- Using uniform wall thickness throughout the cross section makes all dimensions easier to control.
- Rounding inside corners makes angles easier to control than when corners are sharp.
- The dimensions of symmetrical shapes are generally easier to control than nonsymmetrical shapes.

Note how some of the issues here are similar to those in injection molding; the reason is that both are internal flow processes.

Extrusion Profiles. Profiles are products that are long in relation to their cross-sectional dimensions and that have cross-sectional profiles other than those of sheet, plate, rod, bar, wire, and tube. Most profiles are produced by extruding and by extruding plus cold finishing; shapes now are rarely produced by rolling due to economic advantages of the extrusion process. Rolling of profiles, also called caliber rolling, is one of the most complex deformation processes.

Table 6 Standard manufacturing thickness limits for aluminum alloy extrusions

Diameter of circumscribing circle, in.	Minimum wall thickness, in. 1060, 1100, 3003	6063	6061	2014, 5086, 5454	2024, 2219, 5083, 7001, 7075, 7079,
Solid and semi-hollow shapes, rod, and bar					
0.5–2	0.040	0.040	0.040	0.040	0.040
2–3	0.045	0.045	0.045	0.050	0.050
3–4	0.050	0.050	0.050	0.050	0.062
4–5	0.062	0.062	0.062	0.062	0.078
5–6	0.062	0.062	0.062	0.078	0.094
6–7	0.078	0.078	0.078	0.094	0.109
7–8	0.094	0.094	0.094	0.109	0.125
8–10	0.109	0.109	0.109	0.125	0.156
10–11	0.125	0.125	0.125	0.125	0.156
11–12	0.156	0.156	0.156	0.156	0.156
12–17	0.188	0.188	0.188	0.188	0.188
17–20	0.188	0.188	0.188	0.188	0.250
20–24	0.188	0.188	0.188	0.250	0.500
Class 1 hollow shapes(a)					
1.25–3	0.062	0.050	0.062	. . .	. . .
3–4	0.094	0.050	0.062	. . .	. . .
4–5	0.109	0.062	0.062	0.156	0.250
5–6	0.125	0.062	0.078	0.188	0.281
6–7	0.156	0.078	0.094	0.219	0.312
7–8	0.188	0.094	0.125	0.250	0.375
8–9	0.219	0.125	0.156	0.281	0.438
9–10	0.250	0.156	0.188	0.312	0.500
10–12.75	0.312	0.188	0.219	0.375	0.500
12.75–14	0.375	0.219	0.250	0.438	0.500
14–16	0.438	0.250	0.375	0.438	0.500
16–20.25	0.500	0.375	0.438	0.500	0.625
Class 2 and 3 hollow shapes(b)					
0.5–1	0.062	0.050	0.062	. . .	. . .
1–2	0.062	0.055	0.062	. . .	. . .
2–3	0.078	0.062	0.078	. . .	. . .
3–4	0.094	0.078	0.094	. . .	. . .
4–5	0.109	0.094	0.109	. . .	. . .
5–6	0.125	0.109	0.125	. . .	. . .
6–7	0.156	0.125	0.156	. . .	. . .
7–8	0.188	0.156	0.188	. . .	. . .
8–10	0.250	0.188	0.250	. . .	. . .

(a) Minimum inside diameter is one-half the circumscribing diameter, but never under 1 in. for alloys in first three columns or under 2 in. for alloys in last two columns. (b) Minimum hole size for all alloys is 0.110 in.^{2} in area of 0.375 in. in diam.

Standard structural profiles such as I-beams, channels, and angles produced in alloy 6061 are made in different and fewer configurations than similar profiles made of steel; the patterns especially designed for aluminum offer better section properties and greater structural stability than those designed for steel, as a result of more efficient metal use. The dimensions, weights, and properties of the alloy 6061 standard structural profiles, along with other information needed by structural engineers and designers, are contained in the *Aluminum Design Manual,* published by the Aluminum Association, Inc.

Many custom and complex cross-sectional designs are possible with aluminum extrusion leading to the establishment of three broad categories of profiles:

- *Solid profiles:* Extruded cross sections that do not incorporate enclosed or partially enclosed voids (examples of solid profiles are I-beams and C-channels; refer to Table 7 and related information to discern solid from semi-hollow profiles.)
- *Hollow profiles:* Extruded cross sections that contain one or more completely enclosed voids in one or more portions of its overall shape geometry. Hollow sections are feasible, though they cost about 10% more per pound produced. The added cost is often compensated for by the added torsional stiffness that the hollow shape provides. It is best if hollow sections can have a longitudinal plane of symmetry.
- *Semi-hollow profiles:* Extruded cross sections that contain one or more partially enclosed voids in one or more portions of its overall shape geometry (see also Table 8) A semi-hollow feature is one that requires the die to contain a very thin, and, therefore, relatively weak neck. For this reason semi-hollow features should be avoided.

The 6*xxx* series (Al-Mg-Si) alloys, because of their easy extrudability, are the most popular alloys for producing profiles. Alloys of the 2*xxx* and 7*xxx* series are used in applications requiring higher strength.

To further describe hollow and semi-hollow profiles and to provide greater distinction from solid type profiles, classes of profiles have been defined for producers and users (Table 7). The partially enclosed voids of semi-hollow profiles are classified in Table 8, and consider the ratio of the cross-sectional area of the partially enclosed void to the square of the gap dimension. This calculated ratio when greater than the value listed in Table 8 for the applicable semi-hollow class and alloy group confirm the classification as a semi-hollow profile; otherwise, it is deemed a solid-shape profile.

