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Forging of Carbon and Alloy Steels

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FORGING OF STEELS in quantity has an extensive history since the beginning of the Industrial Revolution. Justification for selecting forging in preference to other, sometimes more economical, methods of producing useful shapes is based on several considerations. Mechanical properties in wrought materials are better than cast materials and can be maximized in the direction of major metal flow during working. For complex shapes, only forging affords the opportunity to direct metal flow parallel to major applied service loads and to control, within limits, the refinement of the original ingot structures. Refinement of microstructure is a function of the temperature, the direction, and the magnitude of reduction from the cast ingot to the forged shape. Maximizing the structural integrity of the material permits refinement of design configuration, which in turn permits reduction of weight.

This article provides some general guidelines for the forging of carbon and alloy steels in terms of:

- Forging practices
- Steel selection for forging
- Forgeability and mechanical properties
- Effect of forging on final component properties
- Heat treatments of steel forgings
- Forging die design features
- Machining of forgings
- Special considerations for design of hot upset forgings

In many ways, the forging of steels has been an intuitive, empirical process based on trial and error. This has changed to a significant degree due to engineering application of continuum mechanics, and advances with computer-modeling and simulation software. The focus of this article is on the forging behavior and practices, while other articles in this Volume address computer modeling of forging.

Types of Forgings

Forgings are classified in several ways, beginning with the general classifications open die and closed die. They are also classified in terms of the close-to-finish factor, or the amount of stock (cover) that must be removed from the forging by machining to satisfy the dimensional and detail requirements of the finished part (Fig. 1). Finally, forgings are further classified in terms of the forging equipment required for their manufacture, such as, for example, hammer upset forgings, ring-rolled forgings, and multiple-ram press forgings.

Of the various classifications, those based on the close-to-finish factor are most closely related to the inherent properties of the forging, such as strength and resistance to stress corrosion. In general, the type of forging that requires the least machining to satisfy finished-part requirements has the best properties. Thus, a finished part machined from a blocker-type forging usually exhibits mechanical properties and corrosion characteristics inferior to those of a part made from a close-tolerance, no-draft forging.

It should be anticipated that decreasing the amount of stock that must be removed from the forging by machining will almost invariably result in increased die costs. Also, equipment capacity requirements can be increased to produce a forging that is essentially net forged, or closer to finished dimensions. For example, when a window-frame forging was made as a conventional forging, requiring extensive subsequent machining, the frame could be readily produced by blocking and finishing in a 45 MN (5000 tonf) press. However, when the window-frame forging was produced as a close-tolerance, no-draft forging requiring no subsequent machining other than the drilling and re-arming of fastener holes, a 73 MN (8000 tonf) press was required.

Forging Practices

Carbon and alloy steels are by far the most commonly forged materials and are readily forged into a wide variety of shapes using hot-, warm-, or cold-forging processes and standard equipment. Section thickness, shape complexity, and forging size are limited primarily by the cooling that occurs when the heated workpiece comes into contact with the cold dies. For this reason, equipment that has relatively short die contact times, such as hammers, is often preferred for forging intricate shapes in steel. Adequate control of metal flow to optimize properties in complex forging configurations also generally requires one or more upsetting operations prior to die forging and may require hollow forging or back extrusion to avoid flash formation at die parting lines. The additional operations and equipment required for hollow forging involve significant cost considerations, which must be justified by improved load capability of the forged part.

Open-die forging uses simple tools in a programmed sequence of basic operations (upsetting, drawing out), mostly in the hot-working temperature range, and the products (ranging from the one-off products of the blacksmith to huge turbine rotors) usually require finishing by machining. Rotary forging and swaging on special-purpose machines produce parts of axial symmetry to much tighter tolerances (axles, gun barrels).

Hot impression-die forging (sometimes termed closed-die forging) shapes the part between two die halves; thus, productivity is increased, albeit at the expense of higher die costs. Excess metal is allowed to escape in the flash; thus, pressure is kept within safe limits while die filling is ensured. More complex shapes, thinner walls, and thinner webs may necessitate forging in a sequence of die cavities, as for connecting rods and crankshafts. Die design calls for a thorough knowledge of material flow and is greatly aided by computer models and expert systems. With dies heated to or close to forging temperature (isothermal or hot-die forging), cooling is prevented and thin walls and webs can be produced, provided the die material is stronger than the workpiece at the temperatures and strain rates prevailing in the process.

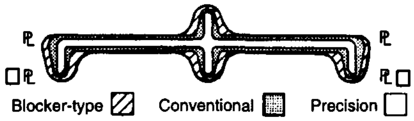

Fig. 1 Schematic composite of cross sections of blocker-type, conventional, and precision forgings

The sequence of operations can be accomplished by moving the heated end of a bar through the die cavities in an upsetter, achieving high production rates. Mechanized transfer between cavities in conventional presses is also possible. In all impression-die forging, die design calls for considerable knowledge and die cost can be high, but the product often has superior properties because material flow can be directed to give the best orientation of the structure relative to loading direction in the service of the part.

Cold forging is related to cold extrusion and, when a complex shape is to be formed in a single step, requires special lubricants, often with a conversion coating, as in making spark-plug bodies. Alternatively, the shape is developed by moving the bar or slug through a sequence of cavities, using a liquid lubricant. Cold forging is often combined with cold extrusion. It is the preferred process for mass producing near-net-shape parts such as bolts, nuts, rivets, and many automotive and appliance components.

Forging Temperature. It is common practice to forge steels over a wide range of temperatures. Cold forging is carried out at ambient temperature, warm forging from about 540 to 870 °C (1000 to 1600 °F) and hot forging from about 900 to 1250 °C (1650 to 2280 °F). The choice of temperature employed depends on a balance between sufficient ductility for required formability and the dimensional tolerance required in the forged workpiece. Ductility increases with increasing temperature, whereas dimensional tolerance decreases with increasing temperature. Warm forging often gives an acceptable compromise between ductility and dimensional tolerance.

Die Materials. Forging of carbon steels is easy and requires relatively inexpensive die block materials. Typically, low-alloy tool steels are sufficient (Table 1). When forging is done in presses, the dies are usually heat treated to a higher hardness than they would be if forging were done in hammers because wear resistance is more important and toughness less important. In some instances, however, die inserts of the more highly alloyed low-alloy steel, or even of the chromium hot work die steels, are recommended in regions of the dies exposed to higher-than-average temperatures or loads.

For forging low- to medium-alloy steels and stainless steels, more stringent demands are made on the forging dies and die materials. In hammer forging, die blocks can often be made of low-alloy steels (Table 1). However, small dies or die inserts should be made of hot work die steels. For press forging these alloys, chromium hot-work steels are often used for both dies and die inserts, with die inserts usually tempered to slightly higher hardness than the die blocks.

Heating practice for the forging stock is the same in open-die and closed-die forging. Alloy composition, the temperature range for optimum plasticity, and the amount of reduction required to forge the workpiece also have some influence on the selection of the appropriate forging temperature. Typical hot forging temperatures for a variety of carbon and alloy steels are listed in Table 2.

Selection of forging temperatures for carbon and alloy steels is based primarily on carbon content (Table 3). The maximum safe forging temperatures for carbon and alloy steels decreases as carbon content increases. The higher the forging temperature, the greater is the plasticity of the steel, which results in easier forging and less die wear. However, the danger of overheating and excessive grain coarsening is increased. If a steel that has been heated to its maximum safe temperature is forged rapidly and with large reduction, the energy transferred to the steel during forging can substantially increase its temperature, thus causing overheating.

For any steel, the heating time must be sufficient to bring the center of the forging stock to the forging temperature. A longer heating time than necessary results in excessive decarburization, scale, and grain growth. For stock measuring up to 75 mm (3 in.) in diameter, the heating time per inch of section thickness should be no more than 5 min for low-carbon and medium-carbon steels or no more than 6 min for low-alloy steels. For stock 75 to 230 mm (3 to 9 in.) in diameter, the heating time should be no more than 15 min per inch of thickness. For high-carbon steels (0.50% C and higher) and for highly alloyed steels, slower heating rates are required, and preheating at temperatures from 650 to 760 °C (1200 to 1400 °F) is sometimes necessary to prevent cracking.

Various types of electric and fuel-fired furnaces are used, as well as resistance and induction heating. The goal of heating is to provide the metal workpiece at the hot-working stage with the desired (typically uniform) temperature across its diameter/thickness as well as along its length and across the width. A piece of stock that is nonuniformly heated can cause problems with premature wear on hammers and presses and may cause problems by requiring excessive force to form the metal.

In recent decades, there has been a shift toward more use of induction heating systems from fuel-fired furnaces that use natural gas, fuel oil, or liquid petroleum gases (which were often used because of the low cost of fuel). There are several reasons for this shift. One reason is that fuel-fired furnaces demand a very long heating tunnel to achieve the desired temperature uniformity. A large required space may present a problem, particularly when it is required to incorporate the heating system into an already existing production line. In addition, fuel-fired heating poses

Table 1 Die steels for forging various alloys

Equipment	Die type	Die steel and hardness for forging of: Carbon steels	Alloy and stainless steel
Hammer forging	Die blocks	6G or 6F2 (37–46 HRC)	6G or 6F2 (37–46 HRC) H11, H12 or H13 (40–47 HRC)
	Die inserts	6F3 or H12 (40–48 HRC)	H11, H12, H13, or H26 (40–47 HRC)
Press forging	Die blocks	6F3 or H12 (40–46 HRC)	H11, H12 or H13 (47–55 HRC)
	Die inserts	H12 (42–46 HRC)	H11, H12 or H13 (47–55 HRC)

Source: Ref 1

Table 2 Typical forging temperatures for various carbon and alloy steels

Steel	Major alloying elements	Typical forging temperature °C	°F
Carbon steels			
1010	...	1315	2400
1015	...	1315	2400
1020	...	1290	2350
1030	...	1290	2350
1040	...	1260	2300
1050	...	1260	2300
1060	...	1180	2160
1070	...	1150	2100
1080	...	1205	2200
1095	...	1175	2150
Alloy steels			
4130	Chromium, molybdenum	1205	2200
4140	Chromium, molybdenum	1230	2250
4320	Nickel, chromium, molybdenum	1230	2250
4340	Nickel, chromium, molybdenum	1290	2350
4615	Nickel, molybdenum	1205	2200
5160	Chromium	1205	2200
6150	Chromium, vanadium	1215	2220
8620	Nickel, chromium, molybdenum	1230	2250
9310	Nickel, chromium, molybdenum	1230	2250

Source: Ref 2

Table 3 Maximum safe forging temperatures for carbon and alloy steels of various carbon contents

Carbon content, %	Maximum safe forging temperature: Carbon steels °C	°F	Alloy steels °C	°F
0.10	1290	2350	1260	2300
0.20	1275	2325	1245	2275
0.30	1260	2300	1230	2250
0.40	1245	2275	1230	2250
0.50	1230	2250	1230	2250
0.60	1205	2200	1205	2200
0.70	1190	2175	1175	2150
0.90	1150	2100	...	...
1.10	1110	2025	...	...

some operational factors in terms of environmental, ergonomic impacts, and poor surface quality control (scale, decarburization, oxidation, etc.) due to significant metal loss during heating. These are some of the factors that have resulted in induction heating becoming a more popular approach for heating of billets, bars, slabs, blooms, tubes, plates, rods, and other components made of both ferrous and nonferrous metals (Ref 3).

Induction heating. A basic challenge in induction heating of forging stock is the necessity to provide the required "surface-to-core" temperature uniformity. Due to the physics of induction heating, the workpiece core tends to be heated more slowly than its surface. Depending on the metal properties and frequency of the induction heating power, 86% of the power is induced within the surface ("skin") layer. The current penetration depth (δ) can be calculated according to the equation:

$$\delta = 503\sqrt{\frac{\rho}{\mu_r F}} \quad \text{(Eq 1)}$$

where ρ is the electrical resistivity of the metal (in metric units of $\Omega \cdot m$); μ_r is the relative magnetic permeability; and F is frequency, Hz (cycle per second). Current penetration depths (δ) of carbon steel at temperature of 1200 °C (2192 °F) versus frequency are:

Frequency	Skin depth (δ), mm
60 Hz	72
500 Hz	25
1 kHz	17.7
2.5 kHz	11.2
4 kHz	8.9
10 kHz	5.6
30 kHz	3.23

Frequency is one of the most critical parameters in these applications. If frequency is too low, an eddy current cancellation within the heated body might take place, resulting in poor coil efficiency. On the other hand, when the frequency is too high, the "skin" effect will be highly pronounced, resulting in a current concentration in a very fine surface layer compared with the diameter/thickness of the heated component. In this case, longer heating time will be required in order to provide sufficient heating of the core. Frequency is always a reasonable compromise. References 2 and 4 provide recommendations with respect to frequency selection and other important operating considerations such as power, coil length, required temperature uniformity, time of heating, and so forth.

Forging Lubricants. Lubricant selection for forging is based on several factors, including: forging temperature, die temperature, forging equipment, method of lubricant application, complexity of the part being forged, environmental concerns, and safety considerations. Previously, oil-graphite mixtures were the most commonly used lubricants for forging carbon and alloy steels. Present lubricants include water/graphite mixtures and water-based synthetic lubricants. Each of these commonly used lubricants has advantages and limitations (Table 4, Ref 5) that must be balanced against process requirements.

At normal hot-forging temperatures for carbon and alloy steels, water-based graphite lubricants are used almost exclusively. The most common warm-forming temperature range for carbon and alloy steels is 540 to 870 °C (1000 to 1600 °F). Because of the severity of forging conditions at these temperatures, billet coatings are often used in conjunction with die lubricants. The billet coatings used include graphite in a fluid carrier or water-based coatings used in conjunction with phosphate conversion coating of the workpiece. For still lower forging temperatures, such as less than about 400 °C (750 °F), molybdenum disulfide has a greater load-carrying capacity than graphite. Molybdenum disulfide can be applied in either solid form or dispersed in a fluid carrier.

When forging is performed at room temperature, the billet is commonly subjected to phosphating, in which a zinc phosphate film that aids retention of a soap lubricant is produced. Stainless steels cannot be phosphated, and oxalate films are often used. At forging temperatures between 400 and 850 °C (750 and 1560 °F), phosphate coatings are ineffective because of oxidation and are not used. Because molybdenum disulfide begins to oxidize at these temperatures, graphite is the lubricant of choice. Graphite is commonly dispersed in either a water or oil carrier and is held in suspension by agitation, as well as by either emulsifiers or polymers. Other materials, such as finely divided oxides of tin or lead, can also be present. The lubricant is normally applied to the dies and billet by spraying as a fine mist to ensure complete coating.

Several factors are important for consistent lubrication. The structure, purity, and particle size of the graphite affects results. Large particles have poor film-forming properties, whereas small particles reduce the threshold temperature of graphite oxidation. Particles below about 0.1 μm (4 μin.) become ineffective because of loss of graphitic structure. Other important factors that require control are the consistency of suspension and the total percent solids.

