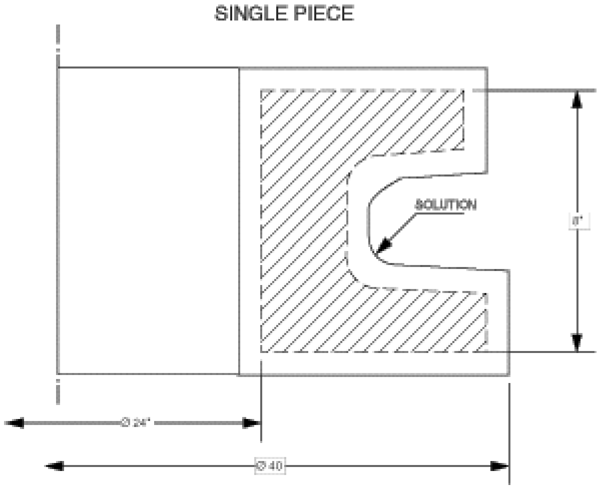


Figure 6-1A

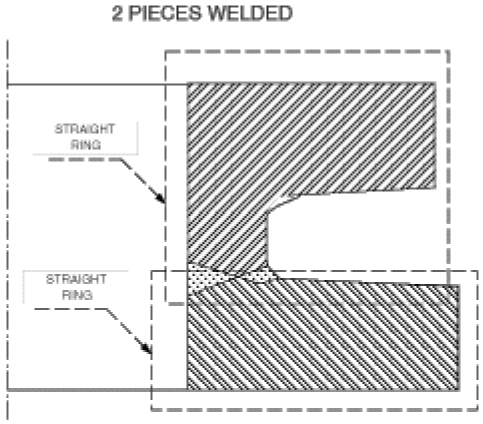


Figure 6-1B

6.2 Case Study No. 2 Socket Plate

Component name:	Socket Plate
Forging Process:	Hot impression die
Size mm (in.):	108 x 95 x 17 (4.2 x 3.7 x 0.65)
Weight, kg (lb):	6 0.14 (0.31)
Alloy:	Aluminum KN432
Tensile strength, MPa (psi):	345 (50,000)
Yield strength, MPa (psi):	215±20 (31±3)
Hardness:	100-119 Brinell

Elongation:	12%
Secondary Operations:	Machining
Heat treatment:	T4
Alternate process:	Casting
Annual Production:	More than 3,000,000

The socket plate, shown in Figure 6-2, is a vital part of air conditioning compressors installed on passenger cars. The plate replaces a crankshaft in the five cylinder reciprocating compressor, resulting in a more compact design that is easier to package in the engine compartment. Performance requirements were driven by a new family of compressors that handle newly developed, environmentally friendly refrigerants. The forged plate replaced a casting, which had failed during development.

The plate incorporates five sockets, which receive the five high strength steel connecting rods, and produces a precise reciprocating motion. The plate must offer high resistance to wear and galling because no lubricant compatible with the refrigerant was available. In addition to wear resistance, the forged plate offers ductility high enough to permit swaging without cracking, fatigue strength high enough to preclude microcracking at the base of the ball sockets, and metallurgical stability that ensured that the properties will be retained despite the thermal cycles encountered in the automotive underhood environment.

The forging company contributed to the program by developing both the forging process and material to optimize both the mechanical properties of the alloy and the dimensional tolerances of the plate. Prototypes were produced in production forging tools, since it was the only way to achieve all of the material properties required by the application.

Figure 6-2

6.3 Case Study No. 3 Countershaft

Component name:	Countershaft
Forging Process:	Upsetter forging
Max O.D., mm (in.):	150 (6.0)
Length, mm (in.):	400 (16)
Weight, kg (lb):	16 (35)
Alloy:	Steel, SAE 8620H
Secondary Operations:	Normalized and cleaned
Heat treatment:	T4
Number of parts:	One
Alternate process:	Five piece assembly
Annual Production:	Approximately 100,000

The one piece countershaft is used in automotive powertrains. It was originally produced as three separate forgings: two gear blanks and a shaft with an integral gear. After each piece was forged, extensive machining was required on each to facilitate assembly. Two keys were required at assembly to secure the gear blanks to the shaft, as shown in Figure 6-3 bringing the piece count to five.

The one piece design, also shown in the figure, generated a substantial cost reduction by reducing machining costs, eliminating assembly cost, and eliminating the purchased and hidden costs associated with the keys.

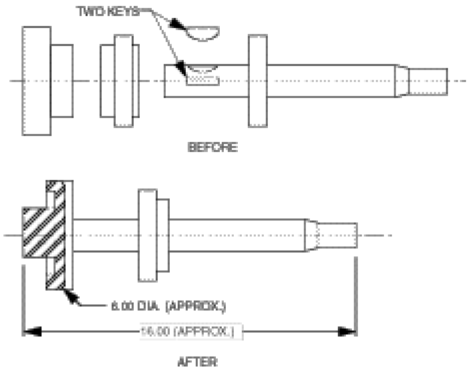


Figure 6-3

6.4 Case Study No. 4 Door Hinge Assembly

Component name:	Door Hinge Assembly
Forging Process:	Hot impression die
Size, mm (in.):	120 (4.6) x 220 (8.7)
Weight, kg (lb):	0.8 (1.75)

Alloy:	Aluminum 7075
Tensile strength, MPa (psi):	480 (70,000)
Yield strength, MPa (psi):	415 (60,000) minimum
Secondary Operations:	Machined and assembled
Heat treatment:	T-73511
Surface treatment:	Powder coated
Number of parts:	2 forgings
Alternate process:	Casting
Annual Production:	5000

The door hinge assembly, shown in Figure 6-4, is currently the only instance of a forged aluminum door hinge for a production North American automobile. It is used on a high performance sport car. Since the hinge is critical to occupant safety, it meets all requirements of Federal Motor Vehicle Safety Standard 206, which applies to door locks and door retention components. The hinge assembly additionally meets the vehicle manufacturer's internal standards for life cycle requirements and door sag. Life cycle requirements were verified by 35,000 cycles of testing over a wide temperature range. The door sag requirements were verified by deflection testing using prototypes machined from forged blocks.

The forged aluminum hinge replaced a cast steel design, reducing vehicle weight by 2 kg (4.5 lb). Purchase price was reduced by 50%. Part of the cost reduction is attributed to the as-forged surface quality of the forgings, which receive a powder coat without requiring any surface finishing.

The vehicle producer's design center supplied CAD models by modem to the forging company, who developed the forging and process. The original steel design required only minor design modifications for production as an aluminum forging. Prototype hinges for pre-production test and development were machined from forged blocks.

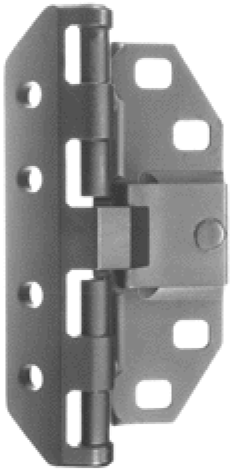


Figure 6-4

6.5 Case Study No. 5 Upper Control Arm for Light Duty Truck

Component name:	Upper Control Arm for Light Duty Truck
Forging Process:	Warm and cold forging
Size, mm (in.):	241[1] (9.5) x 255[2] (10.0)
Weight, kg (lb):	3.7[3] (8.2)
Alloy:	SAE 1541
Tensile strength, MPa (psi):	755-860 (110,000-125,000) typ.
Yield strength, MPa (psi):	620 (90,000) min.
Elongation:	12%
Impact Toughness, J (ft-lb):	20 (15)
Secondary Operations:	Coining, drilling and boring, and riveting to the ball joint.
Heat treatment:	None required
Surface treatment:	Paint and bake
Number of parts:	Two per vehicle (right and left hand)
Alternate process:	Stamping
Annual Production:	More than 1,400,000
[1] Between bushing centers (fore-and-aft in vehicle position)	
[2] Bushing centerline to ball joint centerline (lateral in vehicle position)	
[3] Including bushings	

Most product engineers are conditioned to look for hidden costs. They should also be aware of the counterpart to hidden costs, which may be more difficult to recognize: hidden cost savings. The cold forged upper control arm, Figure 6-5 , which was originally conceived for light and medium duty trucks, is an outstanding example. The cold forged arm was lighter and stronger than its one-piece stamped counterpart, but not less costly to produce. The design freedom allowed by the forged arm resulted in substantial cost and weight reductions in related chassis components.

With the forged upper arm, the shock absorber mounts to a conventional lower control arm and passes through the upper control arm to the mounting point in the chassis. However, the steel stamping required a structural web, which did not provide room for the shock absorber. Instead the shock absorber was required to be mounted either fore or aft of the arm. Mounting the shock absorber inside the forged upper control arm not only allowed the use of a conventional lower control arm and spring, it also allowed the vehicle design team to reduce the chassis length substantially. Thus the weight reduction of approximately 0.91 kg (2 lb) was leveraged into a substantially larger weight reduction realized from the shorter chassis, and substantial cost savings.

Related designs on other vehicles are achieving similar success over stampings. A mini-van application allows greater design freedom for styling, such as the aerodynamic front end. A front tension strut for the redesign of a passenger car achieves tight tolerances and good mechanical properties without requiring heat treatment.

Figure 6-5

6.6 Case Study No. 6 Cylinder Cap for Agricultural Hydraulic System

Component name:	Cylinder Cap for Agricultural Hydraulic System
Forging Process:	Hot impression die (Hammer)

Weight, kg (lb):	1.0 (2.2)
Alloy:	Steel 1045
Secondary Operations:	Broach, turn, face, P-cut, deburr
Alternate process:	Machined from bar stock
Annual Production:	Typically 10,00 to 12,000

The hydraulic cylinder cap shown in Figure 6-6 is one of two that was converted for forging. The objective of the conversion was to develop higher performance, more cost effective hydraulic cylinders for agricultural equipment. Performance is critical because:

- The cap is hinged to a frame, and is used as a lifting device.
- Hydraulic pressures exceed 21 MPa (3000 psi).
- High stresses and shock loading occur constantly.

The cap must also be weldable to the cylinder barrel, which is a steel tube drawn over a mandrel.

The prior design was fabricated from steel bar, using multiple operations including saw cutting, deburring, flame cutting, grinding, drilling and broaching. The result was a cap that was difficult and costly to manufacture. For example, it was difficult to maintain the necessary flatness on the surfaces through which the pin bore was drilled, then broached, because of the very tight tolerance for perpendicularity.

The OEM, working with a forger, redesigned the cap and optimized it for forging. Some of the highlights of the redesign were:

- Combining the trim operation with a hot piercing operation to produce a hole with no draft, which met requirements for perpendicularity with the reference surface and circularity.
- Reducing in-house operations from 13 to 2.
- Reducing scrap rates from approximately 25% to virtually zero.
- Achieving a cost reduction of 65.5%

The success of this program has led to conversion of other parts such as trunions, rod ends and brackets to forging at similar cost reductions.

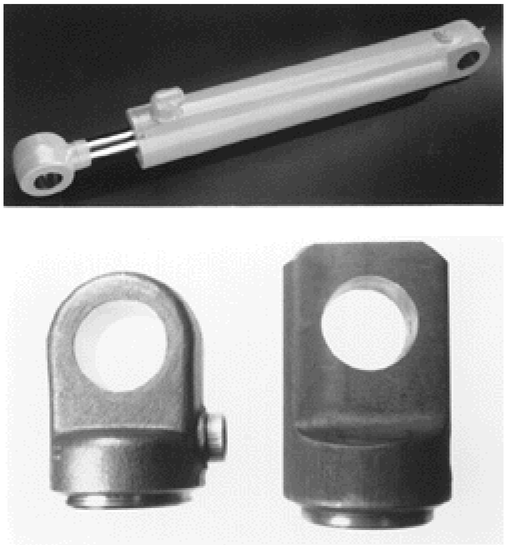


Figure 6-6

6.7 Case Study No. 7 Crankshaft for High Performance V-6 Engine

Component name:	Crankshaft for High Performance V-6 Engine
Forging Process:	Hot impression die
Length, mm (in.):	510 (20)
Weight, kg (lb):	26 (58)
Alloy:	Vanadium modified microalloy steel
Tensile strength, MPa (psi):	825 (120,000)
Yield strength, MPa (psi):	495 (72,000)
Fatigue strength MPa (psi):	380 (55,000) (estimated)
Secondary Operations:	Finish machining, shot peening of journals
Heat treatment:	None
Alternate process:	Austempered ductile iron

The crankshaft for a 3.8 liter supercharged engine, shown in Figure 6-7, utilizes the properties of microalloyed steel with the advantageous grain flow developed in the impression die forging process. The original design specified austempered ductile iron; however the material was not capable of achieving engineering targets for consistency of properties and machinability.

The combination of microalloy steel and impression die forging generates a 31% increase in yield strength and 41% increase in tensile strength compared with nodular cast iron, which is specified for conventional crankshafts. More important for the application, fatigue strength was increased by an estimated 57% and stiffness by as much as 36%. Stiffness, which is critical at higher engine speeds, is proportional to the modulus of elasticity, which is 207 GPA (30,000 ksi) for steel versus 152 GPa (22,000 ksi) minimum for nodular iron. The selection of microalloyed steel allowed the strength properties to be generated as forged, without the quenching and tempering operations that are usually required for carbon steel cranks.

Fatigue strength was further enhanced by shot peening the fillets on main and rod journals. Shot peening induces compressive stresses at and near the surface, which subtract from the tensile stresses imposed in those areas. Usually a deep rolling process is performed on main journals only.

With this combination of material and processes, designers anticipated very long service life, with possibly no failures in service.

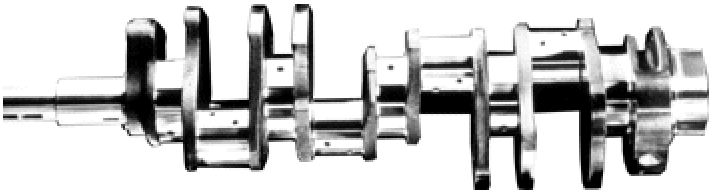


Figure 6-7 Crankshaft shown is the cast version, which was replaced by a forging.

6.8 Case Study No. 8 Hub for Mining Shovel

Component name:	Hub for Mining Shovel
Forging Process:	Open die
Size, mm (in.):	*Base* 685 (27) square X 750 (29-1/2) long *Top* 1065 (42) diameter X 150 (6) long I. D. 520 (20-1/2)
Weight, kg (lb):	1760 (3875)
Alloy:	Steel
Secondary Operations:	Finish machine
Heat treatment:	By forging company
Number of parts:	1
Alternate process:	Casting

When workers discovered several large cracks in the cast hub of a mining shovel, just days short of a catastrophic failure, they immediately sought a replacement. The hub is shown in

Figure 6-8. Shovel functions, including lift, dig, lower and pivot 360 degrees, depend on the hub, which was the central pivot point. The cracks were apparently due to a combination of internal porosity and heat affected zone effects in the weld area.

The supplier of the casting advised that a replacement would require at least four weeks to produce. Estimated downtime cost, in terms of lost production, was approximately $4000 per hour, which would accumulate to more that $500,000, even if the four week minimum time estimate were met.

An open die forger was consulted and within four days (two working days) the shovel operator received a replacement hub. The delivered price was the same as that of the casting. In addition to the cost savings realized from reduced downtime, the forged hub may offer longer service life due to freedom from porosity and other internal defects.

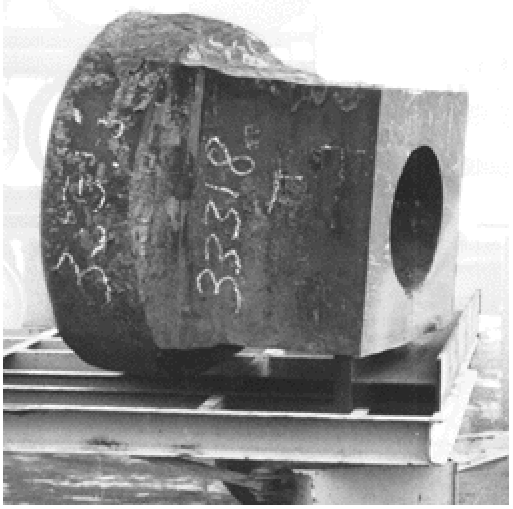


Figure 6-8

6.9 Case Study No. 9 High Performance Gears

Component name:	High Performance Gears
Forging Process:	Hot Closed Impression Die
Size, mm (in.):	6 to 432 mm (3 to 17 in.) diameter, face widths to 203 mm (8 in.)
Alloy:	8620 Steel
Tensile strength, MPa (psi):	[1] 635 (92,000)
Yield strength, MPa (psi):	[1] 355 (52,000)
Hardness, BHN:	[1] 180
Elongation:	[1,2] 26.3%
Reduction in Area:	[1,2] 59.7%

Impact Toughness, J (ft-lb):	[1,2] 99.7 (73.5)
Secondary Operations:	Cold draw through finish sizing die and grind
Heat treatment:	Normalize before shipment
Alternate process:	Forge the blank, rough and finish hob
Annual Production:	5000 to 7000
[1] Standard handbook values	
[2] As normalized	

A family of gears, such as the ones shown in Figure 6-9, is being produced to near-net shape by hot forging in closed impression dies. Finish grinding allowances range from as little as 0.1 mm (0.004 in.) up to 2 mm (0.080 in.). The process offers two distinct advantages over the alternative of forging the blank and hobbing the teeth.

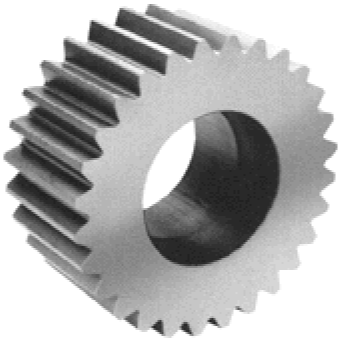
1. Near-net shape forging reduces production costs by requiring only a finish grinding operation, which incurs lower costs both for processing and capital investment than hobbing operations.
2. The continuous and uninterrupted grain flow established in forging the teeth virtually eliminates residual stresses in the teeth, resulting in substantially higher gear life.

These advantages required that several critical manufacturing problems be solved, including high scrap rates, lower die life and high costs of grinding. The problems were solved by interaction of the forging engineers with gear designers and quality technicians and grinding wheel suppliers.

The high degree of forging precision is achieved by very close control of process variables in all stages. For example:

- The steel bar stock is turned and polished to improve the surface, and cut to precise lengths to ensure tight control of the volume of steel that is placed into the closed dies.
- Temperature of the forging stock is maintained to within ±14°C (25°F) in an induction heating furnace.
- Special press controls were developed in-house to ensure repeatability of press operations.

In addition to reduced cost, the process offers the potential for reducing the metal content of the gears by designing to the higher tooth strength that is developed by the process.



6.10 Case Study No.10 Flashless Forged Connecting Rod

Component name:	Flashless Forged Connecting Rod
Forging Process:	Hot Closed Impression Die
Size, mm (in.):	21 (8.25)
Weight, kg (lb):	2.9 (6.3)
Alloy:	Steel, E4340 per Mil Spec 5000, 1100 series
Tensile strength, MPa (psi):	1240 (180,000)
Yield strength, MPa (psi):	[1]1095 (159,000)
Hardness, minimum, HRC:	40
Secondary Operations:	Cracking, finish machining
Heat treatment:	Anneal for finish machining or controlled cooling
Surface treatment:	None required
Alternate process:	Powder Metal Forging
Annual Production:	52,000,000

The closed die forged connecting rod shown in Figure 6-10 is the latest step in the evolution of manufacturing processes for connecting rods. Conventional impression die forging, which was the standard for high performance connecting rods, has given way to powder forging in many applications because it offers two distinct advantages:

1. Closer dimensional precision, and overall cost reduction by reducing the number of machining operations, as evidenced by elimination of the balancing boss on the small end of the rod.
2. "Cracking" capability, allowing the cap to be separated from the rod by a precision breaking process, which does not remove metal and thus does not affect the dimensional precision of the large end of the rod.

The flashless forged closed impression die process produces rods equivalent to powder forged rods in terms of dimensional precision, elimination of trimming operations, and cracking capability. It offers two additional benefits.

1. Lower cost of materials and manufacturing operations. Forging bar stock is less costly than powdered metal, and the intermediate pressing and sintering operations associated with powder forging are eliminated.
2. Higher strength due to the development of optimum grain flow and inherent full density. The powder forging operation concentrates on increasing density, and induces very little advantageous grain flow.

Current designs duplicate the shape of powder forged rods so that the precision forged rods are interchangeable with them in finishing operations. The higher strength potentially allows for redesign to reduce rod weight, which will reduce inertial loads and permit secondary weight reductions in other engine components.

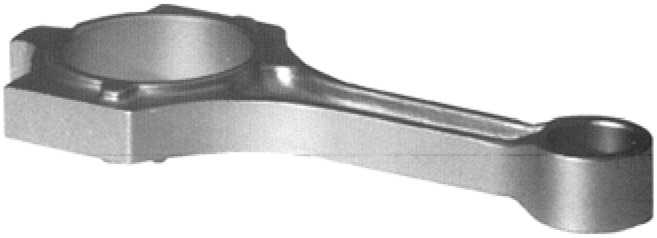


Figure 6-10 Flashless forged connecting rod.

6.11 Case Study No.11 Swing Ring Gear

Component name:	Swing Ring Gear
Forging Process:	Rolled ring (profiled) from hot press forged blank
Size, mm (in.):	
Forged:	5300 (208.5) O.D. X 467 (18.38) high
Finished:	5232 (206) O.D. X 413 (16.25) high
Weight, kg (lb):	
Forged:	17,597 (38,793)
Finished:	12,363 (27,256)
Alloy:	4330 Vanadium modified electric furnace/vacuum degassed
Secondary Operations:	Finish machined

Heat treatment:	Anneal for finish machining or controlled cooling
Surface treatment:	Quenched and tempered 302/341
Alternate process:	Casting
Annual Production:	30-40

The swing ring gear, shown in Figure 6-11, rotates the revolving frame on the top of the car body (track system) of a mining shovel. The gears were originally cast, but service life was not acceptable due to failure at the root of the teeth. The designers turned to forging to optimize fatigue life and impact toughness by developing a continuous grain flow in the ring profile. Vanadium modified steel was chosen to enable the forging company to develop the required mechanical properties while providing sufficient forgeability for the application.

The gear blank is rolled to shape and finish machined as follows:

Dimension, mm (in.)		
Feature	As Rolled	Finish machined
Outside Diameter	5296 (208-1/2)	5232 (206)
Inside Diameter (stepped)	4521 (178) 4813 (189-1/2)	4572 (180) 4864 (191-1/2)
Height	467 (18-3/8)	413 (16-1/2)

Gear teeth are subsequently machined into the outer diameter across the entire 413 mm height.

No attempts were made to produce prototypes; the designers were confident that the required properties could be developed by forging. The only concern was finding a forging company that could produce a profiled (versus rectangular) ring in the required size.

The forged gear has met all expectations by substantially reducing both repair costs and downtime.

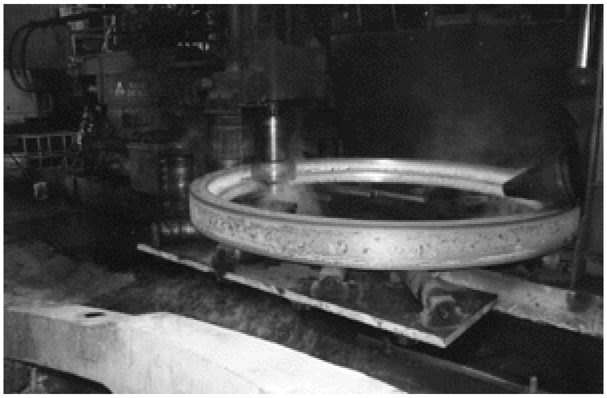


Figure 6-11 Forging the swing gear.

6.12 Case Study No.12 Lower Control Arm for Light Duty Truck

Component name:	Lower Control Arm for Light Duty Truck
Forging Process:	Hot impression die
Size, mm (in.):	00 x 500 (20 x 20) footprint
Weight, kg (lb):	3 (28)
Alloy:	Microalloy steel
Secondary Operations:	Finish machined
Heat treatment:	Anneal for finish machining or controlled cooling
Alternate process:	Fabrication, casting

A front suspension for a light duty truck encountered an unusual problem, which required an unusual solution. The existing fabricated lower control arm, shown in Figure 6-12A, permitted debris to accumulate on top of the wide, cup-shaped surface inboard of the ball stud assembly (left end as shown). In the most rugged four-wheel off-highway applications, the accumulation caused damage to the front wheel drive boot seal. Loss of sealing caused rapid failure of the drive line.

Truck product design engineers sought a manufacturing process and material that would allow a configuration providing a clear space directly under the drive line, eliminating the possibility for debris buildup. For various reasons, both the original fabricated arm and various cast designs were ruled out for the heaviest duty and severest vehicle applications.

The design constraints were reviewed by a forging company, who identified two major problems. First, the large plan view area made forging look impractical. Second, it was necessary to form the hexagonal torsion bar restraint, which is oriented 90o to the plane of forging, in a cost effective manner. The forging company developed novel but practical methods for accomplishing both, and subsequently obtained patents on the process.

The forging company constructed a three dimensional model, shown in Figure 6-12B, and ran extensive stress analyses using available Computer Aided Engineering and Finite Element Analysis software. When the predicted stress levels were approved by the truck manufacturer, prototype arms were forged in the selected microalloy steel, and subjected to rigorous laboratory and field tests. The tests included very severe low temperature impact resistance, extended full load fatigue, full lock steering clearance in worst case events, and severe ball stud retention tests.

Upon successful completion of the testing program, the forging company began supplying the truck manufacturer with fully assembled lower control arms.

Figure 6-12A Fabricated lower control arm.

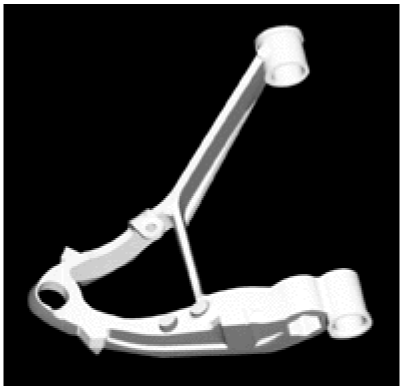


Figure 6-12B Computer model of forged lower control arm

Glossary

Air-lift hammer — A type of gravity-drop hammer in which the ram is raised for each stroke by an air cylinder. Because the length of stroke can be controlled, ram velocity and therefore the energy delivered to the workpiece can be varied. See also Drop Hammer and Gravity Hammer.

Aircraft quality — Denotes stock of sufficient quality to be forged into highly stressed parts for aircraft or other critical applications. Such materials are of extremely high quality, requiring closely controlled, restrictive practices in their manufacture in order that they may pass rigid requirements, such as magnetic particle inspection.

Alloy steel forging — One made from a steel containing additional alloying elements other than carbon (e.g., Ni, Cr, Mo) to enhance physical and mechanical properties and/or heat-treat response.

AMS — Aeronautical Materials Specification

As forged — The condition of a forging as it comes out of the finisher cavity without any subsequent operations.

ASTM (Specifications) — The American Society for Testing and Materials.

Auxiliary operations — Additional processing steps performed on forgings to obtain properties, such as surface conditions or shapes, not obtained in the regular processing operation.

Axial rolls — In ring rolling, vertically displaceable, tapered rolls, mounted in a horizontally displaceable frame opposite from but on the same centerline as the main roll and rolling mandrel. The axial rolls control the ring height during the rolling process.

Axisymmetric forging — A forging where metal flow, during deformation, is predominately in a direction away from a common axis in a radial direction.

Backward extrusion — Forcing metal to flow in a direction opposite to the motion of a punch or die.

Bar — A section hot rolled from a billet to a form, such as round, hexagonal, octagonal, square, or rectangular, with sharp or rounded corners or edges, with a cross-sectional area of less than 16 sq in. (A solid section that is long in relation to its cross-sectional dimensions, having a completely symmetrical cross section and whose width or greatest distance between parallel faces is 3/8 in. or more).

Bar end — See End Loss.

Barreling — Convexity of the surfaces of cylindrical or conical bodies, often produced unintentionally during upsetting or as a natural consequence during compression testing. See also Compression Test.

Batch/batch-type furnace — A furnace for heating materials where all loading and unloading is done through a single door or slot.

Bend or twist (defect) — Distortion similar to warpage, but resulting from different causes; generally caused in the forging or trimming operations. When the distortion is along the length of the part, it is called "bend"; when across the width, it is called "twist."

Bender — A die impression, tool, or mechanical device designed to bend forging stock to conform to the general configuration of die impressions subsequently to be used.

Bending — A preliminary forging operation to give the piece approximately the correct shape for subsequent forming.

Billet — A semifinished, cogged, hot-rolled, or continuous-cast metal product of uniform section, usually rectangular with radiused corners. Billets are relatively larger than bars. See Bloom.

Bite — Amount of the die in contact with the workpiece throughout one entire forging reduction, e.g., heavy bite is three-quarter to full width of the die.

Blank — Raw material or forging stock (also called a "slug" or "multiple") from which a forging is made.

Blast cleaning — A process for cleaning or finishing metal objects by use of an air jet or centrifugal wheel that propels abrasive particles (grit, sand, or shot) against the surfaces of the workpiece at high velocity.

Block — The forging operation in which metal is progressively formed to general desired shape and contour by means of an impression die (used when only one block operation is scheduled).

Block and finish — The forging operation in which the part to be forged is blocked and finished in one heat through the use of a die having both a block impression and a finish impression in the same die. This also covers the case where two tools mounted in the same machine are used, as in the case of aircraft pistons. Only one heat is involved for both operations.

Block, first and second — Blocking operation performed in a die having two blocking cavities in the same die; the part being forged is successively blocked in each impression all in one heat. As many as three blocker dies are sometimes needed for some forgings and up to three operations are sometimes required in each die.

Block, first, second, and finish — The forging operation in which the part to be forged is passed in progressive order through three tools mounted in one forging machine; only one heat is involved for all three operations.

Blocker impression — The forging die impression which gives the forging its general shape, but omits any details that might restrict the metal flow; corners are well rounded. The primary purpose of the blocker is to enable the forming of shapes too complex to be finished after the preliminary operations; it also reduces die wear in the finishing impression.

Blocker-type forging — A forging that approximates the general shape of the final part with relatively generous finish allowance and radii. Such forgings are sometimes specified to reduce die costs where only a small number of forgings are desired and the cost of machining each part to its final shape is not exorbitant.