Extrusion Profile Design. Full utilization of this capability of the extrusion process depends on the ingenuity of designers in creating new and useful configurations. However, the alloy extruded and the cross-sectional design greatly influences tooling cost, production rate, surface finish, and production cost. Producibility is limited by metal-flow characteristics and is a function of alloy composition, extrusion temperature, press size, and profiles complexity. As previously noted, complexity and production difficulty are related to a "shape factor" (Fig. 9), which is the ratio of the perimeter of a shape to its weight per unit length. Limits on minimum practical thickness, which depend on circle size, classification, and alloy, are given in Table 6. Increasing thickness aids extrusion, and profiles s having uniform thickness are most easily extruded. Although weight and metal cost decrease with decreasing thickness, the increasing extrusion cost can offset the savings in metal cost.

Whether a solid, hollow, or semi-hollow profile type, the overall size of the cross section is a basic consideration. The circumscribing circle size, or the diameter of minimum circle that can contain the extremities of the cross section of the profile, is a parameter that is useful in determining the best match to press production equipment, overall economics of manufacture, and opportunities for multihole tooling, where more than one lineal extrusion can be produced simultaneously.

Table 7 Hollow and semi-hollow profile classes

Class	Description
Hollow profiles	
Class 1	Contains a single, round void that is equal to or greater than 25 mm (1 in.) in diameter and is symmetrical to its exterior geometry on two axes
Class 2	Contains a single, round void that is equal to or greater than 9.53 mm (0.375 in.) in diameter or a single, nonround void that is equal to or greater than 0.710 cm^2 (0.110 in.^{2}) in area and that does not exceed a 127 mm (5 in.) diam circumscribing circle of its exterior features and is other than a class 1 hollow
Class 3	Any hollow profile other than Class 1 or Class 2 hollow (Class 3 hollow would include multivoid hollow profiles.)
Semi-hollow profiles	
Class 1	Contains two or less partially enclosed voids in which the area of the void(s) and the area of the surrounding wall thickness are symmetrical to the centerline of the gap feature of the profile
Class 2	Any semi-hollow profile other than class 1 semi-hollow. Class 2 semi-hollow would include nonsymmetrical void surrounded by symmetrical wall thickness, or symmetrical void surrounded by nonsymmetrical wall thickness.

Table 8 Semi-hollow profile classification

	Ratio(a)			
	Class 1(b)		Class 2(b)	
Gap width, in.	Alloy group A	Alloy group B	Alloy group A	Alloy group B
0.040–0.062	2.0	1.5	2.0	1.0
0.063–0.124	3.0	2.0	2.5	1.5
0.125–0.249	3.5	2.5	3.0	2.0
0.250–0.499	4.0	3.0	3.5	2.5
0.500–0.999	4.0	3.5	3.5	2.5
1.000–1.999	3.5	3.0	3.0	2.0
≥2.000	3.0	2.5	3.0	2.0

(a) Ratio = void area (sq. in.)/gap width^2 (in.). (b) Alloy Group A: 6061, 6063, 5454, 3003, 1100, 1060; Alloy Group B: 7079, , 7075, 7001, 6066, 5066, 5456, 5086, 5083, 2024, 2014, 2011. Use void-gap combination that yields the largest calculated ratio, whether the innermost void and gap of the profile or the entire void and gap features.

The circumscribing circle size, together with the profile type and class, are considered with the parameters of extrusion tolerances, the extruded surface finish, and alloy, when developing an extrusion design and its tooling. It is common to select an alloy for extrusion based on more than one material performance characteristic. Parameters often considered in profile design and product performance are:

- Ease of extrusion
- Control of tolerances
- Length of extruded lineal (not alloy dependent)
- Mill finish (or as-extruded) appearance
- Response to subsequent finishing (anodizing)
- Temper and tensile strength
- Electrical conductivity
- Corrosion resistance
- Weldability
- Machinability
- Recyclability

Multipurpose Profile Design. Extrusion profiles can be designed to handle multiple purposes within the same part. An extruded heat sink, for example, can also include screw bosses and dovetails in its design for attachment purposes. As another example, a hollow profile extrusion can have multiple voids for carrying different fluid media, as well as external cooling fins, attachment features, and stiffening ribs.

Alternatively or in addition to multiple function features, extruded profile design can also combine designs and functions of multiple parts into a single, one-piece aluminum extrusion. An integral extruded design that replaces multiple components can eliminate assembly and joining steps, associated jigs and fixtures, fasteners, and multiple part inventories, resulting in a more cost-competitive approach overall. Often, final product reliability and performance are also improved with one-piece, integral extrusion designs.

Connection Features of Extruded Profiles. It is increasingly common to include an interconnecting feature in the design of an extruded shape to facilitate its assembly to a similar shape or to another product. Aluminum extrusions can be designed with connection features and appendages to simplify assembly with other components and materials. Mating surfaces, snap-fits and interlocking joints, dovetails, screw boss slots, nested and tongue-and-groove joints for fasteners and welding, and key-locked joints can be used alone or in combination with other product components or with other extrusions. It is also possible to incorporate rotational joints, such as hinges, into the cross-sectional design of the extruded profile.

Finishes. Extruded profiles, rod, bar, pipe, and tube can be subsequently finished for cosmetic and/or functional purposes. Opaque films such as paint and plating can be applied to aluminum extrusions as well as transparent or semitransparent integral anodized coatings. Most industrial methods of application can also be used, including spray, dip, and powder coating, and electrodeposition.

Mechanical pretreatments, such as scratch brushing and polishing, can precede anodizing or can be applied as the final surface finish. Chemical pretreatments, such as etching and bright dipping, can precede anodizing either alone or in combination with mechanical treatments. Other chemical pretreatments, such as conversion coating, can also be used to improve paint film adhesion.

Anodizing is an electrolytic process and its resultant coating is integral with the aluminum surface, thus the response in appearance from anodizing is alloy dependent. Further, the preceding chemical prefinishes, if used, can also respond differently to different aluminum alloys. Hardcoat anodizing can be applied to aluminum extrusions to provide wear-resistant surfaces.

To assist in the handling of extrusions that have aesthetic applications, portions of the extruded profile that will be exposed in use or areas whose surface condition is crucial are usually identified. This information on exposed surface(s) is communicated to both extrusion production and finishing operations and is used to select handling procedures, protective packaging, and shipping methods.