Selection of Steel

Selection of a steel for a forged component is an integral part of the design process and requires a thorough understanding of the end use of the finished part, required mechanical properties, surface finish requirements, tolerance to nonmetallic inclusions, and the attendant inspection methods and criteria. The selection of a steel for a forged part usually requires some compromise between opposing factors—for example, strength versus toughness, stress-corrosion resistance versus weight, manufacturing cost versus useful load-carrying ability, production cost versus maintenance cost, and the cost of the steel raw material versus the total manufacturing cost of the forging. Steel selection also involves consideration of melting practices, forming methods, machining operations, heat treating procedures, and deterioration of properties with time in service, as well as the conventional mechanical and chemical properties of the steel to be forged.

Despite the large number of steel compositions, carbon and low-alloy forging steels exhibit essentially similar forging characteristics. Most carbon and low-alloy steels are usually considered to have good forgeability, and differences in forging behavior among the various grades of steel are small enough that selection of the steel is seldom affected by forging behavior. Exceptions to this rule are steels containing free-machining additives such as sulfur, which makes these materials more difficult to forge; and steels containing significant quantities of silicon, which require high temperatures to be forged successfully.

Other processing characteristics likely to influence fabricability and finished-part costs are also considered when selecting steel for forgings. Depending on mechanical property requirements, response to heat treatment may be necessary. Most forgings require some machining, so the machining characteristics of the steel chosen may be a pertinent cost factor. If extensive machining is required, the choice of a resulfurized or rephosphorized steel for a forging may be justified. However, the need for extensive machining is not a common occurrence because one of the principal reasons for

Table 4 Advantages and limitations of the principal lubricants used in the hot forging of steels

Type of lubricant	Advantages	Limitations
Water-base micrographite	Eliminates smoke and fire; provides die cooling; is easily extended with water	Must be applied by spraying for best results
Water-base synthetic	Eliminates smoke and fire; is cleaner than oils or water-base graphite; aids die cooling; is easily diluted, and needs no agitation after initial mixing; reduces clogging of spray equipment; does not transfer dark pigment to part	Must be sprayed; lacks the lubricity of graphite for severe forging operations
Oil-base graphite	Fluid film lends itself to either spray or swab application; has good performance over a wide temperature range (up to 540 °C, or 1000 °F)	Generates smoke, fire, and noxious odors; explosive nature may shorten die life; has potentially serious health and safety implications for workers

Source: Ref 5

considering manufacture by forging is to produce near-net or net-shape parts.

Steel Quality. Semifinished steel products for forging are produced to either specified piece weights or specified lengths. Quality is dependent on many different factors, including the degree of internal soundness, relative uniformity of chemical composition, and relative freedom from surface imperfections. In applications that involve subsequent heat treatment or machining operations, relatively close control of chemical composition and steel manufacture may be needed. The details of testing and quality evaluation may vary from producer to producer and should be a point of inquiry when forging stock is ordered. Should the designer require it, one or more special quality restrictions can be specified. These will bring into effect additional qualification testing by the producing mill. Examples of some general ASTM standards on carbon and alloy steel forging products include:

ASTM designation	Title
ASTM A668/A668M-02	Standard Specification for Steel Forgings, Carbon and Alloy, for General Industrial Use
ASTM A909-03	Standard Specification for Steel Forgings, Microalloy, for General Industrial Use
ASTM A788-02	Standard Specification for Steel Forgings, General Requirements
ASTM A521-03	Standard Specification for Steel, Closed-Impression Die Forgings for General Industrial Use

Other standards cover requirements for specific types of product applications/forms (e.g., fittings, valves, gears, rotors) or service conditions (e.g., notch toughness at low temperature). Reference 6 describes guidelines for forging-quality carbon and alloy steel products, but this document is no longer updated as a consensus standard.

Surface Conditioning. Semifinished steel products for forging can be conditioned by scarfing, chipping, or grinding to remove or minimize surface imperfections. However, despite surface conditioning, the product is still likely to contain some surface imperfections.

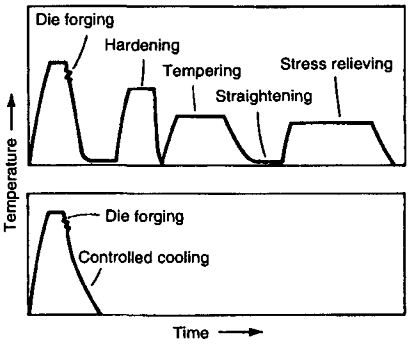

Fig. 2 Processing cycles for conventional (quenched and tempered; top) and microalloyed steels (bottom). Source: Ref 7

Cutting. Semifinished steel products for forging are generally cut to length by hot shearing. Hot sawing or flame cutting may also be used, depending on the steel composition.

Microalloyed Steels. Microalloying of steels with small amounts of elements such as vanadium and niobium to strengthen steels has been in practice since the 1960s to control the microstructure and properties of low-carbon steels. Most of the early developments in microalloying were related to significant strengthening of low-carbon steel plate and sheet products by controlled rolling. The application of microalloying technology to forging steels has lagged behind that of flat-rolled products because of the different property requirements and thermomechanical processing of forging steels. Forging steels are commonly used in applications in which high strength, fatigue resistance, and wear resistance are required. These requirements are most often filled by medium-carbon steels. Thus, the development of microalloyed forging steels has centered on grades containing 0.30 to 0.50% C.

The metallurgical fundamentals of microalloying were first applied to forgings in the early 1970s. A West German composition, 49MnVS3 (nominal composition: 0.47C-0.20Si-0.75Mn-0.060S-0.10V), was successfully used for automotive connecting rods. The steel was typical of the first generation of microalloy steels, with a medium-carbon content (0.35 to 0.50% C) and additional strengthening through vanadium carbonitride precipitation. The parts were subjected to accelerated air cooling directly from the forging temperature. The AISI grade 1541 microalloy steel with either niobium or vanadium has been used in the United States for similar automotive parts for many years.

The driving force for the development of microalloyed forging steels has been the reduction in manufacturing costs. Cost savings occur in microalloyed steels due to a simplified thermomechanical treatment (that is, a controlled cooling following hot forging) that achieves the desired properties without the separate quench and tempering treatments required by conventional carbon and alloy steels. In Fig. 2, the processing sequence for conventional (quenched and tempered) steel is compared with the microalloyed steel-forging process (Ref 8). Elimination of the heat treating operation reduces energy consumption and processing time as well as the materials inventories resulting from intermediate processing steps.

Recent advances in titanium-treated and direct-quenched microalloy steels provide new opportunities for the hot forger to produce tough, high-strength parts without special forging practices. Product evaluations of these microalloy steels indicate that they are comparable to conventional quenched and tempered steels. Warm forging continues to make steady progress as a cost-effective, precision manufacturing technique because it significantly reduces machining costs. Microalloy steels austenitized at 1040 °C (1900 °F), cooled to a warm forging temperature of 925 °C (1700 °F), forged, and cooled by air or water (depending on composition), will produce a range of physical properties. The resulting cost savings has the potential to improve the competitive edge that forging has over other manufacturing techniques.

Types of Microalloyed Forging Steels. Standards for microalloyed forging steels are found in ASTM specification "A921/A921M-93 (1999) Standard Specification for Steel Bars, Microalloy, Hot-Wrought, Special Quality, for Subsequent Hot Forging" (Ref 9). Table 5 shows the typical chemical compositions of microalloyed forging steels. The chemical requirements for the microalloy elements are given in Table 6.

First-generation microalloy forging steels generally have ferrite-pearlite microstructures, tensile strengths above 760 MPa (110 ksi), and yield strengths in excess of 540 MPa (78 ksi). The room-temperature Charpy V-notch toughness of first-generation forgings is typically 7 to 14 J (5 to 10 ft lbf), ambient. It became apparent that toughness would have to be significantly improved to realize the full potential of microalloy steel forgings.

Second-generation microalloy forging steels were introduced in the mid-1980s. These are typified by the West German grade 26MnSiVS7 (nominal composition: 0.26C-0.70Si-1.50Mn-0.040S-0.10V-0.02Ti). The carbon content of these steels was reduced to between 0.10 and 0.30%. They are produced with either a ferrite-pearlite microstructure or an acicular-ferrite structure. The latter results from the suppression of pearlite transformation products by an addition of about 0.10% Mo.

Titanium additions have also been made to these steels to improve impact toughness even

Table 5 Typical chemical compositions of microalloyed carbon steels

Base grade designation	Chemical composition limits, %				
	C	Mn	P	S	V
10V40	0.37–0.44	0.60–0.90	0.040 max	0.050 max	0.02–0.20
10V45	0.43–0.50	0.60–0.90	0.040 max	0.050 max	0.02–0.20
11V37	0.32–0.39	1.35–1.65	0.040 max	0.08–0.13	0.02–0.20
11V41	0.37–0.45	1.35–1.65	0.040 max	0.08–0.13	0.02–0.20
15V24	0.19–0.25	1.35–1.65	0.040 max	0.050 max	0.02–0.20
15V41	0.36–0.44	1.35–1.65	0.040 max	0.050 max	0.02–0.20

These compositions are identical to those in ASTM A 576, with the exception of the addition of vanadium.

Table 6 Chemical requirements for microalloy elements in microalloyed forging steels

	Chemical ranges and limits, %	
Element	Heat analysis	Product analysis
Vanadium	0.02–0.20	0.01–0.21
Columbium (niobium)	0.005–0.07	0.004–0.08
Molybdenum	0.01–0.30	0.31 max

Source: Ref 9

further. Titanium-treated microalloy steels are currently in production in the United States, Germany, and Japan. The resistance to grain coarsening imparted by titanium nitride precipitation increases the toughness of the forgings.

Third-generation microalloy forging steels went into commercial production in the United States in 1989. This generation has five to six times the toughness at −30 °C (−20 °F) and twice the yield strength of second-generation microalloy forging steels. No special forging practices are required except for the use of a water-cooling system.

These steels differ from their predecessors in that they are direct quenched from the forging temperature to produce microstructures of lath martensite with uniformly distributed temper carbides. Without subsequent heat treatment, these materials achieve properties, including toughness, similar to those of standard quenched and tempered steels. The metallurgical principles behind this development are based on:

- Niobium additions sufficient to exceed the solubility limit at the forging temperature so that undissolved Nb(CN) retards the recrystallization and grain growth of austenite during forging, trimming, and entry into the quenchant
- Composition control to ensure that the martensite finish temperature is above 200 °C (400 °F)
- A fast cold-water quench is performed on a moving conveyor through a spray chamber or by other appropriate equipment.

The relatively high martensite finish temperature, combined with the mass effect of a forging, results in an auto-tempered microstructure with excellent toughness.

Microalloying Elements. Various elements have been used for microalloy additions to forging steels. Traditional alloys also have an effect on the microstructure and properties produced in microalloyed steels (Ref 10–12). Rapid induction heating methods for bar and billet to conventional commercial forging temperatures of 1250 °C (2280 °F) are acceptable and allow sufficient time for the dissolution of the microalloying constituents.

Carbon. Most of the microalloyed steels developed for forging have carbon contents ranging from 0.30 to 0.50%, which is high enough to form a large amount of pearlite when slow cooled. The pearlite is responsible for substantial strengthening. This level of carbon also decreases the solubility of the microalloying constituents in austenite.

Vanadium, in amounts ranging from 0.03 to 0.2%, is the most common microalloying addition used in forging steels. Vanadium dissolves into austenite at typical hot forging temperatures, and upon cooling, it precipitates as vanadium carbonitrides. These precipitates provide a strength increase to the final forged product (Ref 13, 14).

Niobium (Columbium). The range of niobium addition is from 0.02 to 0.1%. Niobium dissolves at very high forging temperatures. If it dissolves, it will precipitate on cooling in a similar fashion to vanadium. If the forging temperature is below the dissolution temperature, the niobium carbonitrides pin the austenite grain boundaries and prevent significant grain growth from occurring. The smaller austenite grain size decomposes into a finer ferrite-pearlite microstructure on cooling. The finer final microstructure enhances both the strength and toughness of the forged product. Often niobium is used in combination with vanadium to obtain the benefits of austenite grain size control (from niobium) and carbonitride precipitation (from vanadium).

Titanium. Titanium additions of 0.01 to 0.02% enhance strength and toughness in the final forged product by providing control of austenite grain size. The titanium nitrides do not dissolve at even high forging temperatures; hence, they pin the austenite grain boundaries and prevent excess grain growth (Ref 15).

Molybdenum. At the 0.1% level, molybdenum has an effect on the austenite decomposition kinetics. Even at these low levels it will delay the formation of pearlite and enhance the formation of a bainitic structure, especially if accelerated cooling, such as fans or fine water mist, occurs as the forging is conveyed from the press or hammer to the holding bin. Several grades of microalloyed forging steels have been developed that rely upon the bainitic structure to provide higher strength in the final forging (Ref 7).

Manganese. Relatively large amounts (1.4 to 1.5%) of manganese are used in many microalloyed forging steels. It tends to reduce the cementite plate thickness while maintaining the interlamellar spacing of pearlite developed (Ref 16); thus, high manganese levels require lower carbon contents to retain the large amounts of pearlite required for high hardness. Manganese also provides substantial solid solution strengthening, enhances the solubility of vanadium carbonitrides, and lowers the solvus temperature for these phases.

Silicon. Most commercial microalloyed forging steels contain about 0.30% Si; some grades contain up to 0.70% (Ref 17). Higher silicon contents are associated with significantly higher toughness, apparently because of an increased amount of ferrite relative to that formed in ferrite-pearlite steels with lower silicon contents. Silicon also causes an increase in the amount of retained austenite, especially in the bainitic microalloyed steels (Ref 18, 19).

Sulfur. Many microalloyed forging steels, particularly those destined for use in automotive forgings in which machinability is critical, have relatively high sulfur contents. The higher sulfur contents contribute to their machinability, which is comparable to that of quenched and tempered steels (Ref 20, 21). Sulfur in combination with vanadium can increase the amount of intragranular ferrite that forms in the cooled product. The intragranular ferrite nucleates on the MnS inclusions and has the benefit of increasing the relative toughness of product (Ref 22, 23).

Aluminum. As with hardenable fine-grain steels, aluminum is important for austenite grain size control in microalloyed steels (Ref 16). The mechanism of aluminum grain size control is the formation of aluminum nitride particles.

Nitrogen. It has been shown that nitrogen is the major component of vanadium carbonitrides (Ref 24). For this reason, moderate to high nitrogen contents are required in vanadium-containing microalloyed steels to promote effective precipitate strengthening.

Controlled Forging of Steel

The concept of grain size control has been used for many years in the production of flat-rolled products. Particularly in plate rolling, the ability to increase austenite recrystallization temperature using small niobium additions is well known (Ref 25). The process used to produce these steels is usually referred to as controlled rolling.

The benefits of austenite grain size control are not limited to flat-rolled products. Although the higher finishing temperatures required for rolling of bars limit the usefulness of this approach to microstructural control, finishing temperatures for microalloyed bar steels must nonetheless be controlled. It has been shown that, although strength is not significantly affected by finishing temperature, toughness of vanadium-containing microalloyed steels decreases with increasing finishing temperature (Ref 8, 26). The effect is shown in Fig. 3, which compares Charpy V-notch impact strength for a microalloyed 1541 steel finished at three temperatures. The detrimental effect of a high finishing temperature on impact toughness also carries over to forging operations; that is, the lower the finish temperature in forging, the higher is the resulting toughness. It is recommended that finishing temperature for forging be reduced to near 1000 °C (1800 °F) (Ref 8). The low forging temperature results in impact properties equal to or better than those of hot-rolled bar. Rapid induction preheating is also beneficial for microalloyed forging steels, and that cost savings of 10% (for standard microalloyed forgings) to 20% (for resulfurized grades) are possible (Ref 8).

