FORGING SOLUTIONS
Design Engineering Information From FIA

OPEN DIE – ARTICLES

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FORGED GRAIN FLOW BOOSTS FATIGUE LIFE

Greatly improved fatigue life and impact strength in aerospace, automotive and other industrial applications, along with higher strength in thinner sections (which directly results in lighter parts), are the reasons why emphasis is placed on optimizing grain flow in forged components.

Orienting the grain structure can enhance mechanical properties, boosting service life several times. This provides one of the intrinsic benefits of forgings. Typical examples of these benefits include:

- **Six to ten times greater impact fatigue life** in precision-forged straight bevel gears and 100% to 300% better fatigue life in near-net-shape spiral bevel gears add up to longer lasting drive-train components in heavy trucks, construction, marine and agricultural equipment, as compared to standard “cut” steel gears. Optimum grain flow patterns in forged, net teeth make these performance increases possible.

- **Higher strength in reduced cross-sections** is achieved in forged truck and passenger car wheels, because controlled grain flow in the flange area puts the strength where it is needed. When compared to cast wheels, forged wheels save material, cut weight, and more easily meet mileage requirements.

- **Improved performance and cost effectiveness** are routinely achieved in structural aircraft and aerospace components, including many with large plan-view areas. Control of grain flow in precision aluminum forgings makes components stronger in several directions, permitting weight savings and facilitating part consolidation. Extensive labor savings are a major benefit over weldments and built-up composite structures.

**Pushing performance**

Orientation of grain flow-alignment of the metal microstructure with the geometry of the part being forged-is directly responsible for developing maximum tensile strength, toughness (impact strength), fatigue resistance and, ultimately, the greater service-life expectancy that is characteristic of forged net-shaped parts.

No other metalworking components (including castings, machined bars and plates, weldments, and other fabricated assemblies) permit this degree of grain control and subsequent property enhancement. In castings, grain flow cannot be optimized since grain direction is characteristically random as a result of the solidification process. Similarly, machined components exhibit discontinuous grain flow. Because of extensive metal removal, grains are broken at the part surface, and the surface is where facture usually initiates. At best, grain orientation in machined parts is unidirectional, taking on the prior patterns of the original bar, billet, or plate.
“Classical” grain flow follows the contour of a forged part, as is characteristic of a forged crankshaft. However, certain geometries and performance requirements may benefit from a different type of grain flow. For example, circumferential-type hoop strength or strength in the axial direction may be needed, depending on the part geometry and stresses that the part will see in service. What can be accomplished in terms of grain flow is also dependent on the forging techniques and tooling utilized, both of which can affect cost as well as ultimate part performance.

In rib- and web-type forgings, longitudinal grain flow (the strongest orientation in terms of properties) coincides with the primary grain direction of the starting billet. This initial orientation is created by deformation during stock fabrication, which typically elongates the grains in a direction parallel to the primary working direction. Further working by closed-die forging modifies and refines the starting-billet grain structure to produce the best combination of properties in all test directions.

In most forgings, the initial grain flow direction (longitudinal and the strongest) is oriented within the part along the axis that will see the highest in-service loads. However, grain-flow modifications made by judicious use of tooling and forging techniques can be utilized to maximize strength in other directions without sacrificing properties along the principal direction.

Grain-flow sensitivity

Some metals and alloys exhibit a “grain-flow sensitivity,” which is reflected by the degree of isotropy of the material being forged. Materials with high grain-flow sensitivity exhibit greater differences in properties between the longitudinal and transverse grain-flow directions. (This does not imply that forgings are strong in only one direction, since tests show that properties in any direction usually exceed those of non-wrought products, like castings.) The table below lists various metals according to their grain-flow sensitivity.

Grain-flow patterns can be controlled to a far greater extent in aluminum and other alloy precision forgings than in parts conventionally forged between two-piece upper and lower dies, due to the use of multi-segment dies. This type of tooling is standard for aluminum and some other alloy precision parts, and it creates controlled paths for the material to flow into several regions of the die cavity or into gutter areas surrounding the cavity. As with conventional forgings, additional modifications to grain direction can be achieved by the use of bending or preforming dies prior to blocking and finishing.

Grain-flow sensitivity is a function of material

Depending on the type of metal or alloy and its microstructural characteristics, grain-flow sensitivity - reflected in the degree of anisotropy or property directionality - can vary widely. This dependence should be taken into account in forging design.

**Least sensitive**

*Pure metals:* aluminum, nickel, cobalt, silver and copper.

*Solid-state alloys:* nickel/copper and aluminum/copper alloys.

**Moderate sensitivity**

*Precipitation-hardenable alloys:* 300 series stainless steels, magnesium alloys, and nickel/chromium alloys.

*Steels:* carbon and alloy; 400 Series stainless.

**High sensitivity**

*Two-phase alloys:* Most high-strength aluminum alloys, 2014, 7075, 7079, etc.; many nickel and cobalt-based superalloys including INCO 718, Waspalloy and Astroloy.

*Two-phase alloys (not fully recrystallized):* Titanium alloys like Ti-6Al-4V, certain alloys of zirconium, molybdenum alloys like Mo-Ti-Zr.
Two-way street
Proper development of grain-flow patterns, along with the ultimate property profile, can only be achieved by good communication between the design engineer and the forger. It is this two-way communication that facilitates a truly effective cost/performance balance.

Key to this balance is specifying grain-flow requirements only where they are absolutely necessary. In practice, only a few areas of a forging require optimum grain flow, and most non-critical areas are subject to considerably lower stresses. Highly stressed areas (aptly named “hotspots”) can readily be identified by determining the failure mode.

Such analysis helps to avoid over-specifying grain flow, which increase costs. In many cases, optimum grain flow (hence, optimum properties for a particular component) is achieved by employing one or more clocker dies, and then finish dies. Conversely, multiple dies cannot improve the grain flow of some designs, and specifying a blocker operation merely increases the tooling cost. It always pays to discuss final component application with the forger in order to determine how best to optimize grain flow while simultaneously keeping tooling and production costs down.
Design engineers routinely find they can take greater advantage of the ultimate property values of forgings, as compared to metal components fabricated by other processes. This means that forgings can be lighter and smaller. Depending on the application, designs for forged components can be based on 75 to 80% of the yield strength, for instance. Not surprisingly, this design percentage is considerably lower for castings.

A specific example is the use of forgings with a high tensile strength in industrial dryers and rotary kilns, permitting the use of design limits that are 36% higher than castings. Similarly, forged gears can be designed to withstand higher stresses. Structural integrity, overall quality, higher strength, and the consistent properties of forgings place them above castings and components produced by other metalworking processes. The inherent soundness of forged components is reflected in their structural, metallurgical, and dimensional characteristics. Consequently, where metal components are concerned, forgings are the first choice for many applications, ranging from high-speed gears to critical aerospace components.

Reliability via strength

When it comes to strength, the reputation that forgings possess is well deserved. Significantly higher property values for forged versus cast steel are dramatically depicted in the bar chart above. Through the reduction achieved in the forging process and the accompanying homogeneous microstructure, forged components consistently attain higher strength levels than castings and metal parts made by other methods. Even when transverse properties are increased to equal longitudinal property values via an upsetting operation prior to conventional forging, tensile properties and fatigue limits surpass those of competitive fabrication methods. Similarly, the corresponding toughness and ductility...
achievable in forging surpass all other metalworking processes.

As frequency distributions for selected properties aptly demonstrate, the higher strength and ductility (indicated by reduction of area) of forged steel translate into higher reliability. See figure on the right. Similarly, the high ductility of forgings contributes an extra safety margin, should unexpected peak loads exceed the design-stress calculations. In addition, the much greater strength-to-weight ratio of forgings facilitates the design of lighter-weight parts with corresponding cost savings, and without sacrificing safety.

**High structural integrity**

Microstructurally, forgings are optimal, achieving 100% density in contrast to porosity-prone castings and powder metal components. Castings, which are known for their inherent voids, segregation, microcracks, and non-uniform metallurgical structure, often have inconsistent properties. The better microstructure allows forgings to deliver superior performance as compared to castings. See figure on the left.

Forged large gears are preferred over castings because of their higher strength and structural integrity (absence of porosity, etc.). Both of these factors improve performance in large precision gears for high-speed applications, such as electrical generating equipment, marine power plants, and compressor drives.

Further, the clean, uniform microstructure that forged components possess allows gear makers to achieve higher, more uniform hardnesses, and to benefit from extended gear life and easier machining.

**Low product liability**

Strength is the primary reason why forgings are initially chosen over other alternatives. However, some applications demand the high reliability of forgings.

Loads up to millions of pounds make rams for forging hammers one of the most severe applications imaginable. At the moment of impact, the hammer ram can experience a force up to 2,000 gs. In effect, the weight of a hammer...
mer ram (typically ranging from 500 to 50,000 pounds) increases to 2,000 times that at impact. The resulting high stresses make forged rams the clear choice. Stronger and tougher than cast materials, forged 4140 and 4340 steel rams possess significantly higher endurance limits, making them more fatigue-resistant. Because of product liability considerations, cast rams are not even considered.

A step above machining

Strength-wise, forgings outperform machined components, too. Even though parts machined from bar stock may not suffer from the effects of voids and inclusions, they still do not possess the integral strength of forgings, because the grain flow is interrupted at machined surfaces. In many instances, unusual shapes like a propeller nut can be forged “near-net” with the added benefit of cost savings due to reduced machining. Typically, conversion from machining to near-net shape forging (with its increased strength) boosts service life dramatically. In a number of cases, precision forging not only increases part life significantly, but causes manufacturing costs to drop, as well.

Forged quality means less testing

Reduced testing is another important benefit derived directly from the integrity of forgings. The extreme strain rates generated during forging immediately identify the presence of defective raw material so that forgings are virtually “self-testing.” Because of the part-to-part uniformity of forgings, manufacturers do not have to ascertain the quality of every incoming component before putting parts through further in-house processing. This benefit is especially important with outside purchased components that are subsequently machined. While forgings readily lend themselves to quality control sampling plans, many castings need to be 100% tested to ensure their integrity.
TEN WAYS THAT FORGINGS HELP TO REDUCE COSTS

When properly designed, forgings can be more cost-effective than metal parts produced by alternative methods, such as castings, machined bar and plate, weldments, stampings, built-up structures, sheet metal, and other fabricated assemblies.

Even when forged parts initially cost more than competitive metal products, a look at life-cycle costs often justifies the use of forgings.

1. Greater strength-to-weight versus castings
Higher strength-to-weight ratios often make forgings competitive with castings; not only because of their lighter weight, but also because forgings outperform castings. Forged connecting rods for automobiles are more than 10% lighter on average, and they are also stronger than cast versions.

2. Eliminating weldments
Switching to forgings from multipart weldments also leads to cost reduction by eliminating labor-intensive welding and setup operations. This approach has been successfully utilized in aircraft engines, where massive integral forgings eliminate electron-beam and inertial welds between adjacent components, and in primary missile structures, where a one-piece cylindrical forging with built-in stiffening ribs outperforms a structural shell made by welding sheet and plate to fabricate internal stiffening rings. See figure on the right.

3. Reduced inspection and testing
In pressure vessel applications, such as steam headers for utility boilers and catalytic crackers for petrochemical production, forgings do not require periodic inspections like welded parts do. This benefit is particularly important when welds are encased in concrete or otherwise difficult, if not impossible, to inspect.

When welds are unavoidable, flanges and other features can be incorporated in forged components to allow easily accessible butt welds to be made. In addition, increased section thickness in the boss area will help compensate for any weakness in the heat-affected zone, when welding is necessary.

Reduced quality control testing can also contribute to cost savings because forgings readily lend themselves to

Cost analysis for a nose cowl frame shows that blocker type forgings are 36% cheaper than a sheet metal/extrusion weldment at 1200 parts. The major contributor to the higher cost of the fabrication is assembly labor.
4. **Replacing assemblies, fabrications**

Cost savings are usually achieved when forgings replace complex fabrications and assemblies. For example, replacing a complex construction from a number of components with a single forging can cut overall manufacturing costs dramatically.

Cold forging, too, can be more economical than multicomponent assembly. Cold forging can consolidate the functionality that might have required multiple pieces plus joining into a single piece.

5. **Less machining means lower cost**

There is no doubt that forging is more economical than “hogouts” (fabricating metal components via extensive machining of plate, bar, billet, and block). See figure on the right. However, the magnitude of such savings is often surprisingly great. Particularly in aluminum aircraft applications, part complexity sometimes leads to a metal-removal cost of up to 75% of the total cost. Similarly, net-shape and near-net shape steel forgings for automotive engine, axle and transmission parts can minimize machining.

6. **Quicker production, shorter delivery**

In specific instances, in-place cost effectiveness of forgings can only be measured “after the fact.” Such was the case when a cast steel hub for a mining shovel cracked in service. It was soon discovered that a cast replacement would take at least four weeks to make. Fortunately, an open-die forged hub was produced in a matter of days, saving the customer hundreds of thousands of dollars in lost production.

7. **Keeping competitive by fine-tuning the process**

Specific process refinements are also contributing to cost competitiveness by way of material conservation. The trend worldwide in the transportation industry is to use forgings from hot to warm to cold forging (with increasing precision) in as many critical applications as possible. Drive pinions are warm forged and trunnions are cold formed, while forged connecting rods edge closer to near-net shape. See figure on next page.

Regardless of the level of precision achieved in the finished forging, careful control of billet weight and shape can eliminate flash and result in material savings of up to 40 percent in forged-steel automotive parts.

