

Forging of Aluminum Alloys

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ALUMINUM ALLOYS are forged into a variety of shapes and types of forgings with a broad range of final part forging design criteria based on the intended application. Aluminum alloy forgings, particularly closed-die forgings, are usually produced to more highly refined final forging configurations than hot-forged carbon and/or alloy steels, reflecting differences in the high-temperature oxidation behavior of aluminum alloys during forging, the forging engineering approaches used for aluminum, and the higher material costs associated with aluminum alloys in comparison with carbon steels. For a given aluminum alloy forging shape, the pressure requirements in forging vary widely, depending primarily on the chemical composition of the alloy being forged, the forging process being employed, the forging strain rate, the type of forging being manufactured, the lubrication conditions, and the forging workpiece and die temperatures.

Figure 1 compares the flow stresses of some commonly forged aluminum alloys at 350 to 370 °C (660 to 700 °F) and at a strain rate of 4 to 10 s⁻¹ to 1025 carbon steel forged at an identical strain rate but at a forging temperature typically employed for this steel. Flow stress of the alloy being forged represents the lower limit of forging pressure requirements; however, actual forging unit pressures are usually higher because of the other forging process factors outlined previously. For some low- to intermediate-strength aluminum alloys, such as 1100 and 6061, flow stresses are lower than those of carbon steel. For high-strength alloys—particularly 7xxx series alloys such as 7x75, 7010, 7040, 7x49, 7050, 7085, and others—flow stresses, and therefore forging pressures, are considerably higher than those of carbon steels. Finally, other aluminum alloys, such as 2219, have flow stresses quite similar to those of carbon steels. As a class of alloys, however, aluminum alloys are generally considered to be more difficult to forge than carbon steels and many alloy steels. The chemical compositions, characteristics, and typical mechanical properties of all wrought aluminum alloys referred to in this article are reviewed in the articles “Aluminum mill and Engineered Wrought Products” and “Properties of Wrought Aluminum and Aluminum Alloys” in *Properties and Selection: Nonferrous Alloys* and *Special-Purpose Materials*, Volume 2 of *ASM Handbook*, 1990.

Forgeability

Compared to the nickel/cobalt-base alloys and titanium alloys, aluminum alloys are considerably more forgeable, particularly when using conventional forging process techniques where dies are heated to 540 °C (1000 °F) or less. Figure 2 illustrates the relative forgeability of ten aluminum alloys that constitute the majority of aluminum alloy forging production. This arbitrary unit is based principally on the deformation per unit of energy absorbed in the range of forging workpiece temperatures typically employed for the alloys in question. Also considered in this index is the difficulty of

achieving specific degrees of severity in deformation, as well as the cracking tendency of the alloy under given forging process conditions. There are wrought aluminum alloys, such as 1100 and 3003, whose forgeability would be rated significantly above that of those alloys presented; however, these alloys have limited application in forged products because they cannot be strengthened by heat treatment.

Effect of Temperature. As shown in Fig. 2, the forgeability of all aluminum alloys improves with increasing metal temperature. However, there is considerable variation in the effect of temperature for the alloys plotted. For example, the high-silicon alloy 4032 shows the greatest temperature effect, while the high-strength Al-Zn-Mg-Cu 7xxx series alloys display the least effect of workpiece temperature. Figure 3 presents the effect of temperature on flow stress, at a strain rate of 10 s⁻¹ for alloy 6061, a highly

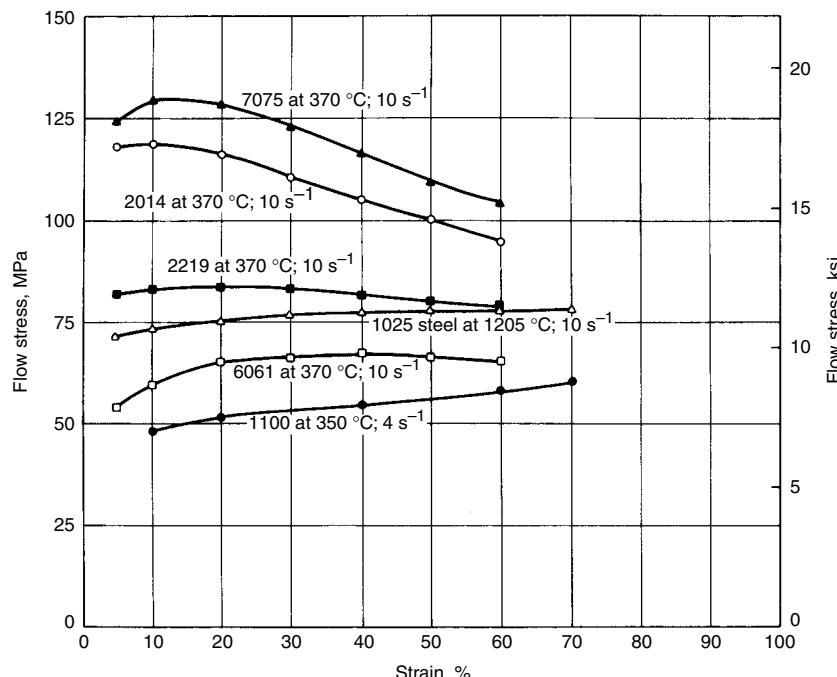


Fig. 1 Flow stresses of commonly forged aluminum alloys and of 1025 steel at typical forging temperatures and various levels of total strain

forgeable and widely used aluminum alloy. There is nearly a 50% decrease in flow stress for the highest metal temperature plotted, 480 °C (900 °F), the top of the recommended forging range for 6061, when compared with a workpiece temperature of 370 °C (700 °F), which is below the minimum forging metal temperature recommended for 6061. For other, more difficult-to-forgo alloys, such as the 2xxx and 7xxx series, the change in flow stress associated with variation in workpiece temperature is even greater, illustrating the principal reason why forging aluminum alloys requires maintaining relatively narrow metal temperature ranges.

Recommended preheating forging metal temperature ranges for aluminum alloys that are commonly forged, along with recently developed alloys, are listed in Table 1. All of these alloys are generally forged to the same severity, although some alloys may require more forging power and/or more forging operations than others. The preheating forging metal temperature range for most alloys is relatively narrow, generally <55 °C (<100 °F), and for no alloy is the range greater than 85 °C (155 °F). Achieving

and maintaining proper preheating metal temperatures in the forging of aluminum alloys is a critical process variable that is vital to the success of the forging process. However, die temperatures and deformation rates play key roles in determining the actual workpiece metal temperature achieved during the forging deformation sequence.

Effect of Deformation Rate. Aluminum alloy forgings are produced on a wide variety of forging equipment (see the section "Forging Equipment" in this article). The deformation or strain rate imparted to the deforming metal varies considerably, ranging from very fast (for example, $\geq 10 \text{ s}^{-1}$ on equipment such as hammers, mechanical presses, screw presses, and high-energy-rate machines) to relatively slow (for example, $\leq 0.1 \text{ s}^{-1}$ on equipment such as hydraulic presses). Therefore, deformation or strain rate is also a critical process element that must be controlled for successful forging of any given alloy and forging configuration.

Figure 4 presents the effect of two strain rates—10 and 0.1 s^{-1} —on the flow stresses of two aluminum alloys—6061 and 2014—at

370 °C (700 °F). It is clear that higher strain rates increase the flow stresses of aluminum alloys and that the increase in flow stress with increasing strain rate is greater for more difficult-to-forgo alloys, such as the 2xxx and 7xxx series. For 6061, the more highly forgeable alloy, the increase in flow stress with the rapid strain rate is of the order of 70%; for 2014, the higher strain rate virtually doubles the flow stress. Although aluminum alloys are generally not considered to be as sensitive to strain rate as other materials, such as titanium and nickel/cobalt-base superalloys, selection of the strain rate in a given forging process or differences in deformation rates inherent in various types of equipment affect the forging pressure requirements, the severity of deformation possible, and therefore the sophistication of the forging part that can be produced.

In addition to influencing the flow stress of the alloy being forged, strain rate during the forging process may also affect the temperature of the workpiece. Most wrought aluminum alloys are susceptible to deformation heating in forging hot-working processes. The extent of deformation heating does, however, depend on the specific alloy and the strain rate conditions present, with rapid strain rates, for example, greater than 10 s^{-1} , inducing greater changes (increases) in workpiece temperature. Consequently, when forging "hard," more difficult to forge 2xxx and 7xxx series alloys in rapid strain rate forging equipment such as hammers, mechanical and screw presses, and so forth, preheating metal temperatures are reduced to the low end of the ranges in Table 1. Some high-strength 7xxx alloys are intolerant of the temperature changes possible in rapid strain rate forging, and as a consequence this type of equipment is not employed in the fabrication of forgings in these alloys.

Effect of Die Temperature. Unlike some forging processes for carbon and alloy steels, the dies used in virtually all hot-forging processes for aluminum alloys are heated in order to facilitate the forging process. Therefore, die temperature is another critical process element affecting the forgeability and forging process optimization of this alloy class. Table 2 summarizes the die temperature ranges typically used for several aluminum forging processes and types of forging equipment. The criticality of die temperature in the optimization of the forging process depends on the forging equipment being employed, the alloy being forged, the severity of the deformation, and/or the sophistication of the forging design. For slower deformation processes, such as hydraulic press forging, the aluminum alloy workpiece rapidly assumes the temperature of the dies. As a consequence, die temperature controls the actual workpiece temperature during deformation. In fact, aluminum alloys forged in hydraulic presses are isothermally forged; that is, the workpiece and the dies are at the same temperature during deformation. Therefore, the recommended die temperatures employed for hydraulic press forging

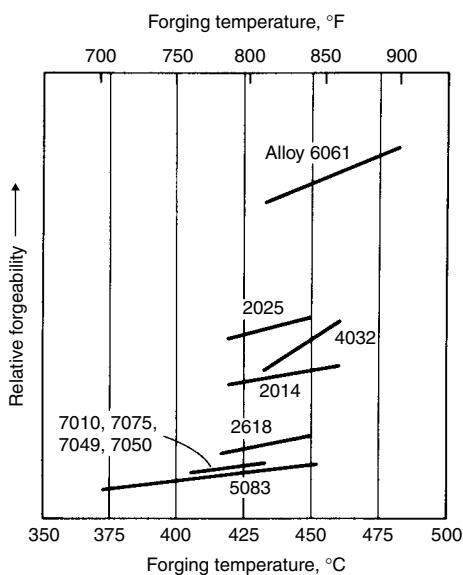


Fig. 2 Forgeability and forging temperatures of various aluminum alloys

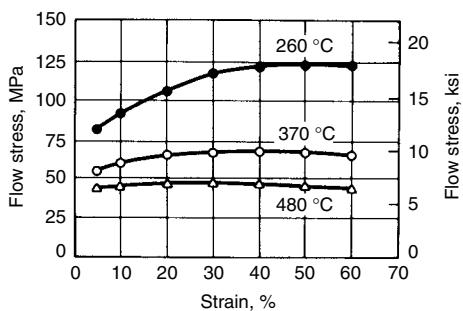


Fig. 3 Flow stress versus strain rate for alloy 6061 at three temperatures and a strain rate of 10 s^{-1}

Table 1 Recommended forging temperature ranges for aluminum alloys

Aluminum alloy	Forging temperature range	
	°C	°F
1100	315–370	600–700
2014	420–460	785–860
2025	420–450	785–840
2219	425–470	800–880
2618	410–455	770–850
3003	315–370	600–700
4032	415–460	780–860
5083	405–460	760–860
6061	430–480	810–900
6069	440–490	825–915
6556	440–490	825–915
7010	370–445	700–830
7033	380–440	720–820
7039	380–440	720–820
7040	360–440	680–820
7049	360–440	680–820
7050	360–440	680–820
7068	380–440	720–820
7075	380–440	720–820
7175	380–440	720–820
7085	360–440	680–820

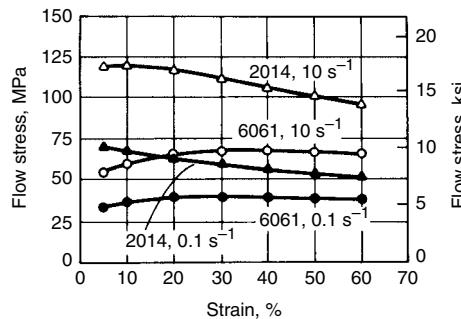


Fig. 4 Flow stress versus strain rate for alloys 2014 and 6061 at 370 °C (700 °F) and two different strain rates

aluminum alloys are much higher than those typical of more rapid deformation processes, such as hammers and mechanical or screw presses. Die heating techniques are discussed in the section "Heating of Dies" in this article.