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However, lower finishing temperatures require higher forging pressure (thus, higher machine capacities are needed) and increased die wear. The improved toughness resulting from lower finishing temperatures, as well as any cost savings that may be achieved as a result of the elimination of post-forging heat treatments, must be weighed against the cost increases in the forge shop.

Powder Metallurgy Steel Forgings. Powder metallurgy (P/M) steels are also hot forged from unsintered, presintered, or sintered powder metal preforms. The process is sometimes called P/M (powder metallurgy) forging, P/M hot forming, or is simply referred to as powder forging (P/F). When the preform has been sintered, the process is often referred to as "sinter forging." Powder forging is a natural extension of the conventional press and sinter (P/M) process, and forging of P/M steel is an effective technology for producing a great variety of net or near-net shape parts with good compositional uniformity. For more details, see the article "Powder Forging" in this Volume and the article "Powder Forged Steel" in *Powder Metal Technologies and Applications*, Volume 7 of the *ASM Handbook*.

The design issues in powder forging (P/F) are similar to the requirement of any precision, closed-die forging. The difference is the starting preform; in the case of P/F, the preform is a sintered powder metal part, typically 80 to 85% of theoretical density, with a shape similar to the final part configuration. By contrast, in a precision closed-die forging the preform is a wrought steel blank with very little shape detail. Preform design for P/F fabrication determines the extent of product shape detail required to meet the performance requirements of the finished P/F part. Preform design is a complex, iterative process currently modeled by computer simulation software programs to help reduce design time and development costs.

In the forging step, the P/M preform is removed from the reheat (or sintering) furnace, coated with a die lube, and forged in a heated, closed-die operation. The forging process reduces the preform height and forces metal into the recesses of the closed die. This step also brings all features to their final tolerances and densities.

Configuration guidelines, typical of precision closed-die forged parts, also apply to P/F parts as follows:

- Radii on inside corners of the forging as large as possible to promote metal flow around corners in the tool and promote complete fill of all details
- Radii of at least 1 mm (0.040 in.) on all outside corners of the forging to aid in material flow to define features
- Shape of the forging should be such that, when placed in the die, the lateral forces will be balanced. Shapes that are symmetrical along a vertical plane, such as connecting rods and shapes that are axisymmetric (or nearly so), are preferred.
- Zero draft is possible on surfaces formed by the die and core rod, but not by the upper punch.
- Re-entrant angles (undercuts) cannot be forged.
- Axial tolerances–in the direction of forging—are driven by variations in the mass of metal in the preform. Lateral tolerances are driven by metal flow as the cavity fills. Typical axial tolerance of 0.25 to 0.5 mm (0.010 to 0.020 in.) are encountered, with diametric tolerances of 0.003 to 0.005 mm/mm of diameter.
- Concentricity of a P/F part is determined by the quality and density distribution in the preform. Concentricity is normally double that of the preform.

Forgeability and Mechanical Properties

Forgeability is the relative ability of a material to flow under compressive loading without fracturing. As previously noted, most carbon and low-alloy steels are usually considered to have good forgeability, except for resulfurized and rephosphorized grades. With the exception of the free-machining grades and hot shortness due to residual elements in the steel like copper, forgeability aspects rarely limit hot forging of carbon and alloy steels into intricate shapes.

Workability or, in this case, forgeability, is evaluated in several ways from various types of tests. Standard (quasi-static) tension tests are not directly relevant to workability, but tension-test data can provide an indirect measure of workability. For example, the difference between the yield and tensile strengths can be a rough indicator of workability for ductile metals; that is, when the magnitude of tensile strength is closer to the yield strength, ductility is lower, and the material is thus more prone to fracture. However, uniaxial tension-test data are inadequate when evaluating workability because the state of stress is a major influence on workability. Even a very ductile material (based on its tension-test behavior) metal can behave in a brittle manner when subjected to stress-state condition of triaxial (hydrostatic) tensile stresses.

Workability is also influenced by strain rates. Forgeability of steels can increase with increasing strain rate, as shown in low-carbon steel in hot-twist testing, where the number of twists to failure increases with increasing twisting rate (Fig. 4). It is believed that the improvement in forgeability at higher strain rates is due to the increased temperature in the material, which can be attributed to the tendency of the material to retain heat from deformation. However, excessive temperature increases may lead to incipient melting primarily at grain boundaries (often

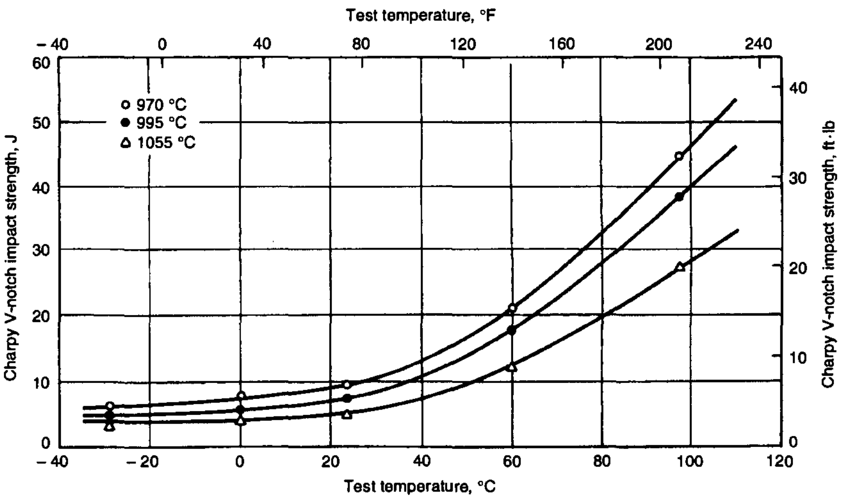


Fig. 3 Effect of hot finishing temperature on impact strength of microalloyed 1541 steel (AISI 1541 plus 0.10% V). Source: Ref 15

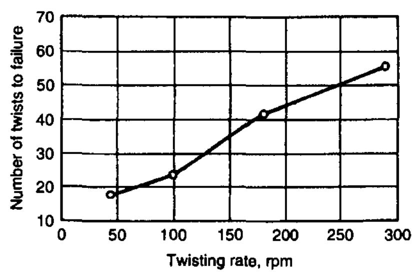


Fig. 4 Influence of deformation rate on hot-twist characteristics of low-carbon steels at 1095 °C (2000 °F). Source: Ref 27

called hot shortness), which can lower forgeability and decrease the mechanical properties of the forged product.

Because forging is a complex process, several specialized testing techniques have been developed for predicting forgeability, depending on alloy type, microstructure, die geometry, and process variables. Specialized forgeability tests can complement so-called primary tests of material workability such as tension and compression testing. Further information on evaluation of workability is provided in the article "Evaluation of Workability for Bulk Forming Processes" in this Volume.

Tension Testing. The tension test is widely used to determine the mechanical properties of a material. However, the extent of deformation possible in a tension test is limited by the formation of a necked region in the tension specimen. For carbon and alloy steels, tension tests are primarily used under special high strain rate, hot tension test conditions to establish the range of hot-working temperatures. The principal advantage of hot tension testing for carbon and alloy steels is that minimum and maximum hot-working temperatures are clearly established. Most commercial hot tensile testing is done with a Gleeble unit, which is a high strain rate, high-temperature testing machine.

Compression Testing. The use of compression has developed into a highly sophisticated test for formability in cold upset forging, and it is a common quality control test in the hot forging of carbon and alloy steels. Compression testing is a useful method of assessing the frictional conditions in hot working. The principal disadvantage of the compression test is that tests at a constant, true strain rate require special equipment.

The compression test, in which a cylindrical specimen is upset into a flat pancake, is usually considered to be a standard bulk formability test. The average stress state during testing is similar to that in many bulk deformation processes, without introducing the problems of necking (in tension) or material reorientation (in torsion). Therefore, a large amount of deformation can be achieved before fracture occurs. The stress state can be varied over wide limits by controlling the barreling of the specimen through variations in geometry and by reducing friction between the specimen ends and the anvil with lubricants.

Ductility Testing. The basic hot ductility test consists of compressing a series of cylindrical or square specimens to various thicknesses or to the same thickness with varying specimen length-to-diameter (length-to-width) ratios. The limit for compression without failure by radial or peripheral cracking is considered to be a measure of bulk formability. This type of test has been widely used in the forging industry. Longitudinal notches are sometimes machined into the specimens before compression. Because the notches apparently cause more severe stress concentrations, they enable the test to provide a more reliable index of the workability to be expected in a complex forging operation.

Torsion Testing. In torsion tests, large strains can be achieved without the limitations imposed by necking, and high strain rates are easily obtained, because the strain rate is proportional to rotational speed. Moreover, friction has no effect on the test, as it does in compression testing. The stress state in torsion may represent the typical stress in metalworking processes, but deformation in the torsion test is not an accurate simulation of metalworking processes because of excessive material reorientation at large strains.

Fracture data from torsion tests are usually reported in terms of the number of twists to failure or the surface fracture strain to failure. The hot-twist test is a common method of measuring the forgeability of steels at a number of different temperatures selected to cover the possible hot-working temperature range of the test material. The optimal hot-working temperature of the test material is the temperature at which the number of twists is the greatest. Figure 5 shows the forgeability of several plain carbon steels as determined by hot-twist testing. Figure 6 also shows the relative hot workability of two steels and the optimal hot-working temperature for each of the two steels.

Specialized Tests for Evaluation of Forgeability. The following tests are described in more detail in the article "Evaluation of Workability for Bulk Forming Processes" in this Volume:

- *Wedge-forging test:* A wedge-shaped piece of metal is forged between flat, parallel dies. The wedge-forging test is a gradient test in which the degree of deformation varies from a large amount at the thick end to a small amount or no deformation at the thin end.
- *Sidepressing test:* Consists of compressing a cylindrical bar between flat, parallel dies, where the axis of the cylinder is parallel to the surfaces of the dies. This test is sensitive to surface-related cracking and to the general unsoundness of the bar because high tensile stresses are created at the center of the cylinder.

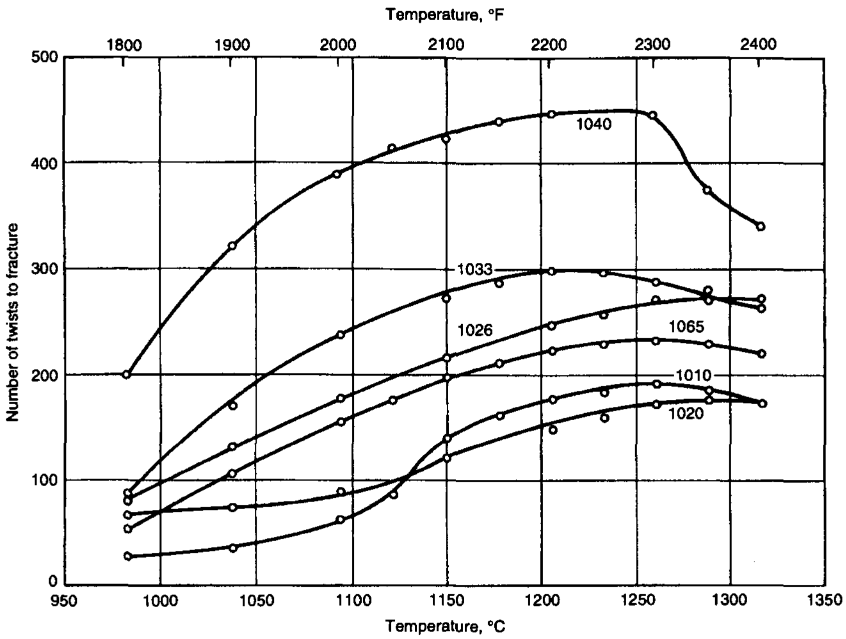


Fig. 5 Forgeabilities of various carbon steels as determined using hot-twist testing. Source: Ref 28

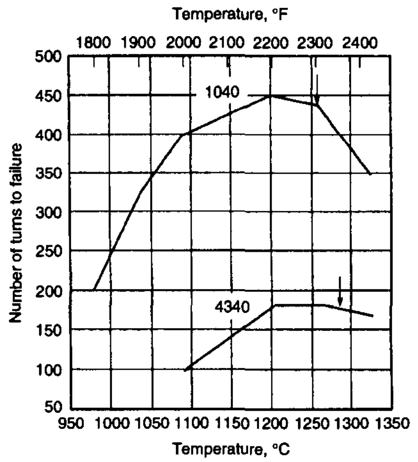


Fig. 6 Ductility of two AISI carbon and alloy steels determined in hot torsion tests. Arrows denote suitable hot-working temperatures.

- *Notched-bar upset test:* Similar to the conventional upset test, except that axial notches are machined into the test specimens. The notched-bar test is used with materials of marginal forgeability for which the standard upset test may indicate an erroneously high degree of workability.
- *Truncated-cone indentation test:* Involves the indentation of a cylindrical specimen by a conical tool. As a result of the indentation, cracking is made to occur beneath the surface of the test piece at the tool/material interface. The truncated cone was developed as a test that minimizes the effects of surface flaws and the variability they produce in workability. This test has been used primarily in cold forging.

Flow Localization. Complex forgings frequently develop regions of highly localized deformation. Shear bands may span the entire cross section of a forging and, in extreme cases, produce shear cracking. Flow localization can arise from constrained deformation due to die chill or high friction. However, flow localization can also occur in the absence of these effects if the metal undergoes flow softening or negative strain hardening.

Nonisothermal Upset Test. The simplest workability test for detecting the influence of heat transfer (die chilling) on flow localization is the nonisothermal upset test, in which the dies are much colder than the workpiece. Zones of flow localization must be made visible by sectioning and metallograhic preparation.

The sidepressing test conducted in a nonisothermal manner can also be used to detect flow localization. Several test specimens are sidepressed between flat dies at several workpiece temperatures, die temperatures, and working speeds. The formation of shear bands is determined by metallography. Flow localization by shear band formation is more likely in the sidepressing test than in the upset test. This is due to the absence of a well-defined axisymmetric chill zone. In the sidepressing of round bars, the contact area starts out as 0 and builds up slowly with deformation. In addition, because the deformation is basically plane strain, surfaces of zero extension are present, along which block shearing can initiate and propagate. These are natural surfaces along which shear strain can concentrate into shear bands.

Flow Strength and Forging Pressure. Flow strength is the inherent resistance of a given material to deformation. It is the stress level that needs to be applied to the material to induce plastic deformation. Flow strength will vary with both temperature and strain rate. Forging pressure is the compressive stress that the equipment needs to apply in order to cause the material to plastically deform. The primary cause of forging pressure is the flow strength of the material. Other factors include frictional resistance at the die/workpiece interface and the geometry of the die cavity. For a simple upset compression test between flat dies with low frictional resistance, the forging pressure and flow strength of the material are essentially equivalent.

Flow strength for steels can be obtained from torque curves generated in a hot-twist test or from hot-compression or tensile testing. Figure 7 shows torque versus temperature curves for several carbon and alloy steels obtained from hot-twist testing. The data indicate that the flow strength for this group of steels does not vary widely at normal hot-forging temperatures. Data for AISI type 304 stainless steel are also included in the figure to illustrate the effect of higher-alloy content on flow strength.