Bar, Rod, and Wire

Bar, rod, and wire are defined as solid products that are extremely long in relation to their cross section. They differ from each other only in cross-sectional shape and in thickness and diameter. When the cross section is round or nearly round and is over 10 mm (0.40 in.) in diameter, it is called *rod*. It is called *bar* when the cross section is square, rectangular, and in the shape of a regular polygon, and when at least one perpendicular distance between parallel faces (thickness) is over 10 mm. *Wire* refers to a product, regardless of its cross-sectional shape, whose diameter or greatest perpendicular distance between parallel faces is 10 mm or less.

Rod and bar can be produced by either hot rolling or hot extruding and brought to final dimensions with or without additional cold working. Wire usually is produced and sized by drawing through one or more dies, although roll flattening also is used. Alclad rod and wire for additional corrosion resistance is available in certain alloys. Many aluminum alloys are available as bar, rod, and wire; among these alloys, 2011 and 6262 are specially designed for screw-machine products, and 2117 and 6053 for rivets and fittings (Table 1). Alloy 2024-T4 is a standard material for bolts and screws. Alloys 1350, 6101, and 6201 are extensively used as electrical conductors. Alloy 5056 is used for zippers, and Alclad 5056 for insect-screen wire.

Extruded Rod, Bar, and Wire. Extruded rod is a specific form of solid extrusion, though not termed as a solid "profile;" that is, a round cross section of 10 mm (0.375 in.) or greater in diameter. Extruded bar follows the criteria for extruded rod except rather than round in shape, extruded bar is square, rectangular, hexagonal, and octagonal, and has a width between parallel faces of 10 mm or greater. Square extruded bar, rectangular bar, hexagonal bar, and octagonal bar can have either sharp or rounded corners. Extruded wire is extruded rod or bar where the dimension across the shape is less than 103 mm.

Hot-Rolled Rod. In hot rolling, usually square sections are converted by into intermediate shapes or passes, that is, roll pass design. Aluminum bars, rods and profiles are made by hot rolling cast ingots, usually 10 × 10 cm and 20 × 20 cm (4 × 4 in. and 8 × 8 in.), with rolls shaped to produce the desired end product. Two types of roll pass design for rolling rod are illustrated in Fig. 10. The hot bar or rod is passed automatically through a number of sets of rolls that have smaller and smaller openings.

Tubular Products

Tubular products include tube and pipe. They are hollow wrought products that are long in relation to their cross section and have uniform wall thickness except as affected by corner radii. Tube is round, elliptical, square, rectangular, and regular polygonal in cross section. When round tubular products are in standardized combinations of outside diameter and wall thickness, commonly designated by "nominal pipe sizes" and "ANSI schedule numbers," they are classified as pipe.

Tube and pipe can be produced from a hollow extrusion ingot, by piercing a solid extrusion ingot, and by extruding through a porthole die and bridge die. They also can be made by forming and welding sheet. Tube can be brought to final dimensions by drawing through dies. Tube (both extruded and drawn) for general applications is available in such alloys as 1100, 2014, 2024, 3003, 5050, 5086, 6061, 6063, and 7075 (Table 1). For heat-exchanger tube, alloys 1060, 3003, Alclad 3003, 5052, 5454, and 6061 are most widely used. Clad tube is available only in certain alloys, and is clad only on one side (either inside or outside).

Extruded tube (Fig. 11) is a specific form of hollow extrusion, though not termed as a hollow "profile." Extruded tube is symmetrical with uniform wall thickness and can be round, elliptical, square, rectangular, hexagonal, and octagonal. Square extruded tube, rectangular tube, hexagonal tube, and octagonal tube can have either sharp or rounded corners. Extruded pipe is a specific form of hollow extrusion that meets the criteria for extruded tube and also meets certain standardized combinations of outside diameter and wall thickness.

Large thick-walled tubes, or "blooms," for subsequent tube drawing are made by extrusion. Methods used to produce blooms include:

A steel tapered mandrel is placed in the ram end of a hollow extrusion billet so it protrudes into the die of the extrusion press (Fig. 12a). The extrusion billet for the process is either a casting with a hollow center, or made from a solid casting by drilling out the center. The tube bloom is formed during extrusion, the die shapes the outer surface and the mandrel shapes the inner surface.

A floating mandrel (one which is not fixed to the ram) can be used instead of the fixed mandrel described above. The metal flows in the same way as in the fixed-mandrel method.

A porthole die can be used to extrude small diameter soft aluminum alloy-tubing blooms. The die consists of two parts (Fig. 12b). In the first part, or antechamber, there are several entry ports and an integral mandrel that protrudes through the die opening of the second part. The aluminum enters the portholes in separate streams and is reunited in the welding chamber. The metal is then forced through the clearance between the mandrel and die to form a continuous tubing bloom.

Hot rotary piercing of billets. Another method of production involves hot rotary piercing of billets between skewed rolls, with a mandrel that ensures a high inner-surface quality (Fig.13a). Because the mandrel is in contact with virgin metal at high temperatures, adhesion and wear can be severe. Solutions to the problem include use of heat-resistant materials and surface coatings, and lubrication through a hollow plug.

Rolling of the hollow bloom. Further rolling of the hollow bloom can be done on a pilger mill (Fig. 13b), which performs periodic rolling on a mandrel. The mandrel is lubricated using high-temperature lubricants such as graphited grease, phosphate-containing mixtures, and salt mixtures. The tube can also be rolled on a lubricated mandrel in a continuous mill. In cold pilgering (cold reducing), lubricants appropriate for the metal are used, such as mineral oil with fatty acids for aluminum.