Forging Methods

Aluminum alloys are produced by all of the current forging methods available, including open-die (or hand) forging, closed-die forging, upsetting, roll forging, orbital (rotary) forging, spin forging, mandrel forging, ring rolling, and forward and reverse extrusion. Selection of the optimal forging method for a given forging shape is based on the desired forged shape, the sophistication of the forged-shape design, and cost. In many cases, two or more forging methods are combined in order to achieve the desired forging shape and to obtain a thoroughly wrought structure. For example, open-die forging frequently precedes closed-die forging in order to prework the alloy (especially when cast ingot forging stock is being employed) and in order to preshape (or preform) the metal to conform to the subsequent closed dies and to conserve input metal.

Open-die forging is frequently used to produce small quantities of aluminum alloy forgings when the construction of expensive closed dies is not justified or when such quantities are needed during the prototype fabrication stages of a forging application. The quantity that warrants the use of closed dies varies considerably, depending on the size and shape of the forging and on the application for the part. However, open-die forging is by no means confined to small or prototype quantities. In some cases, it may be the most cost-effective method of aluminum forging manufacture. For example, as many as 2000 pieces of biscuit forgings have been produced in open dies when it was desired to obtain the properties of a forging but closed dies did not provide sufficient economic benefits.

Open-die forgings in aluminum alloys can be produced in a wide variety of shapes, ranging

from simple rounds, squares, or rectangles to very complex contoured forgings (see the article "Open-Die Forging" in this Volume). In the past, the complexity and tolerances of the open-die forging of aluminum and other materials depended on the skill of the press operator; however, with the advent of programmable computer-controlled open-die forging presses, it is possible to produce such shapes to overall thickness/width tolerances bands of 1.27 mm (0.050 in.). Because the open-die forging of aluminum alloys is also frequently implemented to produce preforms for closed-die forgings, these state-of-the-art forging machines also provide very precise preform shapes, improving the dimensional consistency and tolerances of the resulting closed-die forging and reducing closed-die forging cost through further input material conservation. More information on open-die forging is available in the article "Open-Die Forging" in this Volume.

Closed-Die Forging. Most aluminum alloy forgings are produced in closed dies. The four types of aluminum forgings shaped in closed dies are blocker-type (finish forging only), conventional (block and finish forging or finish forging only), high-definition (near-net shape produced by forging in one or more blocker dies followed by finish forging), and precision (no draft, net shapes produced by forging with or without blocker dies followed by two or more finish forging steps in the finish dies). These four closed-die forging types are illustrated in Fig. 5, which includes a description of key design and dimensional tolerancing parameters for each forging type.

Blocker-type forgings (Fig. 5a) are produced in relatively inexpensive, single sets of dies. In dimensions and forged details, they are less refined and require more machining than conventional or high-definition closed-die forgings. A blocker-type forging costs less than a comparable conventional or high-definition forging, but it requires more machining.

Conventional closed-die forgings (Fig. 5b) are the most common type of aluminum forging. They are produced with either a single set of finish dies or with block-and-finish dies, depending on the design criteria. Conventional forgings have less machine stock and tighter tolerances than blocker-type forgings but require additional production costs, both for the additional die set and for additional forging fabrication steps required to produce this type.

High-Definition Forgings. With the advent of state-of-the-art forging press and supporting equipment and enhanced forging process control, as are discussed below, high-definition, near-net-shape, closed-die forgings illustrated in Fig. 5(c) can be produced. High-definition closed-die forgings offer superior forging design sophistication and tolerances over conventional or blocker-type forgings and therefore enable even further reduction in final component machining costs. High-definition forgings are produced with multiple die sets, consisting of one or more blocker dies and finish dies, and are

frequently used in service with some as-forged surfaces remaining unmachined by the purchaser.

Precision forgings (Fig. 5d) represent the most sophisticated aluminum forging design produced. These forgings, for which the forger may combine forging and machining processes in the fabrication sequence, cost more than other aluminum forging types. However, by definition precision forgings require no subsequent machining by the purchaser and therefore may be very cost effective. Net-shape aluminum forgings are produced in two-piece, three-piece through-die, and/or multiple-segment wrap-die systems to very restricted design and tolerances necessary for assembly. Net-shape aluminum forgings are discussed more thoroughly in the section "Aluminum Alloy Precision Forgings" in this article and in the article "Precision Hot Forging" in this Volume. More information on the closed-die forging process is available in the article "Closed-Die Forging in Hammers and Presses" in this Volume.

Upset forging can be accomplished in specialized forging equipment called upsetters (a form of mechanical press) or high-speed, multiple-station formers. Upset forging is frequently used to produce forging shapes that are characterized by surfaces of revolution, such as bolts, valves, gears, bearings, and pistons. Upset forging may be the sole process used for the shape, as is the case with pistons, or it can be used as a preliminary operation to reduce the number of impressions, to reduce die wear, or to save metal when the products are finished in closed-dies. Wheel and gear forgings are typical products for which upsetting is advantageously used in conjunction with closed-die forging. As a rule, in the upset forging of aluminum alloys, the unsupported length of forgings must not exceed three diameters for a round shape or three times the diagonal of the cross section for a rectangular shape. The article "Hot Upset Forging" in this Volume contains more information on upsetting.

Roll forging can be used as a preliminary preform operation to preshape the material and reduce metal input or to reduce the number of subsequent closed-die operations. In roll forging, the metal is formed between moving rolls, either or both containing a die cavity, and the process is most often used for parts, such as connecting rods and suspension components, where part production volumes are high and relatively restricted cross-sectional variations typify the part. Roll forging is discussed at length in the article "Roll Forging" in this Volume.

Orbital (rotary) forging is a variant of closed-die mechanical or hydraulic press forging in which one or both of the dies is caused to rotate, usually at an angle to the other die, leading to the incremental deformation of the workpiece between the moving and stationary die. Orbital forging is used to produce parts with surfaces of revolution (such as impellers and discs) with both hot and cold forging processes for aluminum alloys. Orbital forging provides highly

Table 2 Die temperature ranges for the forging of aluminum alloys

Forging process/ equipment	Die temperature	
	°C	°F
Open-die forging		
Ring rolling	95–205	200–400
Mandrel forging	95–205	200–400
Closed-die forging		
Hammers	95–150	200–300
Upsetters	150–260	300–500
Mechanical presses	150–260	300–500
Screw presses	150–260	300–500
Orbital (rotary) forging	150–260	300–500
Spin forging	150–315	200–600
Roll forging	95–205	200–400
Hydraulic presses	315–430	600–800

refined, close-tolerance final shapes. Additional information on orbital forging is available in the article "Radial Forging" in this Volume.

Spin forging combines closed-die forging and computer numerically controlled (CNC) spin forgers or spin formers to achieve close-tolerance, axisymmetric hollow shapes including those shown in Fig. 6. The forgings in this figure were produced using both hot and cold

spin-forging techniques for the aluminum alloy fabricated, illustrating the flexibility of this process. Because spin forging is generally accomplished over a mandrel, inside diameter contours are typically produced to net shape, requiring no subsequent machining. Outside diameter contours can be produced net or with very little subsequent machining and to much tighter out-of-round and concentricity tolerances than

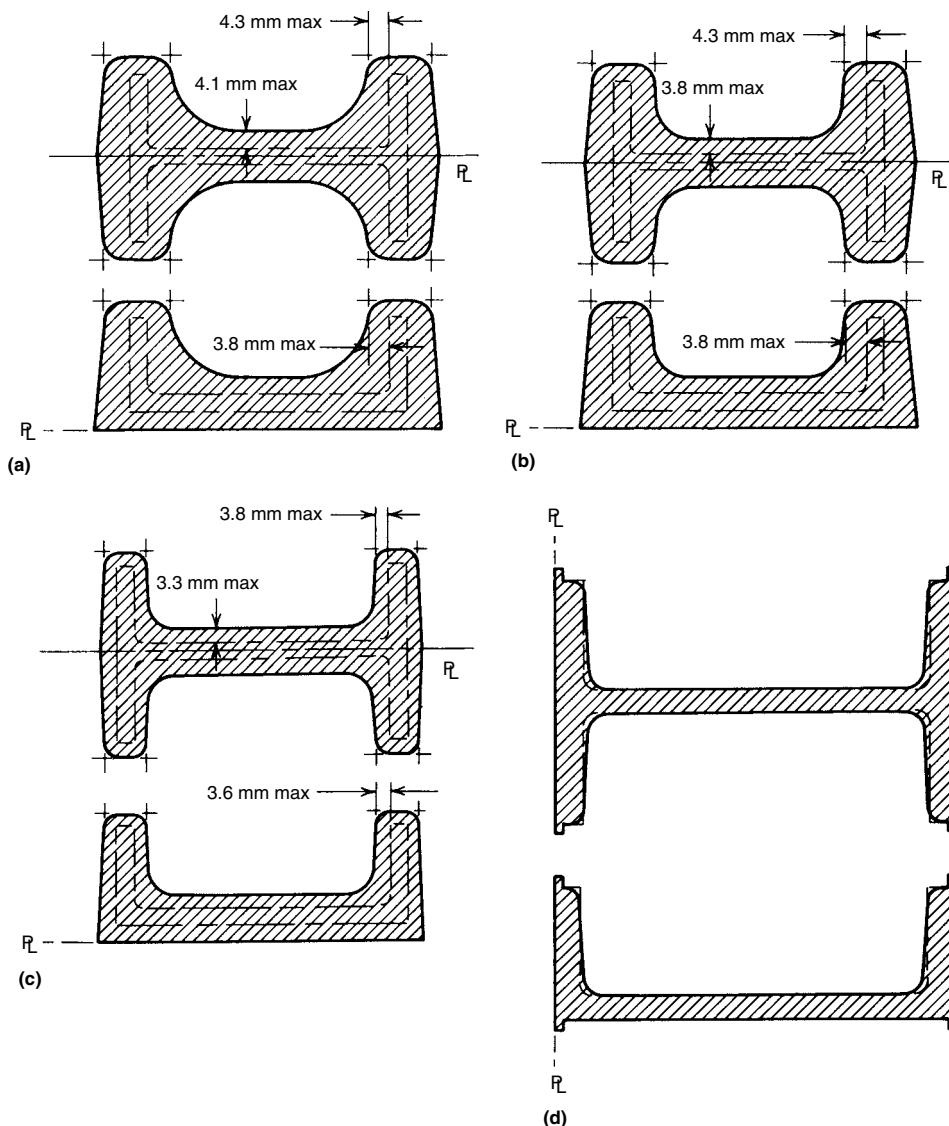
competing forging techniques, such as forward or reverse extrusion (see below), resulting in material savings. Parts with both ends open, one end closed, or both ends closed can also be produced.