Figure 8 shows measured forging pressure for 1020 and 4340 steels and AISI A6 tool steel for reductions of 10 and 50%. The forging pressure for 1020 and 4340 varies only slightly at identical temperatures and strain rates. Considerably greater pressure is required for the more highly alloyed A6 steel, and this alloy also exhibits a more significant increase in forging pressure with increasing reduction.

Effect of Strain Rate on Forging Pressure. The forging pressure required for a given steel increases with increasing strain rate. Studies of low-carbon steel (Ref 30) indicate that the influence of strain rate is more pronounced at higher forging temperatures. Figure 9 shows the stress-strain curves for a low-carbon steel forged at various temperatures and strain rates. Similar effects have been observed in alloy steels. Figure 10 shows the forging pressure required for upset 4340 steel at several temperatures and strain rates.

Effects of Forging on Component Properties

A major advantage of bulk working by rolling, forging, or extrusion is the opportunity to improve mechanical properties and control of grain flow in a pattern parallel to the direction of the major applied service loads. The typical longitudinal mechanical properties of low- and medium-carbon steel forgings in the annealed, normalized, quenched and tempered conditions are listed in Table 7. As expected, strength increases while ductility decreases with increasing carbon content. In addition, sound, dense, good-quality metal of sufficiently fine grain size can be produced.

The forging process can improve certain mechanical properties, such as ductility, impact

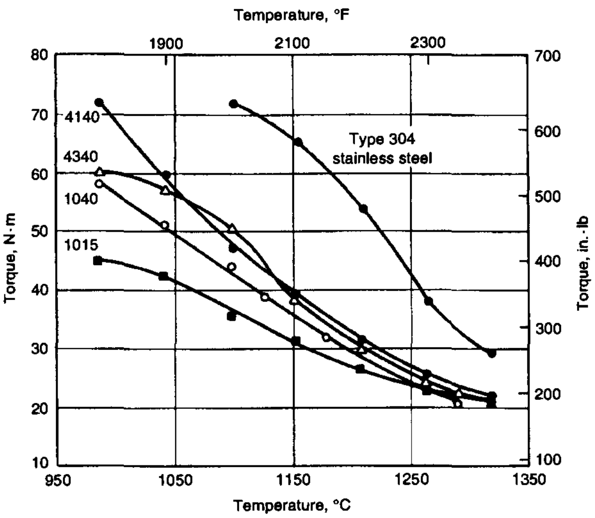


Fig. 7 Deformation resistance versus temperature for various carbon and alloy steels. Source: Ref 27

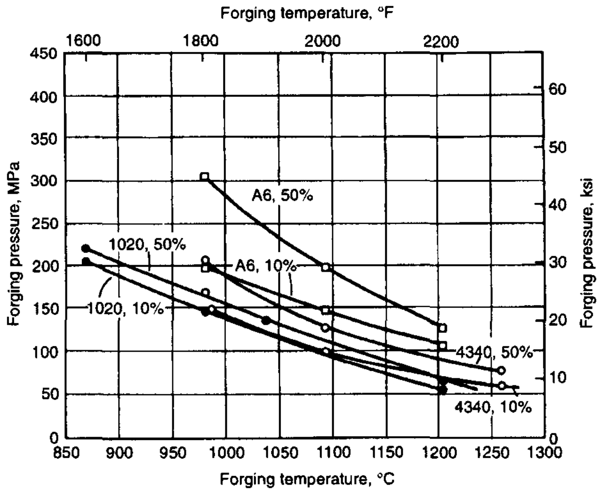


Fig. 8 Forging pressure vs. temperature for three steels. Data are shown for reductions of 10 and 50%. Strain rate was constant at 0.7 s^{-1}. Source: Ref 29

strength, and fatigue strength. These improvements in properties occur because forging:

- Changes as-cast structure by breaking up segregation, healing porosity, and promoting homogenization
- Produces a fibrous grain structure that enhances mechanical properties, which are based on crack propagation perpendicular to the grain flow
- Reduces as-cast grain size

The rearrangement of the metal has little effect on the hardness or strength of the steel, which are primarily controlled by the post-forged heat treatments.

It should be recognized that closed-die forgings are normally made from wrought billets that have received considerable prior working. However, open-die forgings may be made from either wrought billets or as-cast ingots. Metal flows in various directions during closed-die forging. For example, in the forging of a rib and web shape such as an airframe component, nearly all flow of the metal is in the transverse direction.

Typical improvements in ductility and impact strength of heat treated steels as a function of forging reduction are shown in Fig. 11 and 12. The figures illustrate that maximum improvement in each case occurs in the longitudinal specimens because the crack during testing had to propagate across the grain flow. Toughness and ductility reach a maximum after a certain amount of reduction, after which further reduction provides little property improvement.

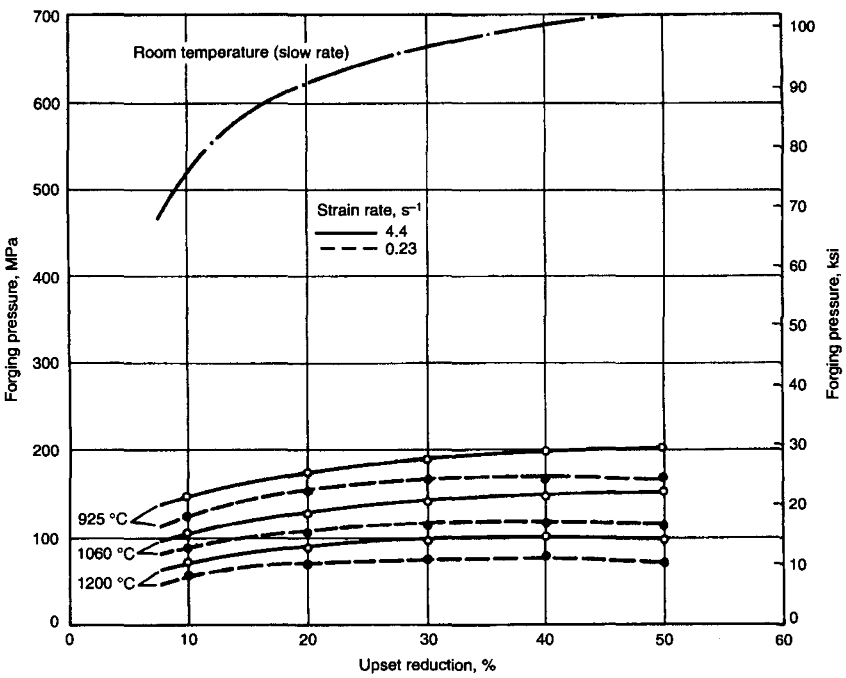


Fig. 9 Forging pressure for low-carbon steel upset at various temperatures and two strain rates. Source: Ref 30

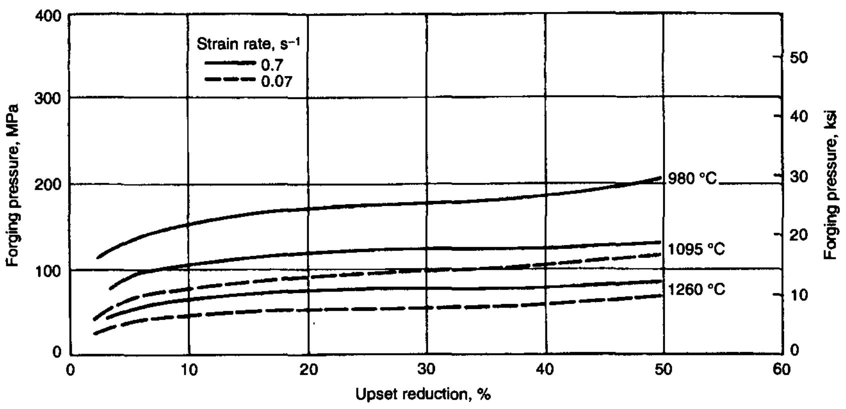


Fig. 10 Forging pressure for AISI 4340 steel upset at various temperatures and two strain rates. Source: Ref 29

Material control procedures must ensure that the final forging has undergone sufficient plastic deformation to achieve the wrought structure necessary for development of the mechanical properties on which the design was based. Although some plastic deformation is achieved during the breakdown of a cast ingot into a forging billet, far more is imparted during the closed-die forging process. Material control for high-strength forgings may require determination of the mechanical properties of the forging billet, as well as those of the forging.

A measure of ductility or toughness is determined by measuring the reduction in area obtained in transverse tension test specimens. When corresponding tests are made of transverse and longitudinal specimens taken from forgings heat treated to the same strength level, it is possible to compare the mechanical properties of billet stock and forgings and to estimate the proportion of the final wrought metallurgical structure contributed by each.

The amount of reduction achieved in forging has a marked effect on ductility, as shown in Fig. 13, which compares ductility in the cast ingot, the wrought (rolled) bar or billet, and the forging. The curves in Fig. 13(a) indicate that when a wrought bar or billet is flat forged in a die, an increase in forging reduction does not affect longitudinal ductility but does result in a gradual increase in transverse ductility. When a similar bar or billet is upset forged in a die, an increase in forging reduction results in a gradual decrease in axial ductility and a gradual increase in radial ductility.

The ductility of cast ingots varies with chemical compositions, melting practice, and ingot size. The ductility of steel ingots of the same alloy composition also varies, depending on whether they were poured from air-melted or vacuum arc remelted steel. When starting with a large ingot of a particular alloy, it is at times practical to roll portions of the ingot to various billet or bar sizes with varying amounts of forging reduction. The minimum amount of reduction is not standard but is seldom less than 2 : 1 (ratio of ingot section area to billet section area). Reduction of steel ingot to billet is usually much greater than 2 : 1. In contrast, some heat-resisting alloy forgings are forged directly from a cast ingot. Often, it is not feasible to prepare billets for forgings that are so large they require the entire weight of an ingot.

The amount of forging reduction represented by wrought metallurgical structures is best controlled by observation and testing of macroetch and tension test samples taken from completed forgings. These samples permit exploration of critical areas and, generally, of the entire forging.

They are selected from the longitudinal, long-transverse, and short-transverse grain directions, as required. Etch tests permit visual observation of grain flow. Mechanical tests correlate strength and toughness with grain flow.

End-Grain Exposure. Lowered resistance to stress-corrosion cracking (SCC) in the long-transverse and short-transverse directions is related to end-grain exposure. A long, narrow test specimen sectioned so that the grain is parallel to the longitudinal axis of the specimen has no exposed end grain, except at the extreme ends, which are not subjected to loading. In contrast, a corresponding specimen cut in the transverse direction has end-grain exposure at all points along its length. End grain is especially pronounced in the short-transverse direction on die forgings designed with a flash line. Consequently, forged components designed to reduce or eliminate end grain have better resistance to SCC.

Residual Stress. In the past, little attention has been paid to the control of residual stresses caused by forging; most of the interest was in predicting the filling and the direction of material flow. Now, due to recent advances in computer-simulation techniques, prediction and control of residual stresses in forged parts is an important consideration. Finite element simulation software is used to predict residual stresses in parts depending on process factors such as die shape and material, forging temperature, die speed, and lubrication at the die/workpiece interface. Because a significant amount of energy is dissipated during forging in the form of heat due to plastic deformation, a coupled thermo-mechanical analysis becomes necessary, especially for nonisothermal forging. Other factors contributing to the complexity of the finite element simulation of this class of problems are: temperature-dependent thermal and mechanical properties of the materials (especially for a nonisothermal forging); the choice of solution algorithm and remeshing due to large plastic deformation in the workpiece; and mathematical treatment of the die/workpiece interface that includes heat transfer, lubrication, and contact.

Table 7 Longitudinal properties of carbon steel forgings at four carbon contents

	Ultimate tensile strength		Yield strength, 0.2% offset				Fatigue strength(a)		
Carbon content, %	MPa	ksi	MPa	ksi	Elongation, %	Reduction of area, %	MPa	ksi	Hardness, HB
Annealed									
0.24	438	63.5	201	29.1	39.0	59	185	26.9	122
0.30	483	70.0	245	35.6	31.5	58	193	28.0	134
0.35	555	80.5	279	40.5	24.5	39	224	32.5	157
0.45	634	92.0	348	50.5	24.0	42	248	35.9	180
Normalized									
0.24	483	70.0	247	35.8	34.0	56.5	193	28.0	134
0.30	521	75.5	276	40.0	28.0	44	209	30.3	148
0.35	579	84.0	303	44.0	23.0	36	232	33.6	164
0.45	690	100.0	355	51.5	22.0	36	255	37.0	196
Oil quenched and tempered at 595 °C (1100 °F)									
0.24	500	72.5	305	44.2	35.5	62	193	28.0	144
0.30	552	80.0	301	43.7	27.0	52	224	32.5	157
0.35	669	97.0	414	60.0	26.5	49	247	35.8	190
0.45	724	105.0	386	56.0	19.0	31	277	40.2	206

(a) Rotating beam test at 10^7 endurance limit. Source: Ref 31

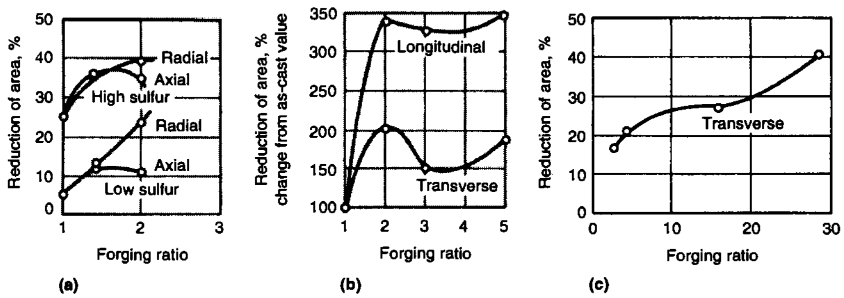


Fig. 11 Effect of forging ratio on reduction of area of heat treated steels. (a) 4340 steel at two sulfur levels. (b) Manganese steel. (c) Vacuum-melted 4340 with ultimate tensile strength of 2000 MPa (290 ksi). Forging ratio is ratio of final cross-sectional area to initial cross-sectional area. Source: Ref 30, 32, 33

Heat Treatment of Carbon and Alloy Steel Forgings

Usually, steel forgings are specified by the purchaser in one of four principal conditions: as

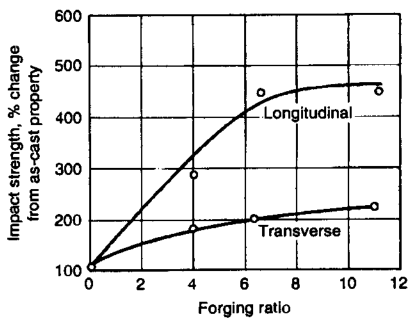


Fig. 12 Effect of hot-working reduction on impact strength of heat treated nickel-chromium steel. Forging ratio is the ratio of initial cross-sectional area to final cross-sectional area. Source: Ref 34

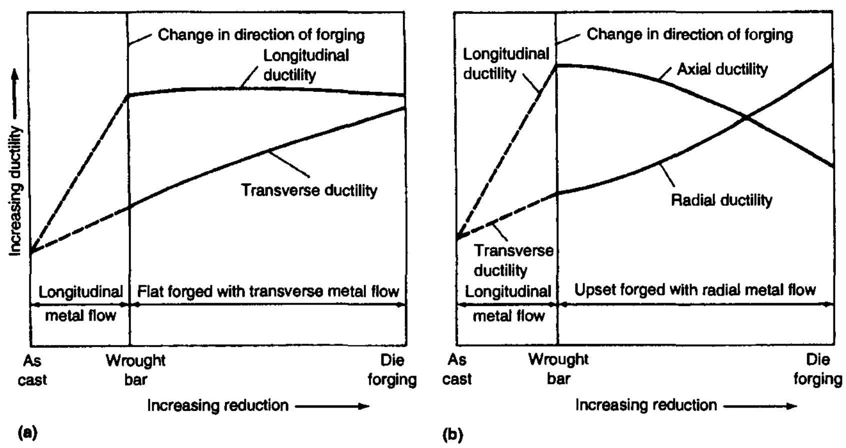


Fig. 13 Metal flow in forging. Effect of extent and direction of metal flow during forging on ductility. (a) Longitudinal and transverse ductility in flat-forged bars. (b) Axial and radial ductility in upset-forged bars

forged with no further thermal processing; heat treated for machinability; heat treated for final mechanical/physical properties; or specially heat treated to enhance dimensional stability, particularly in more complex part configurations (Ref 35).