Cold Drawing is a cold working process in which tubes, wires, and rods are produced by pulling suitable starter stock through a die. In producing drawn aluminum tubing, lengths of thick-wall extruded bloom are swaged on one end, then drawn through a die and with a mandrel inserted inside the tube (Fig. 14). The tube is drawn through a series of progressively smaller dies until the desired outside diameter, inside diameter, and wall thickness are obtained. Intermediate annealing could be necessary if the material work hardens to a point that it will break. Likewise, to produce wire, bar, and rod, stock is drawn through a series of dies until the desired size and shape are obtained.

Forgings

Aluminum alloys are forged into a variety of shapes for a broad range of engineered products. Aluminum alloys are very ductile at hot working temperatures, and they do not develop scale during heating. In addition, the forging temperature is relatively low so dies can be heated to nearly the same temperature as the workpiece, which prevents cooling of the workpiece and facilitates flow of metal into small cavities in the die.

The equipment used for forging aluminum is similar to that used for other metals, but many aluminum alloys forge better under the continuous controlled squeezing pressure of a hydraulic press than by the repeated impact of hammers. Aluminum alloys generally require greater working force for an equal amount of metal deformation than low-carbon steels. This is caused by the difference in flow strength levels at their optimum hot working temperatures. Therefore, equipment used for aluminum must supply higher pressures than that used for steel.

The majority of aluminum forgings are made from heat-treatable alloys to obtain high strength. Wherever a choice is possible, lower costs through longer die life, less expensive dies, better forgeability, and less process scrap can be achieved by selecting one of the alloys more easily forged. Alloys 6061 and 6151 forge readily in hammers and presses. Alloys 2024, 5083, 5456, 7050, and 7075 forge less readily in hammers; they are better suited for hydraulic press forgings, particularly for large, complex forgings.

Forging of aluminum alloys is particularly applicable to producing precise, intricate shapes with good surface finish. 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 (Ref 5). Limiting dimensions in design of die forgings include total plan area, which can be as great as

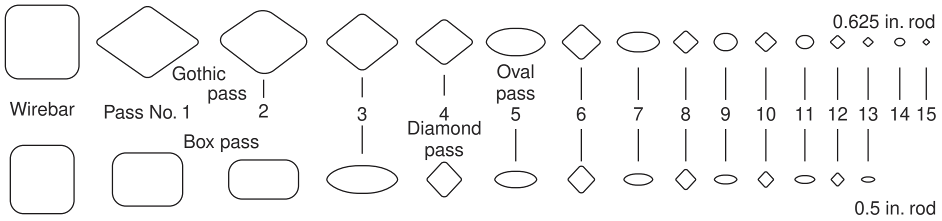

Fig. 10 Example of roll pass designs for aluminum rod rolling

Fig. 11 Tubes used in production of light poles in the Netherlands

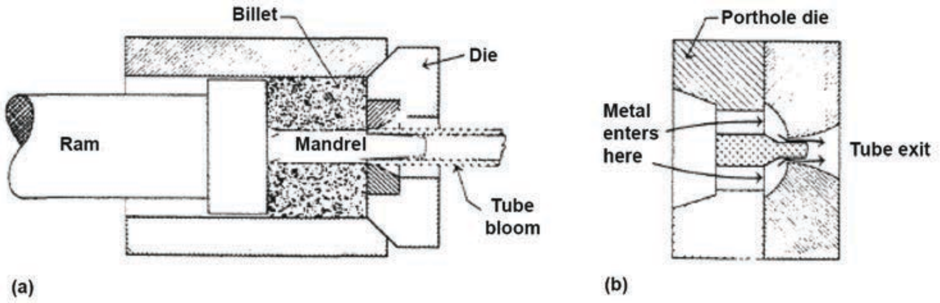

Fig. 12 Direct extrusion of aluminum alloy tube bloom (a) for cold drawing (b)

~0.3 m^2 (~500 $in.^2$) for forgings produced in mechanical presses, ~1.9 m^2 (~3000 $in.^2$) for hammer forgings, and ~3.2 m^2 (~5000 $in.^2$) for parts made in some of the largest hydraulic presses. Very large forging presses (Fig. 15) also are capable of producing large near-net-shape structural forgings (Fig. 16) that can replace multiple-piece sections with high-integrity integral sections. For an equivalent amount of reduction, heavy sections produced by forging have more thoroughly worked structures and more uniform mechanical properties throughout than similar sections that have been produced by rolling and extrusion.

Limiting design features are web thickness, rib thickness and height, draft angles, and minimum radii for fillets and corners (see the article "Forging of Aluminum Alloys" for more details). Part complexity and the design and number of dies used are important in establishing the grain flow pattern in die forgings. Controlling these factors provides optimum metal flow for each part, avoiding transverse flow in areas that are highly stressed in service normal (90°) to the grain flow. Such a condition is usually most pronounced at the parting line, where flash develops and where a strongly defined grain flow results. Forging

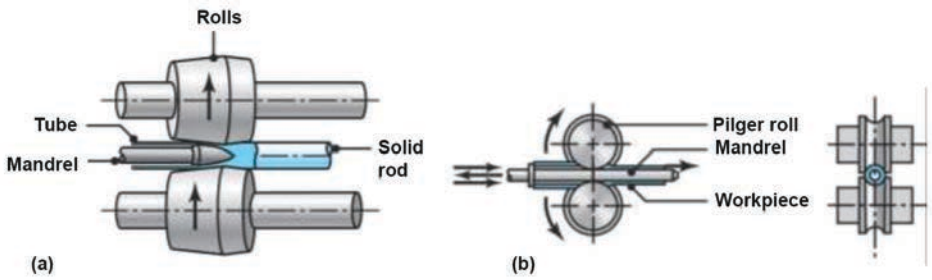

Fig. 13 (a) Roll piercing setup of Mannesmann mill for producing seamless tubing, and (b) pilger rolling over a mandrel and a pair of shaped rolls. Source: Ref 4