Bloom — A semifinished product of square, rectangular, or even round cross section, hot rolled, or forged. For steel, the width of a bloom is not more than twice the thickness, and the cross sectional area is usually not less than about 36 sq. in. No invariable rule prevails for distinguishing between blooms and billets; the terms are frequently used interchangeably.

Board hammer — A type of gravity drop hammer where wood boards attached to the ram are raised vertically by action of contrarotating rolls, then released. Energy for forging is obtained by the mass and velocity of the freely falling ram and the attached upper die. See also Drop Hammer.

Bolster plate — A plate to which dies can be fastened; the assembly is secured to the top surface of a press bed. In press forging, such a plate may also be attached to the ram.

Boss — A relatively short protrusion or projection on the surface of a forging, often cylindrical in shape.

Breakdown — (1) An initial rolling or drawing operation, or a series of such operations, for reducing an ingot or extruded shape to desired size before the finish reduction. (2) A preliminary press-forging operation.

Brinell hardness — The hardness of a metal or part, as represented by the number obtained from the ratio between the load applied on and the spherical area of the impression made by a steel ball forced into the surface of the material tested. The Brinell Hardness Number (BHN) is determined by measuring the diameter of the impression using a low power microscope, then matching this diameter with the load on a standard table.

Buckling — A bulge, bend, kink, or other wavy condition of the workpiece caused by compressive stresses. See also Compressive Stress.

Burning — Permanently damaging a metal or alloy by heating so as to cause either incipient melting or intergranular oxidation.

Burr — A thin ridge or roughness left on forgings by cutting operation such as slitting, shearing, trimming, blanking, or sawing.

Buster (rougher) — An impression employed in a die when considerable metal movement is required and which precedes a blocker cavity and a finisher cavity. Also known as breakdown/pancake, scalebreak, cheese.

Buster (preblocking impression) — A type of die impression sometimes used to combine preliminary forging operations such as edging and fullering with the blocking operation to eliminate blows.

Carbon steel — Steel containing carbon up to about 1.2%, and only residual amounts of other elements except for those added for composition control, with silicon usually limited to 0.60 % and manganese to 1.65%.

Cassette — Also known as sub-bolster, die assembly, trim and pierce assembly. An assembly of top and bottom dies and/or tools of each forming station assembled into one unit.

Cast (proof) — Any reproduction of a die cavity in any material, frequently lead, plaster or epoxy, used to confirm the exactness of the cavity. See Die Proof.

Cavity, die — The machined recess in a die that gives the forging its shape.

Chamfer — To break or remove sharp edges or corners of forging stock by means of straight angle tool or grinding wheel.

Charpy impact test — An impact test in which a specially V-notched specimen is broken by the impact of a falling pendulum. The energy absorbed in fracture is a measure of the impact strength or notch toughness of the sample.

Check — Crack in a die impression, generally due to forging pressure and/or excessive die temperature. Die blocks too hard for the depth of the die impression have a tendency to check or develop cracks in impression corners.

Chop — A die forging defect; metal sheared from a vertical surface and spread by the die over an adjoining horizontal surface.

Chucking lug — A lug or boss to the forging so that "on center" machining and forming can be performed with one setting or chucking; this lug is machined or cut away on the finished item.

Cleaning — The process of removing scale, oxides, or lubricant—acquired during heating for forging or heat treating—from the surface of the forging. (See also Blasting, Pickling, Tumbling.)

Close-tolerance forging — One held to closer-than-conventional dimensional tolerances so that little or no machining is required after forging. See also Precision Forging.

Closed die forging — The shaping of hot metal completely within the walls or cavities of two dies that come together to enclose the workpiece on all sides. The impression for the forging can be entirely in either die or divided between the top and bottom dies. Impression-die forging, often used interchangeably with the term closed-die forging, refers to a closed-die operation in which the dies contain a provision for controlling the flow of excess material, or flash, that is generated. By contrast, in flashless forging, the material is deformed in a cavity that allows little or no escape of excess material. See Impression Die Forging.

Closing-in — The forging operation that locally reduces diameters in hollow forgings.

Closure, die — A term frequently used to mean variations in thickness of a forging.

Cogging — The reducing operation in which an ingot is worked into a billet by the use of a forging hammer or a forging press.

Coining — (1) A post-forging process—on hot or cold parts—used to attain closer tolerances or improved surfaces. (2) A closed-die squeezing operation in which all surfaces of a workpiece are confined or restrained, resulting in a well-defined imprint of the die on the work.

Coining dies — Dies in which the coining or sizing operation is performed.

Cold-coined forging — A forging that has been restruck cold in order to hold closer face distance tolerances, sharpen corners or outlines, reduce section thickness, flatten some particular surface, or, in non-heat-treatable alloys, increase hardness.

Cold forging — Various forging processes conducted at or near ambient temperatures to produce metal components to close tolerances and net shape. These include bending, cold drawing, cold heading, coining, extrusion (forward or backward), punching, thread rolling and others.

Cold heading — Plastically deforming metal at ambient temperatures to increase the cross-sectional area of the stock (either solid bar or tubing) at one or more points along the longitudinal axis. See also Heading and Upsetting.

Cold lap — A flaw that results when a workpiece fails to fill the die cavity during the first forging. A seam is formed as subsequent dies force metal over this gap to leave a seam on the workpiece surface. See also Cold Shut.

Cold saw — Mechanical sawing machine used to produce cut pieces prior to the forging operation. Sawing is carried out on the material at ambient temperature.

Cold shut — Also known as lap or fold. A defect such as lap that forms whenever metal folds over itself during forging. This can occur where vertical and horizontal surfaces intersect.

Cold trimming — Removing flash or excess metal from the forging in a trimming press when the forging is at room temperature.

Cold working — Permanent plastic deformation of a metal at a temperature below its recrystallization point—low enough to produce strain hardening. Usually, but not necessarily, conducted at room temperature. Also referred to as cold forming or cold forging. Contrast with hot working.

Concavity — A concave condition applicable to the width of any flat surface.

Concentricity — Adherence of part features to a common center.

Controlled cooling — Cooling from an elevated temperature in a predetermined manner to avoid hardening, cracking, or excessive internal stresses, or to produce a desired microstructure.

Conventional forging — A forging characterized by design complexity and tolerances that fall within the broad range of general forging practice.

Counterblow forging — One made by equipment incorporating two opposed rams, which simultaneously strike repeated blows on the workpiece.

Counterblow forging equipment — A category of forging equipment in which two opposed rams are activated simultaneously, striking repeated blows on the workpiece at a midway point. Action is vertical or horizontal.

Cross forging — Preliminary working of forging stock in alternate planes, usually on flat dies, to develop mechanical properties, particularly in the center portions of heavy sections.

Decarburization — The removal of carbon from the surface of steel as a result of heating in a medium that reacts with the carbon. Decarburization is usually present to a slight extent in steel forgings. Excessive decarburization can result in defective products.

Die holder — Also known as bolster, insert holder, can. Used to locate, clamp and support dies, die assemblies or die inserts.

Die impression — The portion of the die surface that shapes the forging.

Die lubricant — A material sprayed, swabbed, or otherwise applied during forging to reduce friction and/or provide thermal insulation between the workpiece and the dies. Lubricants also facilitate release of the part from the dies and provide thermal insulation. See also Lubricant.

Die match — Also known as mismatch. The alignment of the upper (moving) and lower (stationary) impression in the die.

Die proof (cast) — A casting of the die impression made to confirm the exactness of the impression.

Die set — The assembly of the upper and lower die shoes (punch and die holders), usually including the guide pins, guide pin bushings, and heel blocks. This assembly takes many forms, shapes, and sizes and is frequently purchased as a commercially available unit. Also, two (or, for a mechanical upsetter, three) machined dies used together during the production of a die forging.

Die shift — The condition that occurs after the dies have been set up in a forging unit in which a portion of the impression of one die is not in perfect alignment with the corresponding portion of the other die. This results in a mismatch in the forging, a condition that must be held within the specified tolerance.

Die shoes — The upper and lower plates or castings that constitute a die set (punch and die holder). Also a plate or block upon which a die holder is mounted, functioning primarily as a base for the complete die assembly. This plate or block is bolted or clamped to the bolster plate or the face of the press ram.

Die sinking — The process of machining impressions in die blocks.

Die straighten — A straightening operation performed in either a hammer or a press using flat or cavity dies to remove undesired deformation and bring the forging within the straightness tolerance.

Dies (die blocks) — The metal blocks into which forging impressions are machined and from which forgings are produced.

Dies, forging — Forms for the making of forgings; generally consist of a top and bottom die. The simplest will form a completed forging in a single impression; the most complex, made up of several die inserts, may have a number of impressions for the progressive working of complicated shapes. Forging dies are usually in pairs, with part of the impression in one of the blocks and the balance of the impression in the other block.

Dies, gripper — Clamping or lateral dies used in a forging machine or mechanical upsetter.

Direct (forward) extrusion — See Extrusion.

Directional properties — Properties whose magnitude varies depending on the relation of the test axis to a specific direction within the metal or alloy.

Disc (disk) — "Pancake" shaped forging (flat with a round cross-section); e.g., a blank for gears, rings and flanged hubs. Abbreviation is "D."

Discontinuities — Includes cracks, laps, folds, cold shuts, and flow-through, as well as internal defects such as inclusion, segregation, and porosity; internal discontinuities can be detected and evaluated using ultrasonic testing equipment.

Double forging — A forging designed to be cut apart and used as two separate pieces.

Draft — The necessary taper on the side of a forging to allow removal from the dies; also applies to the die impression. Commonly expressed in degrees as the draft angle. As applied to open die forging, draft is the amount of relative movement of the dies toward each other through the metal in one application of power.

Draft angle — The angle of taper, expressed in degrees (usually 5° to 7°), given to the sides of the forging and the side walls of the die impression.

Draftless forging — A forging with zero draft on vertical walls.

Drawing — (1) A forging operation in which the cross section of forging stock is reduced and the stock lengthened between flat or simple contour dies. See also Fullering. (2) in heat treating, the same as tempering.

Drawing out — The forging operation in which the length of a metal mass (stock) is increased at the expense of its cross section; no "upset" is involved. The operation covers converting ingot to pressed bar using "V," round, or flat dies.

Dressout — A condition where the dimensions of a part or forging are changed by local grinding or machining to remove one or more defects thereby causing a localized imperfection of a maximum depth. The depth is the dimension of the dressout.

Drifting — In forging, the operation of forming or enlarging a hole by use of a tapered punch.

Drop forging — A forging made in closed or impression dies under a drop or steam hammer.

Drop hammer — A term generally applied to forging hammers wherein energy for forging is provided by gravity, steam, or compressed air. See also Air-Lift Hammer, Board Hammer, Steam Hammer.

Ductility — The property of a metal that enables it to stretch before rupturing.

Dwell — Portion of a press cycle during which the movement of a member is zero or at least insignificant. Usually refers to the interval between the completion of the forging stroke and the retraction of the ram.

Dye-penetrant testing — Inspection procedures for detecting surface irregularities using penetrating liquids containing dyes or fluorescent substances.

Eccentric — The offset portion of the driveshaft that governs the stroke or distance the crosshead moves on a mechanical or manual shear.

Eccentric press — A mechanical press in which an eccentric, instead of a crankshaft, is used to move the ram.

Edger (edging impression) — The portion of the die impression that distributes metal, during forging, into areas where it is most needed to facilitate filling the cavities of subsequent impressions to be used in the forging sequence. See also Fuller.

Edging — The forging operation of working a bar between contoured dies while turning it 90° between blows to produce a varying rectangular cross section.

Efficiency (forging) — The amount of applied energy, in percentage, that is employed in deforming the workpiece to the total energy expended by the forging equipment.

Ejector — Also known as knockout. Heat treated steel rods located within the dies and operated by the press action to remove a completed forging after the forging cycle.

End loss (crop end) — Bar end left over after cutting bar lengths of stock into forging multiples. See also Multiple.

Etch test — The process of revealing the macrostructure of metals by preferential attack of a prepared surface by a suitable reagent.

Expanding — A hollow forging operation whereby the diameters are increased by reducing wall thickness with relatively little increase in length by working on a mandrel.

Extrusion — The process of forcing metal to flow through a die orifice in the same direction in which energy is being applied (forward extrusion); or in the reverse direction (backward extrusion), in which case the metal usually follows the contour of the punch or moving forming tool. The extrusion principle is used in many impression die forging applications.

Extrusion billet — A metal slug used as extrusion stock.

Extrusion defect — See Extrusion pipe.

Extrusion pipe — A central oxide-lined discontinuity that occasionally occurs in the last 10% to 20% of an extruded bar. It is caused by the oxidized outer surface of the billet flowing around the end of the billet and into the center of the bar during the final stages of extrusion. Also called coring.

Feather (Fin) — The thin projection formed on a forging by trimming or when the metal under pressure is forced into hairline cracks or die interfaces.

Fiber — A characteristic of wrought metal, including forgings, indicated by a fibrous or woody structure of a polished and etched section, and indicating directional properties. Fiber is chiefly due to the extension of the constituents of the metal synonymous with flow lines and grain flow in the direction of working.

Fillet — The concave intersection of two surfaces. In forging, the desired radius at the concave intersection of two surfaces is usually specified.

Fin — The thin projection formed on a forging by trimming or when metal is forced under pressure into hairline cracks or die interfaces.

Finish — (1) The forging operation in which the part is forged into its final shape in the finish die. If only one finish operation is scheduled to be performed in the finish die, this operation will be identified simply as finish; first, second, or third finish designations are so termed when one or more finish operations are to be performed in the same finish die. (2) The surface condition of a forging after machining. (3) The material machined off the surface of a forging to produce the finish machine component.

Finish all over (F.A.O.) — A designation that a forging must have sufficient size over the dimensions given on the drawing so that all surfaces may be machined in order to obtain the dimensions shown on the drawing. The amount of additional stock necessary for machining allowance depends on the size and shape of the part, and is agreed on by the vendor and the user.

Finish allowance — The amount of stock left on the surface of the forging to be removed by subsequent machining. Also called "machining allowance" or "forging envelope."

Finish forging — See Conventional Forging.

Finish trim — Flash removal from a forging; usually performed by trimming, but sometimes by band sawing or similar techniques.

Finisher (finish impression) — The die impression that imparts the final shape to a forged part.

Finishing dies — The die set used in the last forging step.

Finishing temperature — The temperature at which hot mechanical working of a metal is completed or discontinued.

Flakes — Randomly oriented internal thermal cracks ("shatter cracks") in steels resulting from critical combinations of stress and hydrogen content. In a fracture surface, flakes appear as bright silvery areas; on an etched surface they appear as short discontinuous cracks.

Flame straightening — The correction of distortion in metal structures by localized heating with a gas flame.

Flange — A projecting rim or edge of a part; usually narrow and of approximately constant width for stiffening or fastening. See Rib.

Flash — Metal in excess of that required to fill completely the blocking or finishing forging impression of a set of dies. Flash extends out from the body of the forging as a thin plate at the line where the dies meet and is subsequently removed by trimming. Because it cools faster than the body of the component during forging, flash can serve to restrict metal flow at the line where dies meet, thus ensuring complete filling of the impression. See also Closed-Die Forging.

Flash extension — Portion of flash remaining after trimming. Flash extension is measured from the intersection of the draft and flash at the body of the forging to the trimmed edge of the stock.

Flash, internal — That portion of the flash located entirely within a forging or enclosed by two or more forgings within a cluster of forgings.

Flash land — Configuration in the blocking or finishing impression of forging dies designed to restrict or to encourage the growth of flash at the parting line, whichever may be required in a particular case to ensure complete filling of the impression.

Flash line — The line left on a forging after the flash has been trimmed off. See Parting Line.

Flashless forging — "True" closed die forging in which metal deformed in a die cavity permits virtually no excess metal to escape.

Flat die forging (open die forging) — Forging worked between flat or simple contour dies by repeated strokes and manipulation of the workpiece. Also known as "hand" or "smith" forging. See Open-Die Forging.

Flattener — Usually a flat surface cut to an exact depth below the parting line in each die to widen the material so as to more nearly cover the next impression.

Flattening — The forging operation of flattening the forging stock prior to further working.

Floating die — (1) A die mounted in a die holder or a punch mounted in its holder such that a slight amount of motion compensates for tolerance in the die parts, the work, or the press. (2) A die mounted on heavy springs to allow vertical motion in some trimming, shearing, and forming operations.

Flow lines — Patterns in a forging resulting from the elongation of nonhomogeneous constituents and the grain structure of the material in the direction of working during forging; usually revealed by macroetching. See also Grain Flow.

Flow stress — A measure of materials resistance to deformation and depends upon such things as temperature and strain rate.

Flow-through — A forging defect caused by metal flow past the base of a rib with consequent rupture of the grain structure.

Fluorescent magnetic particle inspection — Inspection with either dry magnetic particles or those in a liquid suspension, the particles being coated with a fluorescent substance to increase the visibility of the indications.

Fold — A forging defect caused by folding the metal back on its own surface during its flow in the die cavity. See Lap.

Force multiplier — A dimensionless factor that is used to describe the relative force requirement of a forging or a forging section.

Forgeability — The relative ability of material to deform without fracturing, rupturing, or developing flaws. Also describes the resistance to flow from deformation. See also Formability.

Forging — The process of working metal to a desired shape by impact or pressure in hammers, forging machines (upsetters), presses, rolls, and related forming equipment.

Forging billet — A wrought metal slug used as forging stock.

Forging dies — Forms for making forgings; they generally consist of a top and bottom die. The simplest will form a completed forging in a single impression; the most complex, consisting of several die inserts, may have a number of impressions for the progressive working of complicated shapes. Forging dies are usually in pairs, with part of the impression in one of the blocks and the rest of the impression in the other block.

Forging envelope — See Finish Allowance.

Forging machine (upsetter or header) — A type of forging equipment, related to the mechanical press, in which the main forming energy is applied horizontally to the workpiece, which is gripped and held by prior action of the grip dies.

Forging plane — The plane that includes the principal die face and is perpendicular to the direction of ram travel. When parting surfaces of the dies are flat, the forging plane coincides with the parting line.

Forging quality — Term describing stock of sufficiently superior quality to make it suitable for commercially satisfactory forgings.

Forging reduction — Ratio of the cross-sectional areas before and after forging; sometimes refers to percentage reduction in thickness.

Forging roll — Also known as reducer roll. A machine situated alongside the forging machine for pre-forming. The operation is carried out by passing the work-piece between contra-rotating shafts, which carry appropriately shaped dies.

Forging stock — A wrought rod, bar, or other section suitable for subsequent change in cross section by forging.

Forging stresses — Elastic residual stresses induced by forging or by cooling from the forging temperature. They can be relieved by subsequent annealing or normalizing.

Form rolling — Hot rolling to produce bars having contoured cross sections; not to be confused with the roll forming of sheet metal or with roll forging.

Forward extrusion — Same as direct extrusion. See Extrusion.

Fracture toughness — The resistance of a given material to catastrophic failure in the presence of an existing sharp crack.

Frame — The main structure of a press.

Free-machining-steel forgings — Those made from steels with special alloying-element additions to facilitate machining.

Friction factor — A factor that, when multiplied by the flow stress, expresses the friction shear stress.

Fuller (fullering impression) — Portion of the die that is used in hammer forging primarily to reduce the cross section and lengthen a portion of the forging stock. The fullering impression is often used in conjunction with an edger (or edging impression).

Fullering — Reducing the cross section of a forging between ends of stock.

Gate (sprue) — A portion of the die that has been removed by machining and permits the bar or tongs to be closer to the impression without being smashed.

Gathering stock — Any operation whereby the cross-section of a portion of the forging stock is increased above its original size.

Gibs — Guides or shoes that ensure the proper parallelism, squareness, and sliding fit between press components such as the ram and the frame. They are usually adjustable to compensate for wear and to establish operating clearance.

Grain — An individual crystal in a polycrystalline metal or alloy.

Grain flow — Fiber-like lines appearing on polished and etched sections of forgings that are caused by orientation of the constituents of the metal in the direction of working during forging. Grain flow produced by proper die design can improves the mechanical properties of forgings.

Grain growth — An increase in the size of the grains of a metal with a proportional reduction of the number of grains.

Grain separation — In forging aluminum, rapid metal flow sometimes causes a separation or rupture of grain. Metal flow is affected by lubricant, die and metal temperature, part shape, alloy, and hammer operator technique; consequently, any one or combination of these factors can cause grain separation. The irregular crevices are seldom more than a few thousandths of an inch deep and can be removed by grinding or polishing.

Grain size — An expression that rates the number of grains per unit area of cross section as determined by metallographic examination.

Gravity hammer — A class of forging hammer wherein energy for forging is obtained by the mass and velocity of a freely falling ram and the attached upper die. Examples are board hammers and air-lift hammers.

Gripper dies — The lateral or clamping dies used in a mechanical upsetter or forging machine.

Grit blasting — See Blasting.

Guide — The parts of a drop hammer or press that guide the up-and-down motion of the ram in a true vertical direction.

Gutter — A shallow impression machined around the periphery of a forging die impression outside the flash land that acts as a reservoir for excess metal.

Hammer — A machine that applies a sharp blow to the work area through the fall of a ram onto an anvil. The ram can be driven by gravity or power. See also Gravity Hammer and Power-Driven Hammer.

Hammer forging — The mechanical forming of metal by means of a hammer. The action of the hammer is that of an instantaneous application of pressure in the form of a sudden blow.

Hand forging — (See also Open Die Forging) (1) A forging made by hand on an anvil or under a power hammer without dies containing an exact finishing impression of the part. Such forgings approximate each other in size and shape but do not have the commercial exactness of production die forgings. Used where the quantity of forgings required does not warrant expenditure for special dies, or where the size or shape of the piece is such as to require means other than die forging. (2) A forging worked between flat or simply shaped dies by repeated strokes and manipulation of the piece. Also known as smith forging or flat die forging.

Hand straightening — A straightening operation performed on a surface plate to bring a forging within the straightness tolerance. Frequently, a bottom die from a set of finish dies is used instead of a surface plate. Hand tools used include mallets, sledges, blocks, jacks, and oil gear presses in addition to regular inspection tools.

Handling hole — Holes drilled in opposite ends of the die block to permit handling by the use of a crane or bar.

Handling marks — Nicks and gouges formed on forgings if improperly handled; most prevalent for forgings in the as-forged condition prior to heat treatment.

Header — See Forging machine.

Heading — The upsetting of wire, rod, or bar stock in dies to form parts that usually contain portions that are greater in cross-sectional area than the original wire, rod, or bar.

Heat — A term used to identify the material produced from a single melting operation. Different heats of the same material can vary in chemical composition within prescribed limits. Stock from a single heat will have a consistent analysis and more uniform properties. Also known in the U.K. as "Cast".

Heat (forging) — Amount of forging stock placed in a batch-type furnace at one time.

Heat analysis — See Ladle analysis.

Heat-resistant steel — Alloy steel designed for application at elevated temperatures.

Heat treatment — A sequence of controlled heating and cooling operations applied to a solid metal to impart desired properties.

Hogout — A product machined from bar or plate stock or from a hand forging, rather than from an impression die forging. The process is commonly known as "hogging out" material.

Hollow forging — (1) Processes for forging tubes or ring forgings. (2) Cylindrical open die forging, e.g., thick-walled tubes or rings.

Hot-die forging — A process in which dies are heated close to the forging temperature of the alloy being forged; used for difficult-to-forge alloys.

Hot forging — Same as hot working—plastically deforming an alloy at a temperature above its recrystallization point, i.e, high enough to avoid strain hardening.

Hot inspection — An in-process examination of forgings, using gauges, templates, or other nondestructive inspection methods to ensure quality.

Hot shortness — Lack of ductility when metal is hot.

Hot trimming — The removal of flash or excess metal from a hot part (such as a forging) in a trimming press.

Hot upset forging — A bulk forming process for enlarging and reshaping some of the cross-sectional area of a bar, tube, or other product form of uniform (usually round) section. It is accomplished by holding the heated forging stock between grooved dies and applying pressure to the end of the stock, in the direction of its axis, by the use of a heading tool, which spreads (upsets) the end by metal displacement. Also called hot heading or hot upsetting. See also Heading and Upsetting.

Hot working — The plastic deformation of metal at such a temperature and strain rate that recrystallization takes place simultaneously with the deformation, thus avoiding any strain hardening. Also referred to as hot forging and hot forming. Contrast with cold working.

Hub — A boss that is in the center of a forging and forms a part of the body of the forging.
Hydraulic hammer — A gravity-drop forging hammer that uses hydraulic pressure to lift the hammer between strokes.

Hydraulic press — A forging press with a hydraulically operated ram.

Impact extrusion — A reverse extrusion process in which metal is displaced backwards between a punch and a die to form a hollow part.

Impact test — Test to determine the energy absorbed in fracturing a notched test bar at high velocity. See also Charpy Test, Izod Test.

Impact velocity — The relative velocity of the forging dies just prior to impact.

Impression — A cavity, or series of cavities (multiple), machined into a forging die to produce a desired configuration in the workpiece during forging.

Impression die forging — A forging that is formed to the required shape and size by machined impressions in specially prepared dies that exert three-dimensional control on the workpiece.

Inclusions — Particles of nonmetallic compounds of metals and impurity elements that are present in ingots and are carried over in wrought products. The shape and distribution of inclusions are changed by plastic deformation and contribute to directionality in metals.

Indirect (backward) extrusion — See Extrusion.

Induction heating — Heating metals by means of an alternating magnetic field.

Ingot — A casting intended for subsequent rolling, forging, or extrusion.

Ingotism — A term used to describe the remnants of dendritic structure which may occasionally be found in forgings.

Insert — A piece of steel that is tightly fixed in a die. The insert may be used to fill a cavity, to replace a portion of the die with a grade of steel that is better suited for service at that point, or to function as a small die with the impression fastened to a master die.

Insert die — A relatively small die containing part or all of the impression of a forging, and which is fitted to the master die block by means of a key.

Isothermal forging — A hot-forging process in which a constant and uniform temperature is maintained in the workpiece during forging by heating the dies to the same temperature as the workpiece. Most commonly conducted at about 2000°F under a controlled atmosphere or in a vacuum to prevent oxidation while forging superalloys.

Izod impact test — A pendulum-type impact test in which the specimen is supported at one end as a cantilever beam and the energy required to break off the free end by the impact of a falling pendulum is used as a measure of impact strength. See Charpy Impact Test.

Knockout — A mechanism for releasing workpieces from a die.

Knockout mark — A small protrusion, such as a button or ring of flash, resulting from the depression of a knockout pin from the forging pressure, or the entrance of metal between the knockout pin and the die.

Knockout pin — A power-operated plunger installed in a die to aid removal of the finished forging.

Ladle analysis — The results of the chemical analysis of a test sample taken during the pouring of a melt. Also called heat analysis.

Lap — A surface irregularity appearing as a fissure or opening, caused by the folding over of hot metal, fins or sharp corners and by subsequent rolling or forging (but not welding) of these into the surface.
Layout — (1) Transferring drawing or sketch dimensions to templates or dies for use in sinking dies. (2) A detailed inspection operation in which significant dimensions of a forging are checked against blueprint specifications.

Layout sample — A plaster, lead, or forged alloy sample taken from new dies to verify accuracy by layout and precise measurement. See also Cast.

Lead proof — A reproduction in lead, or a lead alloy, of the die impression, obtained by clamping the two dies together in alignment and pouring molten metal into the finish impression.

Liftout — The mechanism also known as knockout.

Lock — In forging, a condition in which the flash line is not entirely in one plane. Where two or more plane changes occur, it is called compound lock. Where a lock is placed in the die to compensate for die shift caused by a steep lock, it is called a counterlock.

Locked dies — Dies with mating faces that lie in more than one plane.

Lower punch — The lower part of a die, which forms the bottom of the die cavity and which may or may not move in relation to the die body; usually movable in a forging die.

Lubricant — A material applied to dies, molds, plungers, or workpieces that promotes the flow of metal, reduces friction and wear, and aids in the release of the finished part.

Lubricant residue — The carbonaceous residue resulting from lubricant burned on the surface of a hot forged part.

Machine forging (upsetter forging) — The process of forging in a forging machine (upsetter), in which the metal is moved into the die impression by pressure applied in a horizontal direction by the moving die in the ram.

Machining allowance — See Finish allowance.

Macroetch — A testing procedure for conditions such as porosity, inclusions, segregation, carburization, and flow lines from hot working. After applying a suitable etching solution to the polished metal surface, the structure revealed by the action of the reagent can be observed visually. See Etch test.

Macrostructure — The structure and condition of metals as revealed on a suitably prepared and etched sample, and visible without the use of a microscope or under low magnification (up to 10 diameters).

Magnetic-particle inspection (testing) — A nondestructive method of inspection/testing for determining the existence and extent of possible defects in ferro-magnetic materials. The metal is magnetized, then iron powder is applied. The powder adheres to lines of flux leakage, revealing surface and near-surface discontinuities.

Mandrel — A blunt-ended tool or rod used to retain or enlarge the cavity in a hollow metal product during forging.

Mandrel forging — The process of rolling and forging a hollow blank over a mandrel in order to produce a weldless, seamless ring or tube. See Saddle/Mandrel Forging.

Manipulator — A mechanical device for handling an ingot or a billet during forging.

Master — Wood, metal or plastic reproduction of a proposed forged shape, used to control cutters on tracer-controlled die sinking equipment.

Master block (or master holder) — A forging die block primarily used to hold insert dies.

Match — A condition in which a point in one die half is aligned properly with the corresponding point in the opposite die half within specified tolerance.

Matching draft — Increased draft used on the shallow side of a forging to match its surface at the parting line with a similar surface of less draft on the deeper side.

Mechanical press — A forging press with an inertia flywheel, a crank and clutch, or other mechanical device to operate the ram.

Mechanical upsetter — A three-element forging press, with two gripper dies and a forming tool, for flanging or forming relatively deep recesses.

Metal discontinuities — See Discontinuities.

Microalloyed-steel forging — One made from a microalloyed steel requiring only controlled cooling to reach optimum properties, in contrast to conventional quenched-and-tempered steels that require traditional heat treatments to achieve the same results.

Microstructure — The structure and internal condition of metals as revealed on a ground and polished (and sometimes etched) surface when observed at high magnification (over 10 diameters).

Mill scale — The heavy oxide layer that forms during heating and forging of steel.

Mismatch — The misalignment or error in register of a pair of forging dies; also applied to the condition of the resulting forging.