Spin forging has been very effectively employed to fabricate high-volume automobile and light truck wheels. Spin-forging processes for wheels, primarily in alloy 6061, have employed several spin-forging processing techniques including hot spin forming of closed-die forged preforms to the final wheel shape followed by heat treatment and machining; multiple cold spin forming steps on preforms to precise, finished dimensions requiring little or no final machining; and/or combined hot spin forging of a preform shape followed by cold spin forming after solution heat treatment and quench and prior to age for precise shape, out-of-round and tolerance control, and reduction in final machining costs.

Ring rolling is also used for aluminum alloys to produce annular shapes. The procedure used to ring roll aluminum alloys is essentially the same as that used for steel (see the article "Ring Rolling" in this Volume). Both rectangular and contoured cross section rolled rings, with or without subsequent machining by the forger, are produced in many aluminum alloys. The temperatures employed for the ring rolling of aluminum alloys are quite similar to those for other forging processes, although care must be taken to maintain metal temperature. The deformation achieved in the ring rolling of aluminum typically results in the predominant grain flow in the tangential or circumferential orientation. If predominant grain flow is desired in other directions, such as axial or radial, other ring-making processes, such as hollow-biscuit open-die forgings, mandrel forging, or reverse/forward extrusion, can be employed. The economy of ring rolling in aluminum alloys depends on the volume, size, and contour of the forging. For some ring parts, it may be more economical to produce the shape by mandrel forging or to cut rings from hollow extruded cylinders. Both techniques are discussed below.

Mandrel forging (Fig. 7) is used in aluminum alloys to produce axisymmetric, relatively simple, hollow ring or cylindrical shapes, in which the metal is incrementally forged, usually on a hammer or hydraulic press, over a mandrel. In the incremental forging process, the wall thickness of the preform is reduced, and this deformation enlarges the diameter of the piece. The mandrel forging of aluminum has been found to be economical for relatively low-volume part fabrication and/or in the fabrication of very large ring shapes (up to 3.3 m, or 130 in., in diameter). With control of the working history of the input material and the mandrel-forging process, mandrel-forged rings can be produced with either circumferential or axial predominant grain orientations.

Reverse or forward extrusion, a variant of closed-die forging for aluminum, can be used to produce hollow, axisymmetric shapes in



Characteristic	Tolerance, mm (in.)			
	Blocker-type	Conventional	High-definition	Precision
Die closure	+2.3, -1.5 (+0.09, -0.06)	+1.5, -0.8 (+0.06, -0.03)	+1.25, -0.5 (+0.05, -0.02)	+0.8, -0.25 (+0.03, -0.01)
Mismatch	0.5 (0.02)	0.5 (0.02)	0.25 (0.01)	0.38 (0.015)
Straightness	0.8 (0.03)	0.8 (0.03)	0.5 (0.02)	0.4 (0.016)
Flash extension	3 (0.12)	1.5 (0.06)	0.8 (0.03)	0.8 (0.03)
Length and width	±0.8 (±0.03)	±0.8 (±0.03)	±0.8 (±0.03)	+0.5, -0.25 (+0.02, -0.01)
Draft angles	5°	5°	3°	1°

Fig. 5 Types of aluminum closed-die forgings and tolerances for each. (a) Blocker-type. (b) Conventional. (c) High-definition. (d) Precision

aluminum alloys with both ends open or with one end closed. The terminology of reverse or forward extrusion refers to the direction of metal movement in relation to the movement of the press cross head. In forward extrusion, the metal is extruded (typically downward) in the same direction as the press head movement. Conversely, for reverse extrusion, metal moves opposite the motion of the cross head. Selection of forward versus reverse extrusion is usually based on part geometry and the open or shut height restrictions of the forging press being used. Some presses are specifically equipped with openings (circular or rectangular holes) in the upper cross head and platen to accommodate the fabrication of very long reverse extrusions, either solid or hollow, that pass through the

moving upper cross head as the deformation progresses.

Extrusion as a metal deformation process frequently plays an important role in closed-die forging of commercially important aluminum alloy parts in addition to the hollow, annular shapes discussed previously, including high-volume automobile and light and heavy truck wheels. In this case, the skirt of the wheel is forward extruded from an appropriately shaped blocker. After hot forward extrusion, the skirt is immediately hot or warm formed to the required finish forged wheel shape that has appropriate machining allowance over the final wheel design. More information on extrusion is available in the articles "Cold Extrusion" and "Conventional Hot Extrusion" in this Volume.

Forging Equipment

Aluminum alloy forgings are produced on the full spectrum of forging equipment, ranging from hammers and presses to specialized forging machines. Selection of forging equipment for a given forging shape and type is based on the capabilities of the equipment, forging design sophistication, desired forging process, and cost. Additional information on the types of equipment used in the manufacture of forgings is available in the Section "Forging Equipment and Dies" in this Volume.

Hammers. Gravity and power-drop hammers are used for both the open-die and closed-die forging of aluminum alloys because of the relatively low fabrication costs associated with such equipment, although the power requirements for forging aluminum alloys frequently exceed those for steel. Hammers deform the metal with high deformation speeds; therefore, control of the length of the stroke and of the force and speed of the blows is particularly useful in forging aluminum alloys, because of their sensitivity to strain rate and their exothermic nature under rapid deformation processes. Power-drop hammers are used to manufacture closed-die forgings if an applied draft of about 5 to 7° can be tolerated. Hammers are frequently used as a preliminary operation for subsequent closed-die forging by other forging processes, and for some products, such as forged aluminum propellers, power-assisted hammers are the optimal forging process equipment because of their capacity for conserving input material and their ability to

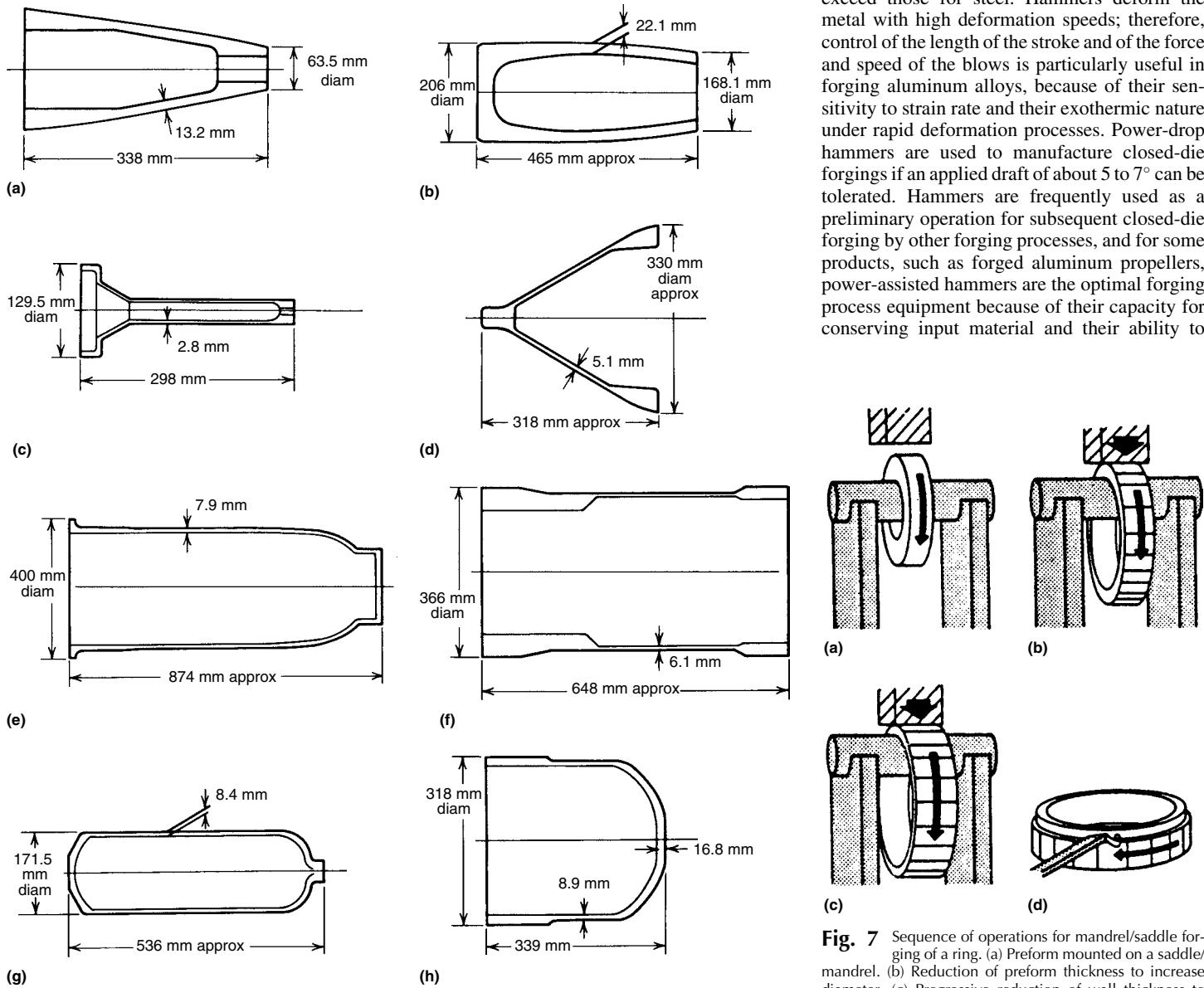


Fig. 6 Examples of spin-forged aluminum alloy shapes. (a) Ordnance ogive. (b) Ordnance center section. (c) Ordnance fuse. (d) Jet engine spinner. (e) Missile nose cone. (f) Missile center section. (g) Bottle. (h) Missile forward case

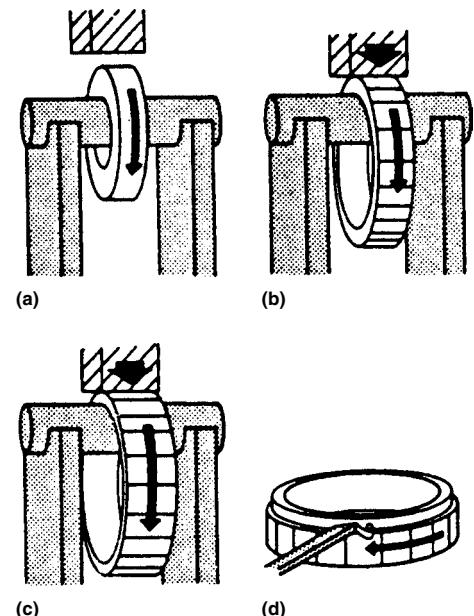


Fig. 7 Sequence of operations for mandrel/saddle forging of a ring. (a) Preform mounted on a saddle/mandrel. (b) Reduction of preform thickness to increase diameter. (c) Progressive reduction of wall thickness to produce ring dimensions. (d) Machining to near-net shape. Source: Ref 1

produce a finished blade that has essentially net airfoil contours. State-of-the-art power-assisted hammers with programmable blow sequencing significantly improve the repeatability and consistency of deformation processes and therefore enhance the consistency of aluminum forgings produced on hammers.