As Forged. Although the vast majority of steel forgings are heat treated before use, a large tonnage of low-carbon steel (0.10 to 0.25% C) is used in the as-forged condition. In such forgings, machinability is good, and little is gained in terms of strength by heat treatment. A number of widely used ASTM and U.S. federal specifications permit this economic option. Compared with the properties produced by normalizing, strength and machinability are slightly better, which is most likely attributable to the fact that grain size is somewhat coarser than in the normalized condition.

Heat Treated for Machinability. When a finished machined component must be produced from a roughly dimensioned forging, machinability becomes a vital consideration to optimize tool life, increase productivity, or both. The purchase specification or forging drawing may specify the heat treatment. However, when specifications give only maximum hardness or microstructural specifications, the most economical and effective thermal cycle must be selected. Available heat treatments include: full anneal, spheroidize anneal, subcritical anneal, normalize, or normalize and temper. The heat treatment chosen depends on the steel composition and the machine operations to be performed. Some steel grades are inherently soft, and others become quite hard when cooled from the finishing temperature after hot forging. Some type of annealing is usually required or specified to improve machinability.

Heat Treated to Final Physical Properties. Normalizing or normalizing and tempering may produce the required minimum hardness and minimum ultimate tensile strength. However, for most steels, an austenitizing and quenching (in oil, water, or some other medium, depending on section size and hardenability of the steel) cycle is employed, followed by tempering to produce the proper hardness, strength, ductility, and impact properties. For steel forgings to be heat treated above the 1034 MPa (150 ksi) strength level and having section size variations, it is general practice to normalize before austenitizing to produce a uniform grain size and minimize internal residual stresses. In some instances, it is common practice to use the heat for forging as the austenitizing step and to quench immediately after forging at the hammer or press. The forging is then tempered to complete the heat treat cycle. Although there are obvious limitations to this procedure, definite cost savings are possible when the procedure is applicable (usually for symmetrical shapes of carbon steels that require little final machining).

Special Heat Treatments. To control dimensional distortion, to relieve residual stresses before or after machining operations, to avoid quench cracking, or to prevent thermal shock or surface (case) hardening often requires a special heat treatment. Although most of the heat treating cycles discussed previously can apply, very specific treatments may be required. Such heat treatments are often used for forging with complex configurations, especially adjacent differences in section thickness, or to high hardenability steels. When stability of critical dimensions in the finished parts permit only light machining of the forging after heat treatment, special treatments can be used, including marquenching (martempering), stress relieving, and multiple tempers.

Many applications, such as crankshafts, camshafts, gears, forged rolls, rings, certain bearings, and other machinery components, require increased surface hardness for wear resistance. The important surfaces are usually hardened after machining by flame or induction hardening, carburizing, carbonitriding, or nitriding. These processes are listed in the approximate order of increasing cost and decreasing maximum temperature. The latter consideration is important in that dimensional distortion usually decreases with decreasing temperature. The decrease in distortion is particularly true of nitriding, which is usually performed below the tempering temperature for the steel used in the forging.

Design Features

Many small forgings are made in a die that has successive cavities to preshape the stock progressively into its final shape in the last, or finish, cavity. Dies for large forgings are usually made to perform one operation at a time. The upper half of the die, having the deeper and more intricate cavity, is keyed or dovetailed into the hammer or press ram. The lower half is keyed to the sow block or bed of the hammer or press in precise alignment with the upper die. After being heated, the forging stock is placed in one cavity after another and is thus forged progressively to the final shape.

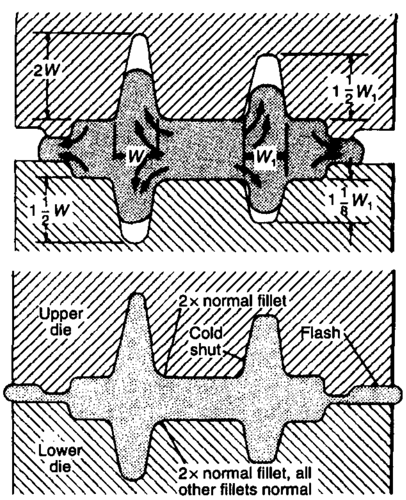


Fig. 14 Two stages of metal flow in forging. Top diagram shows limitations on height of ribs above and below the parting line.

Parting Line. The parting line is the plane along the periphery of the forging where the striking faces of the upper and lower dies come together. Usually, the die has a gutter or recess just outside the parting line to receive overflow metal or flash forced out between the two dies in the finish cavity (Fig. 14). More complex forgings may have other parting lines around holes and other contours within the forging that may or may not be in the same plane as the outer parting line.

For the greatest economy, the outer parting line should be in a single plane. When it must be along a contour, either step or locked dies (that is, dies with mating faces that lie in more than one plane) may be necessary to equalize thrust, as shown in Fig. 15. This may increase costs as much as 20% because of the increased cost of dies and cost increases from processing difficulties in forging and trimming. Sharp steps or drops in the parting line should be limited to about 15° from the vertical in small parts and 25° in large forgings to prevent a tearing instead of a cutting action in trimming off the flash. Locked dies can sometimes be avoided by locating the parting line as shown in Fig. 16.

The specification of optional parting lines on forgings to be made in different shops allows these lines to vary from shop to shop. Unless the draft has been removed, this variation may cause difficulties in locating forgings when they are being chucked for subsequent machining. However, shearing the draft is not always an adequate remedy if trimming angles vary. Forgings made in different shops are likely to be more consistent in quality and to have less variation in shape when a definite parting line is specified.

Draft on the sides of a forging is an angle or taper necessary for releasing the forging from the die and is desirable for long die life and economical production. Draft requirements vary with the shape and size of the forging. The effect

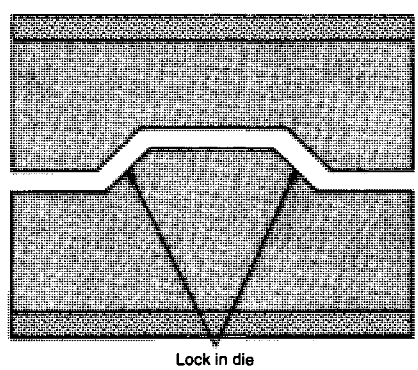


Fig. 15 Locked or stepped dies used to equalize thrust

of part size on the amount of metal needed for draft is illustrated by Fig. 17.

Inside draft is draft on surfaces that tightens on the die as the forging shrinks during cooling; examples are cavities such as narrow grooves or pockets. Outside draft is draft on surfaces such as ribs or bosses that shrink away from the die during cooling. Both are illustrated in Fig. 18, which shows inside draft to be greater than outside draft—the usual relation. Recommended draft angles and tolerances are given in Table 8.

Increased draft, called blend draft or matched draft, may be needed on a side that is not very deep below the parting line in order to blend with a side of the forging of greater height above the parting line (Fig. 19). Increased draft is sometimes desirable or required in locked dies in order to strengthen the dies or trimmer so as to reduce breakage and cost. This can often be anticipated by sketching the die needed to shape a given forging. Cylindrical, spherical, square, rectangular, and some irregular sections can be forged without draft when the parting line is specified (Fig. 20), but with some additional risk of breakage of dies. Other parts, such as the ends of cylinders, can be forged in locked dies at an angle so as to avoid draft on the ends.

Ribs and Bosses. Forgings that have ribs or bosses at or near the maximum heights recommended in Fig. 14 are usually forged at higher-than-normal temperatures (1230 to 1260 °C, or 2250 to 2300 °F) to ensure flow of the metal into the die cavities. Ribs are more readily formed in

Table 8 Draft and draft tolerances for steel forgings

Height or depth of draft		Commercial standard		Special standard	
mm	in.	Draft, degree	Tolerance(a), degree	Draft, degree	Tolerance(a), degree
Outside draft					
6.35–12.7	1/4–1/2	...	...	3	+2
19–25	3/4–1	5	+3	...	...
>12.7–25	>1/2–1	...	...	5	+2
>25–76	>1–3	7	+3	5	+3
>76	>3	7	+4	7	+3
Inside draft					
6.35–25.4	1/4–1	7	+3	5	+3
>25.4	>1	10	+3	10	+3

(a) The minus tolerance is zero.

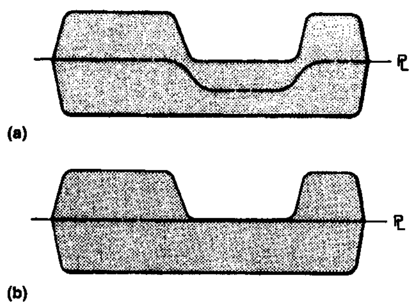


Fig. 16 Orientation of a forging in the die to avoid counterlocked dies and to eliminate draft. Workpiece forged (a) with and (b) without lock in die

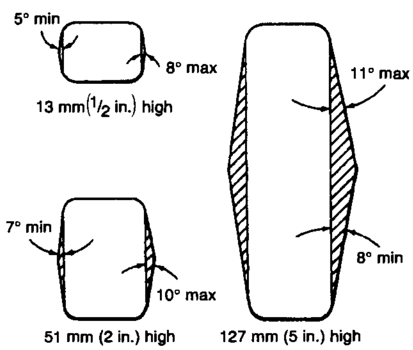


Fig. 17 Effect of part size on the amount of metal needed for draft in a forging

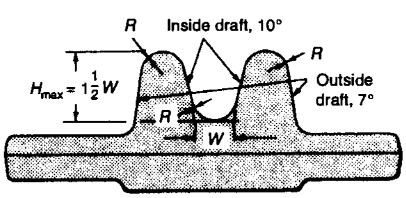


Fig. 18 Definition of inside and outside draft and limitations on the depth of the cavities between the ribs. Typically, inside-draft angles exceed outside-draft angles.

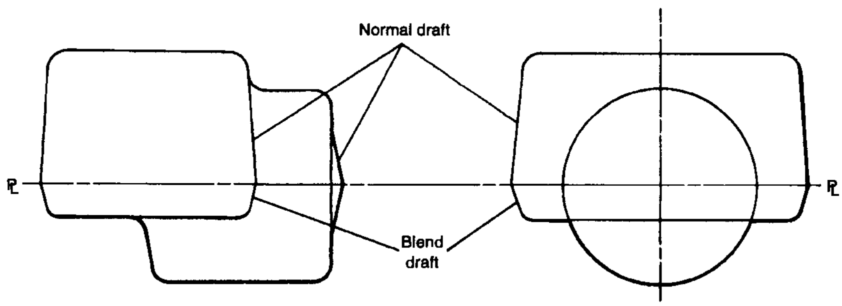


Fig. 19 Normal draft and blend draft in a forging

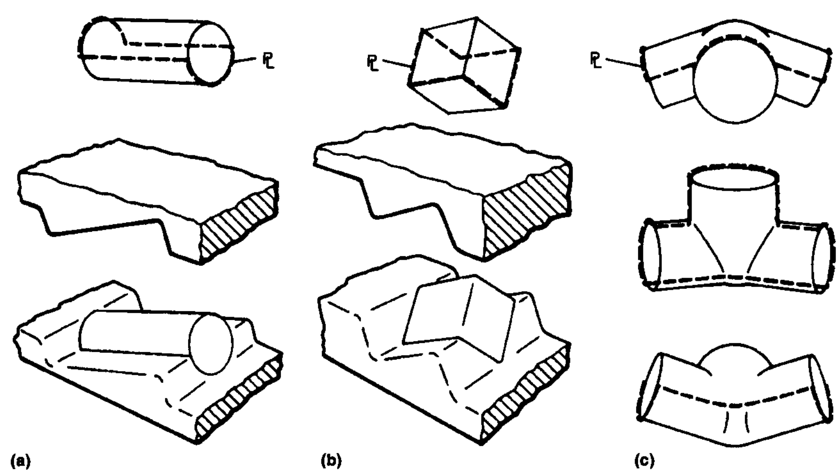


Fig. 20 Selection of parting lines to eliminate draft in (a) cylindrical, (b) square, and (c) tube-shaped forgings

the upper die, where the temperature is higher; the lower die extracts heat from the forging, which is in continuous contact with it. The ribs formed by the upper die have better surface quality than those in the lower die, because scale left by the part is more easily removed.

The maximum height of a rib depends on its width at the base and on blocking operations that preshape the stock. Fillets of minimum size cannot be used at the base of a rib of maximum height if the rib is to be sound and completely filled. Twice the minimum fillet size should be used, a full radius is preferable at the crest of the rib, and draft should be increased if possible.

Fillets and Radii. In forging, some radii wear and grow greater; others become sharper under the combined effects of the pressure of the press or of repeated hammer blows and abrasion. Radii that are too small give the forge die a shearing action and develop high resistance to the flow of the metal, thus increasing die wear and reducing its life. Radii should be as large as the design will permit. Sharp radii in a forging die set up strains that cause the die to check, thus reducing die life and increasing cost. Very little material can be saved by producing a design that includes sharp internal (fillet) radii.

The effects of small and large radii are illustrated in Fig. 14, which shows a forging during two stages of the operation. In small steel forgings (< 0.9 kg, or 2 lb), 3.2 mm (1/8 in.) radii in fillets are considered the absolute minimum. Common practice is to make the fillet radii twice the size of the corner radii. These radii increase in proportion to the size and weight of the forgings (Fig. 21). For steel forgings of average size (1.4 to 3.6 kg, or 3 to 8 lb), 6.4 mm (1/4 in.) fillet radii are normal. Recommended fillet and corner radii for various heights of rib or boss are given in Fig. 22.

Holes and Cavities. Holes should not obstruct the natural flow of the metal in the forging operation. If cavities lie perpendicular to the direction of metal flow, it may be necessary to add breakdown or blocking operations on the forging billet before it is placed in the dies for forging. Such operations add cost and so must be justified economically. In almost all cases in which a hole is to be punched, a forced cavity is provided to displace the metal in order to relieve the workload of the punch in the later operation. Holes and cavities should not be higher or deeper than the base of the widest cross section when normal fillets and radii are used. If a full radius or a hemispherical shape is allowed at the bottom of a cavity, the maximum depth of the cavity may be 1 times the width (diameter), as shown in Fig. 18.