8. **“Value-added” saves on secondary operations**

Another trend is the “value-added” concept of having secondary operations like initial machining and some sub-assembly done at the forging plant, thereby reducing the cost of subsequent processing at the customer's facility.

Even when the customer does the machining, the forger can alleviate the burden of further processing. For instance, the coining process, which is used after parts are forged, produces better locating surfaces and facilitates machining. Benchmarks and positioning points can ease automation of handling and assembly. “Value-added” services at one forging plant that produces large steel blocks for plastics injection and compression molds include rough

*Continued*
machining to with 0.5 in. of final dimensions. Consequently, customers realize both significantly lower machining costs and faster overall production times.

9. Materials innovations
Less expensive, easier-to-process materials options like microalloyed steels deliver great economies in forged components such as automotive transmission and engine parts. Conserving energy by eliminating heat treatment, switching from quenched and tempered alloy steels to air-cooled microalloyed grades, saves as much as 15% on connecting rods, crankshafts, gears, steering arms, and wheel hubs. Also, forgings made from continuous cast steel on automatic presses can be cost-competitive with ductile-iron parts.

10. Design optimization
There are many conventional ways to cut costs—reducing drafts, tolerances, reviewing process options, substituting lower-cost materials, making property trade-offs, and more—that should be considered to achieve the most cost-effective forging. However, optimization of a forging design should be all-inclusive for best economy.

When outside constraints limit the forging design, choosing another alloy or altering the heat-treatment practice can readily meet the increased strength requirements. However, with castings, the only recourse would be a change in design or configuration.
IMPROVED ALLOYS BOOST QUALITY AND ECONOMY OF FORGED COMPONENTS

Materials developments and refinements on existing alloys can deliver higher quality, improved part performance, and significant economies for forged parts versus alternative metal components. At the top of the improved materials list are microalloyed steels, strand-cast steels, and titanium alloys.

Microalloyed Steels

Microalloyed steels—intermediate carbon steel alloys (0.3 to 0.6% C) that incorporate small amounts of vanadium, niobium, or other elements—for forging applications offer potential economies, because mechanical properties are achieved “as-forged” via controlled cooling. See figure on right.

A myriad of high-strength, forged components have been documented for their overall cost savings. These components include crankshafts, connecting rods, motorcycle flywheels, truck-wheel spindles, steering knuckles, lifting hooks and related hardware, and railroad coupling cylinders.

Although microalloy forgings have been utilized in Europe, Japan, and elsewhere since the early 1970s, their widespread usage in the U.S. was deferred in part because of concerns for adequate toughness and product liability. Things changed with the introduction of “second-generation” lower-carbon-content (0.1 to 0.3% C) microalloys with improved toughness and “third-generation” (0.15% C) microalloys with toughness up to six times that of earlier versions.

In fact, the third-generation microalloys with self-tempered martensite microstructures exhibit toughness and impact properties that equal or exceed those of higher alloys like quenched-and-tempered 4140, while delivering tensile strengths up to 190 ksi. See next figure. These higher-performance microalloys are targeted for automotive, agricultural, truck, and heavy equipment applications, some of which are nearing full production.

Equally significant are microalloyed steels with ferrite-bainite microstructure and low carbon content. They are suit-
able for a wide range of forging processes, from cold heading through conventional hot forging.

With the first-generation microalloyed steels, the Mn-Mo-Nb composition achieved a grain size of 5 microns under controlled rolling conditions. The toughness of these steels is definitely impressive: for a water quenched 138-ksi tensile strength steel, Charpy V-notch toughness exceeds 50 ft-lb at room temperature. See bottom figure. In addition, these new alloys responded well to surface hardening treatments, where extra fatigue- or wear-resistant properties are desired.

Faster and better strand-cast materials

Steel suppliers have increased the production of strand-cast steel bar—practically all carbon and low-alloy steel grades—for forged components. Streamlined processing is moving from cast billet or bloom to forging stock to save both energy (virtually no reheating) and processing time (one rolling process versus two), resulting in cost reductions on the forging stock.

Just as important is the improved quality that is routinely achieved in strand-cast products for forging. Strand cast materials possess good internal structures, due to the incorporation of shrouding and electromagnetic stirring.

Shrouding the teeming stream prevents oxides from forming and produces a much cleaner steel that boosts fatigue performance. It also increases transverse toughness, and facilitates machinability of forged parts. Other benefits include forgings with improved surface finishes and highly uniform chemical compositions throughout.

Materials for aerospace/high temperatures

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<thead>
<tr>
<th>STEEL/CONDITION</th>
<th>MECHANICAL PROPERTIES *</th>
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<tbody>
<tr>
<td></td>
<td>YS (KSI)</td>
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<tr>
<td>1045/O&amp;1</td>
<td>82</td>
</tr>
<tr>
<td>1045/HR2</td>
<td>86</td>
</tr>
<tr>
<td>MA/WQ3 (FERRITE-BAINITE)</td>
<td>114</td>
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<tr>
<td>MA/AC4 (FERRITE-BAINITE)</td>
<td>62</td>
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* BAR FORGING TRIALS (1-IN. THICK DISKS)
1. QUENCHED AND TEMPERED.  2. HOT-ROLLED.  3. MICROALLY.  4. MICROALLY, AIR-COOLED.

Microalloyed steels with a ferrite bainite microstructure exhibit good properties as compared to quenched and tempered steels.

Improved materials expanded the scope for precision forging of aerospace structural components. Although developments in hot-die technology, isothermal forging, and conventional forging techniques increased the capability to manufacture titanium net-shape forgings, alloy developments have also played a significant role.

For example, alloy Ti 10-2-3, a near-beta alloy, permits forging at lower temperatures and increases forgeability over alpha-beta alloys like Ti 6-4. Ti precision forgings can be produced with extended plan view areas (PVAs).
VALUE-ADDED FORGINGS OFFER DESIGN OPTIONS FOR READY-TO-INSTALL PARTS

Original equipment manufacturers (OEMs) continue to demand more value-added services from their suppliers. They realize that their business should focus on design and assembly, of automobiles, trucks, planes, heavy equipment, or whatever their end product may be.

OEMs no longer want to support expensive, captive-component manufacturing operations such as forging, machining, finishing, grinding, and plating. Ideally, they want finished components delivered on a just-in-time (JIT) basis in special containers, pre-tested and ready to assemble.

Many custom forgers have been adding value to their products via heat treating and machining operations. See figures on this page. Forging companies have further augmented their capabilities with finish-machining, painting, plating, testing, and other capital equipment to facilitate the design and manufacture of ready-to-install or assemble products.

Value-added forgings aid designers

While many value-added services translate directly into production-related economic benefits for the forging consumer, there are also inherent benefits for the designer. Based on design criteria—stresses the part will undergo, environmental conditions, service life, and more—designers can rely on the forger’s expertise in identifying the most efficient and economical forging, heat-treating and finishing operations to produce the optimum part. A case in point is a forged slack adjuster that achieves greater levels of reliability and cuts production costs, thanks to a forger’s redesign.

When a forger produces a finished, value-added forging, the limitations of in-house capabilities, the need to identify and perform interim processing steps, and the evaluation of potential secondary suppliers are no longer primary concerns. In effect, a single forging supplier requires less technical coordination than multiple suppliers or in-house operations. The range of services available expands the number of options open to the designer.

Perhaps even more important, the forger can make the designer’s job easier by recommending processing changes and ancillary operations that
in the forger’s experience yield a nearer-to-net-shape part. Often, the forger can help come up with subtle design changes, features, or processing refinements that permit a smaller, lighter, or higher-performance forged component to do what otherwise might not have been possible.

**Significant cost savings**

Why opt for value-added forgings? Simply put, studies point out that significant cost and time savings can be realized for just about any type of forged component. For the forged part consumer, fewer secondary operations mean fewer headaches, reduced in-process controls and inspection, less manpower, and a smaller capital investment in equipment. (See Table 1 for additional benefits.)

**Wide range of value-added services**

Adding value to a forged product by performing ancillary operations normally done by the OEM can range from supplying pre-qualified parts (ready to go through further processing, such as machining) to fully finished assemblies that incorporate forgings as the major component. In general, value-added services include just about any operation or process performed after forging, but are not limited to post-forging capabilities.

Some major value-added services may include:

- Custom processing results in more dimensionally accurate or closer-to-net shape parts, and it also helps reduce secondary operations. For instance, coining processes produce closer tolerances or better locating surfaces, which reduce a customer’s machining operations. Combinations of hot and cold forging or warm forging produce components closer to net shape, eliminating expensive machining operations.

- Testing includes destructive and nondestructive (NDT) testing, as well as statistical data analysis for SPC (statistical process control), coordinate measuring machines, and others.

- Computerized design/analysis can be used to help design parts to the optimum configuration. CAD/CAM (computer-aided design/manufacturing), flow modeling, AI (artificial intelligence) systems, etc. can expedite accurate designs and shorten production schedules.

- Electronic data transfer includes transfer of engineering drawings, CAD data, and CAM data for machining at customers’ plants and to conduct entire purchasing transactions-purchase orders, shipping and certification data, delivery dates, quotations, and more.

- Heat treating ranges from typical annealing and normalizing to full hardening and tempering, but also includes nitriding, vacuum heat treatments, and special treatments such as strain-aging, precipitation hardening, and double tempering, where deemed necessary for high performance alloys.

- Target dimensioning puts “targets” (benchmarks or reference points) on a part so that the customer can do subsequent machining without having to re-qualify the part. Coordinate measuring machines and six fixture points are sometimes used, especially for aerospace structural forgings, where up to 75% of the component weight is typically removed.

- Machining operations range from rough to finish operations with a specified surface roughness. Drilling holes, cutting threads, surface grinding, center drilling, CNC (computer numerical control) machining, and just about any other metal-removal operation are within the realm of these services.

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Continued
Finishing operations run the gamut of plating, anodizing, and protective-coating operations, including durable epoxy finishes for subassemblies.

Subassembly work can be performed especially when automated assembly/manufacturing operations can occur due to long-term contracts.

Special requirements, often requested by the customer, are becoming more prevalent. A prime example is the use of special containers, supplied by the customer and designed to facilitate assembly or further processing at the customer’s plant. Another forger pre-balances forged wheels to save the customer this burden after delivery.

Teamwork essential

Not surprisingly, taking full advantage of value-added forgings requires open communications. Your forging supplier must have a firm understanding of design criteria, and accurate final part drawings should be submitted as early as possible. All component details should be specified, including mating-surface conditions, subassembly work, and potential options on design features.
FOR CUSTOM PARTS, EXPAND YOUR OPTIONS WITH OPEN-DIE FORGINGS

Open-die forging can be considered the ultimate option in “custom-designed” metal components. High-strength, long-life parts optimized in terms of both mechanical properties and structural integrity are produced in sizes that range from a few pounds to hundreds of tons in weight. Whether the competition is tubing, plate, round bar, weldment, casting, or another metal form, open-die forging outperforms them all. See figure on the right.

Basically the hot forging of metal (which is not confined laterally, as in impression-die forging), open-die forging makes use of a hammer, press, or ring roller to progressively work the starting stock into the desired shape, most commonly between flat-faced dies. It is the most flexible method for producing complex, high-strength components that routinely fulfill or surpass design criteria in virtually any structural application. With improved processing, equipment, and controls, parts can be produced with: 1) closer to finish dimensions, 2) more complex configurations, 3) greater part-to-part uniformity; and 4) material savings. All this can be achieved at a very competitive cost.

Why design for open-die forging?

The answers are simple. Open-die forging has tremendous design versatility and impressive performance advantages, and they include:

Unequaled range of part sizes and shapes. Size and weight capabilities are much greater than most alternatives, including impression-die (closed-die) forging. Open-die forgings are limited only to the largest ingot that can be cast. Shapes range from simple solid shafts to contour-formed pressure vessels, hollow forgings, and large-diameter rings. See figure on the left.

Broadest choice of materials expands design potential. Virtually all forgeable alloys can be open-die forged, including even exotic materials, such as superalloys and Inconel 625 for high-performance rotating parts.

Design refinement through prototyping. No better way exists to test initial closed-die forging designs, because open-die forging imparts similar grain-flow orientation, deformation, and other beneficial characteristics. In addition, extra material on part surfaces permits design modifications before the part geometry is finalized.

Size flexibility is a large advantage of open die forging as illustrated by these forged over mandrel rings.

Large, high performance metal components like this huge valve body can be made by only one method -- open die forging. Alternative processing routes would not meet design criteria.

Continued
Structural superiority is an intrinsic benefit of open-die forging. The fully deformed microstructure achieved in the hot-worked metal provides an optimum combination of structural integrity and mechanical properties. The overall degree of deformation or hot working in open-die forgings makes them far superior to hot-rolled billets of most medium- to high-alloy steels, not to mention multicomponent weldments, machined plate, bar, and tubing. More importantly, controlled deformation eliminates cast defects. When an as-cast ingot is used as starting stock, a typical 3-to-1 forging reduction yields maximum consolidation, or densification, by deforming metal to the center of the workpiece, eliminating porosity and breaking up inclusions. In rolling, reductions of 7-to-1 are required for full consolidation because only the surface is heavily deformed.

Directional property enhancement can be readily achieved in one or more particular directions (radial, axial, tangential) by optimizing the combination and type of forging operations, such as upsetting, drawing, cross-forging, piercing, punching, and hot trepanning.

Demanding design criteria are readily met. If resulting parts must withstand cyclic stresses that approach the yield strength of the specified metal alloy, open-die forgings become the preferred choice. At this point, forgings surpass castings in both performance and structural integrity (no porosity).