Mechanical and Screw Presses. Both mechanical and screw presses are extensively used for the closed-die forging of aluminum alloys. They are best adapted to aluminum forgings of moderate size, high volume (cost consideration), and relatively modest shapes that do not require extensive open-die preforming. In forging aluminum alloys on mechanical or screw presses, multiple-die cavities, frequently within the same die block, and multiple forging stages, frequently without reheating, are used to enhance the deformation process, to increase the part design sophistication, and to improve tolerance control. The automotive rear knuckle suspension component in alloy 6061 shown in Fig. 8 illustrates the complexity of high-volume aluminum alloy forgings that are producible on mechanical and screw presses. It should be noted that the suspension component forging in Figure 8 requires very limited final machining and that about 80% of the surface area of the part is used in end-product service with as-forged and cleaned surfaces and with no surface treatment.

Mechanical and screw presses combine impact with a squeezing action that is more compatible with the flow characteristics of aluminum alloys than hammers. Screw presses differ from mechanical presses in that the former have a level of strain rate and blow energy control that can be exploited to enhance the overall control of the deformation in forging aluminum alloys. State-of-the-art mechanical and screw presses have programmable press operation, press load and operation monitoring and control, and press energy and press operation control systems. These systems, combined with automated handling and supporting equipment, such as reheat furnaces and trim presses, can be used to achieve full forging process automation and highly repeatable and precise forging conditions

in order to enhance the uniformity of the resulting aluminum alloy forgings. Typically, the minimum applied draft for mechanical or screw press forged aluminum alloys is 3°; however, both press types have been used to manufacture precision, net-shape aluminum alloy forgings with draft angles of 1°. Screw presses are particularly well suited to the manufacture of the highly twisted, close-tolerance aluminum blades used in turbine engines and other applications.

Hydraulic Presses. Although the fastest hydraulic presses are slower acting than mechanical or screw presses, hydraulic presses are frequently best suited to producing either very large aluminum closed-die forgings (Fig. 9) or very intricate aluminum alloy forgings. The deformation achieved in a hydraulic press is more controlled than that typical of mechanical and screw presses or hammers. Therefore, hydraulic presses are particularly well adapted to the fabrication of conventional, high-definition, and precision no-draft, net-shape aluminum alloy forgings in which slow or controlled strain rates and controlled strain minimize the resistance of the aluminum alloy to deformation, reduce unit pressure requirements, and facilitate achieving the desired shape.

State-of-the-art hydraulic forging presses used to forged aluminum alloys, including very large machines of up to 715 MN (80,000 tonf), include speed and pressure controls and programmable modes of operation. With organization of these machines into press cells along with automated workpiece handling and lubrication, state-of-the-art die preheating and on-press die heating and supporting equipment, such press cells provide a high degree of forging process automation and forging process control that enables forging process and product optimization and consistency, improved product uniformity, and significantly enhanced throughput. The minimum applied draft angle for high-definition hydraulic press forged aluminum alloys is 3°; for hydraulic press forged precision, net-shape aluminum forgings, the minimum draft angle is 0 to 0.5° on outside contours and 0.5 to 1° on inside contours.



Fig. 8 Complex aluminum alloy automotive suspension components forged on a mechanical press



Fig. 9 Examples of very large blocker-type aluminum alloy airframe forgings

Die Materials, Design, and Manufacture

For the closed-die forging of aluminum alloys, die materials selection, die design, and die manufacturing are critical elements in the overall aluminum forging process, because the dies are a major element of the final cost of such forgings. Further, forging process parameters are affected by die design, and the dimensional integrity of the finished forging is in large part controlled by the die cavity. Therefore, the forging of aluminum alloys requires the use of dies specifically designed for aluminum because:

- The deformation behavior of aluminum alloys differs from that of other materials; therefore, the intermediate and final cavity die designs must optimize metal flow under given forging process conditions and provide for the fabrication of defect-free final parts.
- Allowances for shrinkage in aluminum alloys are typically greater than those for steels and other materials.
- Temperature control of the dies used to forge aluminum alloys is critical; therefore, the methods used for die preheating and maintaining die temperatures during forging must be considered in the design.

The die materials used in closed-die forging of aluminum alloys are identical to those employed in forging steel alloys except that, because of the higher forces applied in aluminum alloy forging and the design sophistication of the aluminum parts produced, the die materials are typically used at lower hardness levels in order to improve their fracture toughness. Commercially available die materials were primarily designed for the forging of steels and are not necessarily optimized for the demands of aluminum alloy forging processes. However, with advanced steelmaking technology, such as argon oxygen decarburization refining, vacuum degassing, and ladle metallurgy, the transverse ductility and fracture toughness of available standard and proprietary die steel grades have been improved dramatically. As a result, the performance of these grades in the forging of aluminum alloys has also improved dramatically.

Although die wear is less significant with aluminum alloy forging than with steel and other high-temperature materials, high-volume aluminum alloy forgings can present die wear problems in cases in which die blocks have reduced hardness in order to provide improved toughness. Therefore, higher hardness die inserts and/or cavity surface treatments comparable to those used for steel forging dies are often used to improve wear characteristics in order to maintain die cavity integrity for aluminum forging dies. The surface treatments employed include carburizing, nitriding, carbonitriding, and surface alloying using a variety of state-of-the-art techniques.

Beyond die wear, the most common cause of die failure in aluminum forging dies is associated

with die checking or die cracking, which, if left unheeded, can lead to catastrophic loss of the die. Such die checking usually occurs at stress risers inherent in the die cavity features from the design of the forging being produced. Improved toughness die steels, improved die-sinking techniques (see below), improved die design (see below), and lower hardness die blocks serve to reduce the incidence of die checking in dies for forging of aluminum alloys. Numerical modeling of the dies, using state-of-the-art finite element methods (FEM) techniques, is widely used for analysis of die stress, die strain, and thermal conditions as a function of the die design and forging process conditions. With these analytical models, optimization of the die design and/or forging process conditions can be fully evaluated prior to actual die sinking and shop floor use, dramatically increasing die life. Further, aluminum alloy forging dies with die checking or cracking are routinely repair welded using metal inert gas, tungsten inert gas, or other welding techniques. With weld repair and numerical models of the dies, it is possible, through weld rod composition selection, to modify the performance capabilities of critical areas of the die cavity that models have shown to have high stresses or unavoidably severe stress risers.

For hot upsetting, both gripper dies and heading tools are usually made of ASM 6G and 6F2 grade die steels at a hardness of 42 to 46 HRC. This same hardness range applies to 6G and 6F2 dies when used for mechanical and screw presses. Grades 6G or 6F2, or proprietary variants of these steels, are the most widely used die materials in all closed-die forging processes for aluminum alloys. For 6G and 6F2 dies to be used for hammer forging aluminum alloys, a hardness range 36 to 40 HRC is recommended, while for dies used for hydraulic press forging, a hardness range of 38 to 42 HRC is recommended. If the quantities to be forged are large enough to justify the added die cost or if the forging process and the part are particularly demanding, hot-work tool steels such as H11, H12, H13, or proprietary variants, are employed, usually at 44 to 50 HRC.

Die Design. A key element in the cost control of dies for aluminum forging and in the successful fabrication of aluminum alloy forgings is die design and die system engineering. Closed-dies for aluminum forgings are manufactured either as stand-alone die blocks or as inserts into die holder systems to reduce the overall cost of the dies for any given forging. Die holder systems may be universal, covering a wide range of potential die sizes, forging parts, and customers, or the holder(s) may be constructed to handle families or parts of similar overall geometries or for a particular end-product application. Design of aluminum forging dies is highly intensive in engineering skills and is based on extensive empirical knowledge and experience. A complete compendium of aluminum forging design principles and practices is available in Ref 2 to 4.

Because aluminum alloy forging design is engineering intensive, computer-aided design (CAD) hardware and software has had an extensive impact on the aluminum alloy die design process. Computer-aided design techniques for aluminum forging parts and dies are fully institutionalized within the forging industry such that most aluminum alloy die forgings, including blocker-type, conventional, high-definition, and precision forgings, are designed with this technique. The CAD databases created are then used, as discussed below, with computer-aided manufacturing (CAM) to produce dies, to direct the forging process, and to assist in final part verification and quality control. Both public domain and proprietary CAD design software packages are used to design the finished forging from the machined part, including the dies, and to design the critical blocker and preform shapes needed to successfully produce the finished shape, including the dies.

Beyond computer-aided design, heuristic techniques, such as artificial intelligence, are being used to complement CAD/CAM systems by capture of extensive aluminum forging design knowledge and experience into expert systems in order to enhance the speed, accuracy, and efficiency of the forging part and die design and manufacture processes. Complementing CAD and expert systems for aluminum alloy forging design is extensive capture of powerful, state-of-the-art finite element process models that include deformation and thermal analytical modeling techniques to aid the designer and the forging engineer in their tasks by enabling evaluation, verification, and optimization of forging part and die design and forging processing on a computer before committing the part, tooling, and process design to any costly die sinking or tryout part fabrication. These state-of-the-art computer-aided engineering (CAE) systems for aluminum alloy closed-die forgings have effected significant collapse of lead and flow times for fabrication of new forging shapes and improvement in the flow times and consistency of existing forging business.

Die Manufacture. Aluminum alloy forging dies are produced by a number of machining techniques, including hand sinking, copy milling from a model, electrical discharge machining (EDM), and CNC direct sinking including high-speed and ultrahigh-speed die sinking. With the availability of CAD databases, CAM-driven high-speed CNC direct die sinking and EDM die sinking are at the leading edge of the state-of-the-art in aluminum alloy die manufacturing. These techniques serve to reduce the cost of dies, shorten die manufacturing flow times, and, perhaps more importantly, to increase the accuracy of the dies by as much as 50% compared with the other techniques. For example, standard die-sinking tolerances are ± 0.1 mm (± 0.005 in.), but with CAM-driven CNC/EDM die sinking, tolerances are reduced to ± 0.07 mm (± 0.003 in.) on complex dies.

The surface finish on the cavity in dies used for the forging of aluminum alloys is more critical

than that for dies used for steel. Therefore, cavities are highly polished, frequently with automated equipment, by a variety of techniques in order to obtain an acceptable finish and to remove the disturbed surface layer resulting from such die-sinking techniques as electro-discharge machining. However, state-of-the-art high-speed die sinking (e.g., spindle speeds of $>10,000$ rpm) and ultrahigh-speed die sinking (e.g., spindle speeds of $>20,000$ rpm) have dramatically improved the surface finish of dies sunk in the fully hardened state as is the case with die materials used for aluminum alloy forgings. With high- and ultrahigh-speed die sinking, die cavities are suitable for use in forging aluminum without polishing, reducing die manufacturing cost, and flow times.

Processing of Aluminum Alloy Forgings

The common elements in the manufacture of any aluminum alloy forging include preparation of the forging stock, preheating stock, die heating, lubrication, the forging process, trimming, forming and repair, cleaning, heat treatment, and inspection. The critical aspects of each of these elements are reviewed in the sections that follow.

Preparation of Forging Stock. Aluminum alloy forgings are typically produced from cast or wrought stock. The latter includes forged or rolled bar, extruded bar, or plate as primary examples. Selection of forging stock type for a given forging shape is based on the required forging processes, forging shape, mechanical property requirements, and cost. Sawing and shearing are the two methods most frequently used to cut aluminum alloy forging stock into lengths for forging. Abrasive cutoff can be used, but it is slower than sawing.