On shallow cavities, a draft angle of 7° and the required normal radii can be used. On cavities of maximum depth, the draft should be increased to 10 to 12°.

Minimum Web Thickness. The web in a forging is limited to the thickness at which it gets too cold before forging is completed. If the web gets cold enough in forging to look black, it prevents the part from being brought down to size. Figure 23 shows the limiting minimum web dimension as a function of web size. The minimums shown are generally accomplished on various metals with more or less difficulty—particularly in a problem forging that, in a forging hammer, requires more than a few blows for completion. Many web thicknesses that fall into the band between the two curves can be made only with difficulty and at extra cost. Some that fall below the curve are regularly produced, while the web thicknesses that fall above the upper curve are almost always made without extra cost in forgings that can be completed rapidly. When a web thinner than recommended is required, some advantage may be gained by tapering it 5 to 8° toward the thinnest section, at the center, but the average minimum thickness of the web must be retained to meet strength requirements.

Lightening Holes in Webs. Holes are not always desirable as a means of reducing weight because of the effect on the strength of the part and stress concentration. Lightening holes are almost always produced by an added operation, and the expense involved is often unjustified. These holes should be used only in neutral or low-stress areas or to reduce cooling cracks and warpage caused by uneven cooling. Holes should be kept away from edges and provided with a strengthening bead to reduce stress concentration (Fig. 24). A hole near the edge of a forging usually leaves inadequate material in the highly stressed area around the hole, thus increasing the possibility of crack nucleation and severe distortion.

Scale Control. The reduction of scale formation and the removal of scale during the forging process are important considerations in meeting design requirements economically. Gas- and oil-fueled preheat furnaces should be adjusted to produce a reducing atmosphere and thus minimize the creation of scale. Induction heating can be a useful alternative to fossil fuel

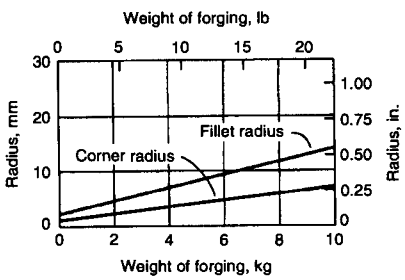


Fig. 21 Minimum fillet and corner radii for steel forgings

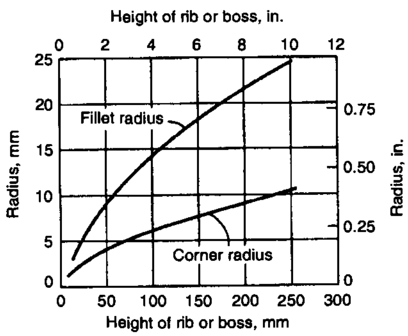


Fig. 22 Recommended fillet and corner radii in relation to height of rib or boss

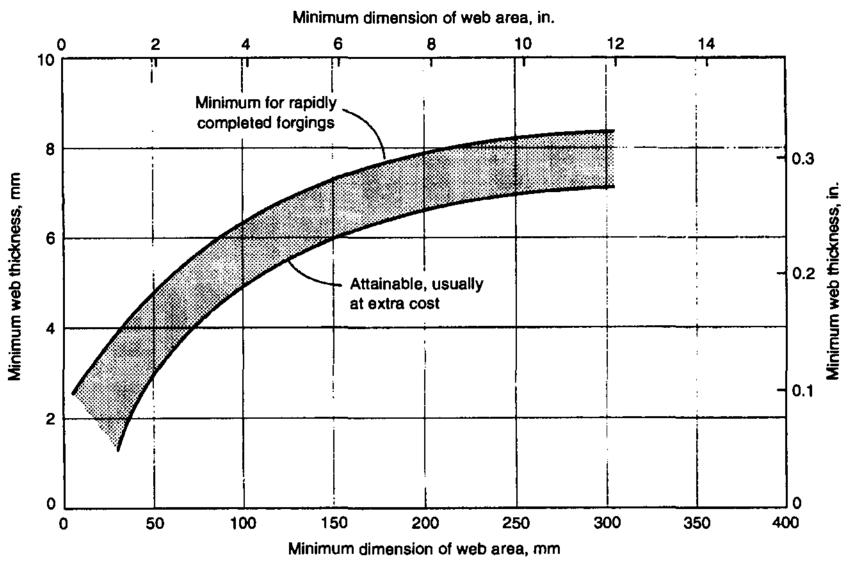


Fig. 23 Recommended minimum web thickness in relation to web dimensions

furnaces. In some cases, the weight loss due to scaling can be reduced from 2 to 3% for gas or oil furnaces to 0.2% for induction heating.

Machining of Forgings

Most forged components are machined before being put into service. Forgings are produced with extra volume, which will be machined off during subsequent processing.

Forging Tolerance. Forging tolerances, based on area and weight, that represent good commercial practice are listed in Tables 9 and 10. These tolerances apply to the dimensions shown in the illustration in Table 9. In using Tables 9 and 10 to determine the size of the forging, the related tolerances, such as mismatch, die wear, and length, should be added to the allowance for machining plus machined dimensions. On average, the tolerances listed in Tables 9 and 10 conform to the full process tolerance of actual production parts and yield more than 99% acceptance of any dimension specified from Tables 9 and 10. In particular, as shown in Table 11, instances may be found of precise accuracy or rarely as much as $\pm 50\%$ error in the tolerances recommended in Table 10. The values in Table 11 represent the product of a die for one run and not the full range of product between successive resinkings of the die.

Mismatch Tolerance. Shift or mismatch tolerance allows for the misalignment of dies during forging (Fig. 25). All angular or flat surfaces of the die will erode or wear away and increase the volume of the forging, depending on the extent to which the forged metal flows over them. This increase is called spread, or die wear, and it must be included in the forging dimensions.

The characteristics of die wear are illustrated in Fig. 26. The part represented was made of 4140 steel, using ten blows in an 11 kN (2500 lbf) board hammer. Tolerances were commercial standard, and the part was later coined to a thickness tolerance of +0.25 mm, −0.000 mm (+0.010 in., −0.000 in.). The die block, 255 by 455 by 455 mm (10 by 18 by 18 in.), was hardened to 42 HRC. After 30,000 forgings had been produced, the die wore as indicated and the dies were resunk.

A range of tolerance is given for mismatch in Table 8. The higher values are to be added to tolerances for forgings that need locked dies or involved side thrust on the dies during forging. On forgings heavier than 23 kg (50 lb), it is sometimes necessary to grind out mismatch defects up to 3.2 mm (1/8 in.) maximum.

Length Tolerance. The length tolerance in Table 9 refers to variations in shrinkage that occur when forgings are finished at different temperatures. Length tolerance should be applied to overall lengths of forgings as well as to the locations of bosses, ribs, and holes.

Areas of a forging can be coined to hold closer tolerances, provided the metal is free to flow into an adjacent open area of the part. Under these circumstances, the tolerances shown in Fig. 27 can be held in production without difficulty. Over a hot-sheared surface, the coining operation will bring the high points of the serrations within tolerance without removing all the depressions.

On average, Table 10 represents full process tolerance. Figure 28 indicates the relationship of the number of acceptable parts to the process tolerance. In application, the full process tolerance must be derived from the process capability, the full value of which is represented on the chart as full process tolerance within which 100% (theoretically 99.7%) acceptability will result.

For a given process and tolerance, if the designer chooses to narrow the tolerance to two-thirds of its full value, the acceptability will be reduced to 95%. Similarly, a reduction to one-third of the full tolerance would result in acceptability of 68%. Such reduction in tolerance incurs added expense because of the costs

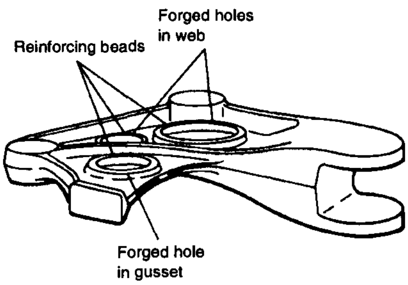


Fig. 24 Lightening holes located in the webs of a forging

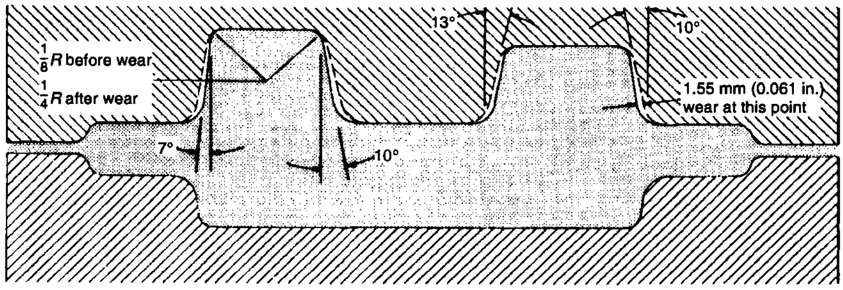


Fig. 26 Schematic showing extent of die wear in a die block hardened to 42 HRC. The block was evaluated for die wear after producing 30,000 forgings of 4140 steel at a rate of 10 blows/workpiece with an 11 kN (2500 lbf) hammer.

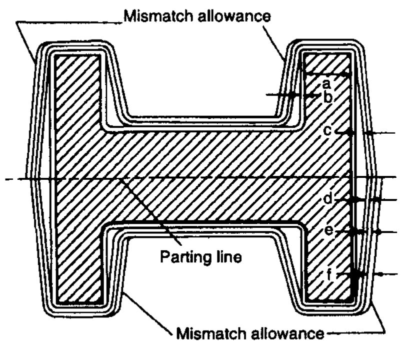
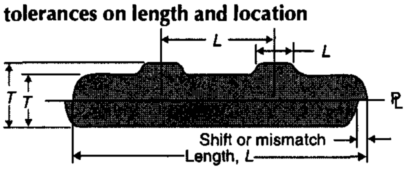


Fig. 25 Application of tolerances and allowances to forgings. The dimensions are not to scale. a, finish machined; b, machine allowance; c, draft allowance; d, die wear tolerance; e, shrink or length tolerance; f, mismatch allowance

Table 9 Recommended commercial tolerances on length and location



Maximum length of forging		Tolerance on length or location	
mm	in.	mm	in.
150	6	+1.19, −0.79	+0.047, −0.031
380	15	+1.57, −1.19	+0.062, −0.047
610	24	+3.18, −1.57	+0.125, −0.062
910	36	+3.18, −1.57	+0.125, −0.062
1220	48	+3.18, −3.18	+0.125, −0.125
1520	60	+4.75, −3.18	+0.187, −0.125
1830	72	+5.56, −3.18	+0.219, −0.125

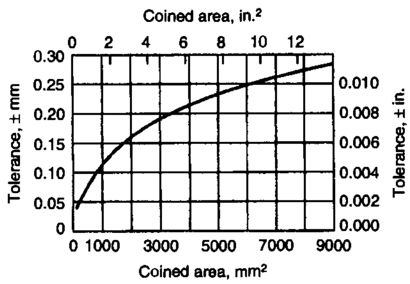


Fig. 27 Tolerances for coining unconfined areas of forgings

of rejected standard forgings and of 100% inspection to separate acceptable from rejected parts. Although it is possible to control the forging process more closely so as to increase the percentage of acceptable parts, the added expense will also increase the cost of the parts.

Trimming Tolerance. Flash is trimmed in a press with a trimming die shaped to suit the plan view, outline, and side view contour of the parting line. The forging can be trimmed with a stated amount of burr or flash left around the periphery at the parting line. It can also be trimmed flush to the side face of the forging, or some of the draft can be trimmed off, provided the serrations or score marks left by the shearing operation are not an objectionable feature. In most commercial forgings, some draft is sheared away.

When the trim must cut through the flash only and leave the side of the forging untouched, it is necessary to use a trim dimension that includes burr tolerance, mismatch, draft tolerance, and die wear plus shrink tolerance. When it is satisfactory to trim draft partially, a closer trim tolerance can be held. Burr tolerance (Table 12) applies to the amount of flash that should remain between the side of the forging at the parting line and the outside edge of the trim cut.

Draft tolerance depends on the height of the face having the draft and applies to the dimension across the forging at the parting line. Draft tolerance (plus) is listed in Table 13 for six different heights of the draft face on forgings.

Die wear tolerance allows for an economical life of tools by providing for acceptability of parts after the die has made a quantity of pieces. The tolerance to be added to trimming and draft tolerances to allow for die wear are given in Table 14. The fourth part of the total tolerance is 0.003 mm/mm (0.003 in./in.) of the greatest dimension across the forging at the trim line, to be added as shrink tolerance.

Example: Trim Tolerance as Summation of Four Individual Tolerances. The use of Tables 10 and 12 to 14 may be illustrated by the following example. Assume a 2.3 kg (5 lb) forging 127 mm (5 in.) high and 127 mm (5 in.)

Table 10 Recommended commercial tolerances for steel forgings

Forging size				Tolerance					
Area		Weight		Thickness(a)		Mismatch(a)		Die wear	
10^3 mm²	in.²	kg	lb	mm	in.	mm	in.	mm	in.
3.2	5.0	0.45	1	+0.79, −0.41	+0.031, −0.016	+0.41 to +0.79	+0.016 to +0.031	+0.79	+0.031
4.5	7.0	3.2	7	+1.57, −0.79	+0.062, −0.031	+0.41 to +0.79	+0.016 to +0.031	+1.57	+0.062
6.5	10.0	0.7	1.5	+0.79, −0.79	+0.031, −0.031	+0.41 to +0.79	+0.016 to +0.031	+0.79	+0.031
7.7	12.0	5.5	12	+1.57, −0.79	+0.062, −0.031	+0.41 to +0.79	+0.016 to +0.031	+1.57	+0.062
12.9	20.0	0.9	2	+1.57, −0.79	+0.062, −0.031	+0.41 to +0.79	+0.016 to +0.031	+1.57	+0.062
12.9	20.0	14	30	+1.57, −0.79	+0.062, −0.031	+0.51 to +1.02	+0.020 to +0.040	+1.57	+0.062
24.5	38.0	2	4.5	+1.57, −0.79	+0.062, −0.031	+0.41 to +0.79	+0.016 to +0.031	+1.57	+0.062
24.5	38.0	36	80	+1.57, −0.79	+0.062, −0.031	+0.64 to +1.27	+0.025 to +0.050	+1.57	+0.062
32.3	50.0	3	8	+1.57, −0.79	+0.062, −0.031	+0.51 to +1.02	+0.020 to +0.040	+1.57	+0.062
32.3	50.0	27	60	+1.57, −0.79	+0.062, −0.031	+0.51 to +1.02	+0.020 to +0.040	+1.57	+0.062
32.3	50.0	45	100	+1.57, −0.79	+0.062, −0.031	+0.64 to +1.27	+0.025 to +0.050	+1.57	+0.062
61.3	95.0	5	11	+1.57, −0.79	+0.062, −0.031	+0.51 to +1.02	+0.020 to +0.040	+1.57	+0.062
85.2	132.0	8	17	+1.57, −0.79	+0.062, −0.031	+0.64 to +1.27	+0.025 to +0.050	+1.57	+0.062
107	166.0	33	73	+2.39, −0.79	+0.094, −0.031	+0.76 to +1.52	+0.030 to +0.060	+2.39	+0.094
113	175.0	68	150	+2.39, −0.79	+0.094, −0.031	+0.76 to +1.52	+0.030 to +0.060	+2.39	+0.094
130	201.0	18	40	+1.57, −0.79	+0.062, −0.031	+0.64 to +1.27	+0.025 to +0.050	+1.57	+0.062
155	240.0	23	51.5	+2.39, −0.79	+0.094, −0.031	+0.76 to +1.52	+0.030 to +0.060	+2.39	+0.094
161	250.0	114	250	+2.39, −0.79	+0.094, −0.031	+0.76 to +1.52	+0.030 to +0.060	+2.39	+0.094
171	265.0	27	60	+2.39, −0.79	+0.094, −0.031	+0.76 to +1.52	+0.030 to +0.060	+2.39	+0.094
177	275.0	30	65	+3.18, −0.79	+0.125, −0.031	+1.19 to +2.39	+0.047 to +0.094	+3.18	+0.125
194	300.0	34	75	+3.18, −1.57	+0.125, −0.062	+1.19 to +2.39	+0.047 to +0.094	+3.18	+0.125
194	300.0	159	350	+2.39, −0.79	+0.094, −0.031	+0.76 to +1.52	+0.030 to +0.060	+2.39	+0.094
242	375.0	205	450	+3.18, −0.79	+0.125, −0.031	+1.19 to +2.39	+0.047 to +0.094	+3.18	+0.125
268	415.0	139	306	+3.18, −1.57	+0.125, −0.062	+1.19 to +2.39	+0.047 to +0.094	+3.18	+0.125
339	525.0	340	750	+3.18, −1.57	+0.125, −0.062	+1.19 to +2.39	+0.047 to +0.094	+3.18	+0.125
580	900.0	455	1000	+3.18, −1.57	+0.125, −0.062	+1.19 to +2.39	+0.047 to +0.094	+3.18	+0.125

(a) The illustration in Table 9 shows locations of thickness and mismatch.