Shape options go beyond shafts

Although a significant portion of open-die forgings are shaft-like parts and stepped shafts—such as steam-turbine shafts, prop shafts for large seagoing vessels, paper-making rolls, and periscope tubes—many more configurations fall within the open-die realm. These include integral shaft/disc geometries, large step slabs (basically, upset or “pancake” forgings, such as gears and wheels), forged hollows, contour formed parts, and ring forgings.

Although casting or hot-rolled bar may be the first thought when it comes to the design of shaft-like parts, forging offers many performance advantages, as well as additional design options. Two examples are: 1) forging the rough shape and then machining the remainder, or 2) forging in design features, such as flanges and reduced sections. Both approaches increase component strength, fatigue life, and integrity. Essentially, open-die forging is a better way of getting large shafts closer to finished contour without going to closed-die forging.

More complex parts are also ideally suited for open-die forging. Stepped shafts with thin flanges, contoured rings, cylinder blocks, and breech blocks for cannons, for example, require innovative forging techniques to produce the optimum in performance.

Forged hollows can be made with steps on the outside and even tapers and steps on the inside. These types of parts are formed similar to the way rings are formed. The starting stock is upset, pierced, and drawn over a mandrel. They offer a high-performance alternative to tubing and traditionally (and more expensively) have been made by solid forging and then trepanning to produce the hollow. Forged hollows are particularly cost efficient when made from costly higher-alloy materials, and not only outperform centrifugal castings, but also often cost less.

Parts that incorporate extruded nozzles, such as pressure vessels, fall into the contour-formed category. Here, the alternative is welding multiple pieces into the final shape. Forging provides not only a less expensive product, but also one that is stronger and has higher structural integrity. Even with good weld quality, putting together two pieces of steel introduces potential defects, such as porosity, compositional differences, and microstructural HAZ (heat-affected zone) effects.

Ring shapes, such as gears, are another open-die shape options, most effectively and quickly produced in small quantities in diameters up to 30 ft. by saddle forging (open-die forging over a mandrel on a press). For larger quantities and contoured rings, ring rolling is preferred.
Many additional benefits

Other benefits of open-die forgings, while not strictly design-related, remain impressive.

Volume versatility.  Limitations in quantity are not so great as generally believed. If only one part is needed, that is ideal, because open-die forging is a “one-part-at-a-time” process. Similarly, 50 or 100 parts are no problem.

No tooling required. Only tooling for machining open-die forgings is necessary. Any required specialized tooling, such as simple rings or bolsters to hold forged rounds for upsetting shaft ends, is usually part of tooling inventory. As a rule, open-die forgers do not charge for tooling costs.

Cost effectiveness. Virtually no additional charge for tooling, plus the inherent process versatility, make open-die forgings surprisingly cost-effective. Large size, combined with a custom configuration, maximizes cost effectiveness. Such considerations can sometimes make open-die forging the only practical manufacturing alternative. Although open-die forging costs for a few parts ordinarily surpass costs for impression-die forgings, the total cost of open-die forgings is less because die fabrication is eliminated.

Fast delivery. Short lead times (weeks instead of months) are more the rule than the exception with open-die forgings.

Finished parts on request. Thanks to value-added operations (heat treating, rough and finish machining, and more), many forgers can supply ready-to-assemble parts.
FORGING SIZE PLUS SHAPE CAPABILITY EXPANDS METAL DESIGN OPTIONS

It is no design secret that forgings are often considered for their high strength, structural integrity, extra long service life, unmatched impact toughness, and other desirable characteristics. But what is not usually thought of is the tremendous design versatility, achievable by the wide range of components that can be forged with current technology.

Evolutionary developments—among them, key processing refinements, computerized equipment, and newly developed alloys—permit larger-size components, more complex configurations, and closer tolerances to be achieved in most forging processes. Part size has expanded while shapes approach an ever-increasing degree of part complexity.

With few limitations, virtually any shape imaginable can be forged, or can be economically put together with forged components. Shapes range from bars with basic cross sections (round, square, hexagonal) and simple shafts to complex, contoured profiles that integrate a thin rib-and-web structure and built-in attachment features. Similarly, size capability for all forging processes covers an enormous range, from ounces to more than 150 tons. However, each of the many forging processes has its own special design niche in terms of size, shape, part complexity, and material options.

Impression-die (closed-die) forging of steel can produce an almost limitless variety of three-dimensional shapes that range in weight from mere ounces up to more than 25 tons. See Figures 1 to 3. Additional flexibility in forming both symmetrical and nonsymmetrical shapes comes from preforming and blocking operations (sometimes bending) prior to forging in finisher dies.

Part geometries range from some of the easiest for forge, such as simple spherical shapes, block-like rectangular solids, and disc-like configurations, to the most intricate components with thin and long sections that incorporate thin webs, as well as relatively high vertical projections like ribs and bosses. Accompanying photos dramatically demonstrate forged-shape capability.

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Most engineering metals and alloy can be forged via conventional impression-die processes, including carbon and alloy steels, tool steels and stainless steels, aluminum and copper alloys, and certain titanium alloys. Strain-rate-and temperature-sensitive materials (magnesium, highly alloyed nickel-based superalloys, refractory alloys and some titanium alloys) may require more sophisticated forging processes or special equipment for forging in impression dies.

Applications span the industrial spectrum ranging from structural parts for automobiles, trucks, aircraft/aerospace, and heavy-duty manufacturing equipment to hardware, fixtures, and hand tools.

Open-die forging can produce forgings from a few pounds up to more than 150 tons. In addition to basic shapes, open-die processes yield stepped cylinders, large step slabs (upset or “pancake”), hollows, hubs, rings and contour-formed metal shells. See Figures 4 and 5. Practically all forgeable ferrous and non-ferrous alloys can be open-die forged, including exotic materials like age-hardening superalloys and corrosion-resistant refractory alloys.

Hollows, formed by open-die forging techniques (either forging over a mandrel or forging between an enlarging bar and the top die of a press) offer unique part geometries. See Figure 6 and 7. Basically cylindrical hollows, these carbon steel and alloy steel forgings can weigh just a few hundred to as much as several hundred thousand pounds.

With certain restrictions on other dimensions, forged hollows can attain 200 in. diameters or 300 in. lengths; smallest diameters are just under 12 in. In general, as diameter decreases, length can increase. Similarly, wall thickness depends on other dimensional constraints. For large diameters, a 2 to 3 in. minimum thickness is required. Hollows have been forged as thick as 24 in.

Hollows can be forged with steps on the outside, as well as steps and tapers on the inside, presenting in many smaller-diameter components a higher-performance alternative to tubing. Even large hollows can be contoured, forged with different diameters along the length, and incorporate forged-in ports or extruded nozzles by use of special forging techniques.

Forged rings, made by ring rolling or hammer forged over a saddle/mandrel set-up, can weigh from 1 lb. up to 350,000 lb., while outer diameters range from just a few inches up to 30 ft. in diameter. See Figure 8.

Seamless ring configurations can be flat (like a washer), or feature higher vertical walls (approximating hollow cylindrical sections). Heights of rolled rings range from less than an inch up to more than 9 ft. Depending on the equipment, wall thickness/height ratios can typically range from 1:6 up to 16:1, although greater proportions have

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been achieved with special processing. In fact, seamless tubes up to 48 in. in diameter and over 20 ft. long are extruded on 20- to 30,000-ton forging presses.

Beyond the basic shapes with rectangular cross-sections are rings with complex cross-sections. These contoured rolled rings can be produced in thousands of different shapes with contours on the inside and/or outside diameters.

High tangential strength and ductility make forged rings well-suited for torque- and pressure-resistant components, such as gears, wheel bearings, and couplings, rotor spacers, sealed discs and cases, flanges, pressure vessels, and valve bodies. Materials include not only carbon and alloy steels, but also nonferrous alloys of aluminum, copper, and titanium, as well as nickel-based alloys.

Upset forgings are ideal for cylindrical parts that incorporate a larger diameter or “upset” at one or more locations along the longitudinal axis. See Figures 9 and 10. Usually forged from bar, upsets typically weigh from 1 lb. up to about 400 lb. for 20 ft-long components, although lengths up to 30 ft. have been forged. Depending on upsetter size, upset diameters range from just under 3 in. up to 17 in.

Once limited to simple parts “headed” on one or both ends, upset forgings include components with larger diameter sections upset in the center, more complex shapes via multiple dies, internal and offset upsets, and even double-ended upset hollow formed from tubular stock.

Targeted for such applications as gears, stub shafts, axles, roller shafts, steel bodies, as well as for blanks for further processing in other forging equipment (e.g., pinion-gear blanks), upsets are typically made of carbon or alloy steel, although any forgeable alloy can be used.

Precision forging produces component designs with most functional surfaces forged to net dimensions with virtually no contour machining required. See Figures 11 to 13. Typical structural part shapes in aluminum include: channel or “C” sections with flat backs; spar-type parts (long narrow parts with an “H” section or a combination of and “H” and channel with cross ribs) than can be 6 to 8 in. wide by 60 to 80 in. long; and large parts in a variety of shapes.

Along with design complexity, the size of precision aluminum forgings has also increased. High-definition parts (web thicknesses in the 0.070 to 0.080 in. range, ribs at about 0.100 in. thick, and contours on both sides) have been produced with plan-view areas (PVA) up to 600 in2.
The achievable PVA of a part depends on how restrictive the rib/web structure is, as well as on rib thicknesses, rib heights, etc. Larger, heavier parts (thicker ribs and webs) with 800 in². PVAs have been produced. Similarly, precision forged titanium components can be fairly large with some complexity.

Precision forging is not limited to only aircraft structural parts of aluminum and titanium. Precision warm forging of steel has been successful in producing gears, geared shaft assemblies and similar shapes.

Cold forging encompasses many processes—bending, cold drawing, cold heading, coining, extrusion, punching, thread rolling and more—to yield a diverse range of part shapes. See Figure 14. These include various shaft-like components, cup-shaped geometries, hollow parts with stems and shafts, all kinds of upset (headed) and bent configurations, as well as combinations.

Parts with radial flow configurations with center flanges, rectangular parts, and non-axisymmetric parts with 3- and 6-fold symmetry have been produced by warm extrusion. With cold forging of steel rod, wire, or bar, shaft-like parts with 3-plane bends and “headed” design features are not uncommon.

Typical parts are most cost-effective in the range of 10 lb. or less, and symmetrical parts up to 7 lb. readily lend themselves to automated processing. Materials options range from lower-alloy and carbon steels to 300 and 400 series stainless steels, selected aluminum alloys, brass and bronze.

Often chosen for integral design features such as built-in bosses and flanges, cold forgings are frequently used in automotive steering and suspension parts; namely, in antilock-braking systems, hardware, defense components, and other applications where high strength, close tolerances, and volume production make them an economical choice.

Hot-die and isothermal forging make it possible to forge exotic vacuum-melted, titanium, and nickel-based alloys, such as Waspaloy, Astroloy, and P/M alloy IN100, which are far more difficult to forge by conventional techniques. See Figures 15 and 16. In this process, dies are heated close to the workpiece temperature, and in the case of isothermal forging to about 2000°F. A controlled atmosphere or vacuum is required.

Most are disk-type shapes with diameters from about 6 to 36 in., weighing from about 70 to 1,000 lb. In general, thicknesses can range from approximately 1/2 in. up to 9 in., while a cross-section in a typical part may have thicknesses that vary from a maximum of 3 to 7 in. down to 1/2 in. in a thinner web section. Part shapes are not as complex as those that can be achieved by precision forging of aluminum, but isothermal forging of titanium alloys can yield rib/web components with rib thicknesses from 1/8 to 1/4 in. Most applications are critical components for gas turbine engines and similar high temperature environments.
THE BEST ANSWER TO THE COST/PERFORMANCE QUESTION

Conversion to forgings is an idea that does not often occur unless previous parts have failed in either service or prototype testing. However, considering success of forgings versus not-so-successful alternative components, designers are discovering many more reasons to convert to forgings. Even though the main thrust is usually higher performance and/or lower cost, equally important considerations (and some not so obvious) justify the switch to forgings. (See table).

It is no secret to forgers that competitive products are often not up to par with forgings, performance-wise. In fact, customers’ requests to replace castings, machinings, weldments, composite assemblies, stampings, and the fabricated parts in virtually all markets are becoming more frequent. This is happening not only in aircraft and aerospace, but also in automobiles, transportation, mining and construction, chemical processing, tooling, and all kinds of heavy-duty and manufacturing equipment.

Not surprisingly, these changes are closely related to life-cycle cost analysis. In terms of service life, a higher-performance forging can cost a mere fraction of metal components made by alternative processes. Back when forging was connotated as a “blacksmith” trade, the advantages of forged hand tools over cast and other versions were quickly realized. The same quality advantage still holds true. 120 million sockets and millions more forged open-end wrenches, ratchets, and handles are sold every year. No one questions their reliability or performance.

One step up are pneumatic power tools like jack hammers, which have critical components made of forged, cast, or machined components. What is the difference? The quality advantage of pneumatic tools with forged fronthead and backhead cylinders permits longer warranties as compared to tools with non-forged critical parts. Higher performance via forgings commands only a 10% to 15% premium upon purchase, while delivering a ten-year life compared to one to two years for other methods. See top figure on next page.

Aircraft, aerospace applications

Structural components in aerospace/aircraft applications have routinely switched to forgings, especially for complex design geometries that cannot be effectively made by any other process. Both conventional
and precision forgings have repeatedly been much more cost-effective and/or deliver higher performance than “hogouts” of plate, castings, advanced polymer-matrix composites, multi-part assemblies, and weldments. In life-critical applications, a larger safety factor is all the more reason to consider a reliable solution.