Sawing with a circular or band saw having carbide-tipped blades is the fastest and generally the most satisfactory method. Sawing, however, produces sharp edges or burrs that may initiate defects when the stock is forged in closed dies. Burrs and sharp edges are typically removed by a radiusing machine. State-of-the-art saws for cutting aluminum alloys are highly automated and frequently have automatic radiusing capability and control systems that permit very precise control of either stock length or stock volume and therefore stock weight.

Shearing is used less for aluminum alloys than for steel because aluminum alloy billets are softer and more likely to be mutilated in shearing and because the sheared ends may have unsatisfactory surfaces for forging without being conditioned. Shearing is successfully used for high-volume aluminum forgings made from wrought bar stock generally less than 50 mm (2 in.) in diameter.

Preheating for Forging. As noted in the section "Effect of Temperature" in this article, workpiece temperature is a critical element in the aluminum forging process. Aluminum alloys

form a very tenacious oxide coating upon heating. The formation of this coating is self-limiting; therefore, aluminum alloys do not scale to the same extent as steel does. However, most aluminum alloys are susceptible to hydrogen pickup during reheating operations such that reheating equipment and practices are also critical elements of forging process control. Recommended preheating temperatures vary with alloy and are contained in Table 1.

Heating Equipment. Aluminum alloys are heated for forging with a wide variety of heating equipment, including electric furnaces, fully muffled or semimuffled gas furnaces, oil furnaces, induction heating units, fluidized-bed furnaces, and resistance heating units. Gas-fired semimuffled furnaces, either batch or continuous, are the most widely used. Heating equipment design and capabilities necessarily vary with the requirements of a given forging process. Both oil and natural gas furnaces must use low-sulfur fuel. Excessive hydrogen pickup in forged aluminum alloys manifests itself in two ways. The first is high-temperature oxidation, which is usually indicated by blisters on the surface of the forging. The second is bright flakes, or unhealed porosity, which is usually found during the high-resolution ultrasonic inspection of final forgings. Both types of hydrogen pickup are influenced by preheating furnace practices and/or furnace equipment in which water vapor as a product of combustion is the primary source of hydrogen. Fully muffled gas-fired furnaces or low relative humidity electric furnaces provide the least hydrogen pickup. Techniques are available for modifying the surface chemistry of aluminum alloys to reduce hydrogen pickup in heating equipment that has higher levels of relative humidity than desired. Protective-atmosphere furnaces are seldom used to preheat aluminum alloy forgings.

Induction heating, resistance heating, and fluidized-bed heating are frequently used in the forging of aluminum alloys in cases in which forging processes are highly automated. State-of-the-art gas-fired furnaces can also be linked with specially designed handling systems to provide full automation of the forging process.

Temperature Control. As noted in Fig. 1 to 3 and in Table 1, aluminum alloys have a relatively narrow temperature range for forging. Therefore, careful control of the temperature in preheating is important. The heating equipment should have pyrometric controls that can maintain $\pm 5^\circ\text{C}$ ($\pm 10^\circ\text{F}$). Continuous furnaces used to preheat aluminum typically have three zones: preheat, high heat, and discharge. Most furnaces are equipped with recording/controlling instruments and are frequently surveyed for temperature uniformity in a manner similar to that used for solution treatment and aging furnaces.

Heated aluminum alloy billets are usually temperature checked by using either contact methods or noncontact pyrometry based on dual-wavelength infrared systems. This latter technology, although sensitive to emissivity, has been successfully incorporated into the fully

automated temperature-verification systems used in automated high-volume aluminum forging processes to provide significantly enhanced temperature control and process repeatability. In open-die forging of aluminum alloys, it is generally desirable to have billets near the high side of the forging temperature range when forging begins and to finish the forging as quickly as possible before the temperature drops excessively. Open-die forging and multiple-blow or stroke closed-die forging of aluminum alloys are frequently conducted without reheating between blows or strokes as long as critical metal temperatures can be maintained.

Heating time for aluminum alloys varies depending on the section thickness of the stock or forgings and the furnace capabilities. However, in general, because of the increased thermal conductivity of aluminum alloys, the required preheating times are shorter than with other forged materials. Recording pyrometric instruments on furnaces can be used to provide an indication of when the metal has reached the desired forging temperature. Generally, times at temperature of 10 to 20 min/in. of section thickness are sufficient to ensure that aluminum alloy workpieces are thoroughly soaked and have reached the desired preheat temperature.

Time at temperature is not as critical for aluminum alloys as for some other forged materials; however, long soaking times offer no particular advantage, except for high-magnesium alloys such as 5083, and may in fact be detrimental in terms of hydrogen pickup. Generally, soaking times at temperature of 1 to 2 h are sufficient; if unavoidable delays are encountered such that soaking time may exceed 4 to 6 h, removal of the workpieces from the furnace is recommended.

Heating of Dies. As noted in the section "Effect of Die Temperature" in this article, die temperature is the second critical process element in the aluminum forging process. Dies are always heated for the forging of aluminum alloys, with die temperatures and die heating for closed-die forging processes being more critical. As noted in Table 2, the die temperature used for the closed-die forging of aluminum alloys varies with the type of forging equipment being employed and the type of forging being produced (open- or closed-die, etc.). Both remote and on-press die heating systems are employed in the forging of aluminum alloys. Remote die preheating systems are usually gas-fired or infrared die systems (usually batch-type) capable of slowly heating and maintaining the die blocks at recommended temperatures in Table 2. These systems are used to preheat dies to the desired temperature prior to assembly into the forging equipment.

On-press die heating systems range from relatively rudimentary to highly engineered systems designed to maintain very tight die temperature tolerances. On-press die heating systems include gas-fired equipment, induction heating equipment, infrared heating equipment, and/or resistance heating equipment. In addition, presses used for the precision forging of alumi-

num alloys frequently have bolsters that have integral heating or cooling capabilities. State-of-the-art on-press die heating equipment for aluminum forging can hold die temperature tolerances to within $\pm 15^\circ\text{C}$ ($\pm 25^\circ\text{F}$) or better. Specific on-press die heating systems vary with the forging equipment being used, the size of the dies, the forging process, and the type of forging produced. On-press die heating equipment is typically more sophisticated for hydraulic press forging of aluminum alloys because the forging process occurs over longer period of time under pressure, and thus die temperature establishes the thermal conditions active during the deformation of the workpiece.

Lubrication. Die and workpiece lubrication is the third critical element in the aluminum forging process and is the subject of major engineering and developmental emphasis, both in terms of the lubricants themselves and the lubricant application systems.

The lubricants used in aluminum alloy forging are subject to severe service demands. They must be capable of modifying the surface of the die and workpiece to achieve the desired reduction in friction, enable the desired deformation without formation of surface defects, withstand the high die and metal temperatures and unit pressures employed, and yet leave the forging surfaces and forging geometry unaffected. Lubricant formulations are typically highly proprietary and are developed either by lubricant manufacturers or by the forgers themselves. Lubricant composition varies with the demands of the forging process used and the forging type. The major active element in aluminum alloy forging lubricants is graphite; however, other organic and inorganic compounds are added to colloidal graphite suspensions in order to achieve the desired results. Liquid carriers for aluminum alloy forging lubricants vary from mineral spirits to mineral oils to water. The trend in liquid-carrier die lubricants for aluminum forging is away from mineral spirits and mineral oils and is moving to increased use of water-based lubricants that significantly reduce emissions, including volatile organic compounds (VOCs). Additionally, powder die lubricants based on graphite and other additives are also available, which not only eliminate VOC emissions but also have less impact on die temperature than water-based lubricants are known to have.

Lubricant application is typically achieved by spraying the lubricant onto the workpiece and dies while the latter are assembled in the press; however, in some cases, lubricants are applied to forging stock prior to reheating or just prior to forging. For liquid carrier lubricants, several pressurized-air or airless spraying systems are employed, and with high-volume, highly automated aluminum forging processes, lubricant application is also automated by single- or multiple-axis robots. Liquid carrier lubricants may be applied with or without heating; however, heating can improve the flowability and performance of the lubricant. For powder lubricants,

electrostatic application techniques are utilized that can also be fully automated. State-of-the-art lubricant application systems have the capability of applying very precise patterns or amounts of lubricant under fully automated conditions such that the forging processes are optimized and repeatable.

Forging Process. The critical elements of the aluminum forging process—workpiece and die temperatures, strain rate, deformation mode, and type of forging process—have been reviewed previously, including state-of-the-art forging process capabilities that have served to enhance control of the forging process and therefore the product it produces. In addition to the enhanced forging equipment employed in the manufacture of aluminum forging, mention was made of the organization of presses and supporting equipment into cells operating as systems; such systems are then integrated with advanced manufacturing and computer-aided manufacturing concepts. Aluminum alloy forging has thus entered an era properly termed integrated manufacturing, in which all aspects of the aluminum forging process from design to execution on the shop floor are heavily influenced by computer technology.

Trimming, forming, and repair of aluminum alloy forgings are intermediate processes that are necessary to achieve the desired finish shape and to control costs.

Trimming. The flash generated in most closed-die aluminum forging processes is removed by hot or cold trimming or sawing, punching, or machining, depending on the size, shape, and volume of the part being produced. Hot or cold die trimming technique is ordinarily used to trim large quantities, especially for moderately sized forgings that are intricate and may contain several punch-outs. The choice of hot or cold trimming is largely based on the complexity of the part, the potential for distortion of the part (greater with hot trimming) and on cost. In cold trimming, two processes prevail: cold trimming after cooling after forging and cold trimming after solution heat treatment and quench. The former process introduces more risk of distortion that will have to be corrected in straightening during heat treatment. The latter process typically results in less straightening but leaves flash intact through heat treatment, reducing throughput in the heat treating processes.

The trim presses employed for cold or hot die trimming are either mechanical or hydraulic. Trimming dies are usually constructed of 6G or 6F2 die steel at a hardness of about 444 to 477 HB. Tools of these steels are less costly because they are often produced from pieces of worn or broken forging dies. Blades for trimming and the edges of trimming dies are frequently hardfaced to improve their abrasion resistance. In addition to these grades, O1 tool steel and/or high-alloy tool steel such as D2 hardened to 58 to 60 HRC have also been used to trim aluminum alloy forgings and may offer longer service lives. Hot trimming of aluminum alloys is usually accomplished immediately after forging without

reheating and generally results in shorter flow times but increased risk of part distortion that will require correction in subsequent processes.

Forming. Some aluminum alloy forging shapes combine hot forging with hot, warm, or cold forming to achieve the shape. As an example, the 6061 alloy aluminum heavy truck wheel shown in Fig. 10 is closed-die forged, which includes forward extrusion of the wheel skirt, and then hot formed to the final shape. Forming is accomplished on mechanical and hydraulic presses and on specialized forming equipment, such as spin formers discussed previously, that are frequently integrated as a part of a forging cell with the forging press.

Repair or conditioning is an intermediate operation that is conducted between forging stages in aluminum alloys. It is frequently necessary to repair the forgings, by milling, grinding, and so forth, to remove surface discontinuities created by the prior forging step so that such discontinuities do not affect the integrity of the final forging product. The need for repair is usually a function of part complexity and the extent of the tooling manufactured to produce the part. There is typically a cost trade-off between increased tooling (or number of die sets) and requirements for intermediate repair that is unique to each forging configuration. Intermediate repair of aluminum alloys is usually accomplished by hand milling, grinding, machining, and/or chipping techniques.