Mismatch allowance — An allowance for misalignment (or mismatch) included in forging tolerances.

Multiple — (1) Term used to describe a die impression designed to produce more than a single piece at a time. (2) A piece of stock for forging that is cut from bar or billet lengths to provide the exact amount of material needed for a single workpiece.

Natural draft — Taper on the sides of a forging, due to its shape or position in the die, that makes added draft unnecessary.

Near-net-shape forging — Forging components as close as possible to the required dimensions of the finished part.

Nesting — The positioning of multiple pieces in a forging die design.

Net-shape forging — (See also Precision forging) Forging components on one or more sides to net shape requiring no further machining on at least one side. e.g. net forged gear with machined back face.

No-draft forging — A forged shape with extremely close tolerances and little or no draft, requiring a minimum of machining to produce the final part. Mechanical properties can be enhanced by this closer control of grain flow and retention of surface material in the final component.

Nondestructive inspection — Any method of detection or measurement of the properties or performance capabilities of materials, parts, assemblies, or structures that does not impair the surface or internal integrity of the part.

Nonferrous — Metals or alloys that contain no appreciable quantity of iron; applied to such metals as aluminum, copper, magnesium, and their alloys.

Nonfill (underfill) — Forging condition that occurs when the finish die impression is not completely filled with metal. Some causes are: improper distribution of metal in preforming operations such as fullering, edging, and blocking; excessive removal of material by chipping defects prior to finish forging; improper lubrication of die impression; low forging pressure; rough or uneven die finish; inadequate hammer or press capacity.

Nonmetallic inclusions — See Inclusions.

Offset — (1) A condition created in a forging when the dies used in the forging operation do not align properly. (2) The alignment of the upper and lower dies in the hammer or press.

Open die forging — Forging produced by working between flat or simply contoured dies with unrestricted metal flow using repetitive strokes and continuous manipulation of the workpiece; sometimes called hand forging.

Open dies — Dies with flat surfaces that are used for preforming stock or producing hand forgings.

Overheated metal — Metal with an undesirable coarse grain structure due to exposure to an excessively high temperature. Unlike a "burnt" structure, the metal is not permanently damaged but can be corrected by mechanical working.

Overetch — In the normal processing of aluminum forgings, a caustic etch operation is employed for the dual purpose of cleaning parts and emphasizing defects to facilitate visual inspection. Immersion of parts for too long or use of too concentrated a solution will produce a rough, slightly pitted surface.

Pancake forging — A rough forged shape, usually flat, that can be obtained quickly with minimal tooling. Considerable machining is usually required to attain the finish size.

Parting line — (1) The line along the surface of a forging where the dies meet, usually at the largest cross section of the part. Flash is formed at the parting line. (2) The plane that divides the two forging die halves.

Penetration rate — Depth rate of working.

Pickling — The process of removing oxide scale from forgings by treating in a heated acid bath.

Pick-up — Small particles of oxidized metal adhering to the surface of a mill product.

Pierce — In ring rolling, the process of providing a through hole in the center of an upset forging using a tapered or cylindrical punch. See Drifting.

Plan view area — The area of the plan view of a forging; sometimes used to indicate the relative size of a forging.

Planishing — A finishing operation for the purpose of removing the trim line of forgings or of obtaining closer tolerances. Usually done by rolling, pressing or hammering, hot or cold.

Plaster cast — See Lead Proof.

Platter — The entire mass of metal upon which the hammer performs work, including the flash, sprue, tonghold, and as many forgings as are made at one time.

Plug — (1) A protruding portion of a die impression for forming a corresponding recess in the forging. (2) A false bottom in a die.

Poisson's ratio — The ratio of strain in the longitudinal direction to that in the transverse direction. Typical values range from 0.28 to 0.33 for most forging alloys.

Powder forging — The plastic deformation of a powder metallurgy compact or preform into a fully dense finished shape by using compressive force; usually done hot and within closed dies.

Power-driven hammer — A forging hammer with a steam or air cylinder for raising the ram and augmenting its downward blow.

Power rolls — Power-driven rolls used in preforming bar or billet stock that have shaped contours and notches for introduction of the work.

Precision forging — (See also Net-shape forging) A forging produced to closer tolerances than normally considered standard by the industry.

Preform — (1) The forging operation in which stock is preformed or shaped to a predetermined size and contour prior to subsequent die forging operations. When a preform operation is required, it will precede a forging operation and will be performed in conjunction with the forging operation and in the same heat. (2) Ring blanks of a specific shape for profile (contour) ring rolling. (3) The initially pressed powder metallurgy compact to be subjected to repressing.

Preform impression — Any one or a combination of preliminary die impressions used in producing a preform. Also known as blocker, buster, scalebreak, and extrusion.

Preheating — (1) A preliminary heating of ingots, billets, or forgings to reduce the hazards of thermal shock upon subsequent heating to higher temperatures. (2) A high-temperature soaking treatment used to change the metallurgical structure in preparation for a subsequent operation, usually applied to the ingot.

Preparation charge — A one-time charge covering the cost of sinking dies and preparing required auxiliary tooling for producing forgings to a particular design. In usual practice, this charge conveys to the customer the exclusive right to purchase forgings produced on this tooling. The dies themselves are the property of the forger, who also has the responsibility for maintaining and replacing the dies as required for satisfactory production of forgings.

Pre-pierce — (1) In ring rolling, a vertically mounted piercing (punching) tool used for preparation of ring blanks on the ring blank press. (2) A tapered tool of various diameters and lengths.

Press — A machine tool with a stationary bed and a slide or ram that has reciprocating motion at right angles to the bed surface; the ram is guided in the frame of the machine.

Press capacity — The rated force a press is designed to exert at a predetermined distance above the bottom of the stroke of the ram.

Press forging — The shaping of metal between dies on a mechanical or hydraulic press. The action is that of kneading the metal by relatively slow application of force as compared with the action of hammering.

Pressure profile — A tabulation of the change in pressures across a forging section, usually in graphical form.

Profile (contour) rolling — In ring rolling a process to produce seamless rolled rings with a predesigned shape either on the outside or the inside diameter, requiring less volume of material and less machining to produce finished parts.

Progressives — A collection of sample forgings taken following the first and subsequent blows of the forging sequence. Also known as a progression.

Prolongation — An extra portion of metal added in a mutually agreeable location of a forging to permit removal and subsequent testing without destroying the forging. Generally applies to open die and some large rolled rings.

Proof — Any reproduction of a die impression in any material. See also Lead Proof.

Punchout — Metal removed when punching a hole in a forging.

Ram — The main reciprocating member of a press, guided in the press frame, to which the punch or upper die is fastened.

Ram adjustment — The distance that a press ram position can be altered to change the shut height of the die space. The adjustment can be made by hand or by power mechanism.

Rib — A relatively flat (but generally with draft) thin portion of a forging, generally perpendicular to the forging plane.

Sadden — To forge an ingot lightly in the initial forging operation in order to break up and refine coarse, as-cast structure at the surface.

SAE (specifications) — The Society of Automotive Engineers.

Shoe — A holder used as a support for the stationary portions of forging and trimming dies.

Shot blasting — A process of cleaning forgings by propelling metal shot at high velocity by air pressure or centrifugal force at the surface of the forgings. See also Blast cleaning.

Shrinkage — The contraction of metal during cooling after hot forging. Die impressions are made oversize according to precise shrinkage scales to allow the forgings to shrink to design dimensions and tolerances.

Shrink scale — A measuring scale or rule, used in die layout, on which graduations are expanded to compensate for thermal contraction (shrinkage) of the forging during cooling.

Shut height — For a press, the distance from the top of the bed to the bottom of the ram with the stroke down and adjustment up. In general, it is the maximum die height that can be accommodated for normal operation, taking the bolster plate into consideration.

Shuts (cold) — Faults produced in a forging by incorrect tool design or incorrect flow of steel that results in the formation of a crack in the forging surface.

Side thrust — Lateral force exerted between the dies by reaction of the forged piece on the die impressions.

Sinking — The operation of machining the impression of a desired forging into die blocks.

Sizing — Secondary forming or squeezing operations needed to square up, set down, flatten, or otherwise correct surfaces to produce specified dimensions and tolerances. Often accomplished with a coining press. See Coining.

Sliver — A slender fragment or splinter that is a part of the material, but that is incompletely attached. A torn fiber of metal forced into the surface of a forging.

Slot furnace — A common batch-type forge furnace where stock is charged and removed through a slot or opening.

Slug — (1) Forging stock for one workpiece cut to length. See also Blank. (2) Metal removed when punching a hole in a forging (also termed "punchout").

Smith — The blacksmith, forger, or pressman.

Smith forging — See Flat die forging, Hand forging.

Smith hammer — Any power hammer where impression dies are not used for the reproduction of commercially exact forgings.

Snag grinding (snagging) — The process of removing portions of forgings not desired in the finished product, by grinding.

Sow block — A block of heat-treated steel placed between a hammer anvil and a forging die to prevent undue wear to the anvil. Sow blocks are occasionally used to hold insert dies. Also called Anvil cap.

Splitter impression — (1) A die cavity used to divide laterally or split the material being worked so that it better covers the impression and reduces forging load; (2) A die cavity used to cut the material apart in the desired section by means of a shearing action.

Split die — A die made of parts that can be separated for ready removal of the workpiece. Also known as segment die.

Springback — (1) The elastic recovery of metal after stressing. (2) The extent to which metal tends to return to its original shape or contour after undergoing a forming operation. This is compensated for by overbending or by a secondary operation of restriking.

Stainless steels — Steels that are corrosion and heat resistant and contain a minimum of 10% to 12% chromium. Other alloying elements are often present.

Stamp (marking) — An operation performed to identify the particular forgings as specified or requested by the customer.

Station — A regular stopping place in the die during the forging sequence.

Steam hammer — A type of drop hammer where the ram is raised for each stroke by a double-action steam cylinder and the energy delivered to the workpiece is supplied by the velocity and weight of the ram and attached upper die driven downward by steam pressure. Energy delivered during each stroke may be varied.

Stock — The material to be forged regardless of form. Also, an individual piece of metal used to produce a single forging.

Stock marks — In cutting forging stock to specified length for a die-forged part, the ends of the bar always contain surface imperfections caused by the cutting tool; these are often retained on the surface of the finished part. If pronounced, such marks are removed by light grinding. On parts where repeated indications of stock marks are encountered, efforts are usually made to eliminate them by conditioning the stock ends prior to forging by polishing the cut ends and beveling the edge of the cut.

Straighten — Finishing operation for correcting misalignment in a forging or between different sections of a forging. Straightening may be done by hand, with simple tools, or in a die in forging equipment.

Straighten, coin — A combination coining and straightening operation performed in special cavity dies designed to impart a specific amount of working in specified areas of the forging to relieve stresses set up during heat treatment.

Straighten, die — A straightening operation performed in either a hammer or a press using flat or cavity dies to remove undesired deformation and bring the forging within straightness tolerance.

Straighten, hand — A straightening operation performed on a surface plate to bring a forging within straightness tolerance. Frequently, a bottom die from a set of finish dies is used instead of a surface plate; hand tools used include mallets, sledges, blocks, jacks, and oil gear presses, in addition to regular inspection tools.

Strain hardening — An increase in hardness and strength caused by plastic deformation at temperatures below the recrystallization range. Also known as work hardening.

Strain rate — The rate at which metal is deformed.

Strain-rate sensitive — Alloy that can be forged only at low rates of deformation.

Stripper — A lug or ring on the forging or an impression in the dies of a mechanical upsetter to ensure firm clamping of the workpiece in the gripper dies.

Stripper punch — A punch that serves as the top or bottom of the die cavity and later moves farther into the die to eject the part or compact. See also Ejector and Knockout.

Stroke (up or down) — The vertical movement of a ram during half of the cycle, from the full open to the full closed position or vice versa.

Structural integrity — Inherent microstructural soundness of forgings as a result of achieving 100% density, uniform metallurgical structure and grain size, as well as the absence of porosity, segregation, large inclusions, and other non-forged part defects.

Sub-sow block (die holder) — A block used as an adapter in order to permit the use of forging dies that otherwise would not have sufficient height to be used in the particular unit or to permit the use of dies in a unit where the shank sizes are different.

Suck-in — A defect caused by the "sucking in" of one face of a forging to fill a projection on the opposite side.

Superalloys — A term broadly applied to iron-base, nickel-base, and cobalt-base alloys, often quite complex, that exhibit high elevated-temperature mechanical properties and oxidation resistance.

Superplasticity — The ability of certain metals to develop extremely high tensile elongations at elevated temperatures and under controlled rates of deformation.

Swaging — (1) Reducing the diameter of or rounding out a section of a forging by a series of blows, tapering the forging lengthwise until the entire section attains the smaller dimension of the taper. (2) Tapering forging stock by forging, hammering, or squeezing.

Table mill — In ring rolling, a type of ring forging equipment employing multiple mandrels with a common main roll. Usually used in high volume production of small-diameter rolled rings.

Target machining — Incorporating a "target" (benchmark or gage point) on a forging to facilitate machining; coined locating surfaces and drilled centers are commonly used.

Temperature (Forging) — The temperature of the forging stock just prior to forging.

Template (Templet) — A gage or pattern made in a die department, usually from sheet steel; used to check dimensions on forgings and as an aid in sinking die impressions in order to correct dimensions.

Thermal cracks — Ruptures in metal set up by stresses due to thermal differentials.

Thermal-mechanical treatment — See Thermomechanical working.

Thermomechanical working — A general term covering a variety of processes combining controlled thermal and deformation treatments to obtain synergistic effects, such as improvement in strength without loss of toughness.

Thermal stress — Stresses in metal resulting from non-uniform distribution of heat.

Tolerance — The permissible deviation from a specification for any design characteristic.

Tong hold — The portion of the forging billet, usually on one end, that is gripped by the operator's tongs. It is removed from the part at the end of the forging operation. Common to drop hammer and press-type forging.

Tongs — Metal holder used to handle hot or cold forgings.

Tool steel — A superior grade of steel made primarily for use in tools and dies.

Tooling marks — Indications imparted to the surface of the forged part from dies containing surface imperfections or dies on which some repair work has been done. These marks are usually slight rises or depressions in the metal.

Tooling pad — See Chucking lug.

Trepanning — Removal of a core of metal by a hollow tool. May be performed by a hollow punch at forging temperatures or by a hollow cutting tool by machining at ambient temperatures.

Trim — The removal of the excess metal or flash produced during the forging process. The operation takes place in tools produced to the peripheral shape of the component, the component being pushed through the female impression by the identically-shaped male punch. The operation may be carried out hot or at room temperature.

Trim and punch — (1) A shearing operation to remove both an inner and an outer section of metal from a blocked or finished forging. (2) A combination of two operations whereby flash and punchout are removed simultaneously. The operation is generally performed on a trim press using a combination trim and punch die.

Trimmer — The combination of trimmer punch, trimmer blades, and perhaps trimmer shoe used to remove flash from a forging.

Trimmer blade — The portion of the trimmers through which the forging is pushed to shear off the flash. The shearing edge may be in more than one plane in order to fit the parting line of the forging.

Trimmer die — The upper portion of the trimmer that comes in contact with the forging and pushes it through the trimmer blades; the lower end of the trimmer punch is generally shaped to fit the surface of the forging against which it pushes. Also termed Trimmer punch.

Trimming press — A power press suitable for trimming flash from forgings.

Tryout — Preparatory run to check or test equipment, lubricant, stock, tools, or methods prior to a production run. Production tryout is run with tools previously approved; new die tryout is run with new tools not previously approved.

Tumbling — (1) The process for removing scale from forgings in a rotating container by means of impact with each other and abrasive particles and small bits of metal. (2) A process for removing scale and roughness from forgings by impact with each other, together with abrasive material in a rotating container.

Turning — Removing metal from the outside of a part by means of a tool in a lathe or similar machine tool.

Ultrasonic testing — A method of nondestructive testing of solid metal for internal flaws utilizing high-frequency sound waves.

Undercuts — Sections of a forging which, if driven into the impression while the metal is hot, would lock themselves into a die impression and prevent removal of the forging without distortion.

Underfill — A portion of a forging that has insufficient metal to give it the true shape of the impression.

UNS — The Unified Numbering System. A system that provides a means of correlating many nationally used numbering systems currently administered by societies, trade associations, and individual users and producers of metals and alloys, thereby avoiding confusion caused by use of more than one identification number for the same material. It also avoids having the same number assigned to two or more entirely different materials.

Upset forging — (1) A forging made by upsetting an appropriate length of bar, billet or bloom. (2) Working metal to increase the cross-sectional area of a portion or all of the stock. (3) A forging formed by heading or gathering the material by pressure upon hot or cold metal between dies operated in a horizontal plane.

Upsetter (Forging machine) — A horizontal forging machine where the workpiece is gripped between two grooved dies and deformed by a punch that exerts force on the end of the stock.

Vent — A small hole in a punch or die for admitting air to avoid suction holding or for relieving pockets of trapped air that would prevent die closure or action.

Vent mark — A small protrusion resulting from the entrance of metal into die vent holes.

Warm forging — Deformation at elevated temperatures below the recrystallization temperature. The flow stress and rate of strain hardening are reduced with increasing temperature; thus, lower forces are required than in cold working. For steel, the temperatures range from about 1000° F to just below the normal hot working range of 1900 to 2300° F. See also Cold Working and Hot Working.

Warpage — Term generally applied to distortion that results during quenching from heat-treating temperatures; hand straightening, press straightening, or cold restriking is employed, depending on the configuration of the part and the amount of warpage involved. The condition is governed by applicable straightness tolerances; beyond tolerances, warpage is defect and cause for rejection. The term is not to be confused with "bend" or "twist."

Ways — The fitted V-shaped grooves in the ram and columns of a hammer or press that guide the descent and ascent of the ram.

Web — A relatively flat, thin portion of a forging, generally parallel to the forging plane—that connects ribs and bosses. See also Rib.

Wrought steel — A descriptive term for any particle of steel that has been produced by hot mechanical working.

Appendices

GUIDELINE TOLERANCES FOR CUSTOM FORGINGS

The purpose of this information is to make available to purchasers, producers, consumers and all other interested persons, information concerning the manufacture of forged parts or products on the basic types of mass production forging equipment.

The information contained herein regarding tolerances, inspection and measurement procedures and related subjects substantially represents the manufacturing standards and practices of the many producers of forged parts or products as reported to the Association or as obtained from other scientific and technical sources.

This Appendix contains modified versions of the previously published tolerance guidelines offered by the Forging Industry Association. This section is divided into four subsections of guideline tolerances as follows:

A - TOLERANCES FOR IMPRESSION DIE FORGINGS

TOLERANCES for Impression Die Forgings

There are practical limitations in dimensions and other characteristics of forged parts or products which vary according to the part or product and the producer's equipment. The degree of precision attainable in the manufacture of forged parts or products is dictated by the essential character of forging equipment and unavoidable contingencies in forging operations.

Theoretical exactness is seldom attained, and it is therefore necessary to make allowance for deviations. The tolerances set forth herein represent what the Forging Industry Association believes to be typical within the industry, as determined by actual measurements of forgings produced under normal operating conditions on standard forging equipment.

Experience within the industry shows that dimensional variations in forging are commonly functions of the dimensions involved, and the tolerances herein are based upon this observed fact.

The experience of producers and purchasers of forged parts and products indicates that the tolerances set forth herein will provide adequate dimensional accuracy for most applications.

THE TOLERANCES OUTLINED HEREIN ARE GUIDELINES BASED ON HISTORICAL, AVERAGED DATA. THE TERMS OF EACH TRANSACTION BETWEEN A FORGING PRODUCER AND A PURCHASER, INCLUDING TOLERANCES APPLICABLE TO THAT TRANSACTION, MUST BE NEGOTIATED AND CONFIRMED IN ADVANCE OF PRODUCTION.

There are several special ways of providing closer tolerances on selected dimensions on forgings with added operations. These include, cold and warm coining to achieve closer thickness tolerances, using special pressure padded trimmers for improving straightness, cold sizing of holes for improved tolerances on hot pierced holes, and warm forging as a manufacturing process. Be sure to contact technical personnel at your forging source for help in determining such special capabilities.

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GUIDELINE TOLERANCES FOR IMPRESSION DIE FORGINGS

A word about national standard ASME Y14.5. This tolerance guide provides dimensioning and tolerancing that is considered linear and not geometric. Geometric dimensioning and tolerancing to ASME's ANSI Y14.5M standard are being increasingly applied to forged products. Giving consideration to the fact that forgings undergo dimensional changes due to cooling and because forgings are formed in most cases between two impression dies that are not precisely on the same centerline, the ANSI Y14.5M guidelines for tolerancing are not totally appropriate to forgings.

These are reasons for FIA to refer also to the 1989 version of ASME Y14.8M an American National Standard for "Engineering Drawing and Related Document Practices for Castings and Forgings". This document more closely interprets the needed dimensional and tolerance modifications for forgings discussed in this booklet.

PRINTS AND SPECIFICATIONS

It is important that forging drawing be accurate and complete. The purchaser should indicate his first operation locating points, normally a part of the drawing, and give prior notice should these points be changed.

It is equally important that the purchaser provide drawings of the finish machined part, or equivalent information. This will assist in the design of forging dies and tools, and in establishing effective inspection procedures.

Unless the purchaser's drawings and specifications direct otherwise, all dimensions are normally assumed to refer to lines intersecting at right angles to each other (commonly referred to as X, Y, and Z axes). Furthermore, unless the purchaser's drawings or specifications direct otherwise, circular shapes are normally assumed to be figures of revolution with a center on an axis, and all circular dimensions are normally shown as diameters.

GENERAL

All individual tolerances apply to each and every forged part unless specifically noted otherwise.

Tolerances as stated in all tables are considered for use by final inspection departments at the forge plant and/or by receiving or by customer source inspection.

UNITS OF MEASURE

Tolerances in this publication are expressed in decimal inch with metric equivalents (sometimes referred to as "soft" metric conversion) in the belief that this represents a practice most common in the industry at the time of publication.

NOTE: THESE ARE GUIDELINES BASED ON AVERAGES IN THE FORGING INDUSTRY. REFINEMENTS TO THE ENCLOSED TOLERANCES CAN BE MADE IN RELATIONSHIP TO SMALLER DRAFT ANGLES, TIGHTER SQUARENESS, ROUNDNESS, PARALLELISM, HOLD STEP DESIGNS

AND STRAIGHTNESS. OPERATIONS CAN BE PERFORMED BY FORGE PLANTS TO PROVIDE ADDITIONAL SERVICES WHICH IN MANY CASES REPLACE THE NEED FOR MACHINING.

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DIMENSIONAL PRACTICES FOR FORGING DRAWINGS

The following procedures will apply concerning dimensioning on forging drawings: (1) Metric System _ Metric dimensions on forging drawings will be extended to one place decimal millimeter for both part dimensions and tolerances (0.1); and (2) Decimal Inch System _ Inch units of measure on forging drawings will be extended to two place decimals for both part dimensions and tolerances (0.01).

FORGINGS PRODUCED ON HAMMERS AND PRESSES LENGTH/WIDTH TOLERANCES

SCOPE

1. Length/Width Tolerances represent variations in dimensions measured parallel to the fundamental parting line of the dies. Normally, they are in addition to tolerances for die wear.

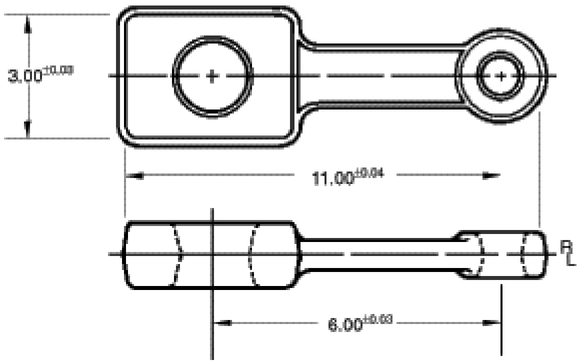
TOLERANCE

2. The Length/Width Tolerance is ±0.003 mm per mm, ±0.003 in. per inch and applies to all dimensions of length/width including diameters. This tolerance includes allowance for shrinkage, die sinking and die polishing variations. (The minimum should be plus or minus 0.8 mm or 0.03 in.)

UNITS OF MEASURE

3. Length/Width Tolerances, normally combined with tolerances for die wear are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

Fig. 1



LENGTH & WIDTH

METRIC CONVERSION

INCH	mm
0.03	0.8
0.04	1.1
3.00	76.2
6.00	152.4
11.00	279.4

DIE WEAR TOLERANCES

SCOPE

1. Die wear varies according to the material that is forged and the shape of the forging. Consequently, Die Wear Tolerances for various materials are applied in addition to Length/Width Tolerances on dimensions pertaining to forged surfaces only. Die Wear Tolerances do not apply on center-to-center dimensions. (See example 4).

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TOLERANCE

2. (a) Die Wear Tolerances for all length, width, and diameter dimensions under 750 mm or 30 in. are computed by multiplying the largest length or diameter (measured parallel to the fundamental parting line of the dies) by the appropriate factor in Table I below. Die Wear Tolerances for all length, width and diameter dimensions over 750 mm or 30 in. are taken directly from Table I.

(b) Die Wear Tolerances on external dimensions are expressed as plus values only. (See examples 5 and 6.) Die Wear Tolerances on internal dimensions are expressed as minus values only. (See examples 7 and 8.)

(c) Die Wear Tolerances per surface, on both external and internal dimensions are one-half the computed amount.

NOTE:

Allowances for die wear occuring on dimensions measured perpendicular to the fundamental parting line of the dies are included in Die Closure Tolerances (Table II).

TABLE I: DIE WEAR TOLERANCES

Materials	**Under 30 in. or 750 mm Factor (in./inch) (mm/millimeter)**	**Over 30 in. or 750 mm Constant**	
		in.	**mm**
Carbon, Low Alloys	0.005	0.15	3.81
Stainless	0.007	0.21	5.33
Heat Resistant Alloy	0.009	0.27	6.86
Titanium	0.009	0.27	6.86
Aluminum	0.004	0.12	3.05
Brass & Copper	0.004	0.12	3.05

UNITS OF MEASURE

3. Die Wear Tolerances combined with Length/Width Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch, in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or .01 in the inch system.

LIMITATIONS

4. The male portions of dies may, in special situations, tend to mushroom or upset rather than wear. In such cases, the requirements of the forging should be confirmed by purchaser and producer in advance of production.