In such applications, the performance/cost balance is a primary driver. However, considering typical precision forgings with as-forged surfaces and built-in design features, machining cost can be cut by 90%. Overall, total cost can be cut in half, while properties, performance, and service life often improve. In one example of a precision-forged actuator bracket for a wide body jet, a “design stage” conversion cut cost by about 75% over machining a rectangular block, and at the same time, improved fracture toughness, stress-corrosion resistance, and eliminated almost all machining.

Other examples in the aerospace sector include "classic" conversions; namely, those where castings failed because they just were not strong enough. Such was the case with a primary structural component (bulkhead) for a loitering, radar-sensing missile. See bottom figure. Designed as a forging, this application was made as a casting in the interest of lower initial cost. It was then converted in production to a forging because of performance. Similarly, another missile part was originally conceived as a casting, then as a hogout from bar stock. In the final analysis, it became a forging.

Fuel components for commercial gas turbine engines have been converted to forgings, then to investment castings, and now are back to forged stainless steel and nickel alloys. "True" cost-effectiveness is realized by the inherent quality of forgings plus the use of advanced machining centers. Similarly, a titanium compressor case for an aircraft engine went from a forging to a casting to save money. Unfortunately, casting the complex part created numerous, difficult production problems. It became a forging again.

Other examples of conversions include:

- a propeller nut converted to a near-net-shape forging with cost savings over a machining;
- a precision-forged aluminum blocker door that replaced a built-up composite structure; and
- a structural forging for a VTOL aircraft switched from an advanced-composite part because property "spread" of composites was excessive.

Moving into the "upgrade" mode, higher-performance/efficiency engines demand higher strength-to-weight-ratio forgings. Aircraft-engine forgings can provide 33% higher ultimate tensile strength versus castings, higher pressure capability, 5% to 10% lighter weight, and reduced section sizes.

Ground transport: autos, trucks

Practically every major structural or high-load component in trucks and autos has been evaluated as a forging. Conversions to forging routinely occur when higher performance benefits or longer life are required. In both heavy trucks and luxury automobiles, higher performance has been attained by forged aluminum wheels that outperform cast versions. Crankshafts for high-performance engines have been converted to forged steel from ADI (austempered ductile iron) and cast iron. Worldwide, camshafts have been converted to steel forgings.

Elsewhere in the automobile, many suspension parts are being converted to forgings. In one instance, a steering arm made as a multi-component weldment (two stampings plus one machined part) failed. Fortunately, a hot-forged, carbon steel part was not only stronger, but also lighter, closer to net shape, and less expensive. In parallel,
a cold-forged-steel upper control arm replaced a stamped version.

Other examples of conversions include:

✓ forged-aluminum engine mounts replaced cast iron, cutting weight by more than 60%, reducing machining, and adding functions;
✓ steel gears for heavy trucks and construction vehicles forged with net-shape teeth to deliver up to ten times the impact fatigue life of machined counterparts;
✓ slack adjusted for braking systems of truck trailers switched to a steel forging when castings could not meet industry standards for life, safety, reliability; and
✓ brake-system components switched to forged aluminum for lighter weight.

High pressure and hydraulics

More high-pressure parts than ever are being converted to forgings because of their inherent structural integrity, which translates into freedom from porosity, segregation, large inclusions and other as-cast defects. This makes forgings highly unlikely to leak under high pressures. Examples of conversions include:

✓ "flashless" precision-forged aluminum components for aircraft hydraulic systems, minimized parting-line end grain and replaced castings and machinings;
✓ forged-steel caps, rod ends and ports for 3000 psi hydraulic cylinders replaced leakage-prone bar stock, plate and cast steel for up to 85% cost savings;
✓ critical high-pressure components for submarines switch to forged high-temperature steels from castings for increased safety factors; and
✓ multi-port compressor cylinders that operate at 5000 psi were quickly switched to forgings from castings in the design stage due to as-cast porosity and low property levels.

Energy, processing applications

Energy generation, ore and coal mining, and metal/chemical processing industries present some of the toughest environments for metal components. Forging conversions include:

✓ planetary gears for an industrial gas turbine engine first were made as castings, but manufacturing problems prompted the switch to higher-performance forgings;
✓ stopnut for an oil-field ball valve involved piercing, broaching, welding and drilling - a cold forging needs just one hole, and
✓ cast-steel shoes for mining machines that failed were redesigned as forgings.

Simple parts

Switching to forgings can make economic sense for simple parts, as well as complex geometries. Support brackets, for instance, were converted to forgings at a 80% cost reduction.

If you are a designer, and you have not previously considered forgings for your metal-component designs, contact FIA (www.forging.org) to explore what may be your best cost/performance alternative. Higher performance and/or cost-savings can be realized in aluminum, steel, titanium, and even exotic alloys.
"Quality" has always been a primary concern for metal components. Engineers rank forgings above all other competitors for overall quality, structural integrity, high strength, longest service life, and unsurpassed toughness. The forging industry is not resting on its laurels, and the quest for improved quality continues.

Demands for even higher quality are being met by such techniques as total quality management (TQM), statistical problem solving, statistical process control (SPC) and design of experiments (DOE), as well as by process improvements and refinements, new materials, and technologies like CAD/CAM. The automotive, aerospace, military, and other users of forgings are requiring quality improvements from all suppliers.

In the forging industry, quality improvements are being made by practically every means imaginable, delivering such benefits as better dimensional control, tighter tolerances, improved property uniformity, optimized designs, lower scrap rates, and improved lead times.

- **Appropriate technology** like CAD/CAM is being utilized throughout the total production process to produce more dimensionally accurate forgings. In one instance, use of the CAD/CAM approach for design, die making, and finish machining operations allowed a complex rib/web structural forging to be produced to a 25% tighter-than-normal tolerance band on both die-closure and tolerance dimensions. Similarly, process modeling (metal-flow simulation, for example) is being used to produce optimum designs and, hence, more repeatable forgings.

- **Improved die-making practices** are the first step in producing more accurate forgings. CAD geometry may be utilized to produce the CNC tool path to machine electrodes for EDM (electrical discharge machining) of dies, thereby producing more accurate forgings. Where warranted, forging consumers can opt for more exotic techniques such as electrochemical polishing after EDM. This die-making approach can hold tooth-to-tooth dimensions to within 0.0005 in. on precision-forged steel gears.

- **Fast-tool-change capability** is another way to maintain dimensional repeatability in products forged in larger quantities. Typically, specialized tooling attachments permit fast tool changes to accommodate intentional, preplanned die insert replacement. This approach minimizes the effects of tool wear without decreasing productivity.

- **Target machining or center drilling** is another way that forgers help ensure overall dimensional precision by drilling, machining, or coining built-in X-Y-Z gauge points (reference points) on forged parts. This "prequalifies" forged components for subsequent machining or other operations, helping to maintain dimensional accuracy at the customer's plant.

- **Process combinations and refinements** can also be very effective in achieving closer tolerances. One example is hot forging combined with cold forging (coining) of a steel crankshaft to achieve tolerances half that of hot forging alone.

*Continued*
Better materials, such as the use of microalloyed steels in place of standard heat-treated steels, can dramatically improve the consistency of a forged product. Not only is hardness more consistent, but also strength can be higher and more uniform.

Induction heating is yet another process that is helping to produce more uniform forgings. In contrast to gas-fired furnaces, induction heating evenly heats bar stock, resulting in more uniform properties in forgings. It also significantly reduces surface scale.

Coordinate measuring machines (CMMs) are utilized to confirm greater die accuracy and to measure critical part features, such as angles and complex curvatures, which could not previously be measured. Here, the ability to measure more accurately directly translates into forgings with more repeatable dimensions. When linked to a CAD database, CMMs can minimize or eliminate source inspection.

Statistical means to a “quality” end

With improvement in mind, statistical analysis of the forging process has become a powerful tool to boost the overall quality of forgings. It has been implemented for both ferrous and nonferrous forgings, to achieve tighter tolerances, more consistent properties, lower reject rates, less rework, higher productivity, and other quality-related benefits, including increased cost effectiveness. Statistical process evaluation, process capability studies, process improvement programs, SPC (statistical process control) charting, design of experiments and other techniques have made impressive headway toward improving the forging process.

Process capability studies have proven invaluable for controlling the impression-die forging process. In one instance, tolerances for forged-steel components went from 150% of the product tolerance down to 30%. By adjusting process variables, the spread of dimensional variation was reduced by a factor of five. In another case, once a process capability index $C_{pk}$ of 1.33 was attained, the company was able to adjust the process (and control limits) so that die life was maximized without sacrificing part quality.

The same techniques have yielded good results with aluminum impression-die forgings. For example, with an automotive structural part, a capability study of die-closure dimensions showed that the process was producing too many parts outside the specified range. Here, adjusting process variables brought the process into statistical control, reducing the rework rate from almost 50% down to 0.

Another aluminum-forging process was producing parts with dimensions on the high side of the range. By a simple process adjustment, dimensions were centered to produce a tighter spread. Because of the many process variables involved (some interdependent), some forging companies have ascertained that working toward "target" values for specific variables rather than specification ranges produces much more uniform dimensions and, consequently, more consistent forgings.

Rolled rings have improved in quality (dimensionally, property-wise and even economically) due to statistical problem solving and related techniques. At one forging company, deviations and rework decreased by 42% over two years—with savings of more than $1 million in one year—as a result of analyzing which particular products were most difficult to manufacture. This approach helped to dramatically increase "first time" acceptable parts.

Because rolling operations are very operator-sensitive, the company supplied operators with process history and attribute data, which includes 34 different "cause codes," such as surface imperfections and eccentricity.

Another rolled-ring producer was able to adjust the process and/or directly modify equipment for long-term improvement. Typically, this approach involves investigating a particular area (like blank preparation or temperature control),...
statistically analyzing that area, then making modifications to keep the process variable under control. In one example, the company adjusted the process to reduce ring weight, while still maintaining an optimum process control index. This resulted in cutting weight by 10 lb. per part and reducing machining operations, resulting in a calculated savings for both customer and forger.

During any program to improve the repeatability of forgings, it quickly becomes evident that forging is a very complex process with many variables, including heating, cooling, shrinkage, material-transformation effects, press speed and size, volume, die characteristics, and a host of others. Fortunately, a design of experiments approach can be invaluable in better understanding the forging process and determining which combination of variables yields the best results. A designed experiment identifies critical process variables and implies working toward "target" variable values instead of conventional ranges. The net result can be significant process improvement. This approach allowed one forging company to change key variables for a difficult-to-process alloy, resulting in a significant reduction of internal defects without sacrificing mechanical properties.
CO-ENGINEERED FORGINGS

Co-engineering, simultaneous engineering, or cooperative engineering: no matter what it is called, the meaning is the same—customers working with forging suppliers to create the optimal metal component. This approach provides benefit to customers and forgers alike.

Essentially, co-engineering encompasses mutual cooperation between customer and forging supplier—from the initial design stage on—to achieve the best combination of manufacturability and ease of assembly, as well as maximum cost-effectiveness. In its widest sense, cooperative engineering also encompasses material selection and conservation, as well as interim processing like heat treating, finishing, and even design of mating parts. The table on the right lists the advantages of cooperative engineering.

Cooperative engineering has become easier due to technology. Many forging companies and their customers share and refine CAD and CAM databases to complete new forging designs more quickly and accurately, to produce more accurate dies, to reduce lead times, and to tighten tolerances. Similarly, electronic data transfer is making two-way communication faster, and revisions easier.

A classic example of cooperative engineering is the production of more than 160 parts (all forgings, either redesigns or new designs) as the result of close cooperation between an ambitious forging company and a major manufacturer of agricultural and industrial equipment. In a comprehensive program to reduce costs of hydraulic cylinder components, mounting, and related components, average cost-savings of 50% per component were achieved. A forged part that replaced a cast version is typical of these components. The redesigns and similar new designs replaced machined bar stock, flame-cut plate, and castings. Not surprisingly, newly designed and redesigned forged parts virtually eliminated rework and dramatically increased the number of acceptable parts.

Here are just a few examples co-engineered forgings, developed via close cooperation between manufacturer and forger, and all of which boost performance and lower cost:

✓ a stop nut for a pipeline ball valve, forged in one piece to eliminate practically all machining operations;
✓ a near-net-shape, forged-steel, automotive steering arm, redesigned from a less reliable three-part weldment (including two stampings);
✓ a refined forging design for an industrial-compressor crankshaft that resulted in tighter tolerances via process improvement; and
✓ a slack adjuster for truck braking systems that incorporates built-in lugs to eliminate rivet pins, hold drilling and slow assembly.

Continued
Timely communication is the key

When should cooperative engineering start? The answer is, the sooner, the better. To get the optimum results through cooperative engineering, early vendor involvement is of prime importance. The more that a potential customer can convey about the part, the better the chances are of attaining a final design configuration with an acceptable cost/performance balance.

Whether new designs, redesigns/conversions, or refinements of existing forging designs are involved in cooperative engineering, communication is the key to creative solutions of both design and manufacturing challenges. Success stories of co-engineered forgings abound in unique, weight-saving part geometries, built-in attachment features for mating parts, part consolidations, cost-effective material substitutions, and innovative design features—all due to effective communication.

While it may be standard practice for some, simply sending an engineering drawing will not cause all pieces of the manufacturing puzzle to fall into place. Even an expert designer may not be aware of all the subsequent operations and details for grinding/machining, required fixturing, assembly, finishing, and so forth to produce a part to final dimensions and tolerances.