Cleaning. Aluminum alloy forgings are usually cleaned as soon as possible after being forged. The following treatment is a standard cleaning process that removes lubricant residue and leaves a good surface with a natural aluminum color:

1. Etch in a 4 to 8% (by weight) aqueous solution of caustic soda at 70 °C (160 °F) for 0.5 to 5 min.
2. Rinse immediately in hot water at 75 °C (170 °F) or higher for 0.5 to 5 min.
3. Desmut by immersion in a 10% (by volume) aqueous solution of nitric acid at 88 °C (190 °F) minimum.
4. Rinse in hot water.

The caustic etch, rinse, and nitric desmut process is a potential source of problematic emissions and of excessive pitting of the surfaces of the workpieces. Thus, the process and equipment are carefully controlled and maintained. The immersion time in the first two steps varies, depending on the amount of soil to be removed and the forging configuration. The frequency of cleaning during the forging process sequence also depends on the forging configuration, the process used to produce it, and customer specifications. Some forgings are not cleaned until just before final inspection. However, some forging applications and/or customers require a much more rigorous cleaning protocol that involves cleaning after every forging step, prior to heat treatment and prior to final inspection. Additional information on the cleaning of aluminum

alloys is available in the article “Cleaning and Finishing of Aluminum and Aluminum Alloys” in *Surface Engineering*, Volume 5 of *ASM Handbook*, 1994.

Heat Treatment. All aluminum alloy forgings, except 1xxx, 3xxx, and 5xxx series alloys, are heat treated with solution treatment, quench, and artificial aging processes in order to achieve final mechanical properties. The furnaces used to heat treat and age aluminum alloy forgings are either continuous or batch type, fully muffled gas-fired, electric, fluidized-bed, or other specially designed equipment. Aluminum alloy forgings are immersion quenched because this technique is best suited to the relatively low production volumes of forgings and the wide range of forging shapes produced. Because of the shape complexity of aluminum forgings, immersion quench racking procedures are particularly critical to obtaining the uniform and satisfactory quench rates necessary to achieve the required mechanical properties and to minimize quench distortion and residual stresses. Therefore, in addition to control of solution treatment and age temperature and time, racking techniques for forgings are also the subject of necessary heat treatment control processes.

Furthermore, immersion quenching techniques for aluminum alloy forgings are also critical because of their configuration and frequently widely variant cross-sectional thicknesses within the same forging. Depending on the specific aluminum alloy being processed, immersion quench media for forgings include controlled-temperature water from 20 to 100 °C (75 to 212 °F), synthetic quenchants, such as polyalkylene glycol and others additives in water, and



Fig. 10 Forged and formed aluminum alloy 6061-T6 truck wheels

most recently alternate, proprietary quench technologies. All immersion quench media are designed to achieve the necessary quench rate in order to develop the required mechanical properties without excessive distortion or excessive residual stresses, which adversely affect final machining of the component.

State-of-the-art aluminum forging solution treatment and age furnaces have multiple control/recording systems, microprocessor furnace control and operation systems, and quench bath monitoring and recording equipment, including video camera systems, that provide very precise control and repeatability of the heat treatment process. These systems are interfaced with computer integrated manufacturing systems.

Aluminum alloy forgings are often straightened between solution treatment and quench and artificial aging. Straightening is typically accomplished cold using either hand (frequently press assisted) or die straightening techniques.

Many aluminum alloy open- and closed-die forgings in the 2xxx and 7xxx series are compressively stress relieved between solution treatment and quench and aging in order to reduce or control residual stresses and reduce objectionable machining distortion. Depending on the part configuration, such compressive stress relief is accomplished by cold forging of the part with open or closed dies, achieving a permanent set (deformation) of 1 to 5%. With closed-die compressive stress relief, depending on part configuration, cold forging is accomplished either in the hot finish forging dies (temper designation: Txx54) or in a separate set of specially designed cold-work dies (temper designation: Txx52). Some annular and other shapes of aluminum alloy forgings are stress relieved by cold stretching (temper designation: Txx51).

The aluminum forging industry has focused on improving the machining performance of heat treated aluminum forgings to enhance forging competitiveness with other aluminum product forms, especially plate. Specifically, alternative state-of-the-art quench media, such as synthetic quenchants and recently developed proprietary quenchants, are being captured because they act synergistically with enhanced cold compressive stress relief and achieve superior machining performance. Further, state-of-the-art CAD and FEM numerical deformation modeling techniques have been captured in cold compressive stress relief die, part and process design, and analysis. Together these two technologies have dramatically reduced or improved control of forging residual stresses and have enabled equivalent machining performance to plate for closed-die forged shapes. Additional information on the heat treatment of aluminum alloys, including forgings, is available in the article "Heat Treating of Aluminum Alloys" in *Heat Treating*, Volume 4 of *ASM Handbook* (1991) and in Ref 3, 5, and 6.

Inspection of aluminum alloy forgings takes two forms: in-process inspection and final inspection. In-process inspection, using techni-

ques such as statistical process control and/or statistical quality control, is used to determine that the product being manufactured meets critical characteristics and that the forging processes are under control. Final inspection, including mechanical property testing, is used to verify that the completed forging product conforms with all drawing and specification criteria. Typical final inspection procedures used for aluminum alloy forgings include dimensional checks, heat treatment verification, and non-destructive evaluation.

Dimensional Inspection. All final forgings are subjected to dimensional verification. For open-die forgings, final dimensional inspection may include verification of all required dimensions on each forging or the use of statistical sampling plans for groups or lots of forgings. For closed-die forgings, conformance of the die cavities to the drawing requirements, a critical element in dimensional control, is accomplished prior to placing the dies in service by using layout inspection of plaster or plastic casts of the cavities. With the availability of CAD databases on forgings, such layout inspections can be accomplished more expediently with CAM-driven equipment, such as coordinate-measuring machines or other automated inspection techniques. With verification of die cavity dimensions prior to use, final part dimensional inspection may be limited to verifying the critical dimensions controlled by the process (such as die closure) and monitoring the changes in the die cavity. Further, with high-definition and precision aluminum forgings, CAD databases and automated inspection equipment, such as coordinate-measuring machines and two-dimensional (2-D) and three-dimensional (3-D) fiber optics, can be used in many cases for actual part dimensional verification.

Heat Treatment Verification. Proper heat treatment of aluminum alloy forgings is verified by hardness measurements and, in the case of 7xxx-T7xxx alloys, by eddy-current inspection. In addition to these inspections, mechanical property tests are conducted on forgings to verify conformance to specifications. Mechanical property tests vary from destruction of forgings to tests of extensions and/or prolongations forged integrally with the parts. Additional information on hardness and the electrical conductivity inspection and mechanical property testing of aluminum alloys is available in the article "Heat

Treating of Aluminum Alloys" in *Heat Treating*, Volume 4 of *ASM Handbook*, 1991.

Nondestructive Evaluation. Aluminum alloy forgings are frequently subjected to non-destructive evaluation to verify surface or internal quality. The surface finish of aluminum forgings after forging and caustic cleaning is generally good. A surface finish of 125 rms or better is considered normal for forged and etched aluminum alloys. Under closely controlled production conditions, surfaces smoother than 125 rms may be obtained. Selection of non-destructive evaluation requirements depends on the final application of the forging. When required, satisfactory surface quality is verified by liquid-penetrant, eddy-current, and other techniques. Aluminum alloy forgings used in aerospace applications are frequently inspected for internal quality using high-sensitivity ultrasonic inspection techniques.

Forging Advanced Aluminum Materials

The preceding discussion of aluminum alloy forging technology is based primarily on existing, commercially available wrought alloys. However, aluminum alloy development continues to provide advanced aluminum materials designed to enhance the capabilities of aluminum in critical applications, particularly aerospace and automotive components. Alloy development activities pertinent to forgings have been focused on development of improved wrought alloys with superior combinations of mechanical properties, especially strength in heavy sections, fracture toughness, fatigue crack growth resistance, corrosion resistance, reduced density, and fatigue resistance.

Advanced Wrought Aluminum Alloys

Wrought aluminum alloy development has been focused on significantly enhancing the performance capabilities of forgings and other wrought product forms for key aerospace and automotive markets that aluminum alloy products have dominated for some time. Table 3 outlines the nominal compositions of eight recently developed alloys entering commercial-scale production. Forgings are a strong candidate

Table 3 Nominal compositions of newly developed wrought aluminum alloys

Alloy	Developer	Composition, wt%								
		Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Li
2297	McCook	0.10 max	0.10 max	2.8	0.3	0.25 max	0.11	1.4
6069	NWA	0.9	0.40 max	0.77	0.05 max	1.4	0.18	0.05 max
6056	Pechiney	1.01	0.50 max	0.8	0.7	0.9	0.25 max	0.4
7033	Kaiser	0.15 max	0.30 max	1.01	0.10 max	1.75	0.20 max	5.1	0.11	...
7040	Pechiney	0.10 max	0.13 max	1.9	0.04 max	1.05	0.04	6.2	0.08	...
7068	Kaiser	0.12 max	0.15 max	2.01	0.10 max	2.6	0.05 max	7.8	0.1	...
7085	Alcoa	0.06 max	0.06 max	1.65	0.04 max	1.6	0.04 max	7.5	0.11	...
7449	Pechiney	0.12 max	0.15 max	1.75	0.20 max	2.25	...	8.1	0.25 Ti + Zr	...

product for capture of these alloys, thus the unique performance characteristics of each of these alloys is reviewed. Each of these alloys is readily fabricated into open- or closed-die forgings with the processing sequence, equipment, and techniques that have been reviewed.

Alloy 2297 is the most commercially significant aluminum-lithium alloy to have emerged from extensive research and development over the last ten years. While forging applications to date have been limited, the alloy can be successfully produced via closed-die forging with significant input material savings and low buy-to-fly ratios that enable major cost reduction. The alloy, whose application is airframe components, has demonstrated superior specific strength and stiffness properties, reduced density (weight savings), and superior fatigue crack growth resistance to any incumbent aluminum alloy in use.

Alloys 6069 and 6056 have excellent combinations of strength and corrosion resistance for automotive applications, such as suspension component forgings and in airframe component applications. 6069-T6 has strengths about 10% higher than the incumbent alloy 6061-T6 (widely used in forged automotive components) with comparable corrosion resistance and superior fatigue performance. Alloy 6056-T6 has strength and fatigue capabilities on a par with 2024-T4, but unlike 2024 is fully weldable by all existing techniques. Also, 6056-T6 has superior corrosion resistance to the incumbent material in use.

Alloys 7033, 7068, and 7449 are all high-strength or very-high-strength 7xxx series alloys developed to provide significantly enhanced specific (density compensated) mechanical properties for strength and fatigue critical applications. Forgings in 7033-T6 are designed to provide significant weight reductions in automotive structural components over incumbent 6xxx alloys, but at the same time provide good corrosion resistance. In forgings, 7033 can be successfully hot and cold forged and still retain fine grains and excellent microstructures. Alloy 7449 is an alloy intended for aerospace applications, in particular advanced wing structures. While the sheet, plate, and extrusions will be the predominant product forms supplied in 7449, wing structures typically contain forgings as well and thus forgings of this alloy are expected to be commercially important. Finally, 7068-T6 provides among the highest-strength properties of any commercially available aluminum alloy. Forgings in this alloy, whose strengths approach 690 MPa (100 ksi) but concurrently has good toughness and corrosion resistance, are intended for aerospace applications in competition with existing 7xxx series alloys.