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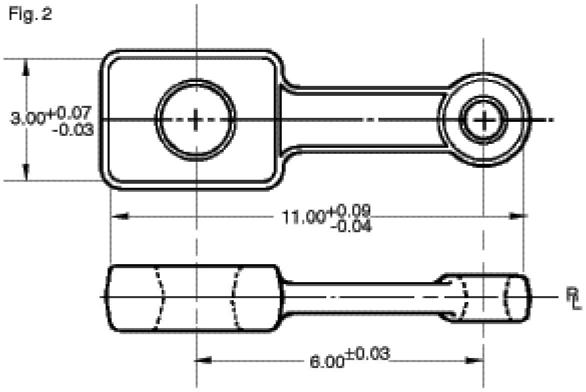
Fig. 2



LENGTH & WIDTH PLUS DIE WEAR

METRIC CONVERSION	
INCH	**mm**
0.03	0.8
0.04	1.1
0.07	1.8
0.09	2.3
3.00	76.2
6.00	152.4
11.00	279.4

COMPUTATION

MATERIAL: CARBON STEEL

(DIMENSIONS UNDER 30 IN. OR 750 mm)

EXAMPLE 1

(SEE FIGURE 2)

	Tolerance on Length Dimension		**Plus**	**Minus**
	Length (mm) x Length/Width Tolerance factor	= 279.4 x 0.003 =	0.839	0.839
METRIC	Length (mm) x Die Wear Tolerance factor	= 279.4 x 0.005 =	1.397	___
	(Table I)		+2.236	-0.839

	Raised to the next highest 0.1mm		+2.3	-0.9*
	Length x Length/Width Tolerance factor	= 11 x 0.003 =	0.033	0.033
INCH	Length x Die Wear Tolerance factor	= 11 x 0.005 =	0.055	___
	(Table I)		+0.088	-0.033
	Raised to the next highest 0.01 in.		+0.09	-0.04

*Variance due to rounding

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EXAMPLE 2 (DIMENSIONS OVER 30 IN. OR 750 mm)

METRIC	**Tolerance on Length Dimension**					**Plus**	**Minus**
	Length (mm) x Length/Width Tolerance factor	=	787.4	x	0.003	=	2.362	2.362
	Length (mm) x Die Wear Tolerance factor	=	3.81	x	0.005	=	3.81	- -
	(Table I)						+6.172	-2.362
	Raised to the next highest 0.1mm						+6.2	-2.4
	Length x Length/Width Tolerance factor	=	31	x	0.003	=	0.093	0.093
INCH	Length x Die Wear Tolerance factor	=		x	0.15	=	0.15	- -
	(Table I)						+0.243	-0.093
	Raised to the next highest 0.01 in.						+.25	-0.1

EXAMPLE 3

(SEE FIGURE 2)

METRIC	**Tolerance on Length Dimension**						**Plus**	**Minus**
	Length (mm) x Length/Width Tolerance factor	=	76.2	x	0.003	=	0.229	0.229
	Greatest Length (mm) x Die Wear Tolerance factor	=	279.41	x	0.005	=	1.397	- -
	(Table I)						+1.626	-0.229

	Raised to the next highest 0.1mm						+1.7	-0.3
	Minimum Tolerance						-.8	
	Wide Length/Width Tolerance factor	=	3	x	0.003	=	0.009	0.009
INCH	Greatest Length x Die Wear Tolerance factor	=	11	x	0.005	=	0.55	- -
	(Table I)						+0.064	-0.009
	Raised to the next highest 0.01 in.						+.0.07	-0.01
	Minimum Tolerance						-0.03	

EXAMPLE 4

(SEE FIGURE 2)

<METRIC	**Tolerance on Length Dimension**						**Plus**	**Minus**
	Dimension (mm) x Length/Width Tolerance factor	=	152.4	x	0.003	=	0.457	0.457
	Raised to the next highest 0.1 mm						+0.5	-0.5
	Minimum Tolerance						+0.8	-0.8
	Dimension x Length/Width Tolerance factor	=	6	x	0.003	=	0.018	0.018
INCH	Raised to the next highest 0.01 in.	=					+0.02	-0.02
	Minimum Tolerance					+0.03	-0.03	

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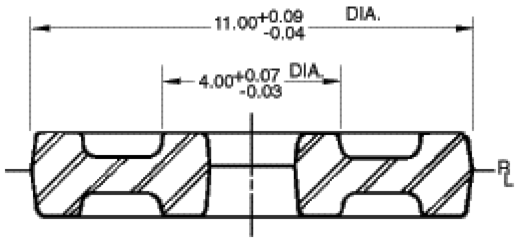
Fig. 3



EXTERNAL DIMENSIONS

METRIC CONVERSION	
INCH	**mm**
0.03	0.8
0.04	1.1
0.07	1.8
0.09	2.3

		4.00	101.6	
		11.00	279.4	

COMPUTATION EXTERNAL DIMENSIONS

MATERIAL: CARBON STEEL

EXAMPLE 5 (SEE FIGURE 3)

METRIC	**Tolerance on External Dimension**						**Plus**	**Minus**
	Diameter (mm) x Length/Width Tolerance factor	=	279.4	x	0.003	=	0.839	0.839
	Diameter (mm) x Die Wear Tolerance factor	=	79.4	x	0.005	=	1.397	- -
	(Table I)						+2.2236	-0.839
	Raised to the next highest 0.1mm						+2.3	-0.9*
	Diameter x Length/Width Tolerance factor	=	11	x	0.033	=	0.033	0.033
INCH	Diameter x Die Wear Tolerance factor	=	11	x	0.055	=	0.055	- -
	(Table I)						+0.243	-0.033
	Raised to the next highest 0.01 in.						+0.09	-0.04

EXAMPLE 6 (SEE FIGURE 3)

METRIC	**Tolerance on External Dimension**						**Plus**	**Minus**
	Diameter x Length/Width Tolerance factor	=	101.6	x	0.003	=	0.305	0.305
	Largest Diameter x Die Wear Tolerance factor (Table I)	=	279.4	x	0.005	=	1.397	- -
							+1.702	-0.3
	Raised to the next highest 0.1mm						+1.8	
	Minimum Tolerance						+0.8	
	Diameter x Length/Width Tolerance factor	=	4	x	0.033	=	0.012	0.012
INCH	Largest Diameter x Die Wear Tolerance factor	=	11	x	0.005	=	0.055	- -

	(Table I)						+0.067	-0.012
	Raised to the next highest 0.01 in.						+0.07	-0.02
	Minimum Tolerance						-0.03	

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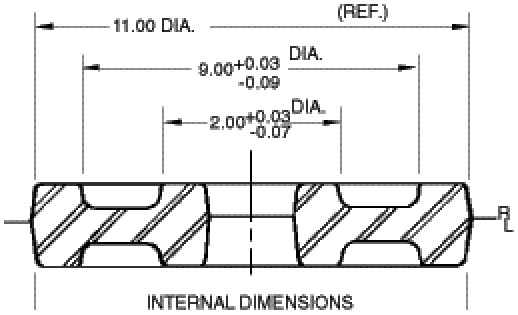
Fig. 4



METRIC CONVERSION	
INCH	**mm**
0.03	0.8
0.07	1.8
0.09	2.3
2.00	50.8
9.00	228.6

COMPUTATION EXTERNAL DIMENSIONS

MATERIAL: CARBON STEEL

EXAMPLE 7 (SEE FIGURE 4)

METRIC	**Tolerance on Internal Dimension**						**Plus**	**Minus**
	Diameter x Length/Width Tolerance factor	=	228.6	x	0.003	=	0.686	0.686
	Largest Diameter (mm) x Die Wear Tolerance factor	=	279.4	x	0.005	=	— —	1.397
	(Table I)						+0.686	-2083
	Raised to the next highest 0.1mm						+0.07	-2.1
	Minimum Tolerance					+0.8		
	Diameter x Length/Width Tolerance factor	=	9	x	0.033	=	0.027	0.033
INCH	Diameter x Die Wear Tolerance factor	=	11	x	0.005	=	— —	0.055
	(Table I)						+0.027	-0.082
	Raised to the next highest 0.01 in.						+0.03	-0.09

EXAMPLE 8 (SEE FIGURE 4)

METRIC	**Tolerance on Internal Dimension**						**Plus**	**Minus**

	Diameter x Length/Width Tolerance factor	=	50.8	x	0.003	=	0.152	0.152
	Largest Diameter x Die Wear Tolerance factor (Table I)	=	279.4	x	0.005	=	— —	1.397
							+0.152	-1.549
	Raised to the next highest 0.1mm						+0.2	-1.6
	Minimum Tolerance					+0.8		
	Diameter x Length/Width Tolerance factor	=	2	x	0.003	=	0.006	0.006
INCH	Largest Length x Die Wear Tolerance factor	=	11	x	0.005	=	— —	0.055
	(Table I)						+0.006	-0.061
	Raised to the next highest 0.01 in.						+0.01	-0.07
	Minimum Tolerance					+0.03		

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DIE CLOSURE TOLERANCES

SCOPE

1. Die Closure Tolerances relate to variations in thickness of forgings as affected by the closing of the dies and die wear, and pertain to variations in dimensions crossing the fundamental parting line.

TOLERANCE

2. Die Closure Tolerances on forgings are based on the projected area of the forging at the trim line, not including flash, but including all areas to be subsequently punched out, and are applied as plus tolerances only. See Table II, below.

TABLE II: DIE CLOSURE TOLERANCES

TABULATED FIGURES ARE PLUS VALUES ONLY

		Area at the Trim Line **Flash not included, expressed in square millimeters**						
METRIC	**Materials**	**0 to 6.5 x 1000**	**Over 6.5 to 20 x 1000**	**Over 20 to 32 x 1000**	**Over 32 to 65 x 1000**	**Over 65 to 300 x 1000**	**Over 300 to 650 x 1000**	**Over 650 x 1000**
	Carbon, Low Alloys	1.1	1.6	2.3	3.3	4.1	4.9	6.4
	Stainless	1.6	2.3	3.4	4.1	4.9	6.4	7.9
	Heat Resistant Alloy	1.6	2.3	3.4	4.9	6.4	7.9	9.7

	Titanium	1.6	2.3	3.4	4.9	6.4	7.9	9.7
	Aluminum	1.1	1.3	1.8	2.3	3.4	4.9	6.4
	Brass & Copper	1.1	1.3	1.8	2.3	3.4	4.9	6.4

		Area at the Trim Line Flash not included, expressed in square inches						
METRIC	**Materials**	**0 to 6.5 x 1000**	**Over 6.5 to 20 x 1000**	**Over 20 to 32 x 1000**	**Over 32 to 65 x 1000**	**Over 65 to 300 x 1000**	**Over 300 to 650 x 1000**	**Over 650 x 1000**
	Carbon, Low Alloys	0.04	0.06	0.09	0.13	0.16	0.19	0.25
	Stainless	0.06	0.09	0.13	0.16	0.19	0.25	0.31
	Heat Resistant Alloy	0.06	0.09	0.13	0.19	0.25	0.31	0.38
	Titanium	0.06	0.09	0.13	0.25	0.25	0.31	0.38
	Aluminum	0.04	0.05	0.07	0.13	0.13	0.19	0.25
	Brass Copper	0.04	0.05	0.07	1.13	0.13	0.19	0.25

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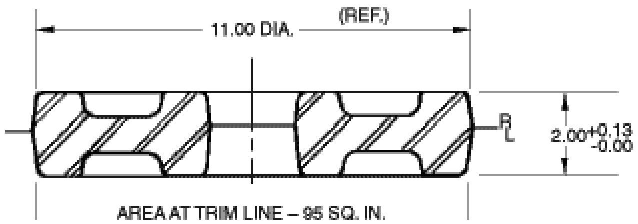
UNITS OF MEASURE

3 .

Die Closure Tolerances are expressed decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch, in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

Fig. 5



AREA AT TRIM LINE – 95 SQ. IN.

Die Closure Tolerance
Material: Carbon Steel

METRIC CONVERSION

INCH	**mm**
0.13	3.4
2.00	50.8

MATCH TOLERANCES

SCOPE

1. (a) Match Tolerances relate to displacement of a point in one die-half from the corresponding point in the opposite die-half in any direction parallel to the fundamental parting line of the dies. (Values from Table III must be doubled when specified as F.I.R. or T.I.R.)

(b) Match Tolerances are applied separately and independently to all other tolerances. Where possible, measurements are made at areas of the forging unaffected by die wear.

TOLERANCE

2. Match Tolerances are based on weight of the forging after trimming and are expressed as decimal inch or decimal millimeters according to Table III, below.

MEASURING FOR MATCH TOLERANCES

3 . In cases where measurements for determining match tolerances must be made from surfaces of the forging where uneven wearing of the dies has caused surplus stock, accuracy depends on making the proper allowances for these wear-caused surpluses, and eliminating their influence from the computation.

UNITS OF MEASURE

4. Match Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch, in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

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TABLE III: MATCH TOLERANCES

		Weights of Forgings after Trimming, in Pounds							
METRIC	**Materials**	**0 to 2.5**	**Over 2.5 to 12.5**	**Over 12.5 to 25**	**Over 25 to 50**	**Over 50 to 100**	**Over 100 to 250**	**Over 250 to 500**	**Over 500**
	Carbon, Low Alloys	0.5	0.8	1.2	1.6	2.4	3.2	4.0	4.8
	300, 400 Stainless Steels	0.8	1.2	1.6	2.4	3.2	4.0	4.8	6.4
	Heat Resistant Alloy	0.8	1.2	1.6	2.4	3.2	4.0	4.8	6.4
	Titanium	0.8	1.2	1.6	2.4	3.2	4.0	4.8	6.4
	Aluminum	0.5	0.8	1.2	1.6	2.4	3.2	4.0	4.8
	Brass & Copper	0.5	0.8	1.2	1.6	2.4	3.2	4.0	4.8

		Weights of Forgings after Trimming, in Pounds

INCH	**Materials**	**0 to 5**	**Over 5 to 25**	**Over 25 to 50**	**Over 50 to 100**	**Over 100 to 200**	**Over 200 to 500**	**Over 500 to 1000**	**Over 1000**
	Carbon, Low Alloys	0.02	0.03	0.05	0.06	0.09	0.13	0.16	0.19
	300, 400 Stainless Steels	0.03	0.05	0.06	0.09	0.13	0.16	0.19	0.25
	Heat Resistant Alloy	0.03	0.05	0.06	0.09	0.13	0.16	0.19	0.25
	Titanium	0.03	0.05	0.06	0.09	0.13	0.16	0.19	0.25
	Aluminum	0.02	0.03	0.05	0.06	0.09	0.13	0.16	0.19
	Brass & Copper	0.02	0.03	0.05	0.06	0.09	0.13	0.16	0.19

Formula refers to Figure 6

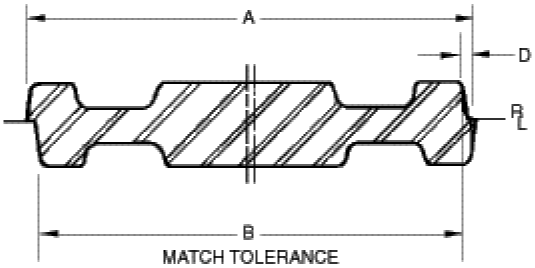
D = Match Tolerance or displacement

A = Projected maximum overall dimensions measured parallel to the main parting line of the dies.

B = Projected minimum overall dimensions measured parallel to the main parting line of the dies.

	A-B
NOTE: F.I.R. or T.I.R. or A-B = 2D ⟹ D=	2

Fig. 6



MATCH TOLERANCE

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RADII TOLERANCES

SCOPE

1. Radii Tolerances relate to all fillet radii and corner radii.

TOLERANCES

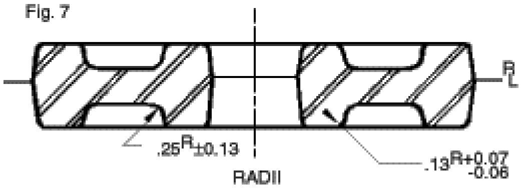
2. Radii Tolerances are plus or minus one-half the specified radii, except where corner radii are affected by subsequent removal of draft by trimming, broaching or punching. If draft is removed as result of trimming, broaching or punching, the minus radius tolerance (-0.5 of specified radius) is commonly modified to allow a square corner to be formed. (See Figures 8 and Example 10.)

UNITS OF MEASURE

3.

Radii Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch, in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

Fig. 7



METRIC CONVERSION

INCH	**mm**
0.06	1.6
0.07	18
0.13	3.4
0.025	6.4

COMPUTATION

EXAMPLE 9

(SEE FIGURE 7)

METRIC	3.4 mm radius is specified				
	Max radius	=	1.5 x 3.4 mm	=	5.1. mm radius
	Min radius	=	0.5 x 2.4 mm	=	1.7 mm radius
	6.4 mm radius is specified				
	Max radius	=	1.5 x 6.4 mm	=	9.4 mm radius
	Min radius	=	0.5 x 6.4 mm	=	3.2 radius

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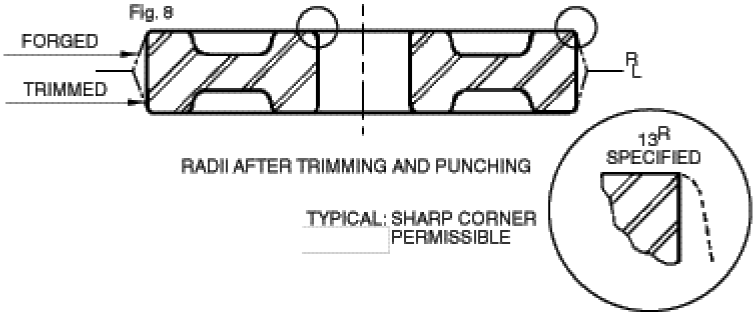
EXAMPLE 9 (continued)

(SEE FIGURE 7)

INCH	0.13 in. radius is specified				
	Max radius	=	1.5 x 0.13 in	=	0.195 in. radius
	Raised to the next highest		0.01in	=	1.7 mm radius
	Min radius	=	0.5 x 0.13 in	=	0.065 in. radius
	Raised to the next highest 0.01 in			=	0.07 in. radius
	0.25 mm radius is specified				
	Max. radius	=	1.5 x 0.25 in		0.375 in. radius
	Raised to the next highest		0.01 in	=	0.38 in. radius
	Min radius	=	0.5 x 0.25 in	=	0.13 in radius

Fig. 8



METRIC CONVERSION

INCH	**mm**
0.13	34

EXAMPLE 10

(SEE FIGURE 8)

METRIC	3.4 mm radius is specified				
	Max radius	=	1.5 x 3.4 mm	=	5.1. mm radius
	Min radius = 0 mm				
INCH	0.13 mm radius is specified				
	Max radius	=	1.5 x 6.4 mm	=	9.4 mm radius
	Min radius = 0 in.			=	

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EXTREMITY TOLERANCES

SCOPE

1. Extremity Tolerances relate to variations in height of protrusions (steps) which are perpendicular to the fundamental parting line and are independent of die closure, die wear and other factors dealt with in this book. This tolerance applies only to steps that are contained in one die.

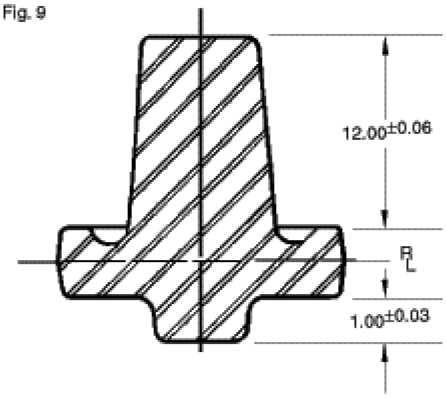
TOLERANCE

2. Tolerances on extremities are determined by taking the step dimension times ±0.005 inch per inch or millimeter per millimeter. This tolerance includes allowances for: non-fill, shrinkage, die sinking, polishing variations, and special die wear considerations. This tolerance is in addition to the Die Closure Tolerance. Minimum tolerance should be ±0.8 mm or 0.03 in.

UNITS OF MEASURE

3. Extremity Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch, in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raided to the next highest 0.1 in the metric system or 0.01 in the inch system.

Fig. 9



EXTREMITIES

METRIC CONVERSION

INCH	mm
0.03	0.8
0.06	1.6
1.00	25.4
12.00	304.8

EXAMPLE 11

FORGINGS HAVING PERPENDICULAR EXTREMETIES

METRIC			**Plus**	**Minus**
	Extremity Tolerance (±0.005 mm per millimeter) for the 305 mm step dimension	305 x 0.005 =	1.525	1.525
	Raised to the next highest 0.1mm		+1.6	-1.6

INCH	Extremity Tolerance (±0.005 in. per inch) for the 12 in. step dimension			
		12 x 0.005 =	+0.060	-0.060
	Min radius = 0 in.			

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FLASH EXTENSION TOLERANCES

SCOPE

1. Flash Extension Tolerances are based on weight of the forging after trimming, and related to the amount of flash extension. Flash is measured from the body of the forging to the trimmed edge of the flash.

TOLERANCES

2. Flash Extension Tolerances are expressed in inches or millimeters according to Table IV below.

UNITS OF MEASURE

3. Flash Extension Tolerances are expressed as decimal inch, in units of 0.01 or greater and expressed as decimal millimeter in units of 0.1 mm or greater.

Fig. 10

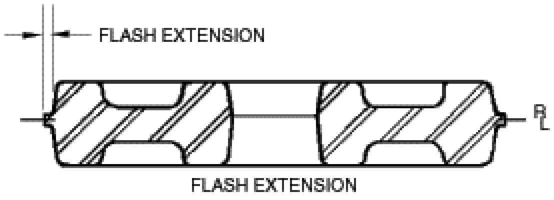

TABLE IV

		Materials		
METRIC	**Weights of Forgings After Trimming, in kilograms**	**Carbon Low Alloy & Aluminum**	**Stainless Heat Resistant Alloys & Titanium**	**Brass 7 Copper**

	5 and under	0 to 0.8	0 to 1.6	0 to 0.8
	Over 5 to 10 incl.	0 to 1.6	0 to 2.3	0 to 1.6
	Over 10 to 25 incl.	0 to 2.3	0 to 3.3	0 to 2.3
	Over 25 to 50 incl.	0 to 3.3	0 to 4.9	0 to 3.3
	Over 50 to 100 incl.	0 to 4.9	0 to 6.4	0 to 4.9
	Over 100 to 250 incl.	0 to 6.4	0 to 7.9	0 to 6.4
	Over 250 to 500 incl.	0 to 7.9	0 to 9.7	0 to 7.9
	Over 500	0 to 9.7	0 to 12.7	0 to 9.7

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TABLE IV (Continued)

		Materials		
METRIC	**Weights of Forgings After Trimming, in kilograms**	**Carbon Low Alloy & Aluminum**	**Stainless Heat Resistant Alloys & Titanium**	**Brass & Copper**
	5 and under	0 to 0.03	0 to 0.06	0 to 0.03
	Over 5 to 25 incl.	0 to 0.06	0 to 0.09	0 to 0.06
	Over 25 to 50 incl.	0 to 0.09	0 to 0.13	0 to 0.09
	Over 50 to 100 incl.	0 to 0.13	0 to 0.19	0 to 0.13
	Over 100 to 200 incl.	0 to 0.19	0 to 0.25	0 to 0.19
	Over 200 to 500 incl.	0 to 0.25	0 to 0.31	0 to 0.25
	Over 500 to 1000 incl.	0 to 0.31	0 to 0.38	0 to 0.31
	Over 1000	0 to 0.38	0 to 0.50	0 to 0.38

STRAIGHTNESS TOLERANCES

SCOPE

1. (a) Straightness Tolerances relate to deviations of surfaces and centerlines from the specified contour. Straightness Tolerances are applied independently of, and in addition to, all other tolerances.

(b) Four general classes of shapes have been selected for guidelines in choosing appropriate Straightness Tolerances.

CLASSES OF SHAPES

Class	Shape of Forging	Examples
A	A Elongated -Length dimension greater than width or height	long connecting rods, shafts, levers, etc.
B	Flat and thin	disc, plates, etc.
C	Flat and thin with protrusion at right angles to the parting line	wear plates, crawler track shoes
D	Block-type forgings with neither length, width. nor thickness being predominant	pump or valve bodies steam chests, etc.

UNITS OF MEASURE

2. Straightness Tolerances are expressed as decimal inch, in units of 0.01 or greater and expressed as decimal millimeter in units of 0.1 mm or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.01 in the inch system or 0.1 in the metric system.

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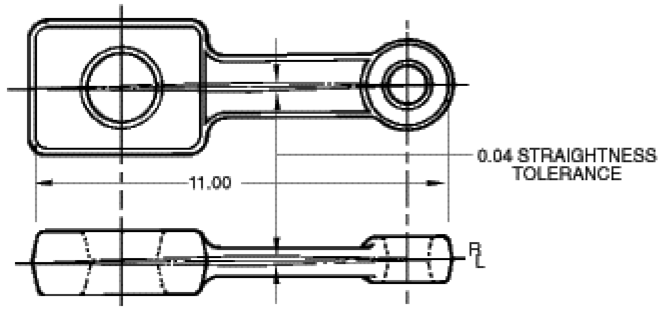
STRAIGHTNESS TOLERANCES

TOLERANCES AND APPLICATIONS

3. (a) CLASS A Shapes (Elongated _ Length dimensions greater than width or height) Tolerance: 0.003 in. per inch or mm per millimeter of the greatest dimension.

Fig. 11



STRAIGHTNESS – CLASS 'A'

METRIC CONVERSION

INCH	mm
0.04	1.1
11.0	279.4

EXAMPLE 12

(SEE FIGURE 11)

METRIC	Greatest dimension x Straightness Tolerance	279.4 x 0.003 =	0.84
	Raised to the next highest 0.1 mm		0.9
	Straightness Tolerance for CLASS A Shape in Figure 11		0.9
		From true center lines in any plane	
INCH	Greatest dimension x Straightness Tolerant	11 x 0.003 =	0.033
	Raised to the next highest 0.01 in.		0.04
	Straightness Tolerance for CLASS A Shape in Figure 11		0.04
		From true center lines in any plane	

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STRAIGHTNESS TOLERANCES

TOLERANCES AND APPLICATIONS (continued)

(b) Class B Shapes (flat and thin)

Tolerance: Straightness Tolerance for CLASS B Shapes as shown in Table V.

TABLE V: STRAIGHTNESS TOLERANCES

		Area at the Trim Line Flash not included, expressed in square millimeters						
METRIC	**Materials**	**0 to 6.5 x 1000**	**Over 6.5 to 20 x 1000**	**Over 20 to 32 x 1000**	**Over 32 to 65 x 1000**	**Over 65 to 300 x 1000**	**Over 300 to 650 x 1000**	**Over 650 x 1000**
	Carbon, Low Alloys	0.9	1.6	2.3	3.3	4.1	4.9	6.4
	Stainless	1.6	2.3	3.3	4.1	4.8	6.4	7.9
	Heat Resistant Alloy	1.6	2.3	3.3	4.8	6.4	7.9	9.7
	Titanium	1.6	2.3	3.3	4.8	6.4	7.9	9.7

	Aluminum	0.8	0.8	1.5	2.3	3.3	4.8	6.4
	Brass & Copper	0.8	0.8	2.5	2.3	3.3	4.8	6.4

		Area at the Trim Line Flash not included, expressed in square millimeters						
INCH	**Materials**	**10 and under**	**Over 10 to 30 incl.**	**Over 30 to 50 incl.**	**Over 50 to 100 incl.**	**Over 100 to 50 incl.**	**Over 500 to 1000 incl.**	**Over 1000**
	Carbon, Low Alloys	0.04	0.06	0.09	0.13	0.16	0.19	0.25
	Stainless	0.06	0.09	0.13	0.16	0.19	0.25	0.31
	Heat Resistant Alloy	0.06	0.09	0.13	0.19	0.25	0.31	0.38
	Titanium	0.06	0.09	0.13	0.19	0.25	0.31	0.38
	Aluminum	0.04	0.05	0.07	0.09	0.13	0.19	0.25
	Brass & Copper	0.04	0.05	0.07	0.09	0.13	0.19	0.25

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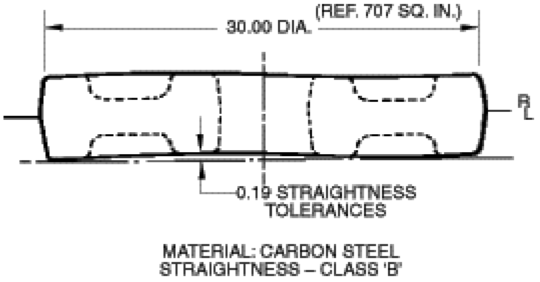
Fig. 13



METRIC CONVERSION

INCH	**mm**
0.19	4.9
30.00	762.0
707.00	456,038.0

EXAMPLE 13

(SEE FIGURE 12 and 13)

METRIC	Computed area at Trim Line	456,038 sq. mm
	Appropriate value from Table V	4.9 mm
	Straightness Tolerance for CLASS B Shape in Figures 12 and 13	4.9 mm
		From the highest to lowest point of contour
INCH	Computed area at Trim Line	707 Sq.in,
	Appropriate value from Table V	0.19 in.
	Straightness Tolerance for CLASS B Shape in Figures 12 and 13	0.19 in.

			From the highest to lowest point of contour

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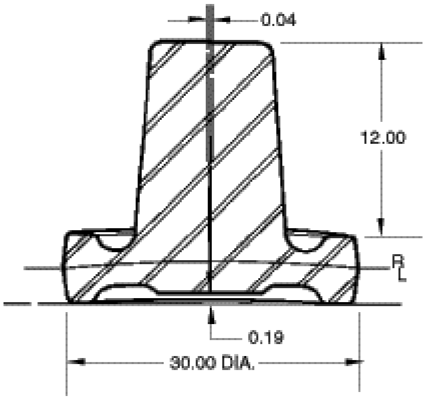
STRAIGHTNESS TOLERANCES

TOLERANCES AND APPLICATIONS (continued)

(c) CLASS C Shapes (flat and thin with protrusion at right angles to the parting line)

Tolerance: The Straightness Tolerance on the flat portion of CLASS C Shapes is computed first. It is considered separately from the tolerance on the protruding portion and is determined in an identical manner as for CLASS B Shapes using Table V. The Straightness Tolerance on a protrusion is 0.003 in. per inch or mm per millimeter.

Fig. 14



STRAIGHTNESS – CLASS 'C'

METRIC CONVERSION

INCH	mm
0.04	1.1
0.19	4.9
12.00	304.8
30.00	762.0

EXAMPLE 14

(SEE FIGURE 14)

METRIC	**Material: Carbon Steel**	=	456,038 sq. mm
	The Tolerance on flat portion is computed first:	=	4.9 mm
	Computed area at Trim Line	=	4.9 mm
	Appropriate value from Table V		
	Straightness Tolerance applied to flat portion		
			From the highest to lowest point of contour
INCH	Computed area at Trim Line	=	707 Sq. In.
	Appropriate value from Table V	=	0.19 in.

	Straightness Tolerance applied to flat portion	=	0.19 in.
		From the highest to lowest point of contour	

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EXAMPLE 15

RIC	The Protrusion is checked against a line perpendicular to the plane established for checking the flat portion:		
	Protrusion x Straightness		
	Tolerance = 304.8 x 0.003	=	0.91
	Raised to the next highest 0.1 mm	=	1.0
		From true center lines in any plane	

Protrusion x Straightness		
Tolerance = 12 in. x 0.003	=	0.036
Raised to the next highest 0.01 in.	=	0.04
	From true center lines in any plane	

d) CLASS D SHAPES (block-type forgings with neither length, width nor thickness being predominant)

Tolerance: Where tolerances are desired, agreement between purchaser and forging producer is normally reached before production proceeds.

DRAFT ANGLE TOLERANCES

E

Draft Angle Tolerances apply to all draft angles, specified on drawings that are not affected by subsequent operations.

RANCE

Draft Angle Tolerances are +2°-0° unless modified by prior agreement between purchaser and producer.

EXAMPLE 15

RIC	The Protrusion is checked against a line perpendicular to the plane established for checking the flat portion:		
	Protrusion x Straightness		
	Tolerance = 304.8 x 0.003	=	0.91

Raised to the next highest 0.1 mm	=	1.0
	From true center lines in any plane	

Protrusion x Straightness		
Tolerance = 12 in. x 0.003	=	0.036
Raised to the next highest 0.01 in.	=	0.04
	From true center lines in any plane	

d) CLASS D SHAPES (block-type forgings with neither length, width nor thickness being predominant)

Tolerance: Where tolerances are desired, agreement between purchaser and forging producer is normally reached before production proceeds.

DRAFT ANGLE TOLERANCES

E

Draft Angle Tolerances apply to all draft angles, specified on drawings that are not affected by subsequent operations.

RANCE

Draft Angle Tolerances are +2°-0° unless modified by prior agreement between purchaser and producer.

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SURFACE TOLERANCES

E

Surface Tolerances relate to depth of dressouts, scale pits and other imperfections on the surface of forgings.

RANCES AND CONDITIONS

a) Dressouts, scale pits and other imperfections are commonly allowed on surfaces to be finish machined unless purchaser's specificatio drawing states otherwise. Where purchaser specified stock for machining, these imperfections are commonly permitted to within 1.6 m 0.06 in. of the finished surface or to within one half of the stock allowance, whichever is smaller. .

b) Where surfaces of forgings are intended for use in "as forged" condition, surface imperfections are commonly permitted as shown in T VI.

RIC	Area at the Trim Line Flash not included, expressed in square millimeters						
	0 to 6.5 x 1000	Over 6.5 to 20 x 1000	Over 20 to 32 x 1000	Over 32 to 65 x 1000	Over 65 to 300 x 1000	Over 300 to 650 x 1000	Over 650 x 10
	0.8	1.2	1.7	2.1	2.5	3.2	4.0

RIC	Area at the Trim Line Flash not included, expressed in square inches						
	Over 10 to 30 incl.	Over 10 to 30 incl.	Over 30 to 50 incl.	Over 50 to 100 incl.	Over 100 to 500 incl.	Over 500 to 100 incl.	Over Over 100
	0.03	0.05	0.07	0.08	0.10	0.13	0.16

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FINISH ALLOWANCES FOR MACHINING

(For the purpose of designing a forging)

Finish allowance refers to the amount of material that is to be machined from the forging to obtain the finished part. Forging dimensions are commonly analyzed independently, with consideration given to all applicable tolerances including match, straightness, length and width but not including die wear.