A good rule of thumb is to avoid the convenient "make the part to print" approach. Considerations such as alignment of mating parts, assembly sequence, gauging requirements, etc. should be thoroughly examined, then discussed with the forging company.

Do not forget “What if?” scenarios

Although it is often assumed that subsequent machining and other operations will be more efficient or cost-effective if done in-house (at the customer's facility), cooperative engineering discussions may reveal that many forging companies can perform value-added services that range from rough machining to finishing and even supplying ready-to-install assemblies.

The customer should do subsequent machining or manufacturing when it is cost-efficient to do so. Even in this instance, forging companies can provide the expertise to make operations like machining more cost-effective than ever. A key example of cooperative engineering is the use of target dimensioning or target machining to facilitate metal removal at a customer's plant.

Target machining

Target machining (or target dimensioning) is just that. It gives forging customers a "target" (benchmark or gauge point) as reference for further machining. This approach prequalifies the part for subsequent machining or other operations, greatly reducing the customer's set up, fixturing expense and overall manufacturing costs for such operations.

This prequalification can be accomplished in various ways, depending on the customer's preference and the forging operations used to manufacture the part. If a part is to be coined as part of the forging sequence, it is a relatively simple matter to incorporate a reference mark at a convenient location. With high-volume production, a separate coining operation may be justified to accomplish this; namely, coining a positive locating feature with a V-die.

Coined locating surfaces and drilled centers are routinely used for such automotive parts as connecting rods, pinions, trunnions, tie rods and other steering gear and suspension components, resulting in certified parts delivered to the customer, thereby eliminating concern that downstream problems will interrupt the manufacturing sequence.
A simple approach to target machining is to utilize punched or drilled holes, which then establish the reference or datum plane for all subsequent gauging and machining. If holes are already an intrinsic part of a forged design, such as for attachment of mating parts, the gauge point already exists. If not, holes may be added as long as they do not interfere with part function. In either case, the forging supplier should machine or punch the holes so components are certified before shipping. This removes the burden and expense of gauging and inspection, sometimes amounting to a significant savings for the customer.

'Targets' for large, structural forgings

Cooperative engineering becomes more important when target machining large structural forgings, especially complex rib/web configurations where up to 75% of the weight is removed. See top figure. Such forgings usually require more involved methods than simpler parts and may utilize coordinate measuring machines to maximize accuracy. Both three-point center-drilling operations and six-point fixturing are used to prequalify forgings for machining. Regardless of the method used for target machining, both forging and finished part requirements should be thoroughly discussed with the forging supplier to determine the best way to locate holes or reference points.

Three-hole center drilling is not only less expensive than the six-point tooling approach, but can more readily accommodate adjustments. Here, the forger prequalifies the forging by optimizing the final part configuration within the machining envelope, based on the finished part geometry supplied by the customer. See middle figure. Three locating holes, typically drilled in the parting-line area where machining stock is usually at a maximum, indicate the optimum orientation for machining of the forging. If the magnitude of the machining envelope is not sufficient for the depth of the tapered holes, a small boss can be added to the forging. See bottom figure.

These three holes effectively restrain six degrees of freedom (motion and rotation) of the forging, and are usually drilled in the forging while in the qualifying fixture, often matching the customer's machining fixture. (This avoids the extra set-up for milling that is required when tooling pads are used to adjust the forging.)

When implemented, center drilling does not compromise the high standards or tolerances normally associated with forged parts. Overall, three-hole center drilling can often be the most cost-effective alternative, since adjustments can more readily (and less expensively) be made for die mismatch, material shifts (from non-fills and grind-outs), and variations in straightness. In addition, localized surface variations can be offset.

Determining the amount of shift and how the finished part fits within the machining envelope can be done by either...
of two ways, both of which require checking numerous positions along the forging to accurately locate the center-drilled holes. One method involves the use of templates (identical to the forging's shape), located at a specified stand off distance (e.g., 0.5 in.) beyond the largest forging and takes into account any shifting of the forging. See top figure. Here, two "go/no-go" gauge balls are used.

An even more accurate, but slower, method makes use of dial indicators to measure the gap around the forging. This results in better positioning of the forging within the envelope, effectively optimizing center drilling.

The 6-point tooling method makes use of as-forged external features to orient the forging for machining. See bottom figure. However, this method cannot accommodate shifts of the forging within the machining "envelope" to improve straightness, to allow for die closure and mismatch, or to adjust for excess material on one side of the parting line and non-fill on the opposite side. In practice, some adjustment is possible if raised pads (which are milled down to the proper height) are added to the forging, or if movable tooling points (which require additional set-up time by a machinist) are used. Ordinarily, a forger mills the tooling pads and then ships a "qualified" part to the customer. Consequently, machining operations at the customer's plant can be accomplished by using the tooling points.
FORGINGS SUPERIOR TO CASTINGS DUE TO LONG-TERM PERFORMANCE

It is no surprise that forgings routinely outperform castings in a host of applications. High structural integrity, maximum strength, improved toughness, longer life, and optimum reliability are just a few of the many reasons.

When designers are not sure if a casting will perform, forging is often designated as the alternate process on engineering drawings. In the past, castings were erroneously selected as a first choice, based on the false assumption that they would cost less. Unfortunately, many castings failed to show repeatable performance in service, making the original "select casting for price" approach a moot point. In fact, the extended service life of forgings often makes them less expensive in the long run, even if forgings have a slightly higher initial cost.

When castings are selected as the result of an uninformed decision, rejects, rework, quality problems, and more can create production delays for the OEM customer because metal components cannot be delivered on time. This was the case when a critical tank component was first specified as a centrifugal casting, because forgings were considered noncompetitive with castings from a cost standpoint. In the end, forgings not only outperformed castings, but also delivered an improved design at lower cost.

Although it is generally accepted that castings perform reasonably well under compressive stress, they usually cannot compete with forgings in applications where toughness and durability are the main requirements. In the order of greatest property advantage, forgings routinely outperform castings under impact, shear, and tensile loading.

Castings should not be selected by the designer on the promise of lower initial cost without taking into account such factors as forgings' higher strength-to-weight ratio, which allows reduced section sizes and lighter-weight components. This can be a big contributor to cost effectiveness when implemented in component designs.

Additionally, the initial cost of some forgings can be less than that of cast counterparts when the component is initially and cooperatively designed as a forging. This allows customers and forgers to take full advantage of cost saving design features and manufacturing economics.

Forgings are becoming more cost-competitive with a wider range of cast products as usage of microalloyed steels grows. Forged microalloyed steel can replace ductile iron and ADI (austempered ductile iron) in automobile crankshaft and diesel camshaft applications with cost savings at production volumes. See figure above. Beyond the cost

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issue, the main drivers for the change are consumer demand for higher-performance components and the need to meet more stringent EPA regulations and CAFE (corporate average fuel economy) standards.

Advantages of forgings versus castings
Many impressive characteristics and superior properties allow forgings to outperform castings in a wide variety of applications. The main performance advantages of forgings include:

- **Structural integrity of forgings**, which far surpasses that of castings, makes forgings far less prone to failure. Not infrequently, the inherent discontinuous structure of castings—notably porosity, large inclusions and segregation effects—are commonly the cause for in-service failures. See figure on the right.

In castings, these discontinuities often become sites for stress concentrations, fatigue crack initiation, and finally, catastrophic failure. Examples of forgings replacing casting due to such failures include: a high-temperature steel for high-pressure submarine applications; a 5,000 psi hydraulic component (aluminum die casting leaked); an open-die-forged steel shovel hub for mining (casting cracked); and a critical component for truck brakes (low-strength porous casting prompted safety concerns).

In the aerospace sector, forged stainless and nickel alloys for fuel components of commercial turbines proved that investment castings could not match the inherent quality of forging. This application was actually shown to be as cost-effective as a forging in combination with CNC machining. Chemical segregation, also associated with casting, is not a significant factor with forgings, which have a very homogeneous microstructure and chemical composition. Because of the amount of reduction performed on ingot or bar during forging, centerline porosity is practically nonexistent.

- **Grain flow optimization**, an intrinsic advantage of forgings, results in orienting the grain structure with a part's geometry, permitting strength to be aligned in the direction of the highest stress which a component will encounter in service. The net effect results in enhanced strength, toughness, fatigue properties, and longer life. Unfortunately, the solidification of castings produces a random grain orientation, which cannot be optimized. Examples where controlled grain flow provides dramatically improved performance over castings include: automotive and truck crankshafts, wheels for all types of vehicles, a 1-ton connecting rod for coal slurry pumps, and dragline chain links for strip mining.

- **Greater strength** in forgings is accomplished through hot-forging reduction, an integral part of forging processes that also helps produce a homogeneous microstructure by eliminating porosity. This allows forging to attain ultimate tensile strengths above 240,000 psi with correspondingly high design strengths; higher, for ultra-high-strength steels and precipitation-hardening stainless steels. Tremendous improvements in as-cast properties are achieved by this reduction. For example, true stress at failure for quenched and tempered 4140 steel increases from 200,000 psi (as-cast) to 243,000 psi after a 4:1 reduction. In parallel, impact toughness increases by 50%. Such properties are responsible for many forging successes, where castings just cannot handle the loads. Such was the case when sand castings were tried as the main structural components for a missile system—insufficient strength resulted in failure. Fortunately, the forging "alternate" performed within design requirements.
• Higher design stresses as compared to castings typify forgings. Up to 75% to 80% of yield strength can be used in design calculations for forgings, but significantly less for castings. Use of design limits 36% higher than cast A27 steel has been reported for rolled-ring forgings made of 1045 steel. Similarly, aircraft component manufacturers, who have looked to forgings for 1/3 more ultimate tensile strength than castings.

• Improved toughness is one reason why forgings endure when castings fail. When ductile iron crankshafts failed, while forgings continued to perform, low toughness was suspected. Subsequent Charpy V-notch testing confirmed suspicions. The forged 1045 steel cranks attained greater than 100 ft-lb. values whereas ductile iron, only had 1.5 ft-lb. (see table on the right). Even if more typical 8- to 10 ft-lb. values could be counted on for ductile iron, forgings still have an impressive performance edge.

A property improvement is seen in fracture toughness of rams for forging presses. Here, a greater safety factor is afforded by forged steel. In practice, the high ductility or toughness of forgings is used to advantage in many life-critical applications to provide an additional safety factor in the event design stresses are exceeded in service.

• Longer service life, greater fatigue resistance and considerably higher fatigue endurance limits as compared to castings are to be expected. It is not uncommon for life cycles of forgings to be several times that of cast parts. Examples include forged steel coal-pulverizing hammers with five times the life of cast versions and critical parts of pneumatic tools with life time estimates five to ten times greater than cast parts.

Operations such as shot peening, shot-blasting and deep rolling can further enhance the fatigue properties and service lives of forged parts over cast parts. With a forged microalloyed crank, whose fatigue strength was already 57% greater than nodular iron, shot peening boosted that value by another third.

• Near-isotropic property profile instead of the more typical directional profile is also possible with forgings. The ability to increase long- and short-transverse properties of steel forgings up to more than 90% of that of the longitudinal direction can be accomplished by special forging techniques (such as upsetting prior to conventional forging or cross-working) and by ladle additions to control shape and size of inclusions.

• Higher strength-to-weight ratio of forgings translates into lighter weight parts and reduced sections, compared to castings. Forged-steel automobile connecting rods are 10% lighter, yet stronger than cast counterparts. Other load-bearing parts, such as wheel spindles, cranks and camshafts can yield similar results. When forged aluminum replaced cast iron in brake and suspension components and engine mounts, weight savings as high as 60% were achieved.

Similarly, high-temperature aerospace components, forged of nickel-base alloys and stainless steels, commonly

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weigh 5% to 10% less than castings. Weight savings for precision aluminum forgings are considerably greater.

As-forged surfaces, built-in design features and thin ribs and webs contribute to such savings, rivaling the near-net-shape capability of any other process including casting. Features such as flanges, ribs and webs all have to be thicker in castings to achieve strength levels of forgings.

• **Surface quality** routinely surpasses that of casting because forgings feature 100% density and homogeneous material throughout. Repair work via welding, which is often required to bring castings up to par in bearing and structural applications, is not necessary with forgings. Denser surfaces (no voids, inclusions, etc.) are a benefit even with non-structural forged parts. For example, forged-brass decorative flagpole tops exhibited a very dense surface - smooth enough to replicate fine details even after subsequent chrome plating, if desired. No porosity problems were found.

• **Improved machinability** also typifies forgings due to a consistent chemical composition and uniform microstructure. Unlike castings, there are no voids, inclusions and segregated hard spots to interfere with machining operations. Many applications in which forgings have shown improved machining over castings have been documented, among them: microalloyed crankshafts, hydraulic components, and rolled-ring forgings. In addition, some free-machining steel grades are routinely forged, thereby improving both the ease and economy of machining.

Many other performance advantages of forgings have been demonstrated time and time again, most of which appear in the accompanying box (see table on the right). While castings do have their application niches as far as metal components go, forging companies believe that the overall higher performance of forged products make them a "must" for critical components. Importantly, even non-critical parts where strength is not the prime issue may become economical as forgings due to extended life cycles.