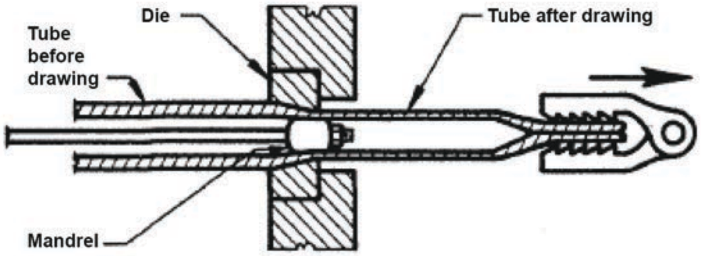

Fig. 14 Schematic of tube drawing

Fig. 15 A 50,000-ton hydraulic press at Arconic-Cleveland

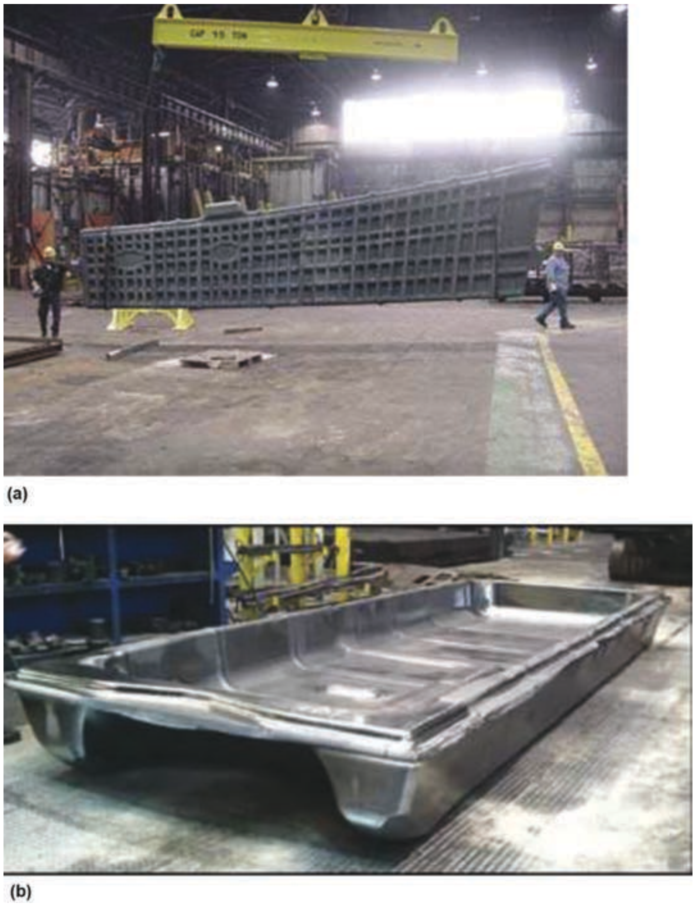

Fig. 16 Large aluminum forgings produced using 50,000-ton hydraulic press at Arconic-Cleveland. (a) Inner wing spar forging for Airbus A380. (b) Single-piece hull forged of aluminum alloy 7020

strength is generally lower across this plane than in any other area, and this factor should be considered in the design of each part.

Forming

Sheet, bar, tube, and wire can be shaped by a variety of forming methods. Bending is the principal forming operation for aluminum bar, tube, shapes and wire. Bending methods include draw bending, various techniques of compression bending, and other more specialized processes such as expanding, flaring, rotary swaging, cold heading, and four-slide forming (see the article "Forming of Aluminum Alloys" in this Volume). Aluminum sheet and plate also can be formed by a wide variety of methods. In addition to the blanking, cutting, and piercing operations of sheet, the commonly used sheet forming operations include bending, stamping, deep drawing, hemming, spinning, embossing, coining, hammer forming, and rubber-die forming (Table 9). These methods are described further in the article "Forming of Aluminum Alloys," but the various methods of sheet forming can be a series of operations in making a product. For example, Fig.17 illustrates the operations used to make an aluminum beverage can.

Aluminum and its alloys are among the more formable materials of commonly fabricated metals. There are differences between aluminum alloys and other metals in the amount of permissible deformation, in some aspects of tool design, and in details of procedure. These differences stem primarily from the lower tensile and yield strengths of aluminum alloys, their lower modulus of elasticity, and their comparatively low rate of work hardening compared with typical draw-quality steels. Some aluminum alloys also have a low, and even negative, strain-rate hardening factor, making them significantly more sensitive to problems related to careless die design.

Table 9 Application of forming processes to aluminum alloy plate, sheet, and foil

	Plate			Sheet			Foil		
Forming process	**Principal**	**Secondary**	**Limited**	**Principal**	**Secondary**	**Limited**	**Principal**	**Secondary**	**Limited**
Blanking									
Die	...	...	X	X	...	...	X	...	...
Laser	...	...	X	X				X	
Fine	...	X	...	X	...	...	...	X	...
Cutting									
Rubber pad	...	...	X	...	X	...	...	X	...
Steel rule dies	...	...	X	X	...	...	...	...	X
Shearing	...	...	X	X	...	...	...	X	...
Sawing	X	...	...	...	...	X	...	...	X
Piercing	...	...	X	X	...	...	X	...	...
Perforating	...	...	X	X	...	...	...	X	...
Bending	X	...	...	X	...	...	X	...	...
Drawing	X	...	...	X	...	...	X	...	...
Spinning	X	...	...	X	...	...	...	...	X
Embossing	...	...	X	X	...	...	X	...	...
Coining	...	...	X	X	...	...	...	...	X
tamping	...	...	X	X	...	...	...	...	X
Hammer forming	...	X	...	X	...	...	...	...	X
Roll forming	...	...	X	X	...	...	...	X	...
Rubber die forming									
Guerin*	...	...	X	X	...	...	...	...	X
Verson-Wheelon*	...	...	X	X	...	...	...	...	X
Marform*	...	...	X	X	...	...	...	...	X
Flexform	...	X	...	X	...	...	...	...	X
Hydroforming**									
Deep Draw	...	...	X	X	...	...	...	...	X
Bulge forming	...	X		X	...	...	...	...	X
Stretch forming	...	...	X	X	...	...	...	...	X
Stretch wrap forming	...	...	X	X	...	...	...	...	X
Expansion forming	...	...	X	X	...	...	...	...	X
CONTRACTING									
Hole flanging	...	X	...	X	...	...	X	...	...
Beading	X	...	...	X	...	...	X	...	...
Ribbing	...	X	...	X	...	...	...	X	...
Explosive forming	X	...	...	X	...	...	...	...	X
Electromagnetic	...	...	X	X	...	...	X	...	...
Electroshape*	...	...	X	X	...	...	...	...	X
Pneumatic mechanical gas	...	...	X	X	...	...	...	...	X
Electrospark (Electrohydraulic)*	...	...	X	X	...	...	...	...	X
Androform*	...	...	X	X	...	...	...	...	X
Peen forming	X	...	...	X	...	...	...	...	X
Air forming	...	...	X	...	...	X	X	...	...
Warm	...	X	...	X	...	...	...	...	X
Superplastic	...	...	X	X	...	...	...	...	X