TABLE VII: FINISH ALLOWANCES

Greatest Dimension				Minimum Finish Stock Per Surface	
Over		But Not Over			
in	mm	in	mm	in	mm
--	--	8	203	0.06	1.6
8	203	16	406	0.09	2.4
16	406	24	610	0.13	3.2
24	610	31	914	0.16	4.0
36	916	--	--	0.19	4.8

B - TOLERANCES FOR HOT UPSET FORGINGS

GUIDELINE TOLERANCES FOR HOT UPSET FORGINGS

INTRODUCTION

Fundamentally, impression die forgings produced on Horizontal Forging Machines (Upsetters) are similar to those produced by Hammers or Presses. Each is the result of forcing metal into cavities in dies which separate at parting lines.

The impression in the ram-operated "Heading Tool" is the equivalent of a Hammer or Press top die. The "grip dies" contain the impressions corresponding to the Hammer or Press bottom die. Grip dies consist of a stationary die and a moving die which, when closed, act to grip the stock and hold it in position for forging. After each workstroke of the machine, these dies open to permit the transfer of stock from one cavity to another in the multiple-impression dies.

After an operation establishes a final contour on a specific portion of an upset forging, subsequent operations may have some effect on that portion. Thus the number and sequence of steps used in shaping the forging must be planned in advance in order that overall tolerance may be anticipated.

Most upset forgings begin with and retain some portion of a hot rolled bar. Permissible mill variations thus have an effect on upset forging tolerances.

As a result of this and other technical considerations, tolerances applying to forgings produced on Forging Machines differ somewhat from those of Hammer and Press forgings.

TOLERANCES

There are practical limitations in dimensions and other characteristics of forged parts or products which vary according to the part or product and the producer's equipment. The degree of precision practicable in the manufacture of forged parts or products is dictated by the essential character of forging equipment and unavoidable contingencies in forging operations.

Theoretical exactness is seldom attained, and it is therefore necessary to make allowances for deviations. The tolerances set forth herein represent what the Forging Industry Association believes to be typical within the industry, as determined by actual measurements of forgings produced under normal operating conditions on standard forging equipment.

Experience within the industry shows that dimensional variations in forging are commonly functions of the dimensions involved, and the tolerances herein are based upon this observed fact.

TOLERANCE ACCUMULATION

Where applicable the enclosed tolerances are accumulative. (Example: overall length tolerance = flange thickness tolerance + stem length tolerance.)

The experience of producers and purchasers of forged parts and products indicates that the tolerances set forth herein will provide adequate dimensional accuracy for most applications.

THE TOLERANCES OUTLINED IN THIS BOOKLET ARE GUIDELINES BASED ON HISTORICAL, AVERAGED DATA. THE TERMS OF EACH TRANSACTION BETWEEN A FORGING PRODUCER AND A PURCHASER, INCLUDING TOLERANCES APPLICABLE TO THAT TRANSACTION, MUST BE NEGOTIATED AND CONFIRMED IN ADVANCE OF PRODUCTION.

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GENERAL

All individual tolerances apply to each and every forged part unless specifically noted otherwise.

Tolerances as stated in all tables are considered for use by final inspection departments at the forge plant and/or by receiving or source inspection by the purchaser.

PRINTS AND SPECIFICATIONS

It is important that forging drawings be accurate and complete. The purchaser should indicate his first operation locating points, normally as a part of the drawing, and give prior notice should these points be changed.

It is equally important that the purchaser provide drawings of the finish machined part, or equivalent information. This will assist in the design of forging dies and tools, and in establishing most effective final inspection procedures.

Unless the purchaser's drawings and specifications direct otherwise, all dimensions are normally assumed to refer to lines intersecting at right angles to each other (commonly referred to as X,, Y, and Z axes). Furthermore, unless the purchaser's drawings or specifications direct otherwise, circular shapes are normally assumed to be figures of revolution with a center on an axis, and all circular dimensions are normally shown as diameters.

DIMENSIONAL PRACTICES FOR FORGING DRAWINGS

At the time of first printing of this publication, a transition period existed dealing with the conversion from the customary decimal inch system to dimensioning to the metric system. The following procedures will apply concerning dimensioning on forging drawings: (1) Metric System _ metric dimensions, on forging drawings, will be extended to one place decimal millimeter for both part dimensions and tolerances (0.1); and (2) Decimal Inch System _ inch units of measure on forging drawings will be extended to two place decimals for both dimensions and tolerances (0.01).

UNITS AND METHODS OF MEASURE METHOD

The forgeman must do much of his measuring (hot inspection) of forgings while they are hot, using practical forge shop instruments such as calipers, rule, straight edge and profile template. The precision of his measurements is therefore limited by the characteristics of such instruments and the conditions under which they must be used.

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UNIT OF MEASURE

Tolerances in this publication are expressed in decimal inch with metric equivalents in the belief that this represents practice most common in the industry at the time of publication.

NOTE: THESE ARE GUIDELINES BASED ON AVERAGES IN THE FORGING INDUSTRY. REFINEMENTS TO THE ENCLOSED TOLERANCES CAN BE MADE IN RELATIONSHIP TO SMALLER DRAFT ANGLES, TIGHTER SQUARENESS, ROUNDNESS, PARALLELISM, STEP DESIGNS AND STRAIGHTNESS. OPERATIONS CAN BE PERFORMED BY FORGE PLANTS TO PROVIDE ADDITIONAL SERVICES WHICH IN MANY CASES REPLACE THE NEED FOR MACHINING.

FLANGE THICKNESS TOLERANCES (Heading Tool Closure)

SCOPE

1. (a) Flange Thickness Tolerances reflect the degree of closure of the heading tool. When more than one flange is formed, these tolerances also apply to the dimension (gap) between flanges.

(b) Flange Thickness Tolerances are applied separately and independently of other tolerances and are accumulative.

TOLERANCE

2. (a) Tolerances for flange thickness and dimensions (gaps) between flanges are such that the effect is to add stock on both internal and external dimensions. The amount of Flange Thickness Tolerance depends on the flange diameter.

(b) When two flanges are formed, the tolerance on the dimension (gap) between them is a minus tolerance only, with a value identical to the thickness tolerance for the flange nearest the unforged stem. (See Figure 15)

(c) Flange Thickness Tolerances are shown in Table VII and Figure 15.

MEASURING FOR FLANGE THICKNESS TOLERANCE

3. Flange Thickness Tolerance depends on the flange diameter.

UNITS OF MEASURE

4. Flange Thickness Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

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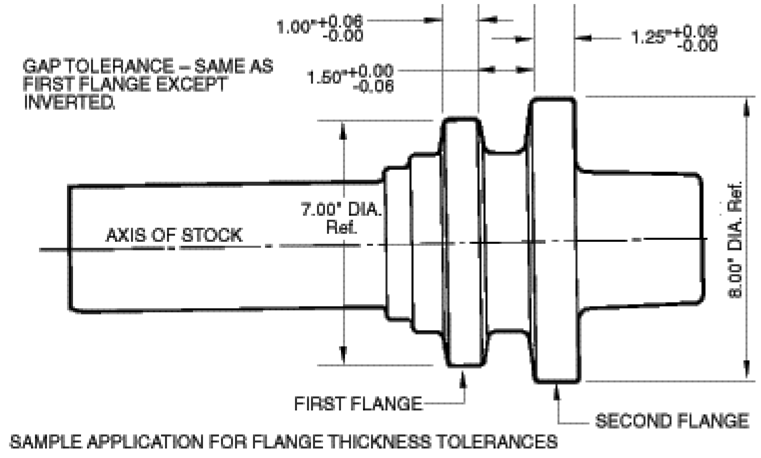

SAMPLE APPLICATION FOR FLANGE THICKNESS TOLERANCES

Fig. 15

MI
INCH
0.06
0.09
1.25
1.50
3.75
7.00
8.00

TABLE VIII

FLANGE THICKNESS TOLERANCES

METRIC	**Diameters**		**TOLERANCES**			
	Over	**But Not Over**	**Plus**	**Minus**		
	0	180	1.6	--		
	180.0	255.0	2.3	--		
	255.0	--	3.4	0.8		

INCH	**Diameters**		**TOLERANCES**			
	Over	**But Not Over**	**Plus**	**Minus**		
	0	7.00	0.06	--		
	7.00	10.00	0.09	--		
	10.00	--	0.13	0.03		

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STEM TOLERANCES

SCOPE

1. Stem Tolerances relate to that portion of the forging from the first flange (flange nearest the unforged end) to the unforged end.

TOLERANCE

2. (a) Stem Tolerances are based on stem length and are expressed as decimals of an inch or mm according to Table IX.

(b) The diameter of the unheated stem is controlled by mill tolerances. The stem length subjected to forging heat is covered by diameter tolerance (Table XI). The portion of the "heated stem" will vary due to the equipment, process and part geometry. Agreement between the forging producer and forging purchaser should be reached prior to acceptance of order.

MEASURING FOR STEM LENGTH TOLERANCE

3. Stem Length Tolerances are measured parallel to the axis of the stock from the first flange to the unforged end.

(b) The diameter of the unheated stem is controlled by mill tolerances. The stem length subjected to forging heat is covered by diameter tolerance (Table XI). The portion of the "heated stem" will vary due to the equipment, process and part geometry. Agreement between the forging producer and forging purchaser should be reached prior to acceptance of order.

NOTE: Line AA, Figure 16 denotes first portion of the forging controlled by the Flange Thickness Tolerance.

UNITS OF MEASURE

4.		Stem Length Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch, in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

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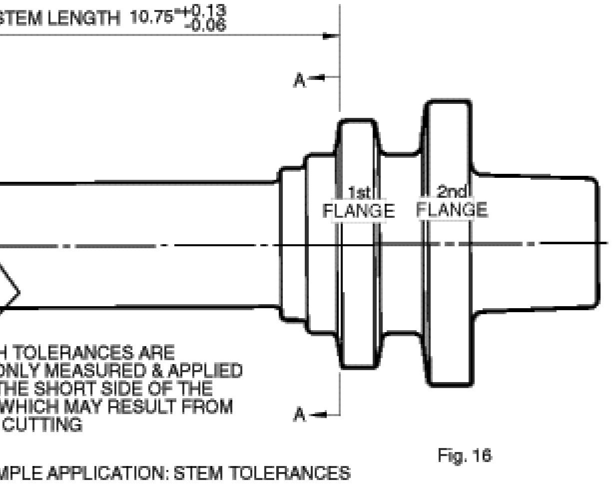

Fig. 16

METRIC CONVERSION	
INCH	**mm**
0.06	1.6
0.09	2.3
0.13	3.4
3.50	88.9
3.75	95.3
10.75	273.1
18.00	457.2

E IX

TOLERANCES

RIC	**Stem Length**		**TOLERANCES**	
	Over	**But Not Over**	**Plus**	**Minus**
	0.0	152.4	1.6	0.08
	152.0	254.0	2.3	.8
	254.0	508.0	3.4	01.6
	508.0	762.0	4.0	1.6
	762.0	--	As Agreed	--

	Stem Length		**TOLERANCES**	
	Over	**But Not Over**	**Plus**	**Minus**
	0.00	6.00	0.06	0.03
	6.00	10.00	0.09	0.03
	10.00	20.00	0.13	0.06
	20.00	30.00	0.19	0.06

30.00	--	As Agreed	--

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SHOULDER LENGTH TOLERANCES
SCOPE

1. Shoulder Length Tolerances apply to portions of the final forging formed as steps to or from a flange and not affected by header closure. Tolerances on the flange thickness, internal length (gap) dimension between flanges and the unforged portion of the stem are toleranced separately and independently of the Shoulder Length Tolerances. Shoulder Length Tolerances include allowances for die wear, shrinkage, die sinking and die polishing variations.

TOLERANCE

2.Shoulder Length Tolerances are plus values only, expressed in decimals of an inch or mm according to Table X.

MEASURING FOR SHOULDER LENGTH TOLERANCE

3. Shoulder Length Tolerances are measured parallel to the axis of the original bar.

UNITS OF MEASURE

4. Shoulder Length Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch, in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

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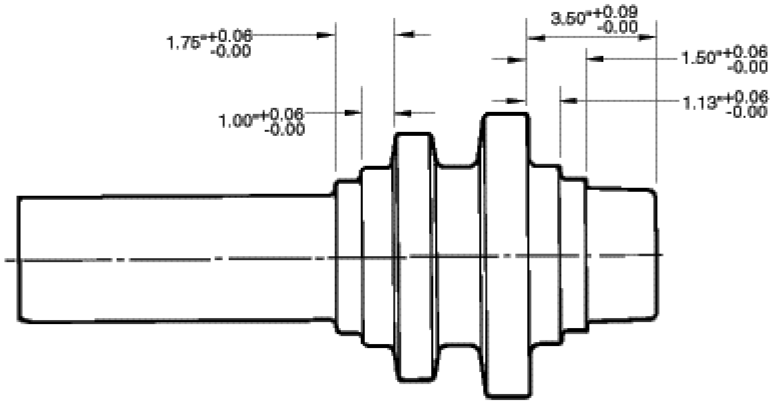

SAMPLE APPLICATION: SHOULDER LENGTH TOLERANCES

Fig. 17

METRIC CONVERSION

INCH	mm
0.06	1.6
0.09	2.3
1.00	25.4
1.13	28.8
1.50	38.1
1.75	44.5
3.50	88.9

TABLE X

SHOULDER LENGTH TOLERANCES

METRIC	Length Dimensions		TOLERANCES
	Over	But Not Over	
	--	76.2	1.6
	76.2	152.4	2.3

	152.4	228.6	3.4
	228.6	--	4.1

INCH	Length Dimensions		TOLERANCES
	Over	**But Not Over**	
	--	3.00	0.06
	3.00	6.00	0.09
	6.00	9.00	0.13
	9.00	--	0.16

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DIAMETER TOLERANCES

SCOPE

1. (a)Diameter Tolerances are applied separately for each of a forging's diameters and only to those diameters formed in the heading tool or dies.

(b)These tolerances apply only to forgings with circular shape. Tolerances for non-circular forgings are customarily determined by special agreement between purchaser and producer in advance of production.

TOLERANCE

2. (a)Tolerances for all external forged diameters are expressed as plus tolerances only, according to Table XI.

(b)Tolerances for internal diameters of holes formed by the heading tool are commonly expressed as minus tolerances only according to Table XI.

(c)Tolerances for Stem Diameters subjected to forging heat are shown in Table XI. Variations in diameter on unheated portions of the stem are commonly governed by mill tolerances.

(d)Tolerance for shear-cut ends and slight irregularities in diameter on the stem caused by grip dies are commonly determined by special agreement between purchaser and producer.

MEASURING FOR DIAMETER TOLERANCES

3. Diameter Tolerances are commonly applied and measured in a plane 90° from the die parting line (perpendicular to the axis of the stock).

UNITS OF MEASURE

4. Diameter Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

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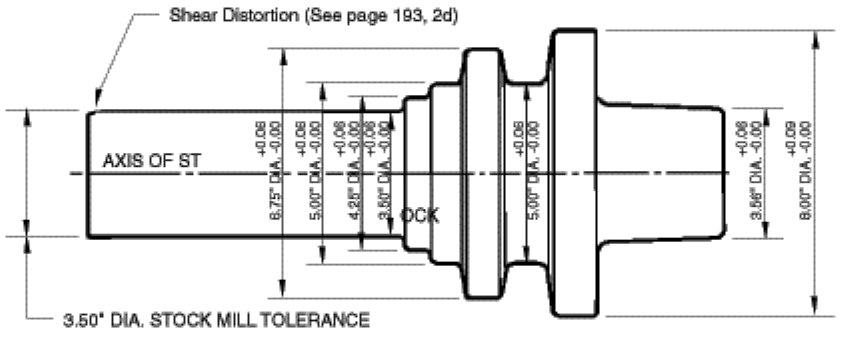

SAMPLE APPLICATION: SHOULDER LENGTH TOLERANCES

Fig. 18

METRIC CONVERSION	
INCH	**mm**
0.06	1.6
0.09	2.3
3.50	88.9
3.56	90.5
4.25	108.0
5.00	127.0
6.75	171.5
6.75	203.2

TABLE XI

DIAMETER TOLERANT

METRIC	**Diameters**		**TOLERANT**	
	Over	**But Not Over**	**Outside Diameters**	**Inside Diameter**
	--	50.8	+ 0.8	- 1.6
	50.8	177.8	+ 1.6	- 2.3
	177.8	254.0	+ 2.3	- 3.4

	254.0	--	+ 3.4	- 3.4

INCH	**Diameters**		**TOLERANT**	
	Over	**But Not Over**	**Outside Diameters**	**Inside Diameter**
	--	2.00	+ 0.03	- 0.06
	2.00	7.00	+ 0.06	- 0.09
	7.00	10.00	+ 0.09	- 0.13
	10.00	--	+ 0.13	- 0.13

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GRIP DIES TOLERANCES

SCOPE

1. Grip Dies Match Tolerances relate to the amount of die displacement in a direction parallel to the parting line of the grip dies. Grip Dies Match describes the results of movement of one die in relation to the other. While this movement is along the die parting line only, it does occur in two ways. Vertical Shift: Where one die is higher than the other. Forward Shift: Where one die is ahead of the other.

TOLERANCE

2. Grip Dies Match Tolerances are based on the largest forging diameter and shown in Table XII. These tolerances are applied independently of and in addition to all other tolerances.

MEASURING FOR SHOULDER LENGTH TOLERANCE

3. Vertical Shift is determined by measuring the difference between AA and BB then dividing by two. (See Fig. 19A.)

Forward Shift is determined by measuring the difference between DD and EE. (See Figure 19B.)

In cases where measurements for determining match tolerances must be made from surfaces of the forging where uneven wearing of the dies has caused surplus stock, accuracy depends on making the proper allowances for these wear-caused surpluses, and eliminating their influence from the computation.

UNITS OF MEASURE

4. Grip Dies Match Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch, in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

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Fig. 19A

VERTICAL SHIFT
(End View)

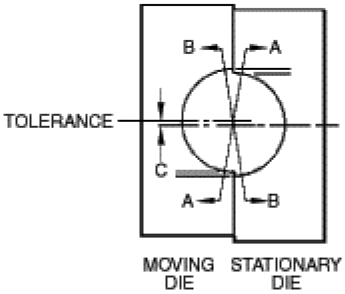

Fig. 19B

FORWARD SHIFT
(Top View)

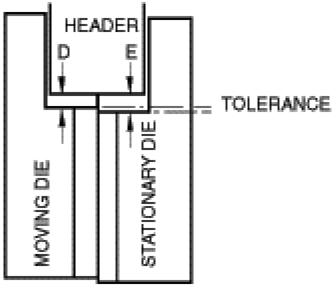

TABLE XXII

GRIP DIES MATCH TOLERANCE

METRIC	**Largest Diameter**		**TOLERANCE**
	Over	**But Not Over**	
	--	101.6	0.6
	101.6	152.4	0.8
	152.4	203.2	1.3
	203.2	254.0	1.6
	254.0	--	2.3

INCH	**Largest Diameter**		**TOLERANCE**
	Over	**But Not Over**	
	--	**4.00**	**0.02**
	4.00	6.00	0.03
	6.00	8.00	0.05
	8.00	10.00	0.06
	10.00	--	0.09

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HEADER MATCH TOLERANCES

SCOPE

1. Header Match Tolerances apply to contours formed by the heading tool and relate to variations of the axis of the header formed contour from the axis of the stock. These tolerances are applied independently of and in addition to all other tolerances.

TOLERANCE

2. Header Match Tolerances are determined by the largest forging diameter and are shown in Table XIII.

MEASURING FOR SHOULDER LENGTH TOLERANCES

3. Measuring for header match is best accomplished by comparing readings of A and B taken at the point of greatest variation and dividing the result by two. (See Figure 20.) The resulting figure equals header match C.

In cases where measurements for determining match tolerances must be made from surfaces of the forging where uneven wearing of the dies has caused surplus stock, accuracy depends on making the proper allowances for these wear-caused surpluses, and eliminating their influence from the computation.

UNITS OF MEASURE

4. Header Match Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

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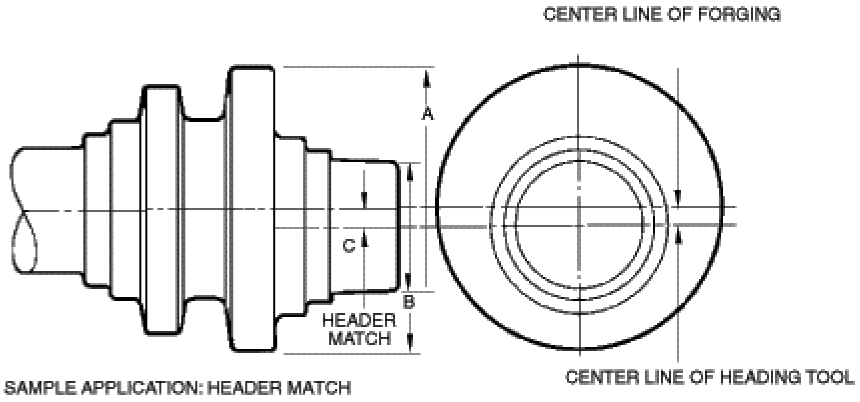

Fig. 20

TABLE XIII

HEADER MATCH TOLERANCES

INCH	**Largest Diameter**		**Tolerance**
	Over	**But Not Over**	
	--	101.6	0.6
	101.6	152.4	0.8
	152.4	203.2	1.3
	203.2	254.0	1.6
	254.0	--	2.3

METRIC	**Largest Diameter**		**Tolerance**
	Over	**But Not Over**	
	--	4.00	0.02
	4.00	6.00	0.03
	6.00	8.00	0.05
	8.00	10.00	0.06
	10.00	--	0.09

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CONCENTRICITY TOLERANCES (HOLES)

SCOPE

1. Concentricity Tolerances apply to holes formed by the heading tools and relate to variations of the axis of the hole to the axis of the forging.

TOLERANCE

2. Concentricity Tolerances will apply only to hole depths of one diameter or more.

(a) Hole depths of less than one diameter are controlled by Header Match Tolerance. (See Table XIII.)

(b) Concentricity Tolerances are independent of Header Match Tolerances (See Table XIV).

MEASURING FOR CONCENTRICITY TOLERANCES

3. Measuring for Concentricity Tolerances is best accomplished by comparing readings of AA and BB in Figure 21 at the point of greatest wall variation.

NOTE: Wall variation is equal to T.I.R.

UNITS OF MEASURE

4. Concentricity Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

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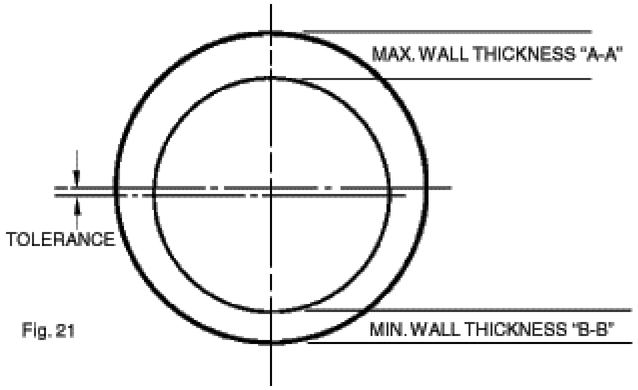

Fig. 21

TABLE XIV

CONCENTRICITY TOLERANCE (HOLES)

METRIC	**Depth of Hole**		**Concentricity TOLERANCE**	**Total Indicator Reading (Wall Variation TOLERANCE)**	
	Over	**But Not Over**			
	--	203.2	1.6	T.I.R.	3.1
	203.2	304.8	2.3	T.I.R.	4.6
	304.8	--	3.4	T.I.R.	6.7
INCH	**Depth of Hole**		**Concentricity TOLERANCE**	**Total Indicator Reading (Wall Variation TOLERANCE)**	
	Over	**But Not Over**			
	--	**8.00**	**0.06**	**T.I.R.**	**0.12**
	8.00	12.00	0.09	T.I.R.	0.18
	12.00	--	0.13	T.I.R.	0.26

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FLASH EXTENSION TOLERANCES

SCOPE

1. Flash Extension Tolerances apply to the raised ridge of metal (flash) which is forced between the dies.

TOLERANCE

2. Flash Extension Tolerances are based on many variables including forging , size, material, shape and equipment size. Therefore any table giving limits is not reasonable. Suffice it to say that a flash extension of 0.06 in. or 1.6 mm is reasonable and normal practice.

MEASURING FOR FLASH EXTENSION TOLERANCE

3. Normal flash extension is measured from the adjacent surface of the body of the forging to the edge. (See Figure 22.)

NOTE; Chucking on or locating from flash extension must be avoided.

UNITS OF MEASURE

4. Flash Extension Tolerances are expressed as decimal millimeter in units of 0.1 mm or greater and expressed as decimal inch in units of 0.01 or greater. Decimals used in computing tolerances are totaled and raised to the next highest 0.1 in the metric system or 0.01 in the inch system.

SAMPLE APPLICATION: SQUARENESS TOLERANCE

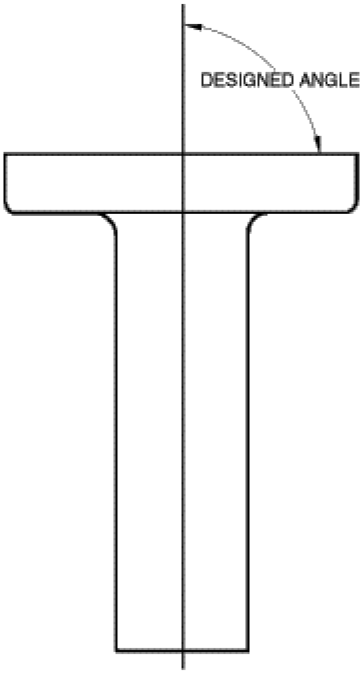

Fig. 22

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SQUARENESS TOLERANCES

SCOPE

1. Squareness Tolerance relates to deviations from the center line of the stem to the designed angle of the upset, (usually 90°).

TOLERANCE

2. Normal tolerance on squareness is 1°. (See Figure 23.)

SAMPLE APPLICATION: SQUARENESS TOLERANCE

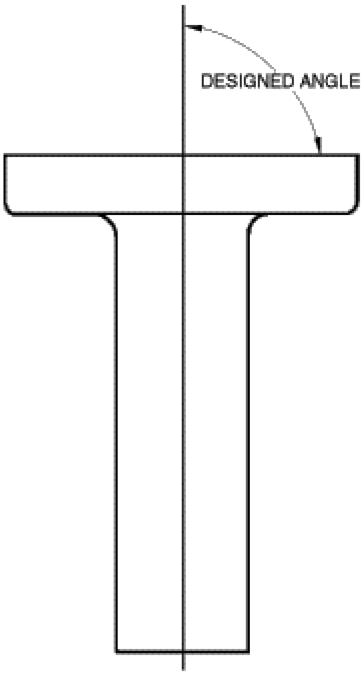

Fig. 22

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STRAIGHTNESS TOLERANCES

SCOPE

1. Straightness Tolerances relate to deviations of the centerline of the stem and body of the forging from the true centerline. These tolerances are closely related to material supplier's standard.

TOLERANCE

2. Straightness Tolerances are 0.25 inches in 5' or 6.4 mm in 1524 mm.

DRAFT ANGLE TOLERANCES

SCOPE

1. When draft angles are required on a forging, the size of the angle is generally dependent on the contour of the forging and therefore commonly determined by agreement between purchaser and producer.

TOLERANCE

2. Draft Angle Tolerances are +2° and -1° on all draft angles, unless modified by prior agreement between purchaser and producer.

RADII TOLERANCES

SCOPE

2. Radii Tolerances relate to variation from radii specifications on all fillet radii and on corner radii.

TOLERANCE

2. Radii Tolerances are plus or minus one-half the specified radii, except where corner radii are affected by trimming in which cases the minus tolerance is commonly modified to allow a square corner to be formed. .

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SURFACE TOLERANCES

SCOPE

1. Surface Tolerances relate to depth of dressouts and scale pits on the forging, based on purchaser's specification or drawing.

TOLERANCE AND CONDITIONS

2. (a) Localized dressouts or scale pits are commonly allowed on surfaces to be finish machined unless purchaser's specification or drawing states otherwise. Where purchaser specifies stock for machining, dressouts or scale pits are commonly permitted to within 0.06 in. or 1.6 mm of the finished surface or to within one-half of the machining allowance, whichever is smaller.

(b) Where surfaces of forgings are intended for use in "as forged" condition, dressouts or scale pits are commonly permitted to a depth equal to one-half of the Flange Thickness Tolerance.

TABLE XV

"AS FORGED" SURFACE CONDITION TOLERANCES

METRIC	**Diameter of Largest Flange**		**Tolerance**
	Over	**But Not Over**	
	0	180.0	0.8
	180.0	255.0	1.3
	255.0	--	1.8

INCH	**Diameter of Largest Flange**		**Tolerance**
	Over	**But Not Over**	
	0	7.00	0.03
	7.00	10.00	0.05
	10.00	--	0.07

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DEVELOPING FORGING DIMENSIONS FOR MACHINING

Forging dimensions for machining are based on maximum forging tolerance accumulations. Surfaces to be machined are forged oversize externally and undersize internally. In allowing extra stock to clean up with a reasonable minimum cut, the designer must consider all forging tolerances that apply plus a sufficient amount of material. He then establishes forging dimensions adequate to maintain the minimum allowance under the most adverse forging tolerance condition.

The minimum cut required which is the lower limit of each machining allowance, is set arbitrarily. (See Table XV.)

Forgings with corner radii that must be a sharp corner after machining should be designed to assure that the corner will clean up. In most cases making the total machining allowance equal to the corner radius will also take care of the sharp corner. Bear in mind that corner radii smaller than 0.13 in. (larger on large O.D. forgings) will cause excessive die wear and premature die failure not to mention a higher scrap rate due to the difficulty in forging a small hard-to-fill corner.