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**ADVANTAGES OF FORGINGS OVER CASTINGS**

- Higher strength
- Unmatched toughness
- Longer service life
- Higher structural integrity (absence of internal defects)
- Higher design stresses
- Greater transverse properties
- Increased safety margin (due to high ductility)
- Greater strength-to-weight ratio (lighter parts, reduced sections)
- 100% density (no porosity)
- Higher overall quality/reliability
- Reduced product liability concerns
- Reduced testing requirements
- More acceptable parts/fewer rejects
- No welding repair required (uniform consistent material throughout)
- More predictable heat-treat response
- More uniform properties (lot to lot, and part to part)
- Directional or isotropic property profile
- More consistent machining (uniform microstructure and chemical composition)
- Better hardness control for abrasion/wear resistance
- Extended warranties more probable on critical parts/assemblies
- More versatile processing options and combinations (upsetting, then forging; forging plus coining, etc.)
OPEN DIE FORGINGS DELIVER HIGH QUALITY, AND GOOD PROPERTIES FOR SHORT-RUN METAL COMPONENTS

For smaller production runs, open die forgings are often the best choice, providing the optimum combination of properties, quality, and structural integrity versus other metal-component alternatives. The wide range of geometric configurations and enormous size capability make open die forging processes the most versatile means of producing "custom" metal shapes. See figures.

Sometimes referred to as flat-die or hand forging, open die forging often makes use of flat or V-shaped dies to progressively forge a shape. It differs from impression die (or closed die) forging in that no impressions are sunk into the top and bottom dies. Like other types of forging processes, open die forging permits control of grain flow to optimize property profiles and increase service life over castings, weldments, and machined plate and bar.

When to use open die forging:
Three criteria dictate when open die forging should be selected over alternative processes: 1) for low quantities; 2) when part size is very large; or 3) when property requirements can only be achieved by forging.

• Quantity considerations
Because open die forging is a "one part at a time" process, it is often practical for producing a single part more economically than casting, machining, or welding multiple components together. Depending on part size and geometry, even 100-piece runs can be routinely produced, and can be cost-effective. In situations where impression die forging will be the eventual means of producing the desired shape, open die prototype parts provide the opportunity to economically refine and/or change functional, property, and geometric requirements prior to sinking costly production tooling.

• Component size range
In some cases, sheer part size dictates that only open die forging can be used to manufacture a part with the desirable characteristics of hot forging. In practice, parts can be much larger than impression die forgings, ranging from just a few pounds up to hundreds of tons, with the upper limit restricted only by the largest ingot that can be cast. Some of the largest shafts that have been open die forged weigh more than 200 tons. Similarly impressive, open-die forged blanks (prior to rolling into rings) can weigh as much as 150 tons. See figure above.

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• Property requirements
As a rule of thumb, open die forging should be chosen over competitive non-forging manufacturing processes when a component must withstand repeated and cyclical stresses that approach half the ultimate strength of the specific alloy. At this level, forged products generally surpass castings in terms of both performance and structural integrity. Cast, welded, or machined parts that failed in high stress environments are the definitive candidates for open die forging.

Other requirements may also dictate open die forging for specific applications. Applications that have a need for increased property values in the short- and long-transverse directions are good candidates for open die forging, as well as components like large crankshafts that need good torsional fatigue resistance.

No matter what the part size, open die forging is frequently the only option that is able to meet design-property requirements and anticipated life expectancy. A prime example is the replacement of leak-prone cast-cylinders with open-die forged versions for a hydraulic press. Longer life and elimination of predicted downtime more than offset the initial higher cost of the forgings.

Versatility via shape options
A host of processes provide the versatility to produce a wide variety of shapes, many of which are not normally associated with open die forging. These include a number of categories: shafts, hollows, contour-formed shells, rings, disks, and other miscellaneous shapes. The table on the right shows the size capability for open die forging of various shapes.

Shaft-like parts range from prototype shaft and gear components to shafts with thin flanges to upset shafts. The latter starts with stock that is forged down to its initial shape, dropped into a hole in a standard die and then upset, creating a larger diameter section that is integral with the shaft. This upset capability is utilized by many open-die forgers to produce forged design features that would not otherwise be possible, such as multiple upsets, larger diameter upsets near the center of a shaft, internal and offset upsets, as well as upset hollows. Not surprisingly, performance and life of shafts with integral hubs like a one-piece gear/blank and hub far surpass counterparts welded from two separate pieces cut from plate and bar.

Open die forgings with upset features do not always approximate long shaft-like shapes; they can also be configured as a basic flat disk with a short protruding shaft, which can either be solid or feature an internal diameter. Applications include stub shafts, axles and pinion-gear blanks.

In the past crankshafts for large diesel marine engines, pumps, and compressors were routinely made via open die forging, but also required specially designed closed-die operations and large presses with capacities of 4,000-8,000 tons—an expensive proposition. With the availability of ladle-refined "super clean" steels combined with innovative, precise open
die forging techniques, large multi-throw crankshafts (15,000-80,000 lb. forge weight) have been produced to a high quality level not previously attainable.

Hollows go beyond plain hollow cylinders to complex open die forgings that replace thick-walled centrifugal castings. An example is the recoil piston for a 105 mm cannon on the M1 tank. Here, as-cast porosity resulted in high rejects, expensive rework, and excessive machining. After economic and performance considerations forced the change to hollow forging, initial part savings were further reduced by having the forge plant perform non-destructive testing (NDT), heat treatment, and rough machining operations.

Hollows can incorporate multiple flanges (multiple steps), both internally and externally, as well as tapers. Many parts traditionally made by forging a solid piece, then removing the center, are much more economically made by open die forging as a hollow, with higher alloys delivering even more impressive cost savings. Also, when function dictates, a hollow can be forged with one end practically closed.

Large inside diameter and/or outside diameters are not uncommon, although a minimum wall thickness of about 2 in. is necessary to support large structures. The majority of hollows fall in the 24 to 40 in. diameter range, weighing a few hundred pounds up to thousands of pounds.

Contour-formed shells for pressure-vessel applications are usually large mandrel-forged cylindrical shapes. These shells can incorporate different diameters along the axis, as well as forged, multiple ports or projections, which otherwise would have to be welded or machined. Basically extruded with special die plates, the integral ports eliminate excessive welding and machining, yielding a higher integrity structure that is often less expensive. The largest of these can weigh up to 200,000 lbs.

Basic shapes are also routinely produced using open die forging to improve properties and ultimate part quality. These include discs—basically round, solid blanks or "pancakes" which are upset from the original ingot or billet—for further processing such as ring-rolling and impression die forging. Correspondingly, rectangular slabs (usually with width greater than thickness) or blocks are regularly made into all types of dies and molds. Here, cross-forging (upsetting and drawing along a transverse axis) can be used as a performance-boosting option.

Open die forging is a successful way of making forging-quality billet (usually square) for subsequent re-forging, most often for high-temperature alloys and specialty grades of material. In parallel, forged quality bar is ideal for longitudinally drawn-out parts with the desired cross-section (round, hex, square, rectangular, etc.), which is then subsequently machined or forged.

**Why open die forging surpasses alternatives**

Many reasons combine to make open die forgings the clear high-performance choice over casting, machining, weldments and other alternatives. Chief among these are grain-flow optimization, maximum structural integrity via densification and the ability to achieve either directional or isotropic property profiles.

- **Optimum grain flow** can be achieved in open die forgings. Continuous grain flow gives forgings, in general,
increased property values and longer life compared to other metal components. Routinely, open die forging operations are custom-tailored to produce the desired shape and ultimate properties.

For example, through the proper combination and sequence of open die forging operations (drawing, upsetting, and others) an integral gear blank/hub possesses the optimum grain flow orientation. This results in improved properties in the gear blank’s radial direction, as well as in the longitudinal (or axial) direction of the hub.

• **Structural integrity** is regularly imparted through the hot working and densification of open-die forged products, virtually eliminating as-cast porosity, and breaking up large inclusions and segregations. It is the depth of penetration of work that makes open-die-forged products superior to hot-rolled billets for most medium to high-alloy steels.

To assure proper densification in practice, the reduction ratio, corresponding to the part category (solid shaft, hollow, etc.) and type of starting stock, is carefully calculated to get adequate depth of penetration in each step of an open die forging sequence. This makes the resulting integrity of forged products far superior to cast, welded or machined materials.

• **Directional or isotropic property profiles** are possible by combining various open die forging techniques, e.g., upsetting (pre-upsetting) or cross-forging performed prior to conventional drawing and other subsequent forging operations. This is especially important for enhancing transverse properties of aluminum alloys whose inherent structure is very directional. Consequently, common practice is to use cross-forging, which involves upsetting, drawing out at 90° to the original ingot axis, re-upsetting, then, continuing to draw along the starting axis. This technique provides additional levels of deformation approaching that of impression die forgings and leads to significant transverse property improvements over products that are drawn continuously in one direction. These open die forging techniques are also used in conjunction with "clean" steels to further augment isotropy. This was the case with multi-port compressor cylinders for large internal-engine compressors. Inclusion shape control, combined with pre-upsetting, yielded components with tensile and fatigue properties within a few percentage points of each other in longitudinal, short-transverse and long-transverse directions.
FORGING FUNDAMENTALS: THE KEY TO OPTIMUM DESIGN PRACTICE

To all but the most seasoned designers, the concept of forging fundamentals may at first appear trivial. But that is not the case. In practice, material- and process-related forging basics can be invaluable. For instance, realizing that certain part shapes are more forgeable in some materials and knowing that the equipment affects how closely the material can be forged to its final configuration are just two aspects involved in creating the optimum design.

For experienced designers, forgings are the optimum choice for metal components, even before the design is on the drawing board. Forgings bring superior performance; they have higher strength, unsurpassed toughness, greatest structural integrity, longer service life, and maximum reliability, as compared to castings, stampings, weldments, and machined parts.

Once the correct metal alloy is selected, based on minimum design requirements for mechanical and/or physical properties, in-service environmental conditions, fatigue life, and more, manufacturability becomes a prime consideration. In practice, creating the optimum design for manufacturability takes cooperative effort among the product designer, the forger, and metallurgical personnel.

The manufacturability of a forging design depends primarily on the material being forged, which influences not only the internal soundness of the forging, but also determines important design characteristics and features. These include:

- the amount of finish required;
- the minimum section thicknesses that can be achieved;
- the degree of shape refinement or part complexity;
- the magnitude of tolerances that can be held; and
- size limitations (plan-view area [PVA], length, or width).

Examining forgeability (how easy it is to forge a material without rupture) is a good first step toward evaluating manufacturability. This property varies greatly depending on the type of alloy. See figure above. The ability to
manufacture an intricate shape by conventional forging is reflected in how easily a particular material fills a die cavity. Both forgeability and flow strength affect the ease of die filling. In general, high-flow-strength materials are more difficult to fill cavities and usually require higher forging pressures. Inevitably, part complexity also affects forgeability. Typically, more complex designs make a material more difficult to forge. See on the right.

**Material basics**

Basic differences between forging materials explains why closer tolerances and more complex shapes are more readily achievable with some alloys. For instance, aluminum forgings can be held to much closer tolerances than steel and provide better shape capability than any other material, with the exception of some copper alloys, forging brasses, and bronzes. Typically, tolerances are about one-third those of steel forgings, due to significantly less shrinkage and reduced die wear. The differences in tolerance and die wear are reflected in the 700-800°F forging temperature range for aluminum versus 1900-2400°F for steels.

In contrast, titanium forgings cannot be held to the same tolerances that carbon-and alloy-steel forgings can because of the abrasiveness of the oxide and other physical factors. Typically, titanium forgings require 20% to 25% greater tolerance than steel forgings.

More exotic materials like superalloys have varying ranges of forging temperatures. Some high-temperature alloys with only a 50 to 60°F forging window have greatly limited forgeability, requiring either hot-die or isothermal forging processes.

**Conventional or precision?**

Depending on the material, a variety of processes, either conventional forging or precision forging, can be used to produce the desired shape. Numerous factors help decide what basic process to use. See table above for guidelines on the pre-selection of forging processes for steels.

When forged to near net shape, expensive materials (such as stainless steels, titanium and nickel-base superalloys) become more economical as a result of material savings. However, many common materials (steel, aluminum, etc.) are conventionally forged routinely to more generous dimensions and subsequently machined, but are often more cost-effective than non-forging processes. Frequently, closer-than-normal tolerances can be achieved with conventional forging plus proper ancillary processing, as in the case of a forged aluminum ejector.

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**PRESELECTION OF FORGING PROCESSES FOR STEELS**

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<th>Factors of Choice</th>
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<td>Size/shape restrictions</td>
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* Includes open-die forging processes. ** Per pound of forging.

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As shapes deviate from basic rectangular configurations, impression die forging becomes more difficult. Parts with thin webs and high ribs are hardest to forge.
Generally, the process selected (and related forging equipment) affects how closely a material can be forged to final dimensions. For example, precision forging of aluminum can yield parts with net-shape surfaces and close tolerances, while conventional forging may require machining all around the part periphery. For higher alloys like superalloys, shape and size limitations become highly equipment-dependent, because of smaller processing windows and the need for precise control of metallurgical factors. As a result, these materials generally require much higher forging pressures than steel, resulting in parts with smaller plan-view areas and other dimensional constraints. In contrast, larger steel forgings can often be produced by utilizing higher capacity (tonnage) equipment. The same holds true for many aluminum alloys.

**Near or net shape**
Emphasis is often on forging closer to net shape or as close as possible to finished contours and dimensions. A fundamental knowledge of the following options, which collectively apply to most forgeable materials, helps identify the appropriate process for a given material.

- **Hot forging in presses** to near-net shapes is possible for most carbon, alloy, and stainless steels, titanium alloys, heat-resistant alloys, and nonferrous materials. While crank-type drives are more readily automated, screw presses are ideal for thin parts like turbine blades and provide greater thickness accuracy. Both symmetrical and axisymmetrical components can be produced. High production quantities are recommended to offset tool design and development costs. Part weights can approach 200 lbs.