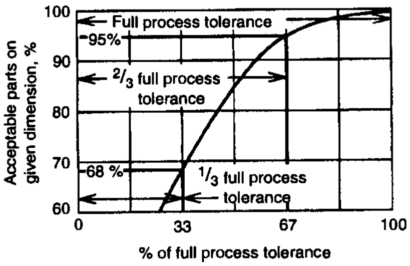


Fig. 28 Relationship of percentage of acceptable parts to process tolerance specified on a dimension

Table 11 Comparison of quality-control data with recommended tolerances for seven production forgings

Values represent the product of a die for one run and not the full range of product between successive resinkings of the die. All tolerances are plus; negative tolerances, zero. Plus signs in the last column indicate that the recommended tolerance is conservative compared with production experience. σ represents standard deviation in distribution of measured dimensions.

Part	Recommended tolerance (from Table 10)		Range of observed variation in length for specific quality-control limits				Difference between tolerance (from Table 10) and 6σ control limit	
			4σ		6σ			
	mm	in.	mm	in.	mm	in.	mm	in.
A	2.39	0.094	1.07	0.042	1.60	0.063	+0.79	+0.031
B	2.39	0.094	1.30	0.051	1.93	0.076	+0.46	+0.018
C	2.39	0.094	1.52	0.060	2.29	0.090	+0.10	+0.004
D	3.18	0.125	1.35	0.053	2.03	0.080	+1.15	+0.045
E	3.18	0.125	2.06	0.081	3.10	0.122	+0.08	+0.003
F	3.18	0.125	2.64	0.104	4.22	0.166	−1.04	−0.041
G	3.18	0.125	2.82	0.111	4.22	0.166	−1.04	−0.041

across at the minimum shearing dimension. The tolerance is the sum of 1.1 mm (0.045 in.) burr tolerance, 4.4 mm (0.175 in.) draft tolerance, 1.0 mm (0.040 in.) die wear tolerance, and 0.38 mm (0.015 in.) shrink tolerance, which equals 7.0 mm (0.275 in.) trim tolerance. Thus,

Table 12 Tolerance on burr for steel forgings

Weight kg	Weight lb	Trim size(a) mm	Trim size(a) in.	Tolerance mm	Tolerance in.
0.45	1	50	2	+0.79, −0.000	+0.031, −0.000
4.5	10	150	6	+1.57, −0.000	+0.062, −0.000
11	25	200	8	+3.18, −0.000	+0.125, −0.000
45	100	625	25	+6.35, −0.000	+0.250, −0.000

(a) The trim size refers to the greatest distance across the forging at the trim line.

Table 13 Draft increment of trim tolerance for steel forgings

Height of draft face mm	Height of draft face in.	Tolerance mm	Tolerance in.
6.35	1/4	+0.38, −0.00	+0.015, −0.000
12.70	1/2	+0.51, −0.00	+0.020, −0.000
25	1	+0.9, −0.00	+0.035, −0.000
51	2	+1.5, −0.00	+0.060, −0.000
127	5	+4.5, −0.00	+0.175, −0.000
254	10	+8.9, −0.00	+0.350, −0.000

Table 14 Die wear increment of the trim tolerance for steel forgings

Weight kg	Weight lb	Trim size(a) mm	Trim size(a) in.	Tolerance mm	Tolerance in.
0.45	1	50	2	+0.79, −0.00	+0.031, −0.000
4.5	10	150	6	+1.19, −0.00	+0.047, −0.000
11	25	200	8	+1.57, −0.00	+0.062, −0.000
45	100	625	25	+3.18, −0.00	+0.125, −0.000

(a) The trim size refers to the greatest distance across the forging at the trim line.

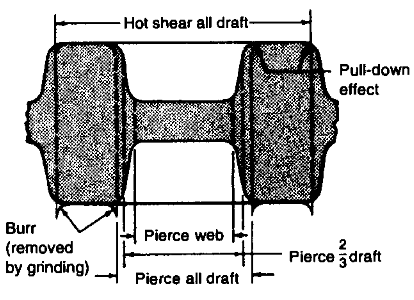


Fig. 29 Pull-down effect in hot shearing, a commonly specified operation for removing the draft from forgings. Pull-down effect, which results from the force of the shearing operation, marks the point where shear begins; burr, where shear ends

134.0 mm (5.275 in.) is the largest dimension allowed for trimming when the side of the forging must not be cut, and 127.0 mm (5.000 in.) is the smallest dimension to be allowed. This tolerance is most economical, but in many forgings the tolerance can be held as close as that shown in Table 14 by close control or extra operations.

Hot shearing removes the draft from forgings with a vertical cut that improves dimensional accuracy and leaves a serrated surface. This characteristic surface and accuracy represent an economical preparation for machining, broaching, coining, and accurate chucking in standard chucks. The surface is a substitute for rough machining or flame cutting.

The least expensive trimming operation on forgings is the cold trimming of small parts made from carbon steel of less than 0.50% C or from alloy steel of less than 0.30% C. However, to hot shear off about two-thirds of the draft is economical because the special locating tools required for shearing off all the draft are not needed. The holes and outside of a forging can be sheared in one operation with a combination trimmer and punch for parts where the sheared burr of the holes and the outside are not required to be on opposite sides of the forging.

The force of the shearing operation results in a rounded contour, called pull down, where the shear begins, and in sharp burr edges on the opposite side of the forging where the shear ends Fig. 29. The trimming and piercing forces are sometimes great enough to crush or distort the forging. For example, the force of piercing a hole in a thin-wall hub may expand the outside dimension if there is no outer flange to support it. If the wall has a flange around the outside, the piercing forces may crush the lower ends of the hub.

Piercing. Expansion may occur in hot piercing a hole in a cylindrical piece when the unsupported outside wall is 1.5 times the diameter of the pierced hole. Parts with an outside diameter only 1.2 times the diameter of the pierced hole will be distorted. In some parts in which the outer surface is sheared in the same operation that pierces the hole, an outside

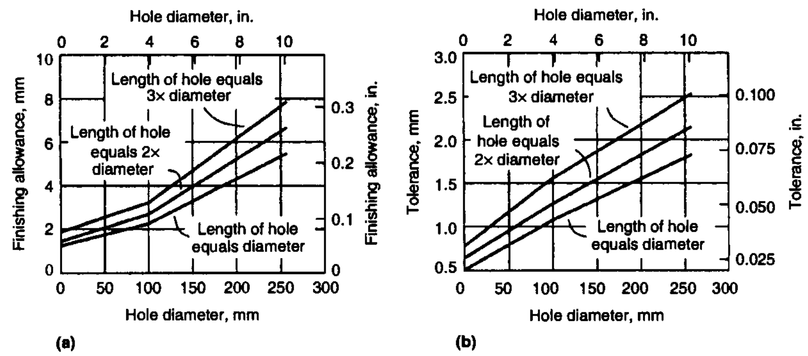


Fig. 30 Allowances (a) and tolerances (b) for hot-pierced holes that are to be broached

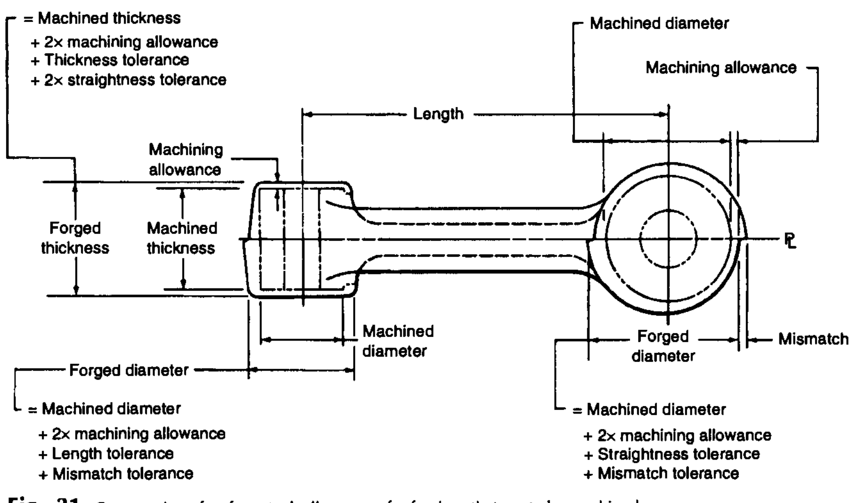


Fig. 31 Computation of surface stock allowances for forgings that are to be machined

diameter 1.4 times the diameter of the hole can sometimes be used with good results. Generally, however, 1.57 mm (0.062 in.) should be added to the end of the piece for such parts to allow for crushing of the ends if the ratio of outside diameter to inside diameter is less than 1.5. If the ratio is about 1.6, an allowance of 0.81 mm (0.032 in.) is satisfactory; for ratios of outside to inside diameter greater than 1.75, this allowance is seldom necessary. All of these ratios refer to dimensions after piercing.

Broaching Allowance. The amount of metal to be removed in broaching a hole in a forging can be controlled economically by hot piercing the hole to close tolerances or, less economically, by machining the hole before broaching. Figure 30 is a graph of the forging stock and tolerances to be allowed in a hole that is to be broached after hot piercing. In using Fig. 30, the allowance value at a given diameter is subtracted from the minimum broach diameter. This is the high limit for the size of the hot-pierced hole. The hole dimension is then specified as the high limit with a tolerance of plus zero, minus the tolerance read from Fig. 30.

Allowance for Machining. Surfaces that are to be machined must be forged oversize externally and undersize internally by an amount equal to the sum of applicable tolerances and machining allowance (Fig. 31). On machined surfaces parallel to the parting line, the stock allowance is affected by the tolerances for thickness and straightness. Machined surfaces perpendicular or nearly perpendicular to the parting plane are affected by the length tolerances, straightness, and mismatch tolerances. The minimum machining allowance, set somewhat arbitrarily at 1.52 mm (0.060 in.) on small forgings and as high as 6.35 mm (0.250 in.) on large forgings, is given in Table 15. The allowances listed are based on weight and shape, which are significant principally as an index of the amount of probable warpage. In all cases, the depths of cut given in Table 13 will also remove permissible amounts of decarburization. The tolerance and allowance for hot piercing of holes that are to be broached are given in Fig. 30.

The precise effect of changes in section on the amount of distortion in heat treatment is unknown. For small parts, the usual method of overcoming distortion is by jig quenching or marquenching.

Decarburization. Because the loss of carbon greatly lowers the resistance to fatigue, the decarburized skin should be removed by machining in highly stressed areas. Table 16 lists the general limits for forgings of various sizes. The machining allowance is usually greater than the depths listed.

Design for Tooling Economy. Considerable reduction in cost may result from forging designs that incorporate provisions for location of the forging for machining and inspection. Forgings that will be clamped to a faceplate or a machine-tool table should be provided with three bosses under the proposed clamping points to locate the part and to avoid both distortion and the tendency to rock (Fig. 32). When the quantity of parts is too small to justify tooling and holes are to be drilled or hot sheared in forging, the holes can be spotted with a cone angle steeper than the drill and about one-half to two-thirds of its diameter. This procedure enables accuracy of locations comparable with length tolerances and squareness predictable from thickness tolerances if the part is not specially located for machining.

Long parts of irregular cross section that may have bow or camber should often be provided

Table 15 Machining allowance on each surface for typical steel forgings

Maximum weight of forging		Machining allowance per surface					
		Tall forgings		Flat forgings		Long forgings	
kg	lb	mm	in.	mm	in.	mm	in.
6.8	15	1.52–2.29	0.060–0.090	1.52–3.05	0.090–0.120	3.05	0.120
34	75	2.29–3.05	0.090–0.120	3.05	0.120	3.05	0.120
450	1000	3.05–4.83	0.120–0.190	3.05–6.35	0.120–0.250	4.83–6.35	0.190–0.250

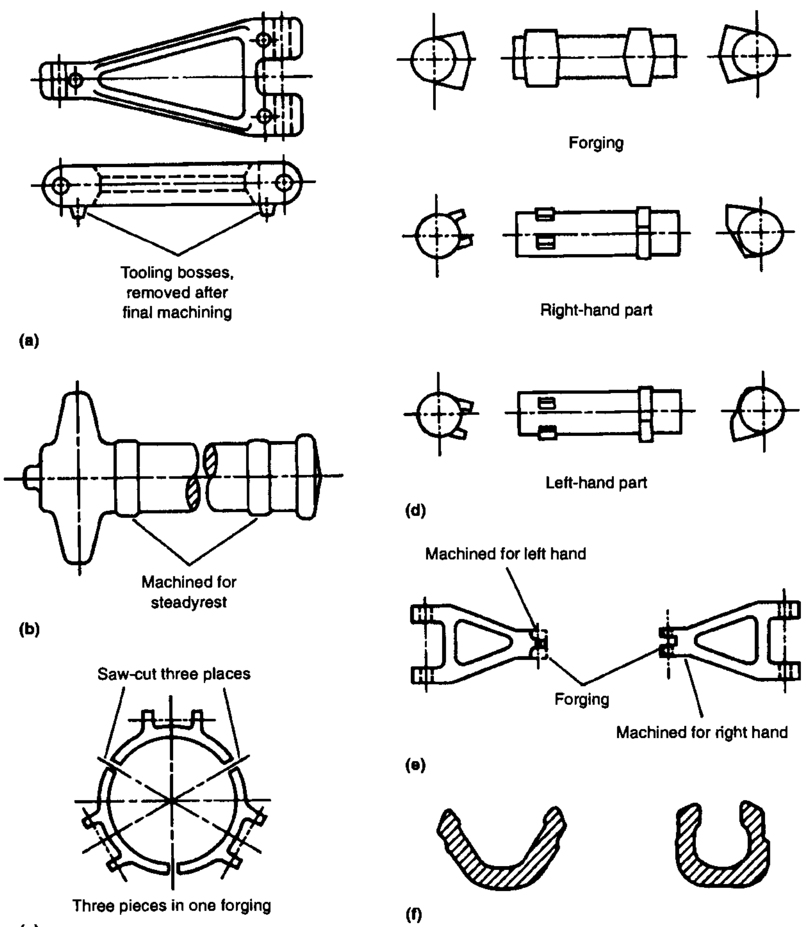


Fig. 32 Workpiece configurations that emphasize cost effectiveness and versatility in terms of tooling design. (a), (b), and (c) Design for economy in tooling. (d) and (e) Combination of right-hand and left-hand parts in the same forging. (f) An unforgeable part that was bent to its final shape after preliminary forging

Table 16 Typical decarburization limits for steel forgings

Range of section size		Typical depth of decarburization	
mm	in.	mm	in.
<25	<1	0.8	0.031
25–100	1–4	1.2	0.047
100–200	4–8	1.6	0.062
>200	>8	3.2	0.125

with steady-rest locations in the forging design for economical machining (Fig. 32). Machining economy and accuracy often result when a forging that presents a problem in machining is designed as a siamese forging with multiple parts on the same forgings to be saw-cut apart after machining is completed.