Alloys 7040 and 7085 are newly developed high-strength alloys that provide superior combinations of strength, fracture toughness, and fatigue and stress-corrosion resistance in very heavy section thicknesses from 150 to 240 mm (6 to 9.5 in.). Forgings, especially large closed-die forgings, are a key product form for capture

of these alloys in critical airframe structure and thereby to reduce weight. Alloy 7040-T7xxx has been demonstrated to provide up to a 10% increase in strength properties in very heavy sections when compared to incumbent materials such as 7010. 7085-T76xx provides at least a 5% increase in strength in combination with at least a 6% increase in fracture toughness when compared to incumbent materials such as 7050 and has demonstrated full mechanical properties in sections up to 180 mm (7 in.).

Aluminum-Base Discontinuous Metal-Matrix Composites

Discontinuous metal-matrix composites are advanced aluminum materials, where the addition of ceramic particles, or whiskers, to aluminum-base alloys through the use of either ingot melting or casting and/or powder metallurgy (P/M) techniques, creates a new class of materials with unique properties. In these materials systems, the reinforcing material (silicon carbide, aluminum oxide, boron carbide, or boron nitride) is not continuous, but consists of discrete particles within the aluminum alloy matrix. Unlike continuous metal-matrix composites, discontinuous metal-matrix composites have been found to be workable by all existing metalworking techniques, including forging. Addition of the reinforcement to the parent aluminum alloy matrix, typically in volume percentages from 10 to 40%, modifies the properties of the alloy significantly. Typically, compared to the matrix alloy and temper, these property modifications include a significant increase in elastic and dynamic moduli, increase in strength, reduction in ductility and reduction in fracture toughness, increase in abrasion resistance, and increase in elevated-temperature properties, and

no effect on corrosion resistance. A number of discontinuous metal-matrix composite alloy systems are becoming commercially available, based on either 2xxx or 6xxx wrought alloy series.

The forging programs with these materials suggest that reinforcing additions to existing aluminum alloys modify the deformation behavior and increase flow stresses. The fabrication history of such materials may also be critical to their deformation behavior in forging and final mechanical property development. Although the recommended metal temperatures in forging these materials remain to be fully defined, current efforts suggest that temperatures higher than those listed in Table 1 for 2xxx and 6xxx matrix alloys are typically necessary. Forging evaluations have demonstrated that discontinuous metal-matrix composites based on existing wrought aluminum alloys in the 2xxx and 6xxx series can be successfully forged into all forging types, including high-definition and precision closed-die forgings. Some evidence suggests that these materials are more abusive of closed-die tooling and that die lives in forging these materials may be shorter than is typical of the parent alloys.

Aluminum Alloy Precision Forgings

Precision-forged aluminum alloys are a significant commercial forging product that has been the subject of significant technological development and capital investment by the forging industry. For the purposes of this article, the term precision aluminum forgings is used to identify a product that requires no subsequent machining by the purchaser other than, in some cases, the drilling of attachment holes. Figure 11 compares precision aluminum forging design characteristics with those of a conventional

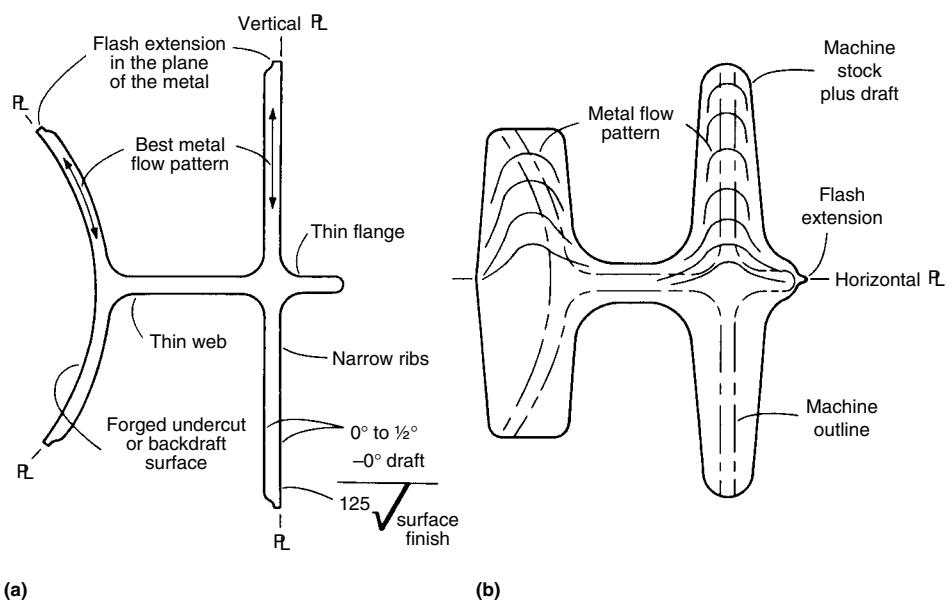


Fig. 11 Cross sections of precision (a) and conventional (b) forgings

aluminum closed-die forging. Precision aluminum forgings are produced with very thin ribs and webs; sharp corner and fillet radii; undercuts, backdraft, and/or contours; and, frequently, multiple parting planes that may optimize grain flow characteristics.

Design and tolerance criteria for precision aluminum forgings have been established to provide a finished product suitable for assembly or further fabrication. Precision aluminum forgings do not necessarily conform to the tolerances provided by machining of other product forms; however, as outlined in Table 4, design and tolerance criteria are highly refined in comparison with other aluminum alloy forging types and are suitable for the intended application of the product without subsequent machining by the purchaser. If the standard design and/or tolerance criteria for precision aluminum forgings are not sufficient, the forging producer frequently combines forging and machining to achieve the most cost-effective method of fabricating the necessary tolerances on the finished aluminum part.

Tooling and Design. Precision aluminum forging uses several tooling concepts to achieve the desired design shape, and selection of the specific tooling concept is based on the design features of the precision-forged part. The three major tooling systems used are illustrated in Fig. 12. A two-piece upper and lower die system

(Fig. 12a) is typically employed to precision forge shapes that can be produced with essentially horizontal parting lines. This system is very similar to the die concepts used for the fabrication of the aluminum alloy blocker, conventional, and high-definition closed-die forgings discussed previously. The three-piece (or through-die) die system, (Fig. 12b) consists of an upper die, a lower die (through-die), and a knockout/die insert. This system is typically employed for parts without undercuts and with vertical parting lines. The final and most complex aluminum precision-forging tooling concept is the holder (or wrap-die) system, which consists of an upper die, a lower die (or holder), and multiple, movable inserts, or wraps (Fig. 12c). The multiple-insert holder/wrap-die system is used to produce the most sophisticated aluminum precision-forged shapes, including those with complex contours, undercuts, and reverse drafts.

The through-die and the holder/wrap multiple-insert die systems for aluminum alloy precision forgings are critical elements in the sophistication of the precision-forging parts that can be produced. Figure 13 provides more insight into the components comprising these two die systems. These tooling concepts emerged in the early 1960s with the development of aluminum alloy precision-forging technology and have since been further refined and developed to provide increases in the size of precision part manufactured (see below).

Because the through-die and holder/wrap-die systems are based on the commonality of significant portions of the tooling to a range of parts or to families of parts, the fabrication of dies for given precision forging is typically restricted to that necessary to produce the inserts. Thus, the cost of die manufacture for precision forgings is reduced when compared to that necessary to produce individual dies for each precision shape. However, aluminum precision forging dies/inserts are usually two to four times more expensive than dies for other forging types for the same part.

The holder/wrap multiple-insert die concept is a highly engineered die system that can use two to six movable segments. Extraction of the part is achieved by lateral opening of the segments (wraps) once they have cleared the bottom die holder. Figure 14 illustrates the components of

the wrap-die system first when the part has been forged (Fig. 14a) and then during extraction of the completed forging (Fig. 14b).

Aluminum alloy precision-forging part and tooling design are engineering-intensive activities that draw heavily on the experience of forging engineers and require interchange between producer and user to define the optimal precision-forging design for utilization, producibility, and cost control. As discussed in the section "Die Materials, Design, and Manufacture" in this article, CAD, CAM, and CAE technologies have been found to be particularly effective in design and tooling manufacture activities for precision

Table 4 Design and tolerance criteria for aluminum precision forgings

Characteristic	Tolerance
Draft outside	$0^\circ + 30', -0$
Draft inside	$1^\circ + 30', -0$
Corner radii	$1.5 \pm 0.75 \text{ mm} (0.060 \text{ to } 0.030 \text{ in.})$
Fillet radii	$3.3 \pm 0.75 \text{ mm} (0.130 \text{ to } 0.030 \text{ in.})$
Contour	$\pm 0.38 \text{ mm} (\pm 0.015 \text{ in.})$
Straightness	$0.4 \text{ mm in } 254 \text{ mm} (0.016 \text{ in. in } 10 \text{ in.})$
Minimum web thickness(a)	$2.3 \text{ mm (0.090 in.)}$
Minimum rib thickness	$2.3 \text{ mm (0.090 in.)}$
Length/width tolerance	$+0.5 \text{ mm, } -0.25 \text{ mm (+0.020 in., } -0.010 \text{ in.)}$
Die closure tolerance	$+0.75, -0.25 \text{ mm (+0.030, } -0.010 \text{ in.)}$
Mismatch tolerance	$0.38 \text{ mm (0.015 in.)}$
Flash extension	$0.75 \text{ mm (0.030 in.)}$

(a) Web thicknesses as small as 1.5 mm (0.060 in.) have been produced in certain forging designs

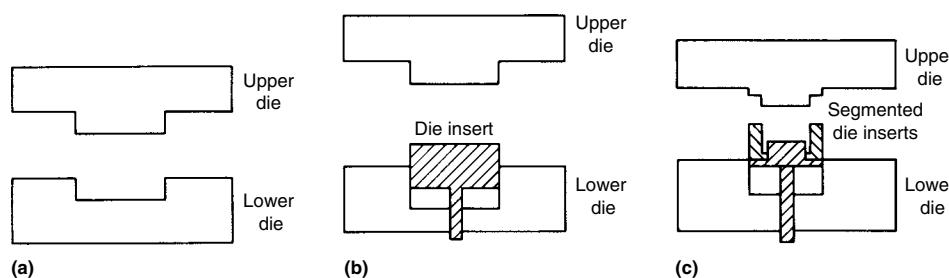


Fig. 12 Tooling concepts used in the manufacture of precision aluminum forgings. (a) Two-piece die system. (b) Three-piece die (through-die) system. (c) Multipiece (wrap) die system. See also Fig. 13

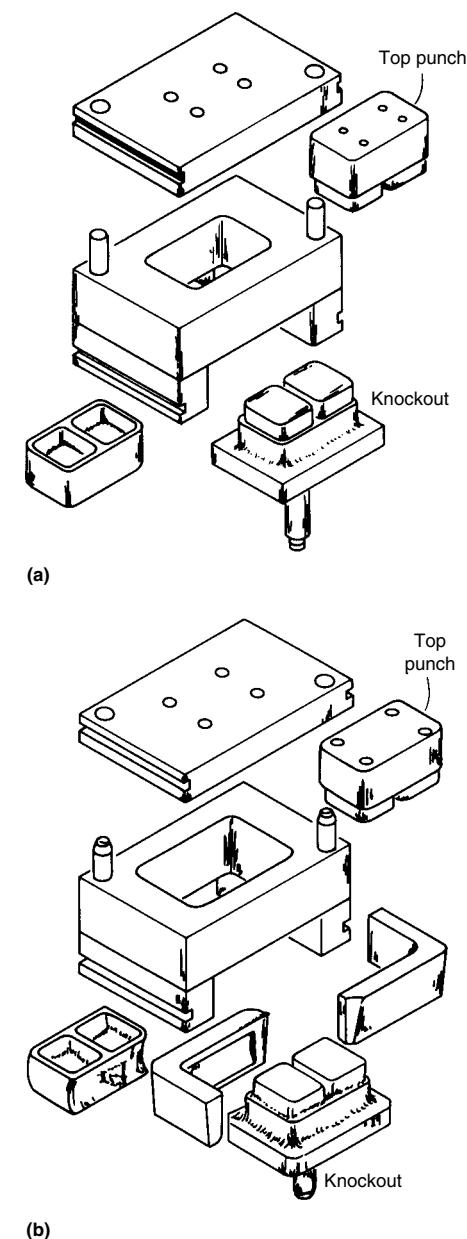


Fig. 13 Components of a three-piece (through-die) system (a) and a multipiece (wrap) die system (b) used for aluminum precision forgings. Source: Ref 7

forgings to improve the design process, to assist in necessary forging process definition, and to reduce the costs of tooling manufacture.