Formability is a function of the wide range of compositions and tempers available in aluminum alloys, (see also the article "Forming of Aluminum Alloys" in this Volume). Tensile strength, yield strength and formability are among the most important characteristics to be considered in designing formed parts and in forming various alloys and tempers. The choice of alloy can also be governed by requirements for a specific finish. Another major aspect of formability relates to the consistency of producing nominally identical parts in sufficient quantity. Variation in yield strength, strain hardening, and gage, or thickness, can all contribute to poor formability in a given coil and lot of material.

Most of the equipment used in the forming of steel and other metals is suitable for use with aluminum alloys. Because of the generally lower yield strength of aluminum alloys, press tonnage requirements are usually lower than for comparable operations on steel and higher press speeds can be used. Similarly, equipment for roll forming, spinning, stretch forming, and other forming operations on aluminum need not be so massive or rated for such heavy loading as for comparable operations on steel.

In many forming operations, especially aluminum, it is necessary to compensate for springback. Springback refers to the elastic response when the external forming forces are removed. The elastic modulus and yield strength are the first-order material parameters that influence undesirable shape change due to springback. The amount of recoverable stored energy (ΔE_r) decreases as the elastic modulus (E) increases and as the yield strength decreases. This can be understood as basic aspect of a stress-strain (σ-ε) curve, where $\Delta E_r \approx \sigma \times \varepsilon = \sigma^2/E$.

Springback is more pronounced in alloys and tempers with high yield strength than in those with low yield strength. For a given metal, the amount of springback is roughly proportional to the yield strength of the metal. With a lower elastic modulus, springback increases. Compared with steel, the elastic modulus of aluminum and aluminum alloys is lower by ratio of about 3 to 1. Aluminum and aluminum alloys also are susceptible to the Bauschinger effect, which is a stress-strain asymmetry that results in a stress-strain hysteresis loop. Two identical sheet metal specimens can have the same final total strains, but have distinctly different springback amounts. The reason is that their deformation histories are different.

For intricate sheet forming operations, it is necessary to use annealed (condition O) material with the solid-solution alloys. Heat-treated alloys also can be formed at room temperature immediately after quenching (W temper). Final strength is developed by heat treating after forming. The forming operation should be carried out as soon after quenching as possible, because natural aging occurs at room temperature on all the heat treatable alloys. The natural aging can be delayed to a certain extent by placing the part in a cold storage area of 0 °C (32 °F) or lower. The lower the temperature, the longer the delay to a point where maximum delay is obtained.

Warm Forming is another way to improve formability, especially of the 5*xxx* and 6*xxx* series used for weight reduction in automotive applications. Aluminum alloys have low formability compared with draw-quality steel, and stamping of aluminum alloys present challenges in obtaining good part definition (e.g., corner and fillet radii, draw depth). Warm forming of aluminum sheet is a way to increase ductility and formability. Warm forming involves heating the blank, controlling the die temperature, and the use of appropriate lubrication and forming press. Costs are increased, but warm forming of aluminum sheet at reasonable production rates has become a realistic alternative to straight stamping (see the article "Forming of Aluminum Alloys" for more details.

Under rapid forming conditions at low forming temperatures, cavitation in aluminum alloys is generally found (Ref 6), and faster forming rates are obtained by punch-die technology sheet stamping at elevated temperatures. This has led to the development of warm forming technologies, which use embedded heating elements in the punch and die systems. Figure 18 shows an arrangement for a heated-die system for warm stamping of aluminum alloys. This was developed with integrally embedded heating elements within punch-die systems rather than gas pressure-forming systems. Part forming with 5083-type aluminum alloys has been demonstrated in less than a minute per part, and hundreds of parts have been produced (Ref 8, 9). Using warm-forming technology, full-scale parts such as the Chrysler Neon inner door panel were successfully formed from fine-grain 5182 aluminum alloy containing 1% Mn at the rate of one minute per part (Fig. 18c).

Punchless-Forming Methods. The use of warm-forming technology in production of full-scale parts such as the Chrysler Neon inner door panel spawned work on rapid gas pressure-forming technologies. In a practical forming operation, the ability to make a part is not only governed by the formability of a material (which is related to the magnitudes of the strains available without failure), but also the ability to uniformly distribute strain is crucial. The total increase in part surface area is related to the total average amount of stretching over the part. In conventional stamping, friction causes the strain distribution to become quite nonuniform. In punchless-forming operations (such as hydroforming, gas-pressure forming, and high-velocity forming), strain distributions can be much more uniform, which facilitates forming many common component geometries, because strains are more uniformly distributed.