Forged Diameter Solid Parts (See Figure 24)

Forged Diameter Deep or Through Pierced Parts (See Figure 25)

Forged Thickness Controlled by Header Closure (See Figure 26)

Forged Shoulder Length Controlled by Die Wear

Shrink, Die Sinking and Tolerance (See Figure 27)

Stem Length (See Figure 27)

Overall Length (See Figure 27)

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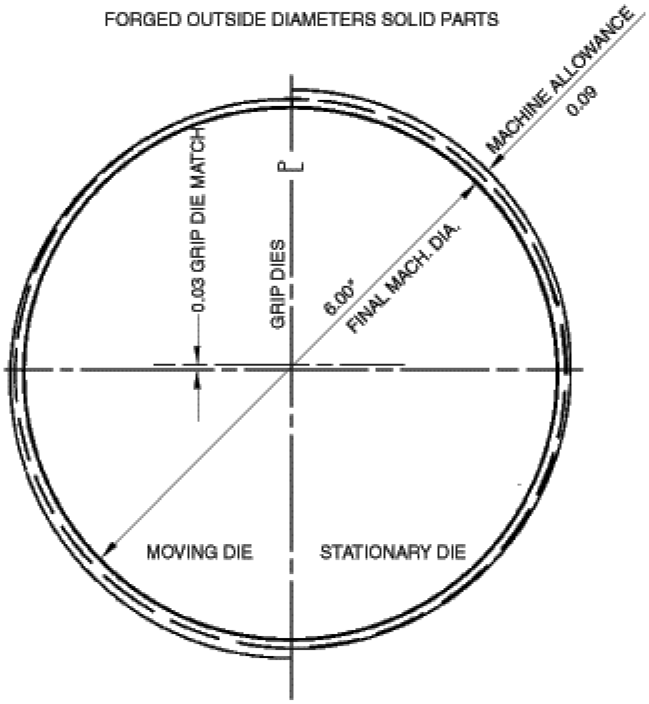
FORGED OUTSIDE DIAMETERS SOLID PARTS



MACHINED DIAMETER	6.00"	
PLUS 2 x MACHINE ALLOWANCE	0.18	
PLUS MATCH TOLERANCE	0.03	
PLUS STRAIGHTNESS TOLERANCE (If applicable)	--	
FORGE DIAMETER TOLERANCE	6.21"	+0.06 -0.00

Fig. 24

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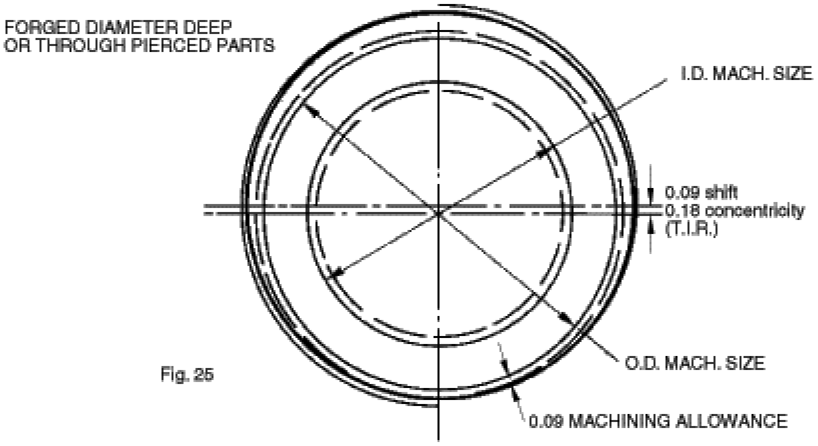

Fig. 25

SETTING DIMENSIONS FOR DEEP OR THROUGH PIERCE FORGINGS

Example 1

For I.D. Chucking, Concentricity and Die Match Tolerances are applied. (Hole Depth 8" - 12")

FINISH MACHINE O.D. SIZE	4.00"
2 x MACHINE ALLOWANCE (Customer Spec)	0.18
CONCENTRICITY TOLERANCE (0.156 T.I.R.)	0.16
DIE MATCH TOLERANCE	0.0
FORGING O.D. SIZE	4.37" +0.06 -0.00

Example 2

For O.D. Chucking, Concentricity Tolerance is applied

FINISH MACHINE I.D. SIZE	3.00"
MINUS 2 x MACHINE ALLOWANCE	0.18
MINUS CONCENTRICITY TOLERANCE	0.16
FORGING I.D. SIZE	2.66" +0.00 -0.06

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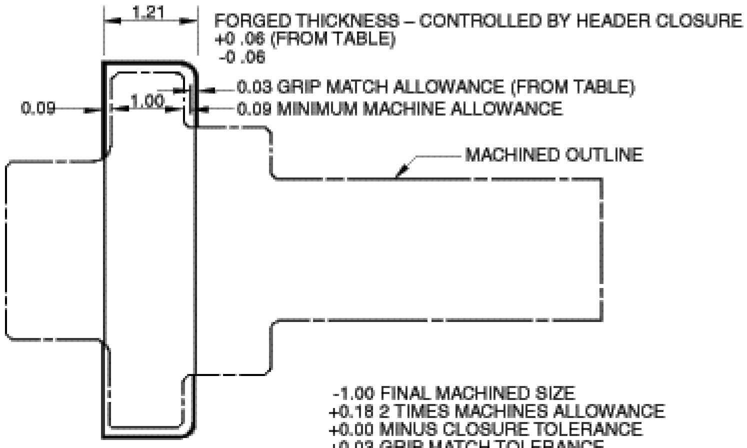


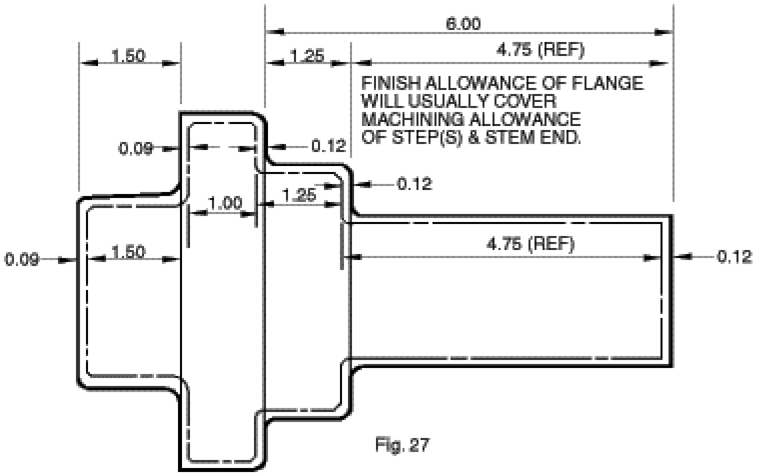
Fig. 26

-1.00 FINAL MACHINED SIZE
+0.18 2 TIMES MACHINES ALLOWANCE
+0.00 MINUS CLOSURE TOLERANCE
+0.03 GRIP MATCH TOLERANCE
1.21 FORGING SIZE

METRIC CONVERSION

INCH	mm
0.03	0.8
0.04	1.1
0.09	2.3
0.18	4.6
1.00	25.4
1.21	30.8

FORGED STEP LENGTHS



FINISH ALLOWANCE OF FLANGE WILL USUALLY COVER MACHINING ALLOWANCE OF STEP(S) & STEM END.

Fig. 27

METRIC CONVERSION

INCH	**mm**
0.09	2.3
0.12	3.1
1.00	25.4
1.25	31.8
1.50	38.1
4.75	120.7
6.00	152.4

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CONVERSION TABLES

FRACTION, DECIMAL AND METRIC EQUIVALENTS

MM						**MM**				
1/64	-	.0156	-	0.397		33/64	-	.5156	-	13.097
1/32	-	.0313	-	0.794		17/32	-	.5313	-	13.494
3/64	-	.0469	-	1.191		.6/11	-	.5455	-	13.855
1/16	-	.0625	-	1.588		35/64	-	.5469	-	13.891
5/64	-	.0781	-	1.984		5/9	-	.5556	-	14.111
1/12	-	.0833	-	2.117		9/16	-	.5625	-	14.288
1/11	-	.0909	-	2.309		4/7	-	.5714	-	14,514
3/32	-	.0938	-	2.381		37/64	-	.5781	-	14.684
1/10	-	.1000	-	2.540		7/12	-	.5833	-	14.817
7/64	-	.1094	-	2.778		19/32	-	.5938	-	15.081
1/9	-	.1111	-	2.822		3/5	-	.6000	-	15.240
1/8	-	.1250	-	3.175		39/64	-	.6094	-	15.478
9/64	-	.1406	-	3.572		5/8	-	.6250	-	15.875
1/7	-	.1429	-	3.629		7/11	-	.6364	-	16.164
1/6	-	.1667	-	4.233		41/64	-	.6406	-	16.272
11/64	-	.1719	-	4.366		21/32	-	.6563	-	16.669
2/11	-	.1818	-	4.618		2/3	-	.6667	-	16.933
3/16	-	.1875	-	4.763		43/64	-	.6719	-	17.066

1/5	-	.2000	-	5.080		11/16	-	.6875	-	17.463
13/64	-	.2031	-	5.159		7/10	-	.7000	-	17.780
7/32	-	.2188	-	5.556		45/64	-	.7031	-	17.859
2/9	-	.2222	-	5.644		5/7	-	.7143	-	18.143
15/64	-	.2344	-	5.953		23/32	-	.7188	-	18.256
1/4	-	.2500	-	6.350		8/11	-	.7273	-	18.473
17/64	-	.2656	-	6.747		47/64	-	.7344	-	18.653
3/11	-	.2727	-	6.927		3/4	-	.7500	-	19.050
9/32	-	.2813	-	7.144		49/64	-	.7656	-	19.447
2/7	-	.2857	-	7.257		7/9	-	.7778	-	19.756
19/64	-	.2969	-	7.541		25/32	-	.7813	-	19.844
3/10	-	.3000	-	7.620		51/64	-	.7969	-	20.241
5/16	-	.3125	-	7.937		4/5	-	.8000	-	20.320
1/3	-	.3333	-	8.467		13/16	-	.8125	-	20.638
11/32	-	.3438	-	8.731		9/11	-	.8182	-	20.782
23/64	-	.3594	-	9.128		53/64	-	.8281	-	21.034
4/11	-	.3636	-	9.236		5/6	-	.8333	-	21.167
3/8	-	.3750	-	9.525		27/32	-	.8438	-	21.431
25/64	-	.3906	-	9.922		6/7	-	.8571	-	21.771
2/5	-	.4000	-	10.160		55/64	-	.8594	-	21.828
13/32	-	.4063	-	10.319		7/8	-	.8750	-	22.225
5/12	-	.4167	-	10.583		8/9	-	.8889	-	22.578
27/64	-	.4219	-	10.716		57/64	-	.8906	-	22.622
3/7	-	.4286	-	10.886		9/10	-	.9000	-	22.860
7/16	-	.4375	-	11.112		29/32	-	.9063	-	23.019
4/9	-	.4444	-	11.289		10/11	-	.9091	-	23.091
29/64	-	.4531	-	11.509		11/12	-	.9167	-	23.283
5/11	-	.4545	-	11.546		59/64	-	.9219	-	23.416
15/32	-	.4688	-	11.906		15/16	-	.9375	-	23.813
31/64	-	.4844	-	12.303		61/64	-	.9531	-	24.209
1/2	-	.5000	-	12.700		31/32	-	.9688	-	24.606
						63/64	-	.9844	-	25.003
						1"	-	1.0000	-	25.400

To convert a decimal to percentage, carry the decimal point two places to the right. Thus, 63/64, or .9844 equals 98.44%

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Forging Industry Association gratefully acknowledges the cooperation of The American Society of Mechanical Engineers in granting permission to reproduce Guideline Standard Subsection 5-3 entitled "Symbology", originally published in American National Standard Engineering Drawing and Related Documentation Practices "Dimensioning and Tolerancing" ANSI Y14.5-1973.

SYMBOLOGY

GENERAL. This subsection establishes the symbols for specifying geometric characteristics on engineering drawings. Symbols should be of sufficient clarity to meet legibility and reproducibility requirements of American National Standard, Y14.2-1973.

INDIVIDUAL FEATURES		CHARACTERISTIC	SYMBOL	NOTES
	FORM TOLERANCES	STRAIGHTNESS	—	1
		FLATNESS	▱	1
		ROUNDNESS (CIRCULARITY)	○	
		CYLINDRICITY	⌭	
INDIVIDUAL OR RELATED FEATURES		PROFILE OF A LINE	⌒	2
		PROFILE OF A SURFACE	⌓	2
RELATED FEATURES		ANGULARITY	∠	
		PERPENDICULARITY (SQUARENESS)	⊥	
	LOCATION TOLERANCES	PARALLELISM	//	3
		POSITION	⌖	
		CONCENTRICITY	◎	3.7
		SYMMETRY	⌯	5
	RUNOUT TOLERANCES	CIRCULAR	↗	4
		TOTAL	↗	4.6

Note:

1) The symbol ~ formerly denoted flatness.

The symbol or formerly denoted flatness and straightness.

2) Considered "related" features where datums are specified.

3) The symbol and formerly denoted parallelism and concentricity, respectively.

	4) The symbol without the qualified "CIRCULAR" formerly denoted total runout. 5) Where symmetry applies, it is preferred that the position symbol be used. 6) "TOTAL" must be specified under the feature control symbol. 7) Consider the use of position or runout. When existing drawings using the above former symbols are continued in use, each former symbol denotes that geometric characteristic which is applicable to the specific type of feature shown

Fig. 28 GEOMETRIC CHARACTERISTIC SYMBOLS

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USE OF NOTES TO SUPPLEMENT SYMBOLS. Situations may arise in which the precise geometric requirement desired cannot be conveyed by symbols. In such instance, a note is used, either separately or supplementing a symbol, to describe the requirement.

SYMBOL CONSTRUCTION. Information related to the construction, form, and proportion of individual symbols described herein are in ANSI Y14.5-1973.

Geometric Characteristic Symbols. The symbols denoting geometric characteristics are shown in Figure 28.

Datum Identifying Symbol. The datum identifying symbol consists of a frame containing the datum reference letter preceded and followed by a dash. See Figure 29. The symbol is associated with the datum feature by one of the methods prescribed in Feature Control symbol Placement, page 64.

Letters of the alphabet (except I, O and Q) are used a datum reference letters. Each datum feature requiring identification should be assigned a different datum reference letter. When datum features requiring identification on a drawing are so numerous as to exhaust the single alpha series, the double alpha series shall be used, that is AA through AZ.

Basic Dimension Symbol. The symbolic means of identifying a basic dimension is to enclose the dimension in a frame, as shown by Figure 30.

MMC and RFS Symbols. The symbols used to designate "maximum material condition" and "regardless of feature size" are shown in Figure 31. In notes, the abbreviations MMC and RFS or their spelled-out terms are used.

Diameter Symbol. The symbol used to designate a diameter is a shown in Figure 31. It precedes the specified tolerance in a feature control symbol. The symbol may be used elsewhere on a drawing in place of the abbreviation DIA.

Projected Tolerance one Symbol. The symbol used to designate a projected tolerance zone is as shown in Figure 31.

Reference Dimension Symbol. The symbolic means of identifying a reference value is by enclosing each such value with parentheses as shown in Figure 31.

Datum Target Symbol. The datum target symbol is a circle divided into four quadrants. The letter placed in the upper left quadrant identifies it associated datum feature. The numeral placed in the lower right quadrant identifies the target. See Figure 32.

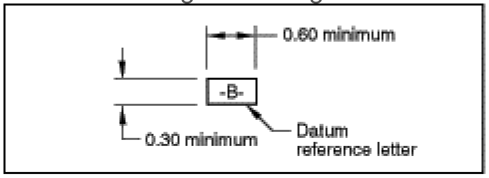


Fig. 29 DATUM IDENTIFYING SYMBOL

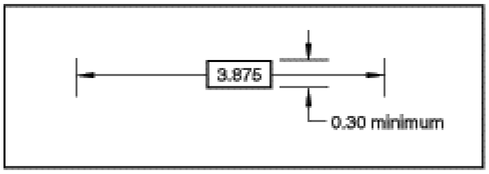
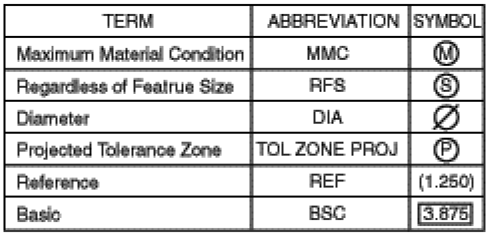


Fig. 30 BASIC DIMENSION SYMBOL



TERM	ABBREVIATION	SYMBOL
Maximum Material Condition	MMC	Ⓜ
Regardless of Featrue Size	RFS	Ⓢ
Diameter	DIA	∅
Projected Tolerance Zone	TOL ZONE PROJ	Ⓟ
Reference	REF	(1.250)
Basic	BSC	$\boxed{3.875}$

Fig. 31 OTHER SYMBOLS

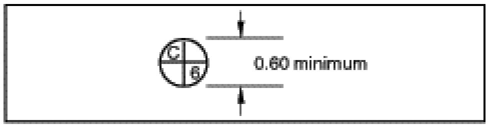


Fig. 32 DATUM TARGET SYMBOL

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COMBINED SYMBOLS. Individual symbols, datum reference letters, and the desired tolerance are appropriately combined to express a tolerance symbolically.

Feature Control Symbol. A position or form tolerance is stated by means of the feature control symbol consisting of a frame containing the geometric characteristic symbol followed by the allowable tolerance. A vertical line separates the symbol from the tolerance. Where applicable, the tolerance shall be preceded by the diameter symbol and followed by the symbol for MMC or RFS. See Figure 33.

Feature Control Symbol Incorporating Datum References. Where a tolerance of position or form is related to a datum, this relationship is stated in the feature control symbol by placing the datum reference letter following either the geometric characteristic symbol or the tolerance. Vertical lines separate these entries Where applicable, the datum reference letter entry includes the symbol for MMC or RFS. The length of frame is increased as necessary to accommodate requirements. Two methods of referencing datums are illustrated in Figure 34. Methods should not be intermixed on a drawing.

Each datum reference letter (supplemented by the symbol for MMC or RFS where applicable) is entered in the desired order of precedence, from left to right, in the feature control symbol. Datum reference letter entries need not be in alphabetical order. Where a single datum reference is established by multiple datum features, the datum reference letters are separated by a dash between letters. See Figure 35.

A composite feature control symbol is used where more than one tolerance of a given geometric characteristic applies to the same feature. A single entry of the geometric characteristic symbol is followed by each tolerance requirement, one above the other, separated by a horizontal line. See Figure 36.

Combined Feature Control and Datum Identifying Symbol. Where a feature is controlled by a positional or form tolerance and serves as datum feature, the feature control and datum identifying symbols are combined. See Figure 37. In such cases, the length of the frame for the datum identifying symbol may be either the same as that of the feature control symbol or 0.60 inch minimum.

Whenever a feature control symbol and datum identifying symbol are combined, datums included in the feature control symbol portion are not considered part of the datum identifying symbol. In the positional tolerance example, Figure 37, a feature is controlled for position (in relation to datums A and B) and identified as datum C. Whenever datum C is referenced elsewhere on the drawing, the reference applies to datum C, not to datums A and B.

Combined Feature Control and Projected Tolerance Zone Symbol. Where a positional or perpendicularity tolerance is specified as a projected tolerance zone, a frame containing the projected height followed by the appropriate symbol is placed beneath the feature control symbol. See Figure 38.

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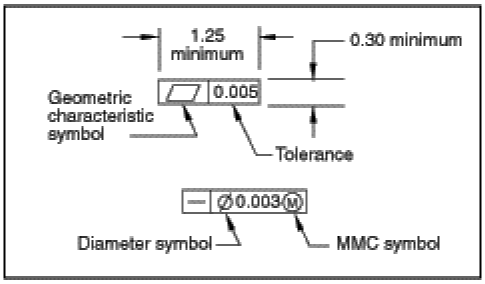

Fig. 33 FEATURE CONTROL SYMBOLS

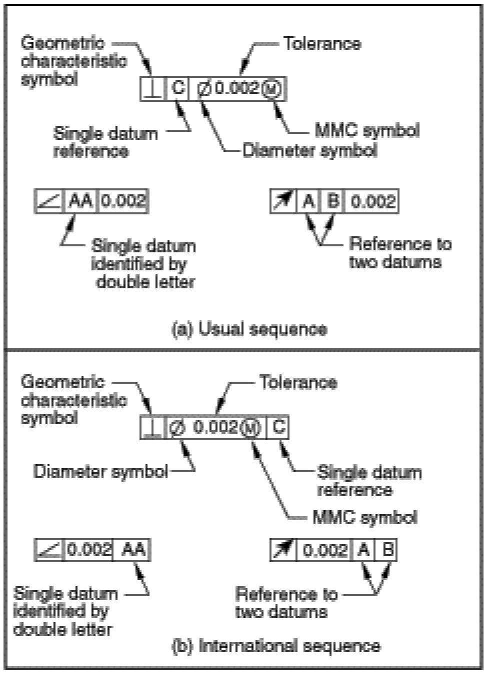

Fig. 34 FEATURE CONTROL SYMBOLS INCORPORATING DATUM REFERENCES

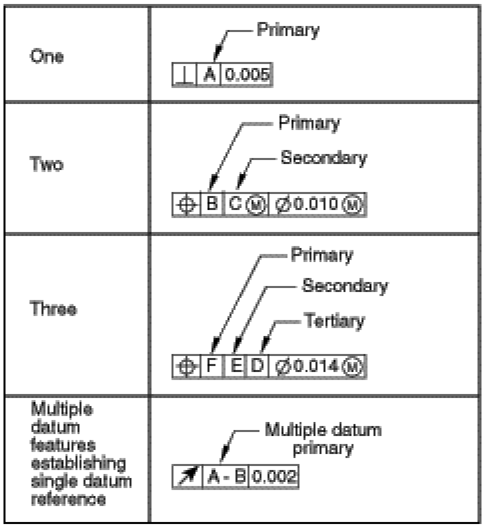

Fig. 35 ORDER OF PRECEDENCE OF DATUM REFERENCES

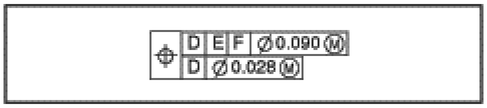

Fig. 36 COMPOSITE FEATURE CONTROL SYMBOL

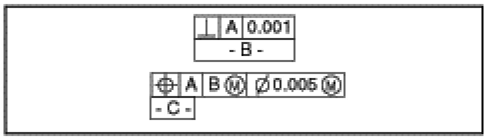

Fig. 37 COMBINED FEATURE CONTROL AND DATUM IDENTIFYING SYMBOL

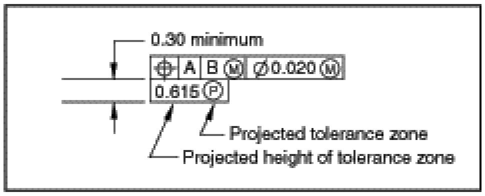

Fig. 38 FEATURE CONTROL SYMBOL WITH A PROJECTED TOLERANCE ZONE

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FEATURE CONTROL SYMBOL PLACEMENT. The symbol is related to the considered feature by one of the following methods. (See Figure 39.):

(a) Adding the symbol to a note or dimension pertaining to the feature.

(b) Running a leader from the feature to the symbol.

(c) Attaching a side, end, or corner of the symbol frame to an extension line from the feature.

(d) Attaching a side or end of the symbol frame to the dimension line pertaining to the feature.

IDENTIFICATION OF TOLERANCE ZONE. Where the specified tolerance value represents the diameter of a cylindrical zone, the diameter symbol shall be included in the feature control symbol. Where the tolerance zone is other than a diameter, identification is unnecessary, and the specified tolerance value represents the distance between two parallel straight lines or planes, or the distance between two uniform boundaries, as the specific case may be. For roundness, cylindricity, or runout, the tolerance value shown shall represent the full indicator movement. If desired, the term TOTAL, WIDE ZONE, or ON RADIUS may be used to supplement the tolerance in the appropriate feature control symbol.

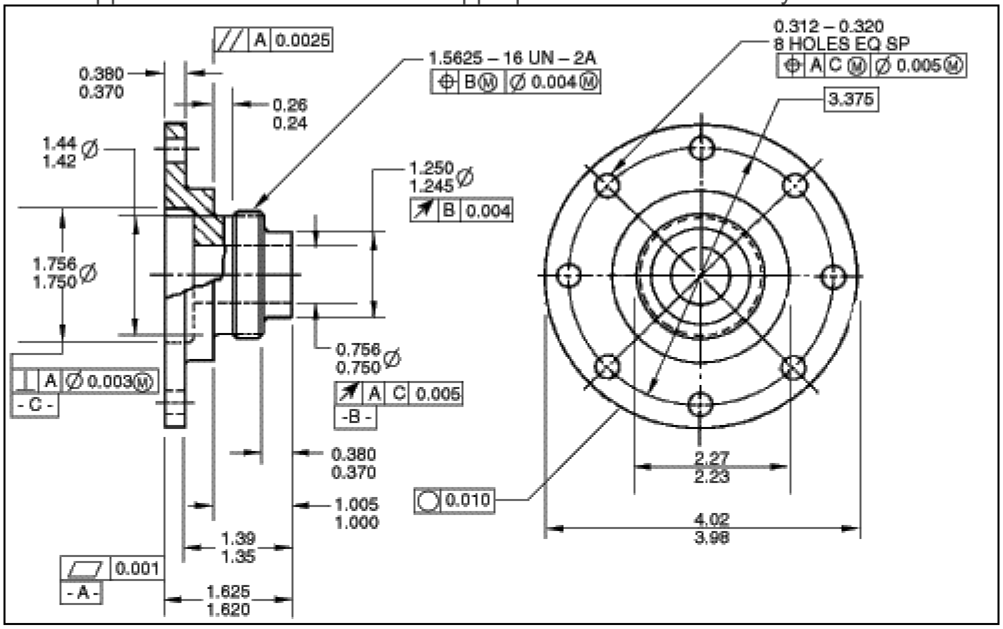

Fig. 39 APPLICATIONS OF GEOMETRIC CHARACTERISTICS SYMBOLS

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TABULATED TOLERANCES. Where the tolerance in a feature control symbol is to be tabulated, the letter representing the tolerance is preceded by the abbreviation TOL, as shown in Figure 40.

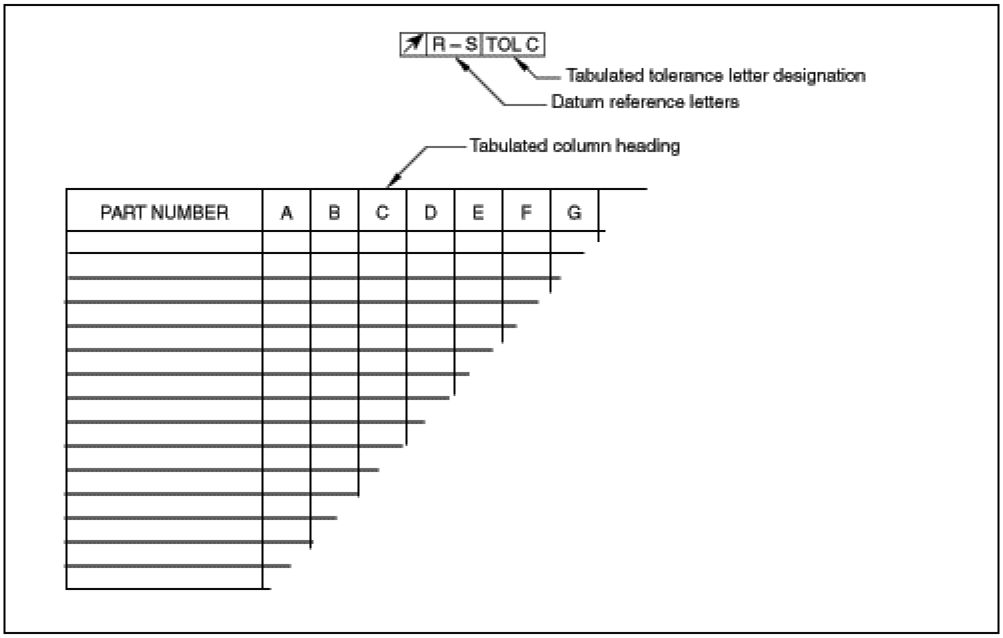


Fig. 40 TABULATED TOLERANCES

C - TOLERANCES FOR ROLLED RING FORGINGS

GUIDELINE TOLERANCES FOR ROLLED RING FORGINGS

ALLOWANCES AND TOLERANCES

There are practical limitations in dimensions and other characteristics of seamless rolled rings which vary according to the right and the producer's equipment. The degree of precision attainable in the manufacture of seamless rolled rings is dictated by the essential character of ring rolling equipment and unavoidable contingencies in rolling operations.

Theoretical exactness is seldom attained, and it is therefore necessary to compensate for deviations. The allowances and tolerances set forth herein represent what the Forging Industry Association believes to be typical within the industry, as determined by actual measurements of rings produced under normal operating conditions.

Experience within the industry shows that dimensional variations in rolling are commonly functions of the dimensions and materials involved. The allowances and tolerances herein are based upon this observed fact.

The experience of producers and purchasers of seamless rolled rings indicate that the allowances and tolerances set forth herein will provide adequate dimensional accuracy for most applications.

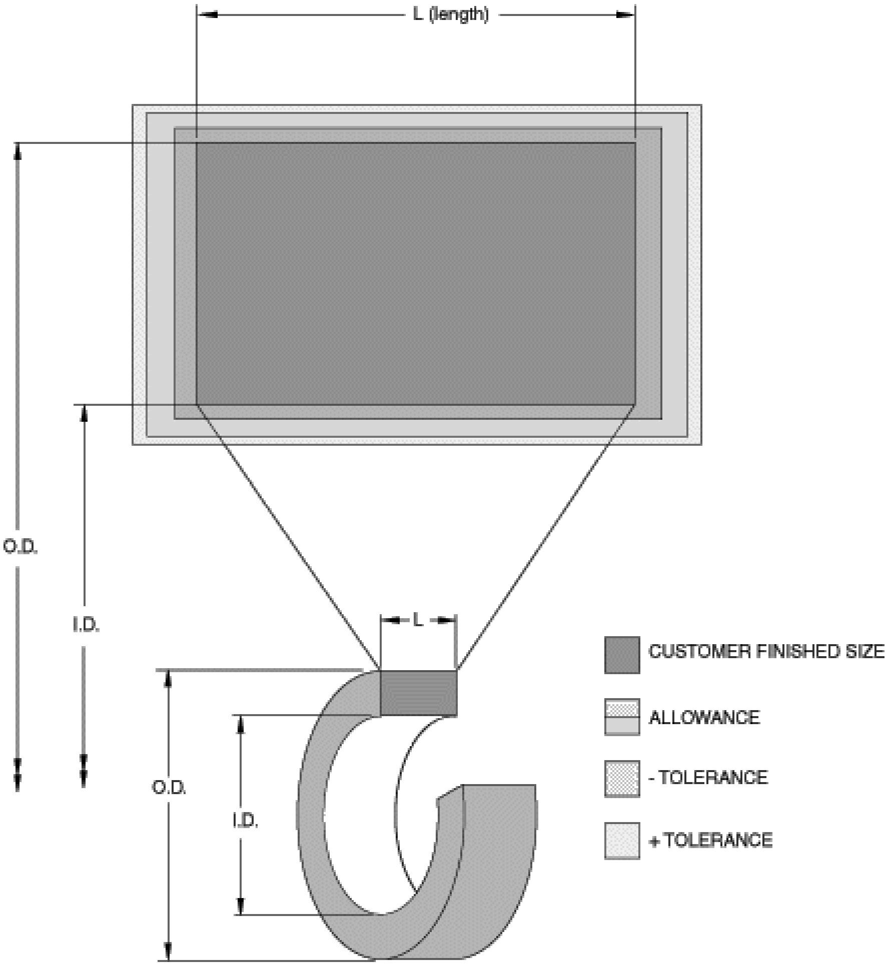
DEFINITION AND EXPLANATION OF SEAMLESS ROLLED RING ALLOWANCES AND TOLERANCES

Allowance

The amount of stock added to insure clean up on any surface that requires a subsequent manufacturing operation.