- **Hot forging in controlled impact hammers** to near-net shapes applies to most alloys, except for magnesium and higher aluminum alloys, such as 7075, 7079, and 7050. Parts with thin sections and close thickness tolerances are readily manufactured. While lower production quantities are more economical than with presses, shape versatility is not as great since tooling restrictions (lack of kick-outs) requires draft on part designs. Forgings up to about 35 lb. can be produced to near-net configurations (even larger if cold coining is used).

- **Warm forging in mechanical presses** to close tolerances is appropriate for steels and some aluminum alloys. Usually requiring progressive forming steps, this process may use automated induction heating to form preconditioned steel slugs. For higher productivity, walking-beam transfers are integral with some machines. Suitable for forging gears with integral teeth, warm forging often requires some type of cutting operation to hold concentricity tolerances on shafts. Typically, tooling costs are moderate to high, and sufficient production quantities are needed to justify this process. Maximum part weight is about 30 lbs.

- **Hot forging in high-speed part formers** to close finish usually applies to carbon and low-alloy steels, which are typically made into axisymmetrical parts with low profiles. Parts generally feature no draft and very little finish allowance. Although production rates can exceed 100 parts per minute, costly machinery and production-line support equipment requires very large quantities (e.g. automotive) to justify use. Generally, parts weigh up to 15 lbs.

- **Cold forging** processes make use of bending, extrusion, coining, etc. to manufacture parts to close tolerances or near-net shapes. All are basically chipless. In practice, ferrous materials are restricted to lower alloy and carbon steels with carbon levels of 0.45% or less; impact extrusions, 0.25% C or less. Although less common, stainless steels and aluminum alloys and bronzes can also be cold forged. Typical shapes include cup- and shift-like parts, struts, and headed components and range from 1/4 to 20 lbs. To justify selection, a minimum of 10,000 lbs. of parts/month is recommended, although there are occasional exceptions to this rough guideline.

- **Hot-die forging** in conventional presses requires specialized tooling heated to near-forging temperatures in air. Suitable for titanium alloys and nickel-based superalloys, this process is not recommended for stainless or alloy steels. Most parts are modified disk shapes 6 to 36 in. in diameter and weighing from about 70 to 1000 lbs. Forging of aluminum alloys in heated tools also falls in this category.

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• Isothermal forging usually applies to nickel-based superalloys prepared initially by powder-metal compaction. The process is not recommended for steels or stainless steels. Expensive refractory-metal tooling and controlled-atmosphere chambers to protect tools and parts from oxidation are standard. Production rates of a few parts per hour make this process cost-effective for only the highest performance parts. Shapes and sizes are similar to hot-die forging, but with closer tolerances on thickness and somewhat thinner sections.

**Size/Shape Limitations**

Shape/size limitations on forging designs are often limited by the equipment used. For instance, aluminum and titanium airframe-type structural components exceeding about 5.5 ft. cannot be forged on many large drop hammers and mechanical presses because the press bed is just not large enough to hold the required tools. Fortunately, large counterblow hammers can handle parts up to 7 ft. long. Beyond that, large hydraulic presses with 50,000 ton capacities can produce components up to 12 ft. long.

However, the total projected area must still be matched to the press capacity. This tends to restrict longer parts to narrower widths (within PVA limitations).

Similarly, disk shapes can be forged of steel on large presses of counterblow hammers up to a maximum 65 in. diameter, but are limited to about 38 in. diameters when forged of nickel-base superalloys, except for simple configurations and fairly thick shapes. The much higher pressures required demonstrate the tie to forgeability (i.e. harder to forge materials restrict plan-view area and overall size, and may also require higher-capacity machines). The number of companies with the largest forging machines is limited.

The features of different forging machines also affect other important design parameters. For example, parts forged in hammers must have draft angles for easy removal from impression dies. The lack of built-in ejection systems makes "no draft" parts impractical. Similarly, multi-section or segmented dies and inserts, which permit such design features as undercuts, lateral protrusions and back draft in aluminum precision forgings, are feasible primarily for hydraulic presses. In practice, such dies cannot be used in hammers or most mechanical presses.
DESIGN FOR FORGINGS-SPECIFICATIONS HELP

Thinking of specifying a forging? It is probably easier than you think. As is often the case, the reasons why steel castings, flame-cut plate, weldments, machined bar, and others were specified years ago are not necessarily valid or obvious. Informed designers switch to forgings in order to upgrade performance.

There is no need for apprehension if you are only familiar with specifications for casting, structural steel, hot-rolled bar or other non-forged product, because cross-references to existing forgings specifications can often be made. Even when they cannot, forging companies can propose alternatives of an equivalent material, but with typically superior performance.

Some knowledge of pertinent specifications will definitely help those who are not familiar with forgings. This article is intended to present designers and potential customers with preliminary knowledge of forging specifications to expedite the process of upgrading to forgings.

Why specify forgings?
The answer is simple: Forgings give higher performance compared to castings, machined parts, weldments, and other metal components. This includes high mechanical properties, unsurpassed impact toughness, longer service life, greater structural integrity, a more homogeneous microstructure (freedom from porosity, gross inclusions, etc.), optimum grain flow orientation, and customized property profiles, among others.

Performance is not the only reason. When upgrading from non-forged parts, some forging customers have been pleasantly surprised by an initial lower cost for forgings. While the latter scenario is not always the case, most forgings are actually less expensive when compared to other metal components on a life cycle cost basis. The longer life of high-performance forged components makes it so. A switch to forgings can streamline the manufacturing process. Resulting cost savings can be even more significant. Such was the case when a forging replaced a casting in a friction-welded assembly.

Open die forgings versus non-forged parts
Because of their higher performance, steel forgings routinely continue to replace steel castings. Knowing what specification to use for a particular application to an open die forging is definitely helpful. Although not always simple, cross-referencing commonly used specifications allow designers to more accurately evaluate forging options and actually facilitate the upgrade process. The comparisons of forging specifications to casting specifications appearing in the table on the following page cover carbon and alloy steels for various applications and environmental conditions. This is meant to serve as a guideline only, and is not intended as a final recommendation for any particular application.

One of the most-used open die forging specs available, ASTM A668 is a broad-based starting point for anyone wishing to specify open die forgings (see on the next page for more details). It covers carbon through alloy steels and specifies a definitive Brinell hardness range, among other requirements. It is useful not only for specifying upgrades to forging from casting, but also for other non-forging alternatives. For example, structural steel shapes, plate, and bar previously purchased under ASTM A36 (Standard Specification for Structural Steel) may be cross-referenced to ASTM A668.
"GUIDELINE" SPECIFICATION COMPARISONS: FORGINGS VERSUS CASTINGS*

<table>
<thead>
<tr>
<th>Castings:</th>
<th>Forgings:</th>
<th>Forging specification covers:</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM A27 - Carbon steel castings, general application.</td>
<td>ASTM A521 - Closed-impression die steel forgings for general industrial use.</td>
<td>A521: Manufacture, chemical comp., tensile prop., testing, dimensional tolerance req., etc.**</td>
</tr>
<tr>
<td>ASTM A781 - Steel and alloy castings, common requirements for general industrial use.</td>
<td>ASTM A668 - Steel forgings, carbon and alloy for general industrial use.</td>
<td>A668: Chemical comp., mech. prop., hardness, test req. etc.** for: solid forgings (shafts, bars, billets); rings and hollow cylinders; and disks, A181: Materials, manufacture, chem. comp., mech. prop., test req. etc. for nonstandard as-forged fittings, valve components, general-service parts.</td>
</tr>
<tr>
<td>ASTM A487 - Steel castings suitable for pressure service.</td>
<td>ASTM A541 - Steel forgings, carbon and alloy, quenched and tempered, for pressure-vessel components. ASTM A508 - Quenched and tempered, vacuum-treated carbon and alloy steel forgings for pressure vessels. ASTM A372 - Carbon and alloy steel forgings for thin-walled pressure vessels. ASTM A105 - Carbon steel forgings for piping components in ambient and higher-temperature pressure systems.</td>
<td>A541: Chemical comp., tensile properties, Charpy V-notch impact requirements, etc.** A508: Chemical, mechanical, tensile, Charpy impact, NDT req. etc.** for vessel closures, shells, flanges, rings, etc. A372: Chemical, mechanical req. for bored and hollow forgings; also, bending properties, mag. particle, etc.** A105: Materials, manufacture, heat treat, chem. comp., mech. prop., hydrostatic test req. etc.** for flanges, fittings, valves and similar parts.</td>
</tr>
<tr>
<td>ASTM A389 - Alloy steel castings, specially heat-treated, for pressure-containing parts. Suitable for high temperature service.</td>
<td>ASTM A336 - Alloy steel forgings for pressure and high-temperature parts. ASTM A182 - Forged or rolled alloy-steel pipe flanges, forged fittings, valves and parts for high-temperature service.</td>
<td>A336: Chem. comp., tensile prop., heat treat, test, grain size, etc.** for boilers, press. vessels, high-temp. parts. ASTM A182: Manufacture, heat treat, chem. comp., prop., hardness, etc.** for piping components pressure systems (flanges, fittings, valves).</td>
</tr>
<tr>
<td>ASTM A217 - Steel castings, martensitic stainless and alloy, for pressure containing parts; suitable for high-temp. service.</td>
<td>ASTM A565 - Martensitic stainless steel bars, forgings and forging stock for high-temperature service. ASTM A182 - Forged or rolled alloy-steel pipe flanges, forged fittings, valves and parts for high-temperature service.</td>
<td>A565: Chemical comp., mech. prop., heat treat, metallurgical req., etc. for chromium steel for high-temperature service. Max. 1200°F service; for oxidation resist. at low stresses, up to 1450°F. ASTM A182: See same, referenced in block above.</td>
</tr>
<tr>
<td>ASTM A352 - Steel castings, ferritic and martensitic, for pressure-containing parts; suitable for low-temperature service.</td>
<td>ASTM A350 - Forgings, carbon and low-alloy steel, requiring notch toughness testing for piping components. ASTM A727 - Carbon steel forgings for piping components with inherent notch toughness.</td>
<td>A350: Manufacture, heat treat, chem. comp., mech. and impact prop., hardness, testing, etc.** for forged or ring-rolled flanges, fittings, valves for low-temp. service. ASTM A727: Materials, manufacture, heat treat, chem. comp., tensile, hydrostatic test req. etc.** for forgings in service from -20 to 650°F.</td>
</tr>
</tbody>
</table>

* Based on standard specifications issued by ASTM (American Society for Testing and Materials), Philadelphia, PA.
** Plus optional supplementary requirements.

Continued
Class D, which calls out tensile requirements as a function of size.

In addition to upgrading for performance reasons, such components as thick-walled tubing, flat bar, plate, hollows, etc. often become forgings because the desired stock sizes of non-forged products are not available. Typically, dimensions such as length, outside diameter, wall thickness, etc. are not as limited in forged products, thereby increasing design flexibility.

Similarly, seamless tubing purchased under ASTM A106-91 (Seamless Carbon Steel Pipe for High-Temperature Service) may be specified as a forging under A105 (Standard Specification for Forgings, Carbon Steel, for Piping Components). This option is sometimes preferred for short runs of hollow seamless rounds in short lengths, namely forged or rolled rings.

### Impression die forgings

As with open die counterparts, existing specifications for impression die forgings provide a relatively easy way to initiate an upgrade. Targeted at impression die forgings in general, ASTM A521 covers untreated carbon steel forgings up through normalized and quenched-and-tempered alloy steel forgings, detailing most of the design parameters that help make forgings the metal component leader. A good starting point for those not as familiar with forgings, this comprehensive specification includes key requirements for chemical composition, mechanical properties, testing, and dimensional tolerances—length/width, die wear, die closure, die match, flash extension, straightness, surface, draft angle, and finish allowance. When applications so demand, supplementary requirements—magnetic particle, grain flow, impact, microstructural, ultrasonic, radiographic, and Brinell hardness—can be specified. The specification also separately addresses forgings made on hammers/presses or on forging machines (upsetters). This general specification also appears in the previous table.

Greater ductility, reflected in significant toughness improvements, is definitely an important factor in the resulting superior performance of forgings. As is almost always the case, this improvement is indicated by higher percent-elongation and reduction-of-area values for forged versus non-forged products. The table on the right compares minimum specification values for impression die forging versus casting. The clear advantage that forgings typically possess is readily seen in the calculated percentage gains.