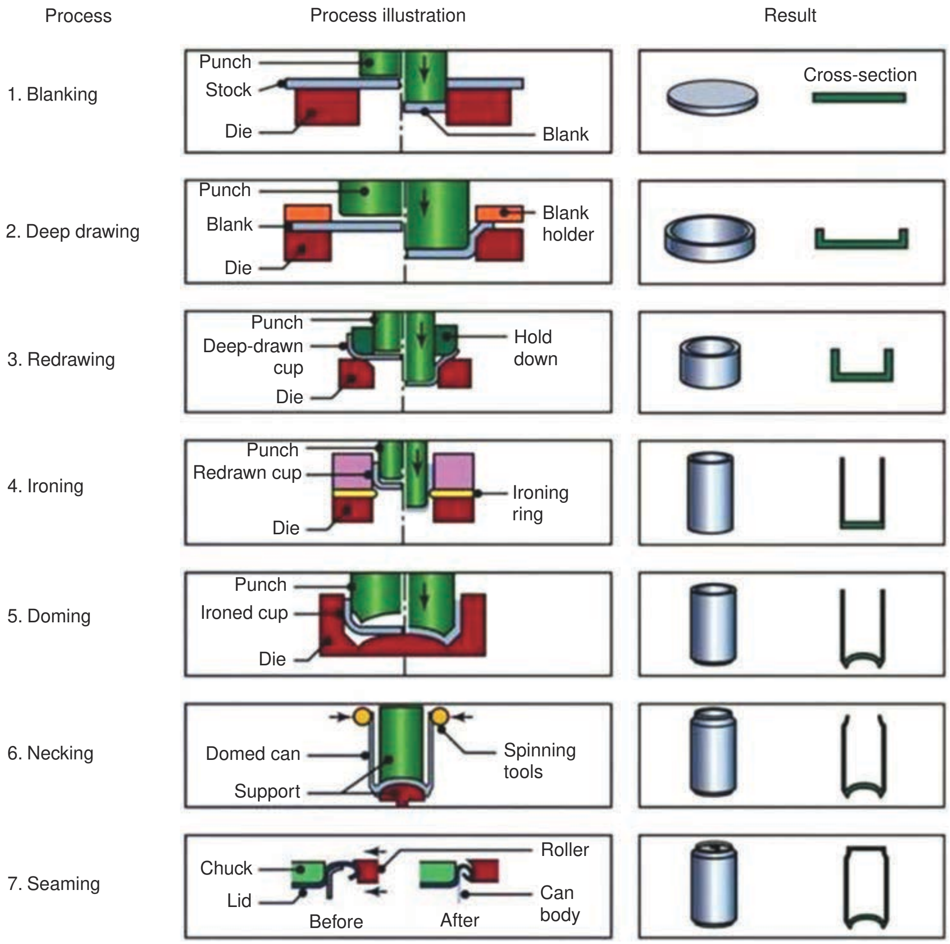

Fig. 17 Forming processes used to manufacture a two-piece aluminum can

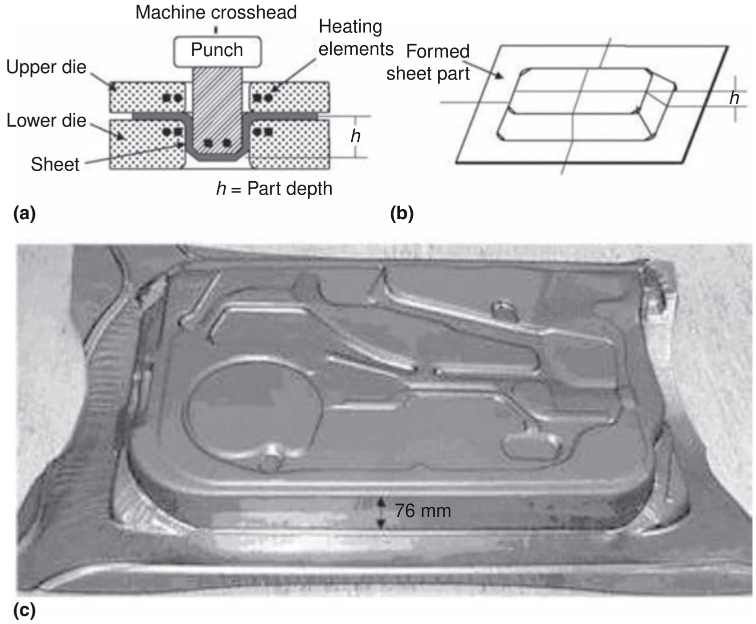

Fig. 18 Heated die system for warm stamping of aluminum alloys. (a) Schematic diagram of warm forming dies. (b) Schematic of formed sheet part. (c) Chrysler Neon door inner panel successfully formed at 350 °C (660 °F) using aluminum alloy 5182 plus manganese sheet. Source: Ref 7

In both superplastic forming (SPF) and quick plastic forming (QPF) processes, a heated blank is pressed against a heated die surface using air or gas pressure. While SPF allows forming of very complex shapes, it requires an alloy with a special superplastic microstructure, which must be formed at slow deformation speeds. QPF can use aluminum alloy 5083 with small grain sizes to form moderately complex parts at relatively short (about 3 min) cycle times. The elevated temperature of 300 to 400 °C (~570 to 750 °F) improves the formability (Fig. 19) and results in reduced springback. The SPF process was introduced in 2008 by General Motors Co. for forming 5083 aluminum-magnesium alloy sheet, and has been used in various GM vehicles including the Envoy® liftgate, the Oldsmobile Aurora® deck lid, the Cadillac STS® deck lid, and the Chevrolet Malibu Maxx® liftgate (Ref 11, 12).