Tolerance

Dimensional variation limits.



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DIMENSIONAL PRACTICES FOR SEAMLESS ROLLED RING DRAWINGS

At the time of first printing of this publication, a transition period existed dealing with the conversion from the customary decimal inch system of dimensioning to the metric system. The following procedures will apply concerning dimensioning on ring drawings: (1) Decimal Inch System _ Inch units of measure on forging drawings will be extended to two place decimals for both part dimensions and tolerances (X.XX); and (2) Metric System _ Metric dimensions on ring drawings will be extended to one place decimal millimeter for both part dimensions and tolerances (X.X).

UNITS OF MEASURE

Tolerances in this publication are expressed in decimal inch with metric equivalents in the belief that this represents practice most common in the industry at the time of publication.

NOTE: THESE GUIDELINES ARE BASED ON TYPICAL OPERATIONS IN THE SEAMLESS ROLLED RING INDUSTRY. REFINEMENTS TO THE ENCLOSED ALLOWANCES AND TOLERANCES CAN BE MADE IN RELATIONSHIP TO ANY OF THE DIMENSIONS. OPERATIONS CAN BE PERFORMED BY ROLLED RING COMPANIES TO PROVIDE ADDITIONAL SERVICES WHICH IN MANY CASES MAY REPLACE THE NEED FOR MACHINING.

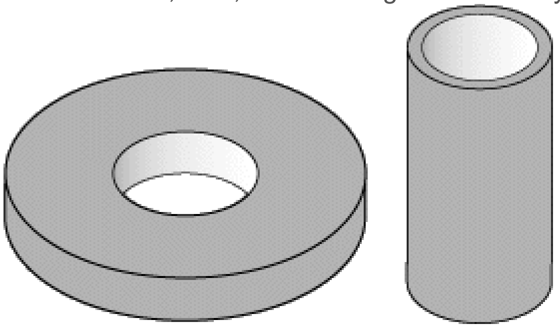
MEASURING FOR DIMENSIONAL VARIATIONS

When measuring for inside diameter, outside diameter, and length of a seamless rolled ring, variations such as roundness, concavity, squareness, etc. must be considered.

USE OF ALLOWANCE AND TOLERANCE CHARTS

a. Extreme length/wall thickness ratios are not necessarily reflected in these guidelines, and thus should be discussed with a seamless rolled ring producer.

b. Outside diameter (OD) and length (L) are the only dimensions necessary when looking for allowances and tolerances on the following charts. (With the exception of those ratios mentioned above in "a", the OD and ID measurements correlate; thus, OD and length are the only necessary axes.)



Extreme Wall Thickness Ratios   Extreme Length Ratios

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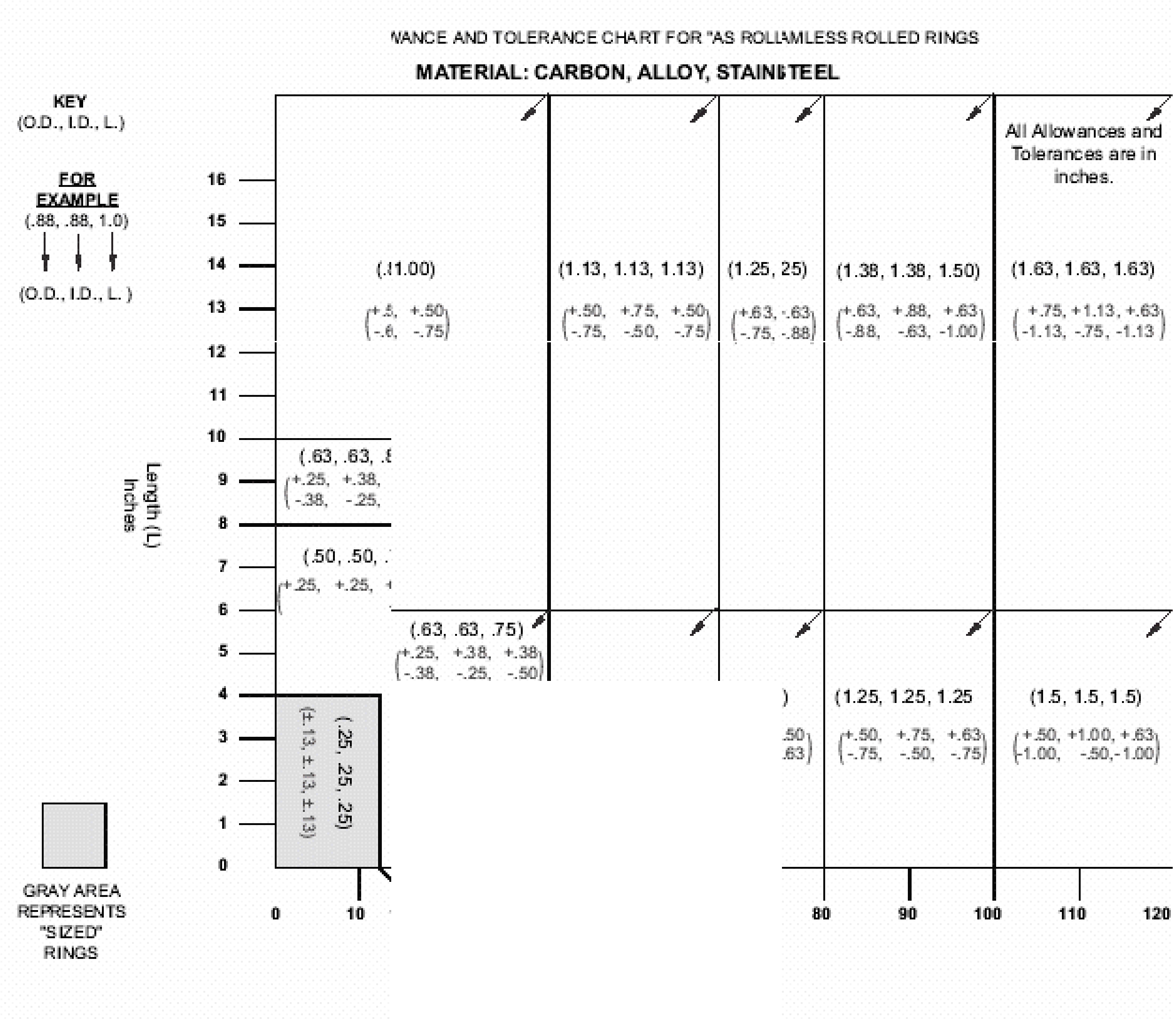

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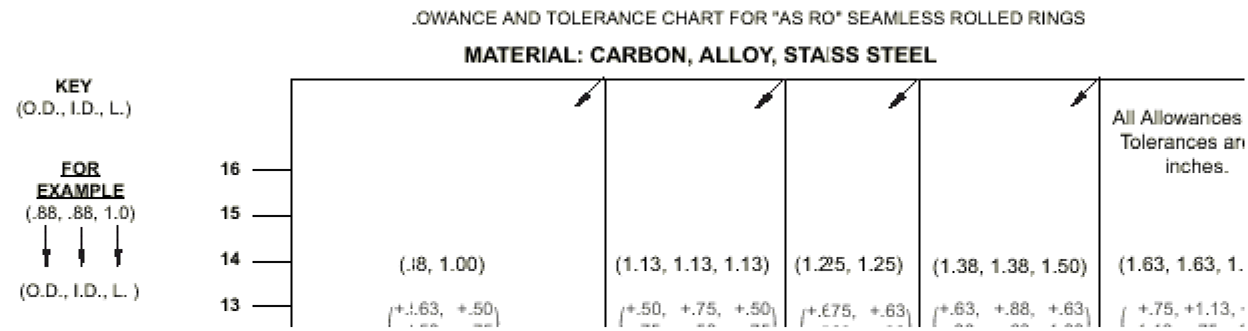

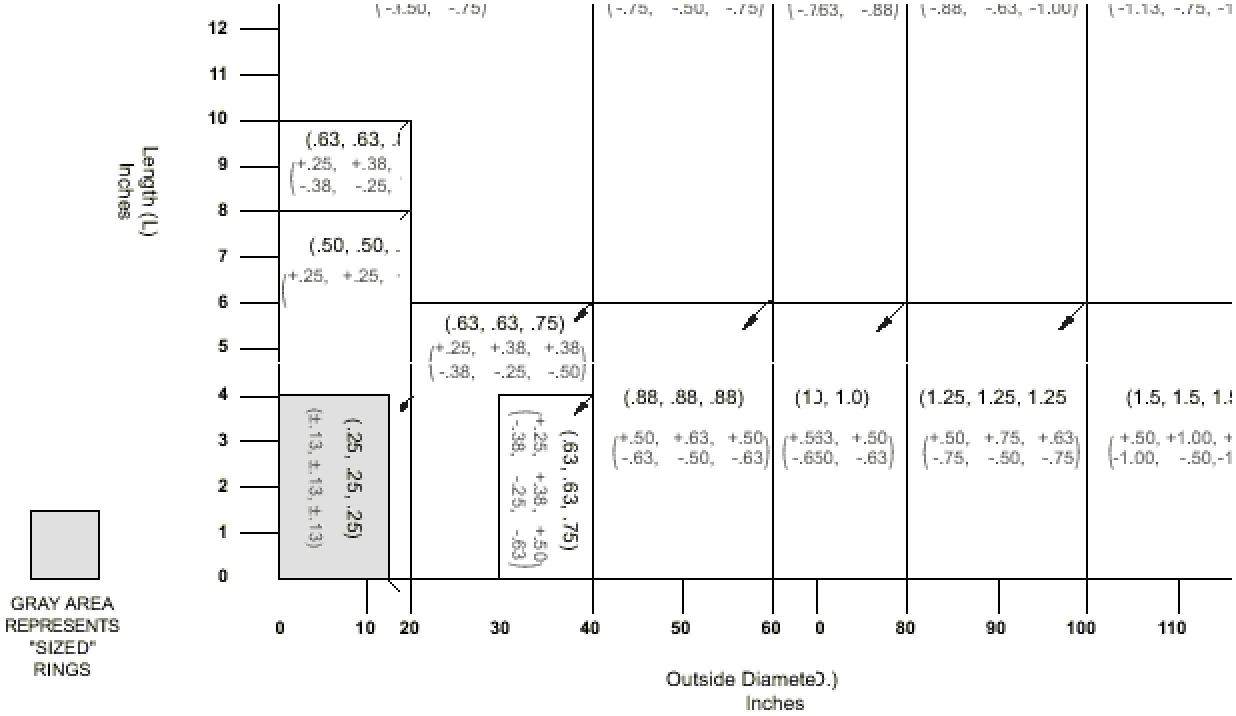

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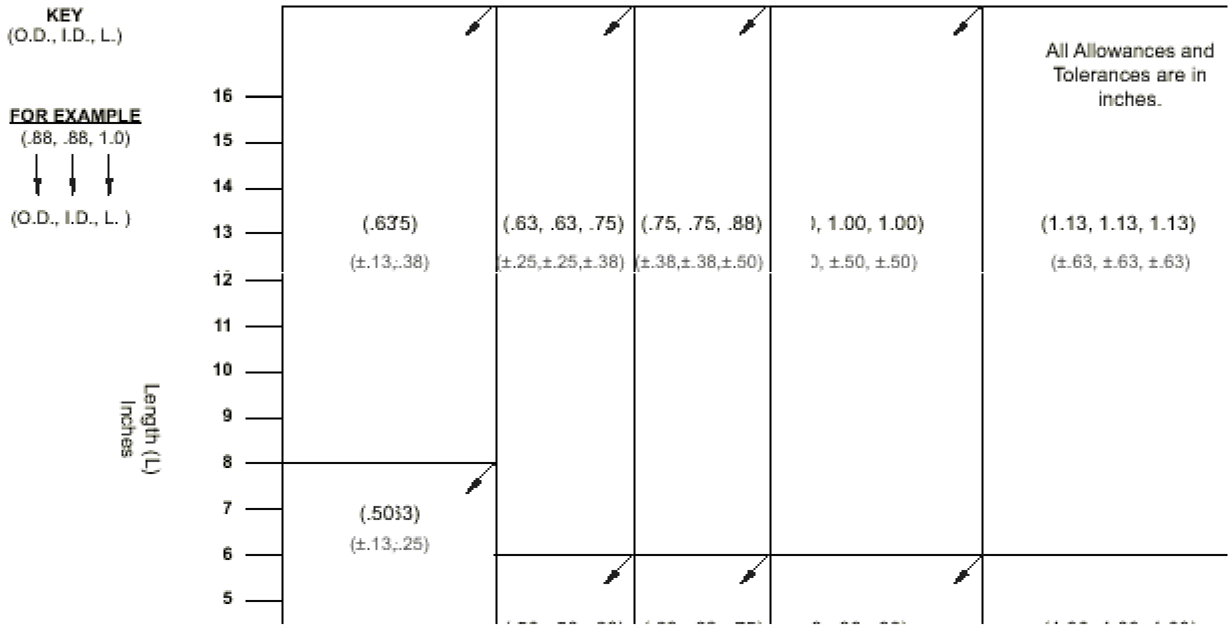
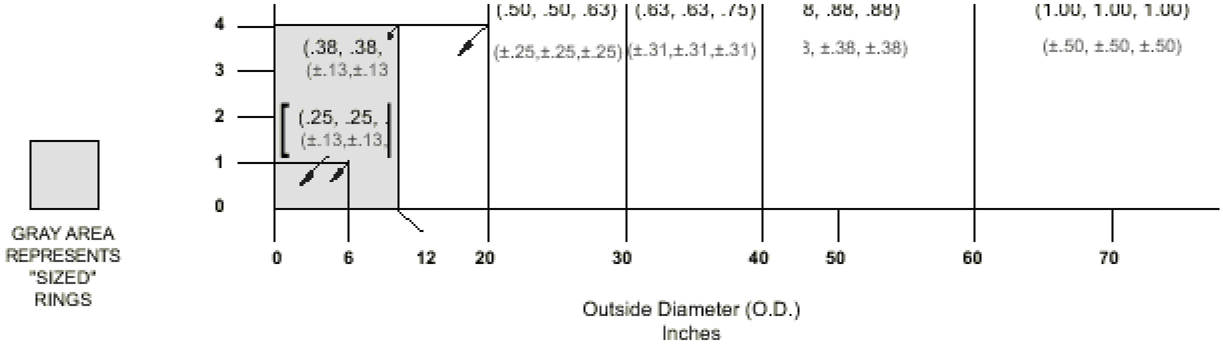
OWANCE AND TOLERANCE CHART FOR "AS RCSEAMLESS ROLLED RINGS

MATERIAL: ALUMINUI





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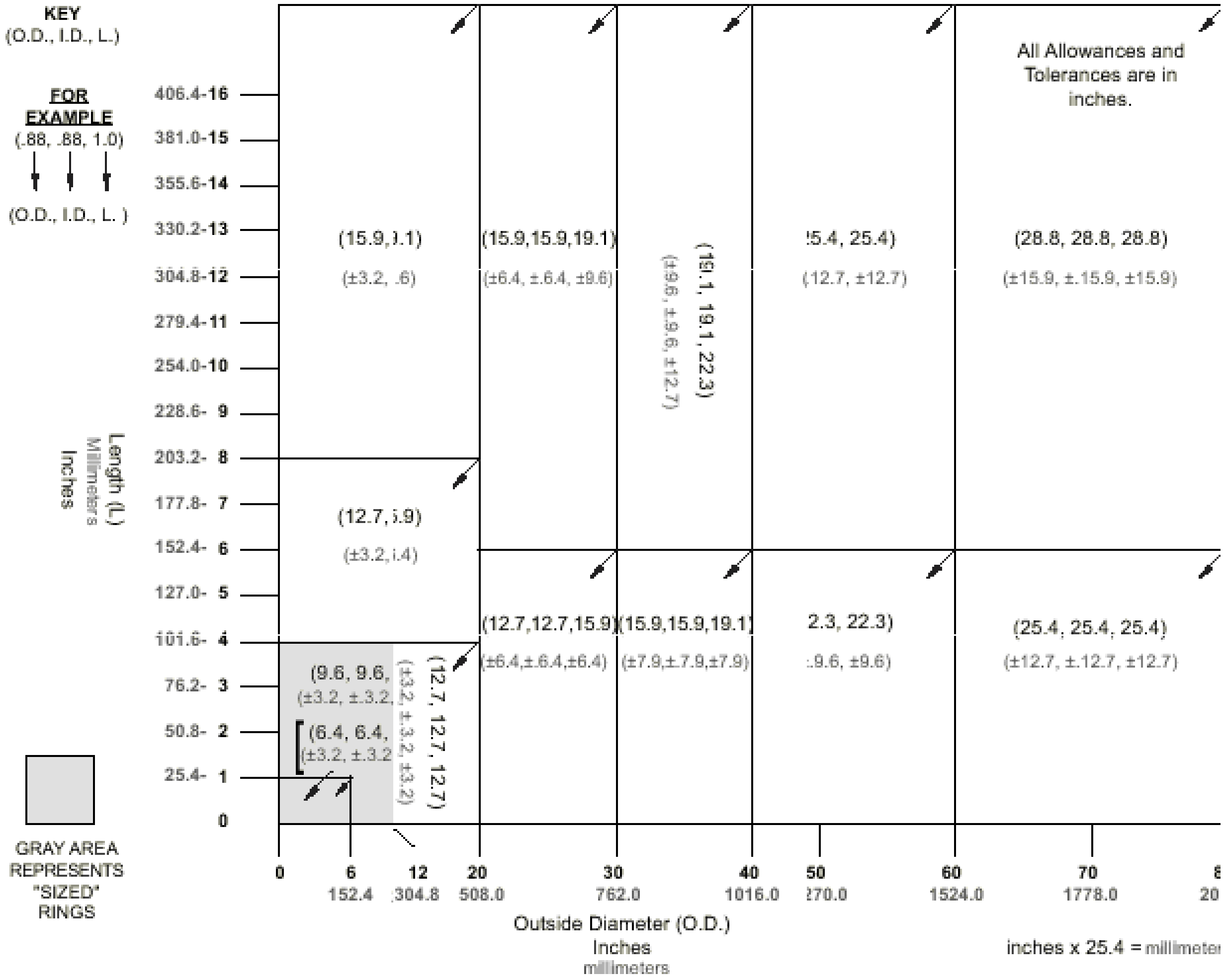
ALLO AND TOLERANCE CHART FOR "AS ROLLED" SE ROLLED RINGS

MATERIAL: ALUMINUM



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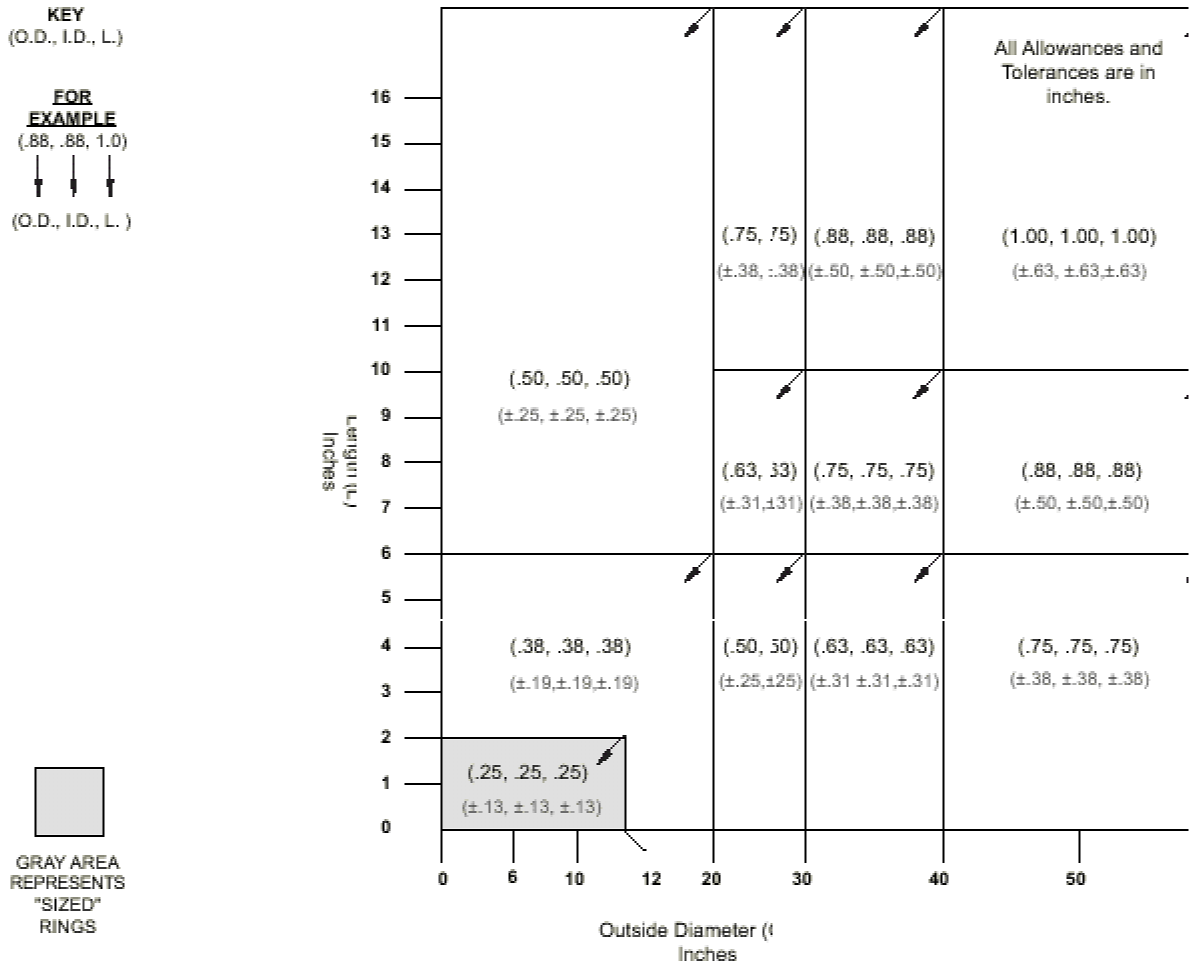
WANCE AND TOLERANCE CHART FOR "AS ROLLSEAMLESS ROLLED RINGS

MATERIAL: TITANIUM



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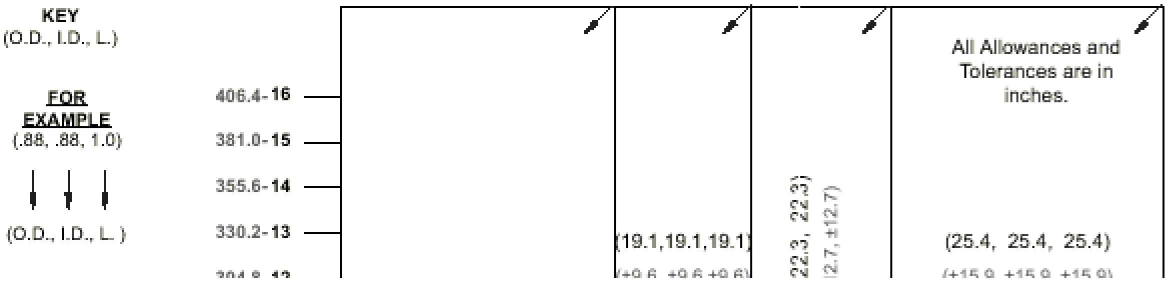
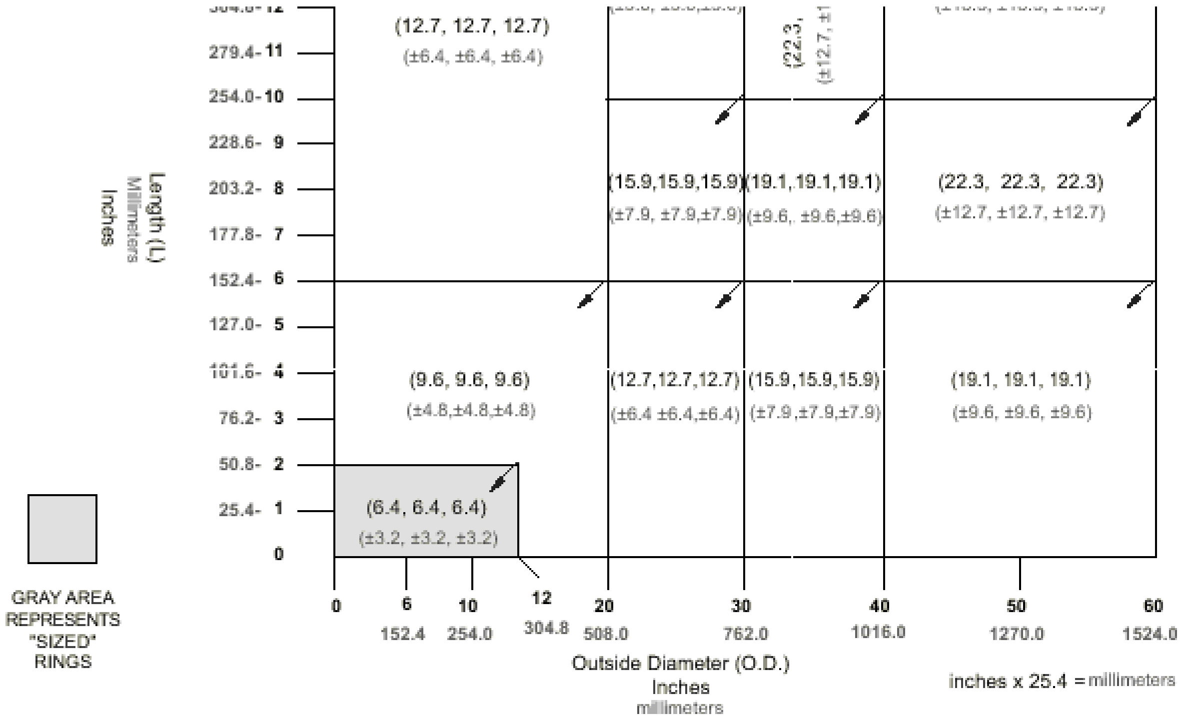
ALLOWANCE AND TOLERANCE CHART FOR "AS ROLLED" SEAMLESS ROLLED RINGS

MATERIAL: TITANIUM





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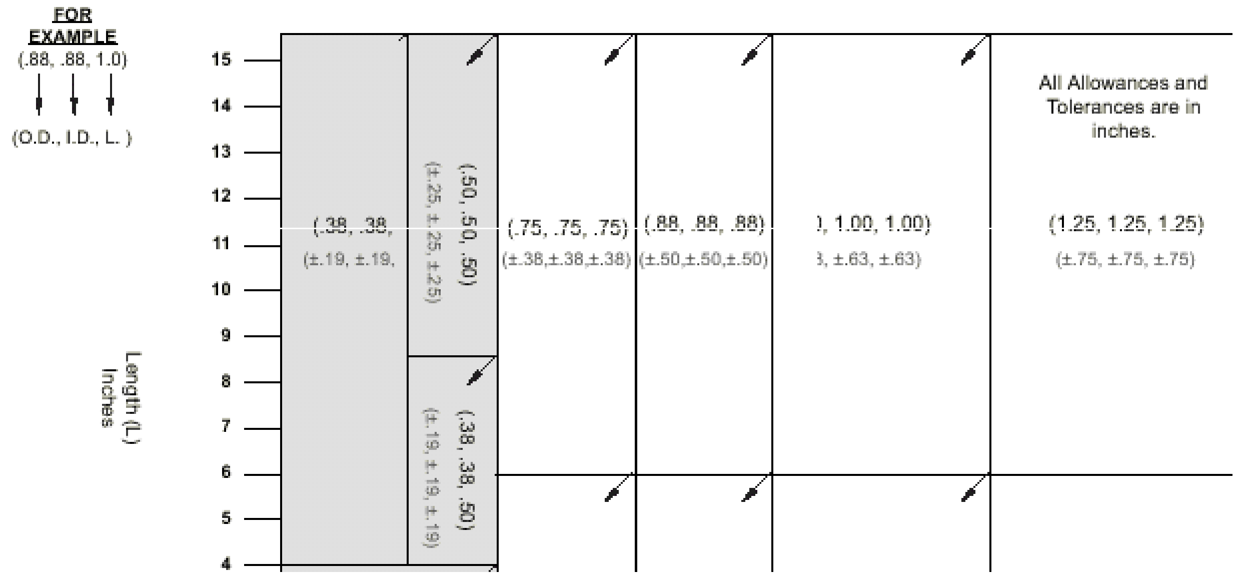
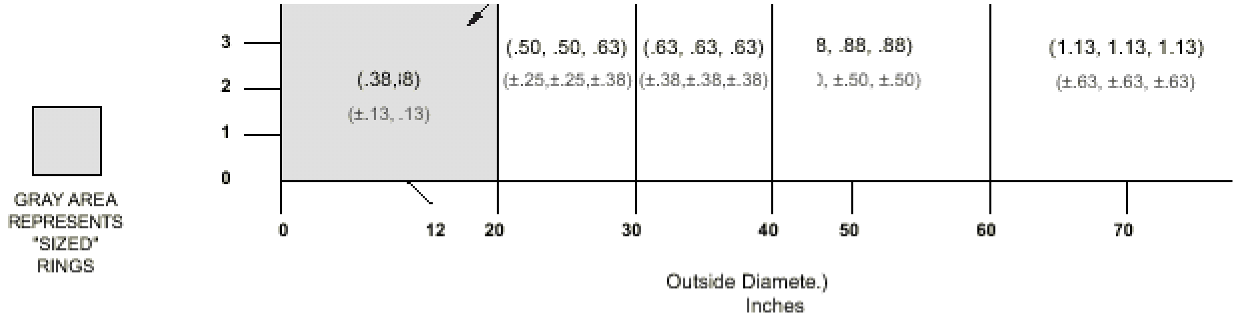
KEY
(O.D., I.D., L.)