The die materials used in dies, holders, and inserts for precision aluminum forgings are typically of the ASM 6F2 and 6G types. In some cases, inserts for high-volume precision aluminum alloy forgings are produced from hot-work grades, such as H12 and H13. Tooling for precision aluminum alloy forgings is produced by using the same techniques described previously for other aluminum alloy forging types; however, CNC direct die sinking or electrical discharge machining has been found to be particularly effective for the manufacture of the close-tolerance tooling demanded by the design and tolerance criteria for precision aluminum alloy forgings.

Processing. Precision aluminum forgings can be produced from wrought stock, preformed shapes, or blocker shapes, depending on the complexity of the part, the tooling system being used, and cost considerations. Precision aluminum forgings are usually produced with multiple operations in finish dies; trimming, etching, and repair are conducted between operations.

Precision aluminum forgings are typically produced on hydraulic presses, although in some cases mechanical and/or screw presses have been effectively employed. Until recently, most precision aluminum forgings were produced on small to intermediate hydraulic presses with capacities in the range of 9 to 70 MN (1000 to 8000 tonf); however, as the size of precision parts demanded by users has increased, large hydraulic presses in the range of 90 to 310 MN (10 to 35,000 tonf) have been added or upgraded to produce this product. Forging process criteria for precision aluminum forgings are similar to those described previously for other aluminum alloy forging types, although the metal and die temperatures used are usually controlled to near the upper limits of the temperature ranges outlined in Tables 1 and 2 to enhance producibility and to minimize forging pressures. The three-die systems described previously are heated with state-of-the-art die heating techniques. As with other aluminum forging processes, die lubrication is a critical element in precision aluminum forging, and the die lubricants employed, although of the same generic graphite-mineral oil/mineral spirits or graphite-water formulations used for other aluminum forging processes, frequently use other organic and inorganic compounds tailored to the process demands.

Because of the design sophistication of precision aluminum forgings, this aluminum forging product is not supplied in mechanically stress-relieved tempers. However, because of the thin sections and the design complexity of this product, controlled quench rates following solution treatment, using such techniques as synthetic and proprietary quenchants, are routinely employed to reduce residual stresses in the final product and/or to reduce distortion and necessary straightening to meet dimensional tolerances. In-process and final inspection for

precision aluminum forgings are the same as described previously for other forging products, including extensive use of automated inspection equipment, such as coordinate-measuring machines.

Precision aluminum forgings are frequently supplied as a completely finished product that is ready for assembly. In such cases, the producer may use both conventional and nonconventional machining techniques, such as chemical milling, along with forging to achieve the most cost-

effective finished shape. Further, the forging producer may apply a wide variety of surface-finishing and coating processes to this product as specified by the purchaser.

Technology Development and Cost Effectiveness. Table 5 presents a summary of the state-of-the-art in the size of aluminum precision forging producible. The size of precision aluminum forging that can be fabricated to the design and tolerance criteria listed in Table 4 has nearly doubled from 1775 cm^2 (275 in.²)

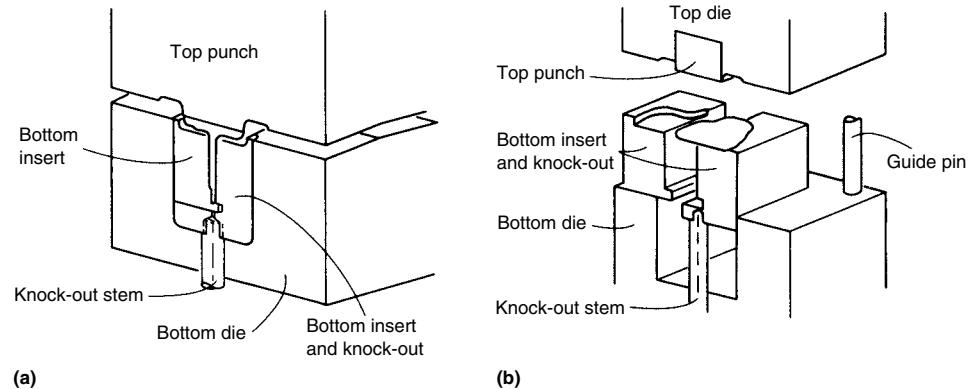


Fig. 14 Multipiece (wrap) die system. (a) During forging. (b) After forging, the die system opens to allow extraction of the completed part

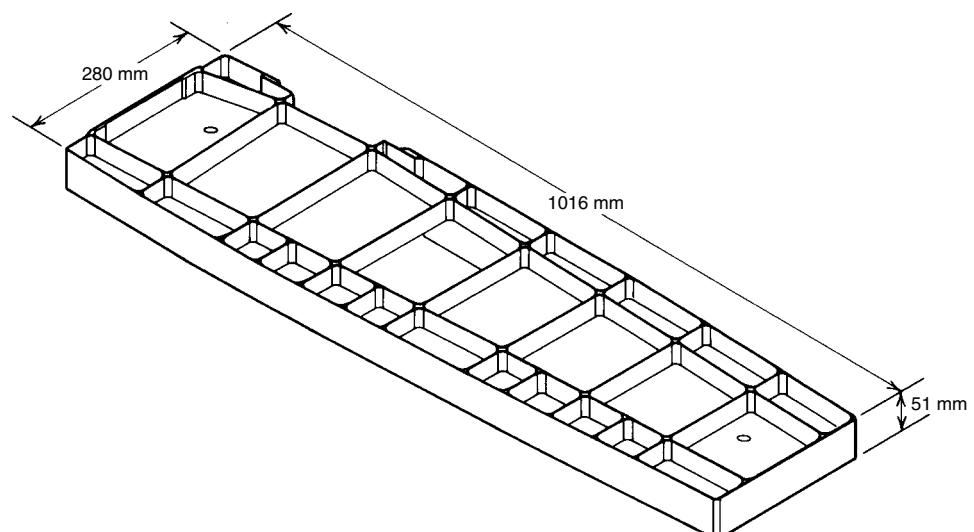


Fig. 15 Very large aluminum alloy 7075-T73 H section precision forging. Plan view area: 2840 cm^2 (440 in.²); ribs 2 to 2.5 mm (0.080 to 0.100 in.) thick, 51 mm (2 in.) deep; webs typically 3 mm (0.120 in.), 2 mm (0.080 in.) in selected areas; finished weight: 5.6 kg (12.3 lb)

Table 5 Capabilities of the precision aluminum forging process based on part size

Forging type	Feature	Maximum size that can be processed	
		Past	Present
T or U section	Plan view area	2580 cm^2 (400 in. ²)	3870 cm^2 (600 in. ²)
H section	Length	1015 mm (40 in.)	1525 mm (60 in.)
	Plan view area	1775 cm^2 (275 in. ²)	2580 cm^2 (400 in. ²)
	Length	610 mm (24 in.)	1015 mm (40 in.)

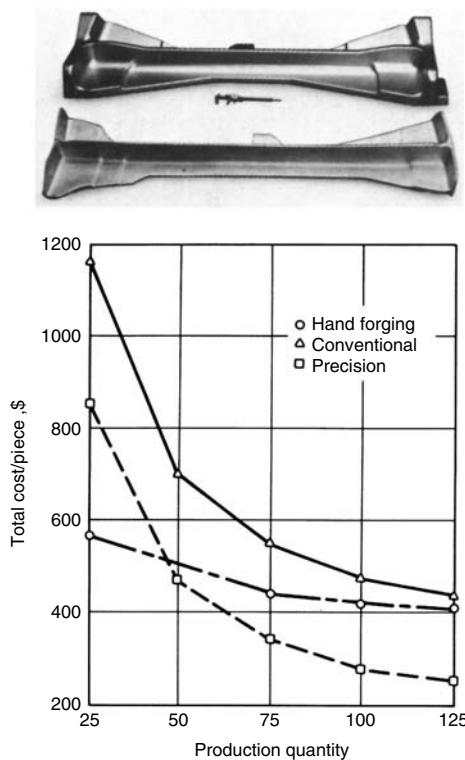


Fig. 16 Cost comparison for the manufacture of an aluminum alloy 7075-T73 component

for H cross sections to more than 2580 cm^2 (400 in.^2) through enhancements in the precision aluminum forging processes and forging and ancillary equipment by forging producers and especially by capture of key enabling technologies such as computer-assisted design and manufacture and 2-D and 3-D FEM deformation and process modeling.

The precision forging shown in Fig. 15 illustrates the very large precision aluminum shapes being fabricated commercially wherein this difficult H cross-section forging has a plan view

area of 2840 cm^2 (440 in.^2). This part incorporates some machining in its manufacturing flow path in selected regions where standard precision-forging tolerances are insufficient for assembly. Critical elements in achieving the current state-of-the-art for aluminum precision parts are enhanced precision forging process control, CAD/CAM/CAE technologies, 2-D and 3-D FEM numerical deformation, process and thermal modeling techniques, advanced and/or integrated manufacturing technologies, and advanced die heating and die lubrication systems. Cost-effective design and fabrication of large, state-of-the-art precision aluminum forgings absolutely demand the capture and exploitation of all of these technologies in order to ensure that the high-strength aluminum precision forged product remains competitive against other component fabrication techniques.

Selection of precision aluminum forging from the candidate methods of achieving a final aluminum alloy shape is based on value analyses for the individual shape in question. Figure 16 presents a cost comparison for a channel-type aluminum alloy part machined from plate, as machined from a conventional aluminum forging, and produced as a precision forging. Costs as a function of production quantity include application of all material, tooling, setup, and fabrication costs. The break-even point for the precision-forging method versus a conventional forging occurs with a quantity of 50 pieces, and when compared to the cost of machining the part from plate, the precision forging is always less expensive. Figure 16 also illustrates the potential cost advantages of precision aluminum alloy forgings. It has generally been found that precision aluminum forgings are highly cost effective when alternate fabrication techniques include multiple-axis machining in order to achieve the final part.

Recent forging industry and user evaluations have shown that precision aluminum forgings can reduce final part costs by up to 80 to 90% in comparison to machined plate and 60 to 70% in comparison to machined conventional forgings.

Machining labor can be reduced by up to 90 to 95%. With such possible cost reductions in existing aluminum alloys and with the advent of more costly advanced aluminum materials, it is evident that further growth of precision aluminum forging use can be anticipated.

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