Special opportunities for economy are present in the design of right- and left-hand forgings to be transformed later (Fig. 32). The method shown for avoiding right- and left-hand forging tooling should always be used for the manufacture of small quantities but may not be economical for large production. Figure 32 also shows a part that could not be forged without a secondary bending operation.

Design of Hot Upset Forgings

Hot heading, upset forging, or, more broadly, machine forging consists primarily of holding a bar of uniform cross section, usually round, between grooved dies and applying pressure on the end in the direction of the axis of the bar by using a heading tool so as to upset or enlarge the end into an impression of the die. The shapes generally produced include a variety of enlargements of the shank or multiple enlargements of the shank and reentrant angle configurations. Transmission cluster gears, pinion blanks, shell bodies, and many other shaped parts are adapted to production by the upset machine forging process. This process produces a looped grain flow of major importance for gear teeth. Simple, headed forgings can be completed in one step, while some that have large, configured heads or multiple upsets may require as many as six steps. Upset forgings weighing less than 0.45 to about 225 kg (1 to 500 lb) have been produced.

Machining Stock Allowances. The standard for machining stock allowance on any upset portion of the forging is 2.39 mm (0.094 in.), although allowances vary from 1.57 to 3.18 mm (0.062 to 0.125 in.), depending on the size of the upset, the material, and the shape of the part (Fig. 33). Mismatch and shift of dies are each limited to 0.41 mm (0.016 in.) maximum. Mismatch is the location of the gripper dies with respect to each other as shown in Fig. 33(a). Shift refers to the relation of the dies to the heading tool. Parting-line clearance is required in gripper dies for tangential clearance in order to avoid undercut and difficulty in the removal of the forging from the dies (Fig. 33a).

Tolerances for shear-cut ends have not been established. Figure 33(b) shows a shear-cut end on a 32 mm ($1\frac{1}{4}$ in.) diam shank. Straight ends can be produced by torch cutting, hacksawing, or abrasive wheel cutoff at a higher cost than shearing.

Corner radii should follow the contours of the finished part, with a minimum radius of 1.6 mm ($\frac{1}{16}$ in.). Radii are not required at the outside diameter of the upset face but can be specified as desired. Variations in thickness of the upset require variations in radii (Fig. 33), because the origin of the force is farther removed and the die cavity is more difficult to fill. When a long upset is only slightly larger than the original bar size, a taper is advisable instead of a radius.

Fillets can conform to the finished contour in most cases. The absolute minimum should be 3.2 mm ($\frac{1}{8}$ in.) on simple upsets (Fig. 33c).

Tolerances for all upset-forged diameters are generally +1.6 mm, −0 mm (+$\frac{1}{16}$ in., −0 in.) except for thin sections of flanges and upsets relatively large in ratio to the stock sizes used, where they are +2.4 mm, −0 mm (+$\frac{3}{32}$ in., −0 in.). The increase in tolerances over the standard +1.66 mm, −0 mm (+$\frac{1}{16}$ in., −0 in.) is sometimes a necessity because of variations in size of hot-rolled mill bars, extreme die wear, or complexity of the part. Tolerances for unforged stem lengths are given in Table 17.

Draft angles may vary from 1 to 7°, depending on the characteristics of the forging design. Draft is needed to release the forging from the split dies; it also reduces the shearing of face surfaces in transfer from impression to impression. For an upset-forged part that requires several operations or passes, the dimensioning of lengths is determined on the basis of the design of each individual pass or operation.

Design of Specific Parts. A study of designs already being manufactured by the hot upset method of forging may serve as a guide for the development of similar applications. The following examples illustrate some typical exceptions to general design rules.

It can be seen from Fig. 34 that the size of stock required to produce the part determines the allowances required for finish machining, thickness of upset, diameter tolerances, and corner radii. The amount of upset stock required depends on bar size and determines whether the stock can be sheared, flame cut, or torch cut, or separated by another method. Figure 34(c) illustrates a few of the simplest upset parts.

Figure 35(a) shows a variation from the straight axle-shaft type of design in which the beveled head of the upset is confined in the heading tool. This method usually requires that the design recognize a position in the forging where a flash, or excess metal, must be trapped between the dies and heading tool. This is indicated in Fig. 35(a) by the 3.2 mm ($\frac{1}{8}$ in.) minimum dimension. Another problem encountered in designs of the type shown in Fig. 35(a) is the filling of the barrel section at the point of transition from original stock size to slightly increased diameter. As noted, an additional amount of finish is required, along with a generous radius.

The same problem, shown in Fig. 35(b), can be overcome by a taper blending from the bar size to the shoulder diameters. This type of design is expedient where the two diameters are within 9.5 mm ($\frac{3}{8}$ in.) of each other.

Figure 35(c) is basically an axle-shaft type of forging with a long pilot. Because the pilot part of the forging must be carried in the heading tools, draft is required for withdrawal from the tool and usually should be no less than $\frac{1}{2}$°. The length of the pilot determines the amount of

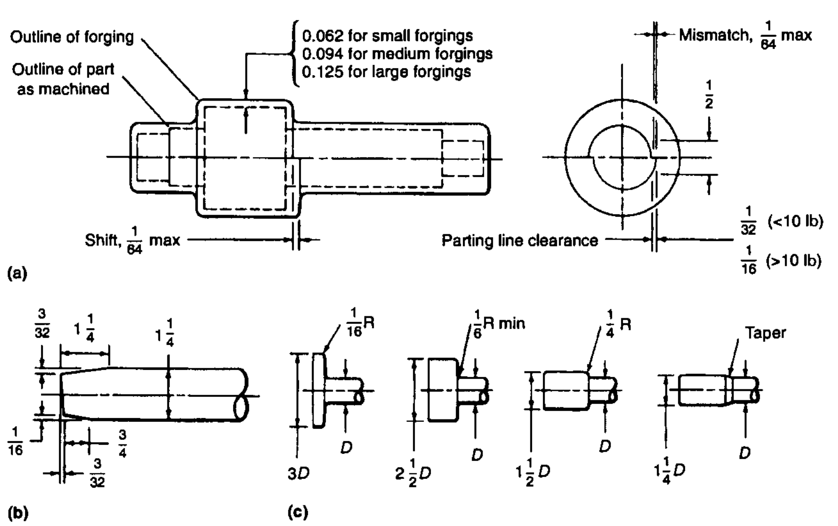


Fig. 33 Machining stock allowances for hot upset forgings. (a) Hot upset forging terminology and standards. (b) Probable shape of shear-cut ends. (c) Variation of corner radius with thickness of upset. These parts are the simplest forms of upset forgings. Dimensions given in inches

Table 17 Length tolerances for unforged stems of upset forgings

Maximum length		Minimum tolerance	
mm	in.	mm	in.
150	6	+1.59, −0.00	+0.062, −0.000
250	10	+2.39, −0.00	+0.094, −0.000
500	20	+3.18, −0.00	+0.125, −0.000
>500	>20	+3.96, −0.00	+0.156, −0.000

draft, which may range to a maximum taper of 3°. Another design rule to be recognized is that the pilot diameter in the heading tool should be 1.6 mm (1/16 in.) larger than the bar diameter to allow the stock to bottom in the heading tool. Contingent on the number of passes required in producing the forging, plus the mill tolerance for the particular bar size, the pilot end diameter may require a maximum of 3.2 mm (1/8 in.) over the bar diameter.

Figure 35(d) illustrates a typical transmission cluster gear forging. The drafts specified are a requirement for this type of forging because the part must be carried in the die after being partially produced. Of necessity, the neck diameter is determined by the stock size required to produce the part, plus an allowance to make a fit with the heading tool similar to Fig. 35(c).

Figure 35(e) shows the radius required when the pilot end must pass into the header. A small radius on the heading tool can scrape off metal along part of the length of the bar end and forge the loose chips into the face of the forged flange.

Figure 35(f) illustrates the minimum tapers and radii required for depressions in upset forgings. A larger draft angle or radius, or both, decreases the possibility of cold shuts.

Figures 35(g) and (j) show variations of size and design of forgings that are pierced or punched. In such forgings, the allowance for machining of the holes varies from 1.0 to 2.0 mm (0.040 to 0.080 in.), according to size, for parts that are to be broached.

In Fig. 35(g), the draft allowances required are similar to those of Fig. 35(d) to facilitate removal of the part from the die during and after forging. In Fig. 35(g), the large diameter shows a tolerance 0.8 mm (1/32 in.) larger than standard because the large flange fabricated in the first pass must be carried in the die while the front flange is being upset. Carrying the flange from pass to pass requires clearance of the flange in the die, and as the punch enters the forging, there is some upsetting action of the back flange, creating a slightly oval condition. The additional

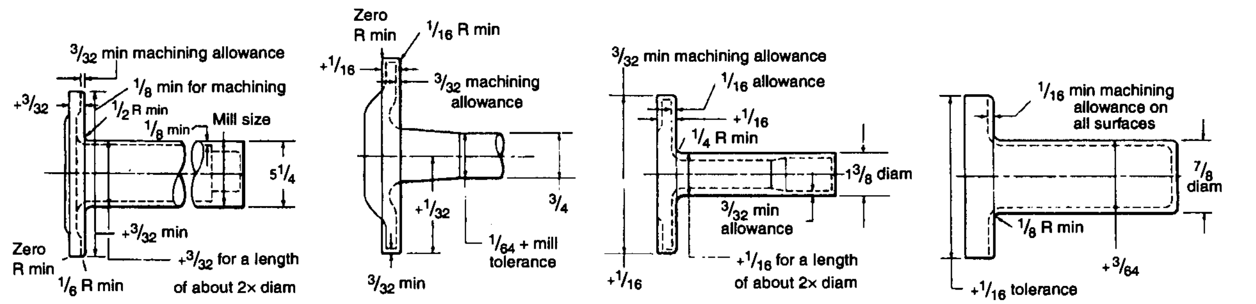


Fig. 34 Design practice for upset forgings with specifications determined by raw material stock diameter. Tolerances (shown with + or − sign), allowances, and design rules for upset forgings of various typical or common shapes. Dimensions given in inches

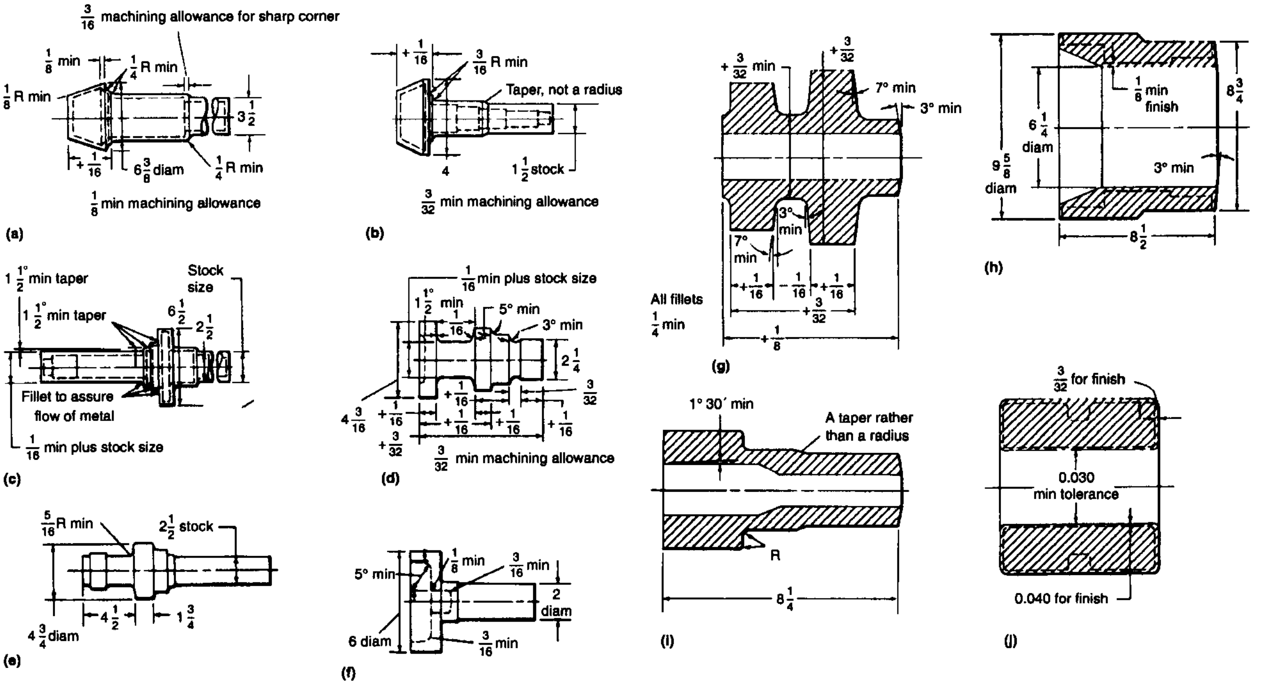


Fig. 35 Design practice for upset forgings in which specifications depend on position of flash in workpiece. Tolerances (shown with + or − sign), allowances, and design rules for upset forgings. See text for discussion. Dimensions given in inches

tolerance reflects not only die wear but also ovality. This also holds true for the neck diameter.

Figure 35(i) shows the amount of taper required when punching relatively deep holes. The length of the taper determines the amount of draft required to permit the punch to be withdrawn from the forging.

In addition to the various types of symmetrical forgings shown, some asymmetrical parts are readily forged. These include bolts of many sizes and designs, rod ends, trunnion forgings, steering sectors, universal joints, and a number of other parts with ends having various contours and dimensions.

ACKNOWLEDGMENT

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