OWANCE AND TOLERANCE CHART FOR "AS ROSEAMLESS ROLLED RINGS

MATERIAL: HI TEMP





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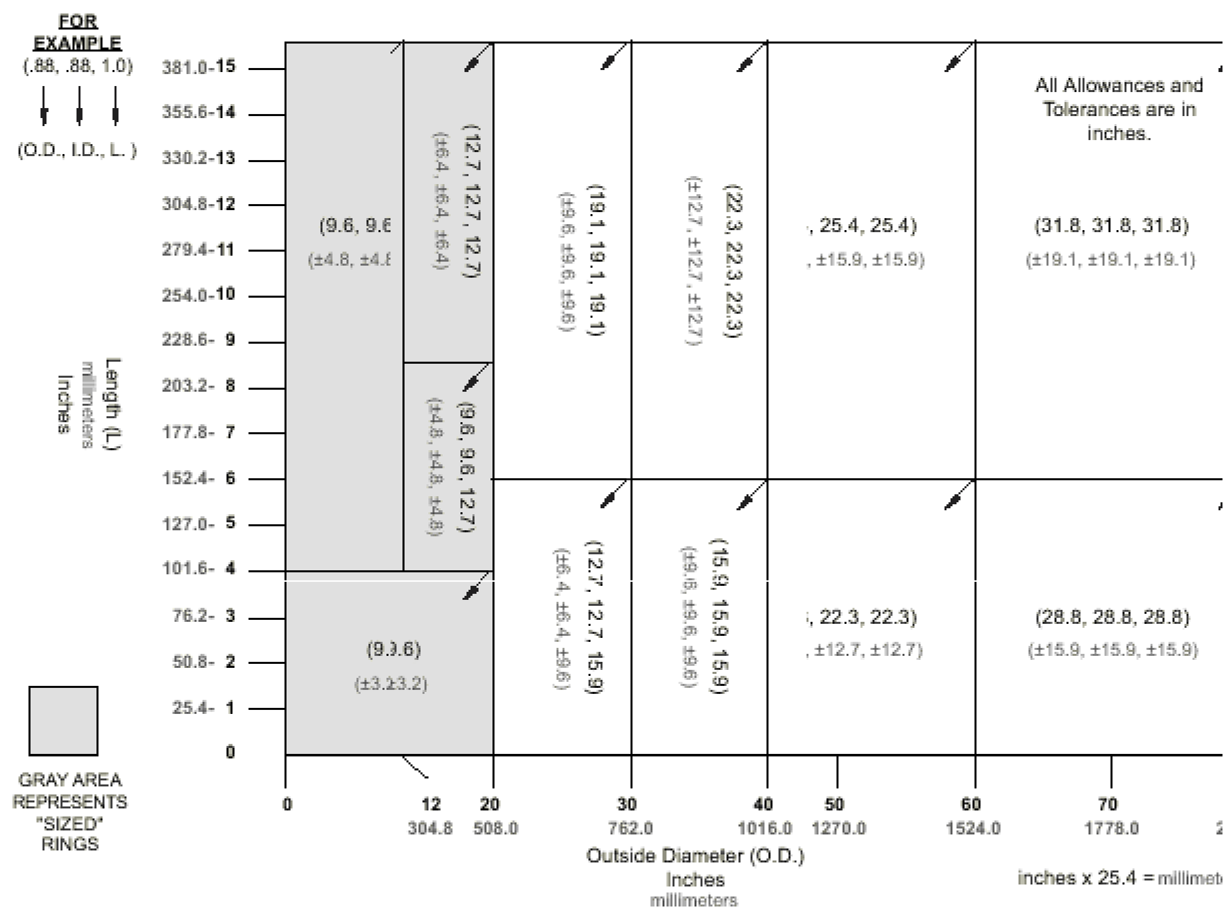
OWANCE AND TOLERANCE CHART FOR "AS RGEAMLESS ROLLED RINGS

MATERIAL: HI TEMP



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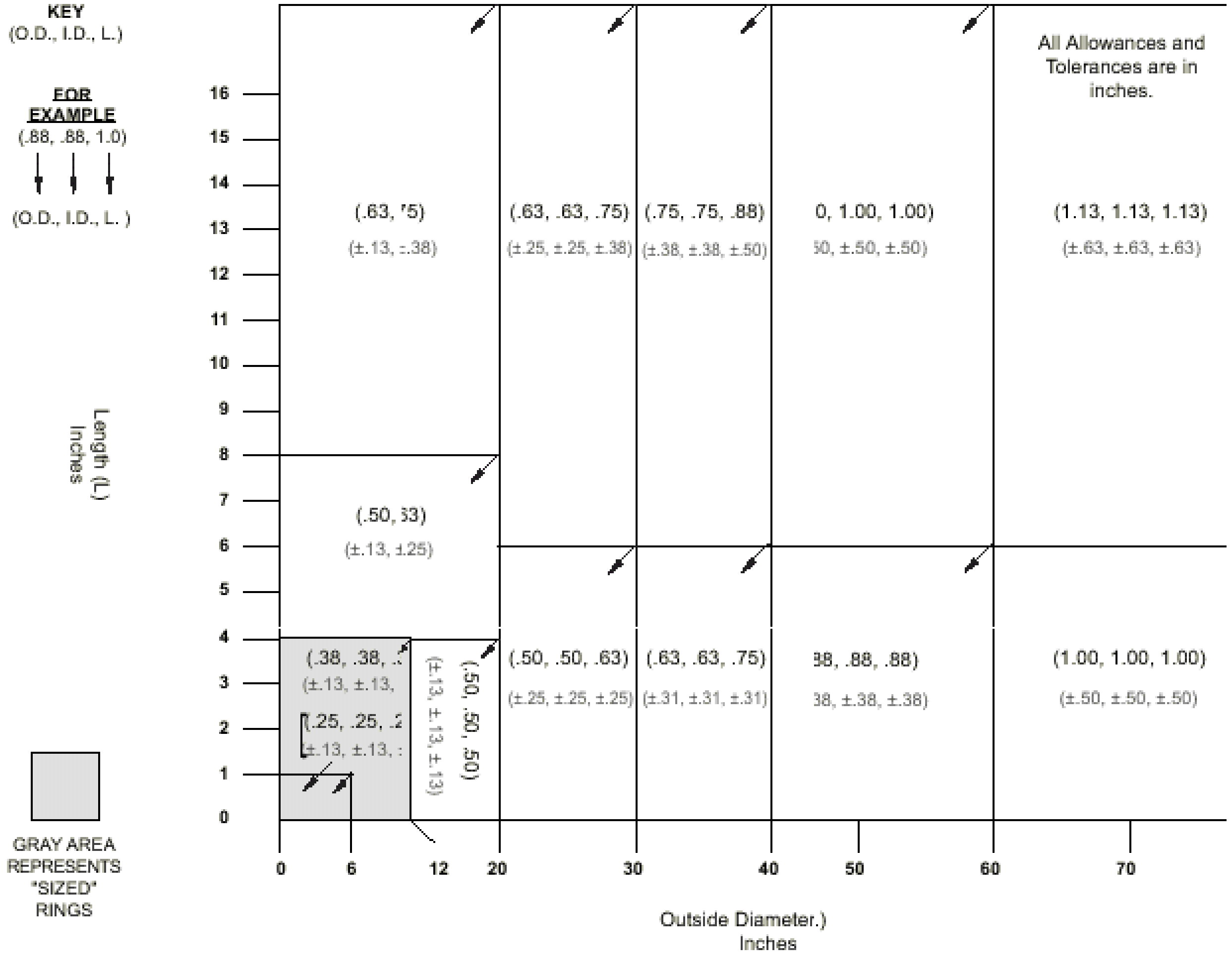
MATERIAL: BRASS AND CCR



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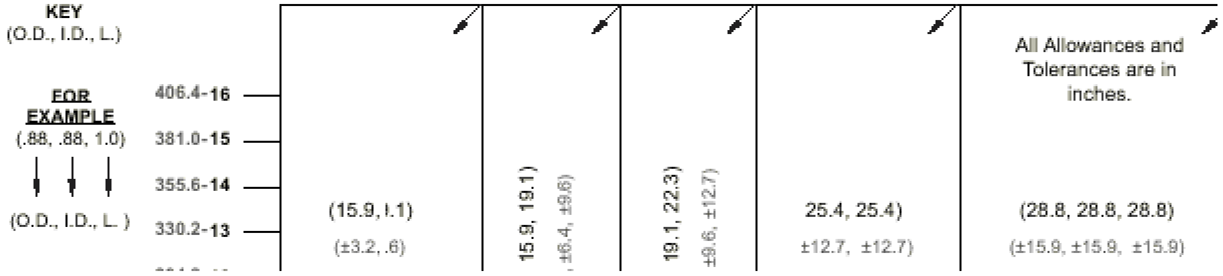
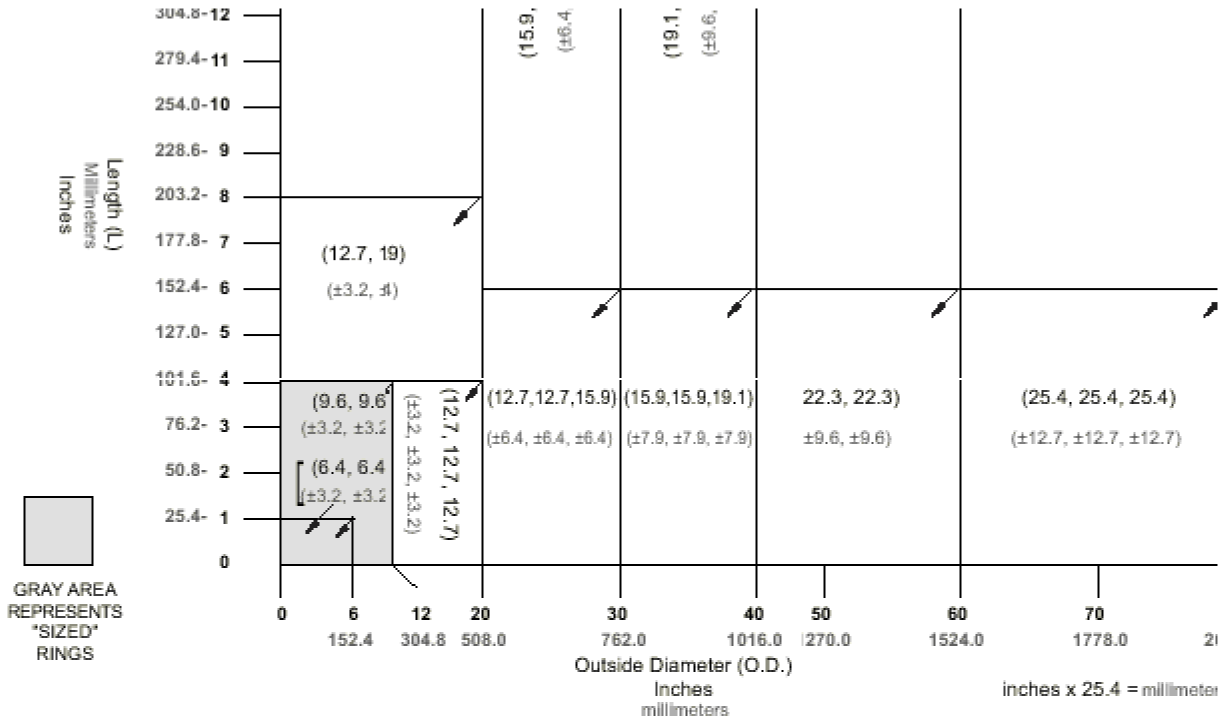
ɔWANCE AND TOLERANCE CHART FOR "AS ROEAMLESS ROLLED RINGS

MATERIAL: BRASS AND CO





D - SPECIALIZED TOLERANCES FOR PRECISION ALUMINUM FORGINGS

INTRODUCTION

Precision aluminum forgings are aluminum components plastically deformed to a finished part shape, engineered and toleranced to require little, if any, subsequent processing. They are characterized by 0° and 1° draft angles, thin sections, small radii and excellent surface condition, and often feature multiple parting lines, permitting optimum grain flow control.

TOLERANCES

The final exactness of a precision forging is the result of the actual dimensional condition of the die cavity at the onset of production, and the interaction of natural variation of the forging processes. The combination of these factors result in practical limitations of dimensional control-tolerances.

The tolerances set forth herein represent what the Forging Industry Association believes to be the prevailing levels within the industry, as determined by actual measurements of specimens precision forged under normal operating conditions on production equipment.

The experience of producers and purchasers of precision forgings indicates that these tolerances are comparable to similar processes used for the same intended applications.

When less restrictive tolerances are acceptable maximum economy is achieved. This should be noted and confirmed by buyer and seller in advance of production.

Consultation between the purchaser and the producer is advisable, should more restrictive tolerances be required. Where special conditions require more restrictive dimensional tolerances, special provisions are generally confirmed by buyer and seller in advance of production.

UNITS AND METHODS OF MEASURE

Precision forgings are measured using instruments such as coordinate measuring machines (CMM), micrometers, dial indicators, calipers, checking fixtures, and templates. The accuracy of measurements is limited by the characteristics of such instruments. Units of measure of one one-thousandth of an inch, or metric equivalents generally are found to be consistent with such limits.

Tolerances are expressed as units of one one-thousandth of an inch or one one-hundredth of a mm.

In the field of precision forging, a dimension will carry a different tolerance depending upon the form in which it is expressed. In the decimal inch system, a two place decimal (6.30 in.) will carry a tolerance of ±0.03 in. For greater precision a three place decimal should be used (6.300 in.) and will carry a tolerance of +0.020, -0.010 in. In the metric system a one place decimal (160.1 mm) will carry a tolerance of ±0.8 mm. For greater precision a two place decimal should be used (160.10 mm) and will carry a tolerance of +0.60 mm, -0.30 mm.

ADVANTAGES OF PRECISION ALUMINUM FORGINGS

- PART CONFIGURATION _ Back drafts, lateral protrusions or undercuts can frequently be made without machining.
- WEIGHT SAVINGS _ Precision Forging technology provides opportunities for economic weight control through techniques for reduced draft, scalloped edges and near net shape configuration.
- TOLERANCES _ Precision forgings require considerably less tolerance than conventional forgings. Advances in forging technology allow for identified key characteristic tolerances to approach machine tolerances ±0.010 for specified critical areas.
- MATING SURFACES _ Zero degree draft is available on specified mating surfaces. In most cases this is achievable on forged surfaces through cooperative part design, but can be achieved through permissible machining in other cases.

- GRAIN FLOW _ Proper placement of the parting line allows utilization of the most desirable grain flow and metallurgical characteristics. End grain exposure is minimized and its location can be controlled through the design process.
- COST SAVINGS _ Precision forgings can provide savings over conventional forgings and machined parts through reduced material requirements and elimination of machining operations.
- SINGLE SOURCE CONVENIENCE _ Precision forging companies can provide raw forgings, finished parts or complete assemblies. This can provide lower cost and reduced lead time.

DEFINITIONS

1. THICKNESS _ The amount of material confined between two parallel surfaces, and measured normal to the surfaces.
2. WEB _ Thin panel member usually parallel to the plan view of forging.
3. WALL _ Members that create the periphery of the forging and are usually perpendicular to webs.
4. RIB _ Thin gusset type internal members usually perpendicular to the web.
5. FLASH EXTENSION _ Excess material remaining on a forging after normal trimming, usually present at all parting line locations.
6. MATCH _ Is the alignment of feature on a forged part formed by opposing segments of a die.
7. DRAFT _ A taper applied to selected surfaces of a forged part to aid its removal from the die Draft normally is larger on internal surfaces, and smaller on external surfaces, where features are formed by more than one piece of the die.
8. NO-DRAFT _ Refers to external surfaces on forgings that are free of draft but are controlled by the implied angular tolerance of ±0 degree 30 minutes. This usually is specified in the drawing title block.
9. PARTING LINE _ The location on the forging where excess material in the form of flash is allowed to exit from the forging during the forging operation.
10. SEAM LINE _ A line that may be visible on finished precision forgings, indicates a junction of mating die components in segmented die construction.
11. PLAN VIEW AREA _ Is the surface area that the press must apply pressure to; it is express in square inches.
12. FORGING DIRECTION _ The direction in which the forging press is applying pressure to produce the part.
13. DIE CLOSURE _ Refers to the function of the closing together of the upper and lower members of a forge die during the process of actually producing a forging. The features of the forging that will be affected by die closure will be all web thicknesses and wall heights.
14. SEAMLESS OR FLASHLESS FORGING _ Refers to method of forging in which the part material if forged into a closed die at a predetermined area only and is restricted from escaping the cavity area in the form of flash. The result is a forging that has superior grain flow characteristics and has no parting line on the critical part surfaces, thus eliminating transverse end grain exposure on these surfaces. lack of parting line increases the mechanical properties in this area.

RECOMMENDED DESIGN PROPORTIONS

Defining specific parameters to apply to all precision forgings is extremely difficult. Often flexibility in technique and tooling concepts enables specific part geometries to be produced to even closer dimensions and tolerances to meet customer needs. On the other hand, a few configurations cannot be economically or technically produced to the parameters indicated in the data published.

Although many or all of the precision forging characteristics discussed in this booklet can be incorporated in a particular forging, the lowest cost per part can be produced when such criteria as minimum thicknesses and tolerances are specified only where they are actually required.

1. DRAFT

(a) external; 0° + 30' -30'

(b) internal; 1° +0° -1° or 0° ±30' if accompanied by machining permissible.

2. EDGE (CORNER) RADII

mm 1.6 +0.8 -1.6

inches 0.06 +0.03 -0.06

3. FILLET RADII

* mm 3.3 ±0.8

* inches .013. ±0.03

4. WEB THICKNESS

Web thickness is one of the most difficult dimensions to obtain in a precision forging. "Lightening Holes," 2.5 in. dia. and larger, in webs will usually permit forging to a thinner web gage.

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WEB THICKNESS GUIDELINE

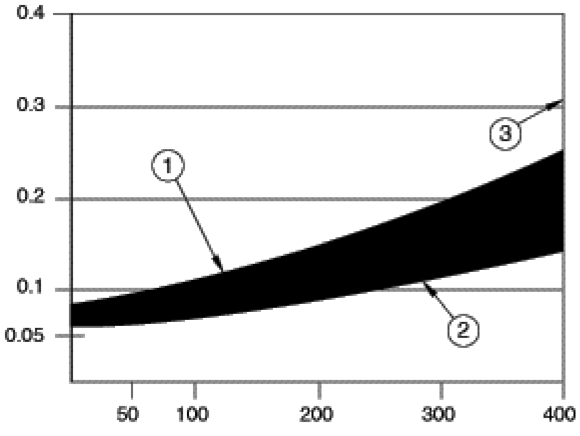

Figure 1

Notes:

1) Required for designs that are approximately rectangular and/or shapes with exterior walls.

2) Limited to shapes meeting one or more of the following:

    a. Long, narrow shapes.
    b. Parts not confined by exterior walls.
    c. Parts with "Lightening Holes."

3) Designs over 400 pva requiring minimum web gage will require vendor coordination prior to release.

4) Reduced web thickness may be achieved by chem-milling or by machining.

5. WALL OR RIB THICKNESS

Figure 2 illustrates the recommended relationship between rib thickness and the height of the rib from the web or the adjoining surface.

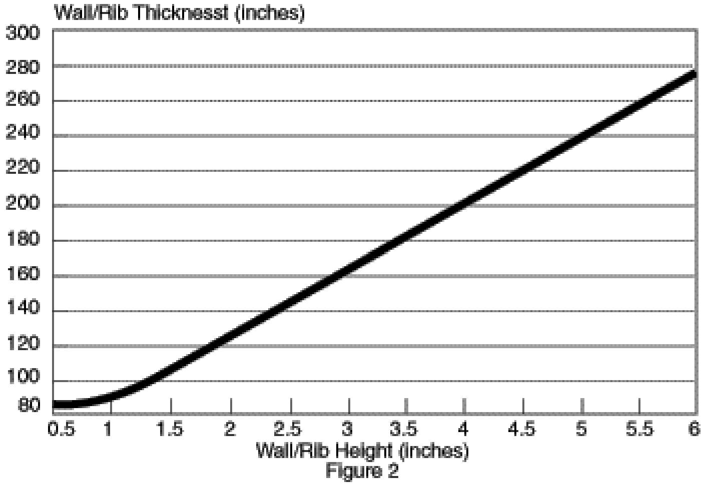

Figure 2

6. SURFACE FINISH

Surface finish of a precision aluminum forging commonly equals, or is better than, a 125 RMS finish.

7. GRAIN DIRECTION AND GRAIN FLOW

Grain direction corresponds to the location of the starting stock in the die cavity and as specified on the customer drawings. Grain flow usually follows the general part configuration and is dictated by part shape and die design.

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LINEAR AND THICKNESS TOLERANCES

SCOPE

1. Linear tolerances represent dimensional variations of specified feature sizes.

TOLERANCE

2. METRIC

	The tolerance for 1 place decimal is	±0.8	(.X ±0.8 mm)
	The tolerance for 2 place decimal if	+0.6	(.XX +0.6 mm)
		-0.3	

INCH

	The tolerance for 2 place decimal is	±0.3	(.XX ±0.3 inches)	
	The tolerance for 3 place decimal if	+0.6	(.XXX +0.020 inches)	
		-0.3		0.010

This includes allowances for temperature variations, die sinking, wear, polishing, and subsequent processing of the forging.

Tighter tolerances are achievable when machining permissible is allowed.

QUALIFIERS OR ADDITIONS

3. For Length, Width, and Height dimensions in excess of 10 inches (254 mm), the following additional tolerance applies.

* ±0.002 mm/mm or in/in

*IMPROVEMENT OVER PREVIOUSLY PRINTED GUIDELINES

STEP DIMENSION TOLERANCES

SCOPE

1. Step dimension tolerances represent variations in dimensions of offsets or "steps" where such incremental dimensions are contained within and controlled by a single die.

TOLERANCE

2. Step dimensions tolerances are ±0.010 (0.025 mm) per step. (This does not include straightness.

MEASUREMENT

3. Step dimensions are typically checked at the tangent point of the step fillet and corner radii, or at the mold point depending on step depth.

(See Figure 3.)

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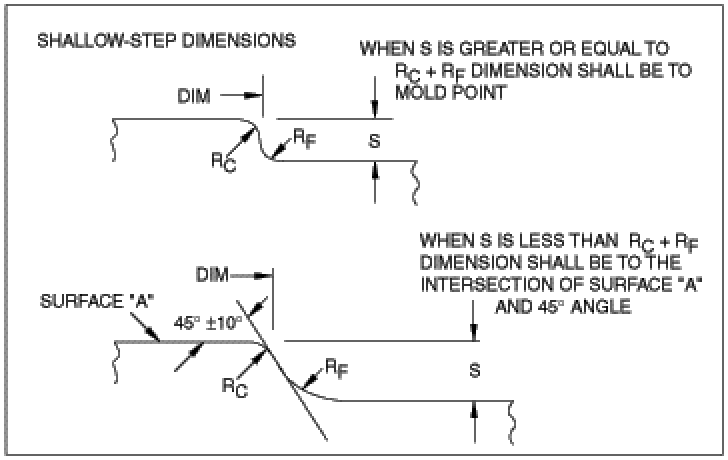

Figure 3

MATCH TOLERANCES

SCOPE

1. (a) Match tolerances relate to displacement of a point in one die from the related point in the opposite die in any direction parallel to the fundamental forging plane. Out of match (mis- match) is included within dimensional tolerance.

ANGULARITY TOLERANCES

SCOPE

1. Angularity tolerances relate to variations in relationships between features of the forging described by angles rather than dimensions. (Note: Coordinate dimensions rather than angular specifications are recommended.)

TOLERANCE

2. Angularity tolerance is ±0° 30'.

DRAFT ANGLE TOLERANCES

SCOPE

1. Draft angle tolerances apply to all draft angles and relate to variation from draft angle specifications.

TOLERANCES

2. External draft angle tolerance is 0°+30'-30'.

* Internal draft angle tolerance is 1°+0°-1° or 0°+30'-30' if accompanied by machining permissible.

When tooling points fall on draft surfaces the draft is added through the tooling point as shown in Figure 4.

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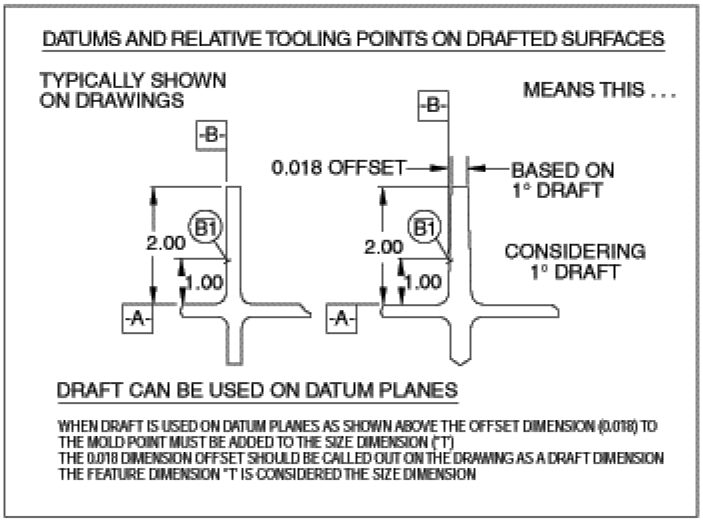
DATUMS AND RELATIVE TOOLING POINTS ON DRAFTED SURFACES

DRAFT CAN BE USED ON DATUM PLANES

WHEN DRAFT IS USED ON DATUM PLANES AS SHOWN ABOVE THE OFFSET DIMENSION (0.018) TO THE MOLD POINT MUST BE ADDED TO THE SIZE DIMENSION ("T")
THE 0.018 DIMENSION OFFSET SHOULD BE CALLED OUT ON THE DRAWING AS A DRAFT DIMENSION
THE FEATURE DIMENSION "T" IS CONSIDERED THE SIZE DIMENSION

Figure 4

* IMPROVEMENT OVER PREVIOUSLY PRINTED GUIDELINES

FILLET RADII TOLERANCES

SCOPE

1. Fillet radii tolerances relate to variations from specified fillet radii.

TOLERANCE

2. * Fillet radii tolerance is (1.6 mm) .03±.030 mm ±0.030 in.

CORNER RADII TOLERANCES

SCOPE

1. Corner radii tolerances relate to variations from specified corner radii.

TOLERANCE

2. Corner radii tolerances are described by a range from plus 0.030 in. (0.8 mm) to square condition with no sharp edge. 0.06+0.03-0.06.

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FLATNESS TOLERANCES

SCOPE

1. Flatness tolerances relate to deviations of surfaces from the specified configuration as caused primarily

by heat treatment and die deflection.

TOLERANCE

2. *The flatness tolerance is 0.016" up to 10 and 0.016 for each additional 10" dimension.

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PROFILE TOLERANCES

SCOPE

1. Profile tolerances relate to variations from nominal contours.

TOLERANCE

2. *Profile tolerance is ±0.010 in. up to 10" inches in length. ±0.015 over 10" inches in length.

FLASH EXTENSION TOLERANCES

SCOPE

1. Flash extension is excess material left on the forging after trimming.

TOLERANCE

2. *Flash extension tolerance is 0.015 in

*IMPROVEMENT OVER PREVIOUSLY PRINTED GUIDELINES

MECHANICAL PROPERTIES OF PRECISION FORGINGS

Aluminum precision forgings are ordered to the same specifications, quality assurance provisions and mechanical property levels that apply to conventional forgings.

However, many users feel that precision forgings used without machining have better mechanical properties, fatigue characteristics and resistance to stress corrosion cracking. This superiority is attributed to the high degree of work during forging, the grain orientation, parting line location and

metallurgical advantages retained when the "as forged" surfaces are not removed. In fact, studies have shown that when precision forgings are compared to machined parts of the same configuration, fatigue life is significantly increased.

Precision forgings are available in all aluminum alloys used for conventional forgings.

The tempers usually specified for these alloys can be produced in precision forgings except that T4, T652, and T7352 are rarely specified since the precision forged parts are not intended to be machined before installation. Most precision forgings are used in the T6, T73 or T74 type tempers.

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Minimum Mechanical Properties of

Aluminum Alloys Commonly Used for Precision Forging

Alloy and Temper	Longitudinal			Transverse		
	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)
2014-T6	65	55	6	64	54	3
2219-T6	58	38	8	56	36	4
2618-T61	58	45	4	55	42	4
6061-T6	38	35	7	38	35	5
7049-T73	72	62	7	71	61	3
7075-T6	75	65	7	71	62	3
7075-T73	66	56	7	62	53	3
7175-T74	76	66	7	71	62	4
7175-T66	86	76	7	77	66	4
7050-T74	72	62	7	68	56	5

NOTE: FOR SPECIFICATIONS OF OTHER ALUMINUM ALLOY FORGING MATERIALS,
CONTACT YOUR PRECISION FORGING SUPPLIER,

FINISHED PARTS CAPABILITY

Although the purpose of this document is to present recommended tolerance guidelines for precision forgings, it is also intended to introduce others areas in which the industry can improve both service and product. One major area is that of finished parts products.

A growing trend among major manufacturers is that of stressing capability to produce a forged product which meets finished part requirements and can be delivered ready for assembly by the customer.

To meet the requirements for a part ready for assembly, the precision forging industry has been steadily developing capabilities for full machining and other post processing. Today, finished parts offered by leading forging suppliers come complete not only with painting and anodizing, but also can be delivered with bushings, bearings, nut plates, and other sub-assembly hardware.

The advantages of purchasing finished parts from precision forge vendors are many. Those most important for customers are:

- Reduced cost
- Entire job/single contact
- Single manufacturing/quality control system
- Elimination of multiple purchasing channels
- Elimination of in-stream parts movement
- Better control of delivery schedules - Reduced lead time