It is estimated that there are hundreds of forging-related ASTM specifications, any of which may be useful for a particular application. Beyond "general" specifications, others cover various applications by end use category (rail, air, automotive); by environmental conditions (high temperature, pressure, low temperature); and even by

<table>
<thead>
<tr>
<th>ASTM spec</th>
<th>Grade or Class</th>
<th>Elong. %</th>
<th>Gain Elong.</th>
<th>Red. of area, %</th>
<th>Gain R of A</th>
<th>Ten./Yield str., ksi</th>
<th>Thick in.**</th>
</tr>
</thead>
<tbody>
<tr>
<td>A148* Casting</td>
<td>115-95</td>
<td>14</td>
<td>—</td>
<td>30</td>
<td>—</td>
<td>115/95</td>
<td>—</td>
</tr>
<tr>
<td>A521^ Impression die forging</td>
<td>16</td>
<td>14%</td>
<td>50</td>
<td>67%</td>
<td>125/105</td>
<td>&lt;4</td>
<td></td>
</tr>
<tr>
<td>A148* Casting</td>
<td>90-60</td>
<td>20</td>
<td>—</td>
<td>40</td>
<td>—</td>
<td>90/60</td>
<td>—</td>
</tr>
<tr>
<td>A521^ Impression die forging</td>
<td>16</td>
<td>14%</td>
<td>45</td>
<td>50%</td>
<td>115/96</td>
<td>4-7</td>
<td></td>
</tr>
<tr>
<td>A148* Casting</td>
<td>80-40</td>
<td>22</td>
<td>10%</td>
<td>44</td>
<td>10%</td>
<td>90/60</td>
<td>&lt;7</td>
</tr>
<tr>
<td>A521^ Impression die forging</td>
<td>18</td>
<td>—</td>
<td>30</td>
<td>—</td>
<td>90/60</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>A27</td>
<td>Casting</td>
<td>70-36^</td>
<td>22</td>
<td>—</td>
<td>30</td>
<td>—</td>
<td>70/36</td>
</tr>
<tr>
<td>A521^ Impression die forging</td>
<td>70-40^</td>
<td>22</td>
<td>22%</td>
<td>36</td>
<td>20%</td>
<td>80/40</td>
<td>&lt;8</td>
</tr>
<tr>
<td>A521^ Impression die forging</td>
<td>24</td>
<td>9%</td>
<td>40</td>
<td>35%</td>
<td>75/37</td>
<td>&lt;8</td>
<td></td>
</tr>
</tbody>
</table>

**Or solid diameter.
*Standard specification for high strength steel castings for structural purposes.
^Standard specification for closed-impression die steel forgings for general industrial use.
*Alloy steel, normalized, quenched and tempered
*Alloy steel, normalized and tempered.
*Carbon steel, normalized and tempered.
Standard specification for carbon steel castings for gen. application.
0.35% C max., 0.7% Mn max.
0.25% C, 1.20% Mn max
Carbon steel: annealed, normalized or normalized and tempered.

Continued
the exact component type (steel rolls for paper machinery, nonmagnetic retaining rings for generators, rings for reduction gears).

In addition, depending on the end use, a variety of standard specifications, for example: ASTM, MIL, QQ(Federal), SAE, ANSI, AMS, ISO, DIN, JIS, etc., may apply to a particular application. Some overlap; some do not. While this may seem to complicate the upgrade process, a knowledgeable forging company can usually answer specifications questions.

No single specification covers all situations. That is why specifications from ASTM and other standards organizations often include supplemental requirements. Such requirements are negotiable between forger and customer, and can be tailored to fulfill specialized needs and unusual performance requirements.

**Practice versus theory**

In reality, a one-to-one cross-reference of a forging specification to a non-forging specification is not always possible. Sometimes, it seems like comparing apples to oranges. But, there is no need to despair. If a part has previously been specified as a casting, machined round bar or other non-forged product, forging companies can offer a viable and economical forging option: namely, a forging that corresponds both compositionally and property-wise to the non-forged product in question. If a casting was previously made to a certain class or grade of material in a cited specification-for example, a 70 ksi tensile strength and 30 ksi yield-these properties can be readily accommodated in an equivalent forging material. As a matter of course, improved properties, greater structural integrity, and longer service life routinely accompany the choice of a forged alternative.

If you know what design criteria (mechanical properties, impact toughness, fatigue life, endurance limit, environmental conditions, etc.) are needed for your application, so much the better. If not, then discuss forging alternatives with FIA members who are more than happy to assist in evaluating your application and present you with options, which may be just what you are looking for, both economically and performance-wise.

When upgrading, keep in mind that some "caveats" may apply.

1) Forgings should not be produced to casting, structural steel, or other metal-component specifications, because each non-forged alternative has its own special inherent requirements that do not usually apply to forgings. While forging companies can provide forgings to meet or surpass chemical compositions and mechanical properties of non-forging specifications, it definitely makes sense to optimize your particular application.

2) Do not inadvertently switch from a casting or other non-forging spec without thorough review of what the requirements entail. Special requirements like ultrasonic testing, which may not be necessary for a particular application, can be automatically invoked by citing a particular specification. When not needed, this just drives up product cost.

3) Do not try to modify existing non-forging specifications. It is usually not feasible and could be counter-productive. Forging companies suggest that you spend this time contacting them with the details on your potential forging application. They can then suggest a forging alternative to your current non-forged product.
THE LANGUAGE OF FORGING: KEY TERMS AND DEFINITIONS

Like other technical fields and engineering disciplines, forging technology has a language all its own. Knowing what these terms mean and how they are applied can be of enormous help in seeking quotations, specifying forged products over other alternatives, and understanding why forged components deliver superior performance over non-forged parts.

General metallurgical and other terms not related explicitly to forging are not covered. Not all terms can be covered; only the most common terms are presented.

**Aluminum precision forging:** a process to plastically deform an aluminum alloy to a finished part shape in special dies. By design, little or no subsequent machining/processing is required as a result of close tolerances, thin sections, small radii and minimum draft angles.

**Alloy steel forging:** once 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.

**Bar:** a section hot rolled from a billet to a round, square, rectangular, hexagonal or other shape with a cross-section less than 16 sq.in.

**Billet:** a semi-finished section (width less than twice the thickness), hot rolled from a metal ingot, generally having a cross-section ranging from 16 to 64 in². Also applies to a hot-worked forged, rolled or extruded round or square.

**Blank:** raw material or forging stock from which a forging is made.

**Bloom:** same as a billet, but with a cross-sectional area greater than 36 in².

**Blocker-type forging:** one with the general shape of the final configuration, but featuring a generous finish allowance, large radii, etc.

**Carbon steel forging:** one made from steel whose major alloying element, carbon, produces the resultant properties and hardness.

**Close-tolerance forging:** one held to closer-than-conventional dimensional tolerances.

**Closed die forging:** see impression die forging.

**Coining:** a post-forging process for hot or cold parts to attain closer tolerances or improved surfaces.

**Cold-coined forging:** one that is re-struck cold to improve selected tolerances or reduce a specific section thickness.

**Cold forging:** various forging processes conducted at or near ambient temperature 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 Figure 1.

**Cold working:** imparting plastic deformation to a metal or alloy at a temperature below recrystallization to produce hardness and strength increases via strain hardening.

*Continued*
Controlled cooling: process used to attain required properties and/or corresponding microstructural phase changes; applies to heat-treatable steels (e.g. quenching) and to microalloyed steels, which require no heat treatment, but only controlled cooling to attain final properties.

Conventional forging: one that, by design, requires a specified amount of finish (or machining) to reach the final dimensional requirements.

Counterblow forging: one made by equipment incorporating two opposed rams, which simultaneously strike repeated blows on the work piece.

Cross forging: the practice of working stock in one or more directions to make resultant properties more isotropic (equal in three directions), for example, by upsetting and redrawing the material.

Directional properties: refers to the inherent directionality within a forging such that properties are optimally oriented to do the most good under in-service conditions. Typically, maximum strength is oriented along the axis that will experience the highest loads.

Disk: a "pancake" shaped forging (flat with a round cross-section), such as a blank for gears, rings, and flanged hubs.

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.

Draftless forging: a forging with zero draft on vertical walls.

Drawing: 1) reducing the cross-section of forging stock while simultaneously increasing the length; 2) in heat treating, the same as tempering.

Drop forging: one produced by hammering metal in a drop hammer between impression dies.

Extrusion: forcing metal through a die orifice in the same direction as the applied force (forward extrusion) or in the opposite direction (backward extrusion). See Figure 2.

Finish: 1) the material remaining after forging that is machined away to produce the final part; 2) the surface condition of a forging after machining.

Finish all over (F.A.O.): designates that forgings be made sufficiently larger than dimensions shown to permit machining on all surfaces to given sizes.

Finish allowance: amount of stock left on the surface of a forging to be removed by subsequent machining.

Flash: excess metal that extends out from the body of the forging to ensure complete filling of the finishing impressions.

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

Flow lines: patterns that reveal how the grain structure follows the direction of working in a forging.

Forgeability: relative ability of a material to deform without failure or fracture.

Forging reduction: ratio of the cross sectional area before and after forging; sometimes refers to percentage reduction in thickness.

Forging stock: wrought rod, bar, or piece used as the raw material or stock in forging.

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

Grain flow: fiber-like lines that show (via macroscopic etching) the orientation of the microstructural grain pattern of forgings achieved by working during forging processes. Optimizing grain flow orientation maximizes mechanical properties.

Hammer forging: one produced on a forging hammer, usually between impression dies but sometimes flat dies; the process of forging in a drop hammer (see drop forging).

Hand forging: one made by manually controlled manipulation in a press without impression dies, usually between flat dies with progressive forging of the work piece; also referred to as flat die forging.

Heat treatment: heating or cooling operations, sometimes isothermal, to produce desired properties in forgings.

High energy rate forging (HERF): forgings made on equipment that utilizes very high ram velocities.

Hogout: product machined from bar, plate, slab, or other material.

Hollow forging: a cylindrical open die forging; namely, thick-walled tubes or rings. See Figure 3 on the next page.
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.

Hub: a boss in the center of a forging that forms an integral part of the body.

Impact extrusion: a reverse extrusion process in which metal is displaced backwards between a punch and a die to form a hollow part. See Figure 4.

Impression die forging: one formed to shape and size in die cavities or impressions; also commonly referred to as closed die forging. See Figure 5.

Isothermal forging is most commonly conducted at about 2000˚F under a controlled atmosphere or vacuum to prevent oxidation while forging superalloys.

Machine forging (upsetter forging): one made in a forging machine or upsetter, in which a horizontally moving die in the ram forces the alloy into the die cavities.

Mandrel forging: see saddle/mandrel forging.

Match: aligning a point in one die half with the corresponding point in the opposite die half.

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

Microstructure: the microscopic structure of metals/alloys as seen on a mounted, ground, polished, and etched specimen to reveal grain size, constituent phases, etc.

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

Open die forging: one produced by working between flat or simply contoured dies by repetitive strokes and continuous manipulation of the work piece; sometimes called hand forging. See Figures 6 to 8.

Parting line: the plane that divides the two die halves used in forging; also applies to the resulting forging and impression dies.

Piercing: forming or enlarging a hold via a tapered or cylindrical punch.

Plastic deformation: permanent distortion of a material without fracturing it.

Plate: a flat hot rolled metal or alloy product whose thickness is much less than its width.

Precision forging: any forging process that produces parts to closer tolerances than conventional forging processes.

Preform: forging operation in which stock is preformed or shaped to a predetermined size and contour prior to subsequent die forging operations; also, ring blanks of a specific shape for profile (contour) ring rolling.

Press forging: the shaping of metal between dies on a mechanical or hydraulic press.

Quenched and tempered steel forging: one that is quenched and tempered to produce the required hardness and properties; should more accurately be referred to as hardened-and-tempered. (Hardening and tempering are heat treatments that follow austenitizing, which is usually the first heat treatment performed on carbon and alloy steel forgings.)

Restriking: a salvage operation following a primary forging operation-rehitting forgings in the same die in which they were last forged.

Rib: a forged wall or vertical section generally projecting in a direction parallel to the ram stroke.

Rib and web forging: one whose basic configuration consists of ribs and webs.

Ring rolling: forming seamless rings from pierced discs or thick-walled, ring-shaped blanks between rolls that control wall thickness, ring diameter, height and contour.

Figure 3. Hollow die forging is an open die forging option, which starts with a punched or pierced disk on a tapered draw bar. Progressive reduction of the outside diameter increases the overall length of the sleeve, while the inside diameter remains constant.

Figure 4. Impact extrusion, another cold forging process, produces hollow parts. Here, the metal flows back around the descending ram.

Figure 5. In impression die forging, a workpiece is plastically deformed between two dies filling the die cavity. A small amount of material of “flash” that flows outside the die impression cools rapidly, creating resistance that facilitates material flow into unfilled impressions.
**Roll forging:** shaping stock between power driven rolls that incorporate contoured dies; used for preforming and to produce finished parts. See Figure 9.

**Rough machining:** an initial machining operation that leaves adequate stock for subsequent finish machining.

**Saddle/mandrel forging:** rolling and forging a pierced disc over a mandrel to yield a seamless ring or tube.

**Slab:** a flat shaped semi-finished, rolled metal ingot with a width not less than 10 in. and a cross sectional area not less than 16 in².

**Standard tolerance:** an established tolerance for a certain class of product; preferred over "commercial" or "published" tolerance.

**Straightening:** a finishing operation for correcting misalignment in a forging or between different sections of a forging.

**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.

**Swaging:** reducing the size of forging stock; alternately, forging in semi-contoured dies to lengthen a blank.

**Target machining:** incorporating a "target" (benchmark or gauge point) on a forging to facilitate machining; coined locating surfaces and drilled centers are commonly used.

**Tolerance:** the specified permissible deviation from a specified or nominal dimension; the permissible variation in the size of a part.

**Trimming:** performed hot or cold, the mechanical shearing of flash or excess material from a forging by use of a trimmer in a trim press.

**Upset forging:** one made by upset of an appropriate length of bar, billet, or bloom; working metal to increase the cross-sectional area of a portion or all of the stock.

**Upsetter (forging machine):** a machine with horizontal action used to produce upset forgings. See Figure 10.

**Warm forging:** forging of steel at temperatures ranging from about 100 °F to just below the normal hot working range of 1900 to 2300 °F.

**Web:** a relatively flat, thin portion of a forging, generally parallel to the forging plane, that connects ribs and bosses.

**Wide tolerance:** any special tolerance wider than "standard."

Space constraints make it impossible to include all terms and definitions that apply to forging processes. For a more comprehensive listing, please refer to the glossary of the Forging Handbook.