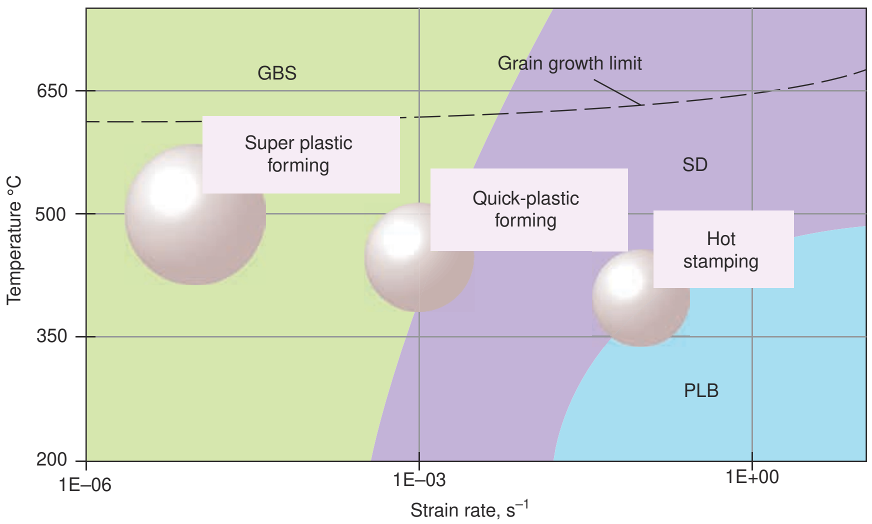

Fig. 19 Deformation mechanism map of aluminum alloy 5083 with superplastic forming, quick plastic forming, and hot stamping. GBS = grain boundary sliding, SD = slip deformation, PLB = persistent Lüders, or slip, bands. Source: Ref 10

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Work Hardening and Annealing of Aluminum Alloys*

Reviewed and revised by Ralph Dorward, Kaiser Aluminum (retired)

WORK, OR STRAIN HARDENING, is a natural consequence of most working and forming operations on aluminum and its alloys. During plastic forming of metals, most of the work is converted to heat, but some energy is stored in the microstructure in the form of dislocations that cause hardening. For aluminum alloys, the stored energy per unit volume due to plastic strain (ε) for deformation at a stress, σ, is $\varepsilon' \times \sigma' = 0.05$; that is, approximately 5% of the work done in deformation is actually stored in the metal. The rest is dissipated as heat.

Products hardened by cold working can be restored to a fully soft, ductile condition by annealing. In principle, all deformed aluminum alloys lose some of their strength from strain hardening when heated or tested at higher temperatures (>200 °C, or 390 °F). For any configuration of dislocations, a higher temperature increases atomic mobility and reduces the stored internal energy from the rearrangement or elimination of dislocations. The microstructural changes that occur during annealing depend on the extent of strain hardening and the applied temperature, time, and heating rate.

Work hardening is used extensively to produce strain-hardened tempers of the non-heat-treatable alloys (Table 1). The severely cold-worked or full-hard condition (H18 temper) is usually obtained with cold work equal to approximately a 75% reduction in area. The H19 temper identifies products with substantially higher strengths because of greater reduction. The H16, H14, and H12 tempers are obtained with lesser amounts of cold working, and they represent three-quarter-hard, half-hard, and quarter-hard conditions, respectively.

Strain hardening also is used in conjunction with partial annealing to produce the H28, H26, H24, and H22 series of tempers; the products are strain hardened more than is required to achieve the desired properties and then are reduced in strength by partial annealing. Figure 1 illustrates a typical annealing curve, which shows the effect of temperature on tensile properties and grain structure. Above a certain temperature, which is dependent on alloy composition and strain energy conditions, the material recrystallizes to an essentially strain free state. A series of strain-hardened and stabilized tempers—H38, H36, H34, and H32—are used for aluminum-magnesium alloys. In the strain-hardened condition, these alloys tend to age soften at room temperature. Therefore, they are usually heated at a low temperature to complete the age-softening process and to provide stable mechanical properties and improved working characteristics. These annealing practices of strain-hardened alloys are described in more detail in this article. Strain hardening also can increase the rate of precipitation hardening in the heat-treatable alloys.

Work Hardening (Ref 1, 2)

Cold work is deformation at relatively low temperature, which, for aluminum alloys, is typically less than 150 °C (300 °F). The crystal lattice is distorted by introduction of defects (dislocations) and microstructural changes that include:

- Elongated grains, with accompanying increase in grain surface per unit volume
- Increase in dislocation density and entanglement (alloy dependent)
- Reorientation of grains relative to the imposed strain (texture formation)

The microstructural changes from plastic deformation produce substantial changes in the mechanical properties of aluminum and its alloys. Tensile properties are among those most affected. Work-hardening curves for several non-heat-treatable alloys (Fig. 1) illustrate

Table 1 Summary of temper designations for strain-hardened alloys

Temper	Description
F	As-fabricated No control over the amount of strain hardening; no mechanical property limits
O	Annealed, recrystallized Temper with the lowest strength and greatest ductility
H1	Strain hardened H12, H14, H16, H18: The degree of strain hardening is indicated by the second digit and varies from quarter-hard (H12) to full-hard (H18), which is produced with approximately 75% reduction in area. H19: An extra-hard temper for products with substantially higher strengths and greater strain hardening than obtained with the H18 temper
H2	Strain hardened and partially annealed H22, H24, H26, H28: Tempers ranging from quarter-hard to full-hard obtained by partial annealing of cold-worked materials with strengths initially greater than desired
H3	Strain hardened and stabilized H32, H34, H36, H38: Tempers for age softening aluminum-magnesium alloys that are strain hardened and then heated at a low temperature to increase ductility and stabilize mechanical properties
H112	Strain hardened during fabrication No special control over amount of strain hardening but requires mechanical testing and meets minimum mechanical properties
H321	Strain hardened during fabrication Amount of strain hardening controlled during hot and cold working
H116	Special strain-hardened, corrosion-resistant temper for aluminum-magnesium alloys

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*Adapted from J.E. Hatch, *Aluminum: Properties and Physical Metallurgy*, American Society for Metals, 1984, p 105–133; and J. Hirsch, Annealing of Aluminum and Its Alloys, *Heat Treating of Nonferrous Alloys*, Volume 4E, *ASM Handbook*, ASM International, 2016, p 137–147

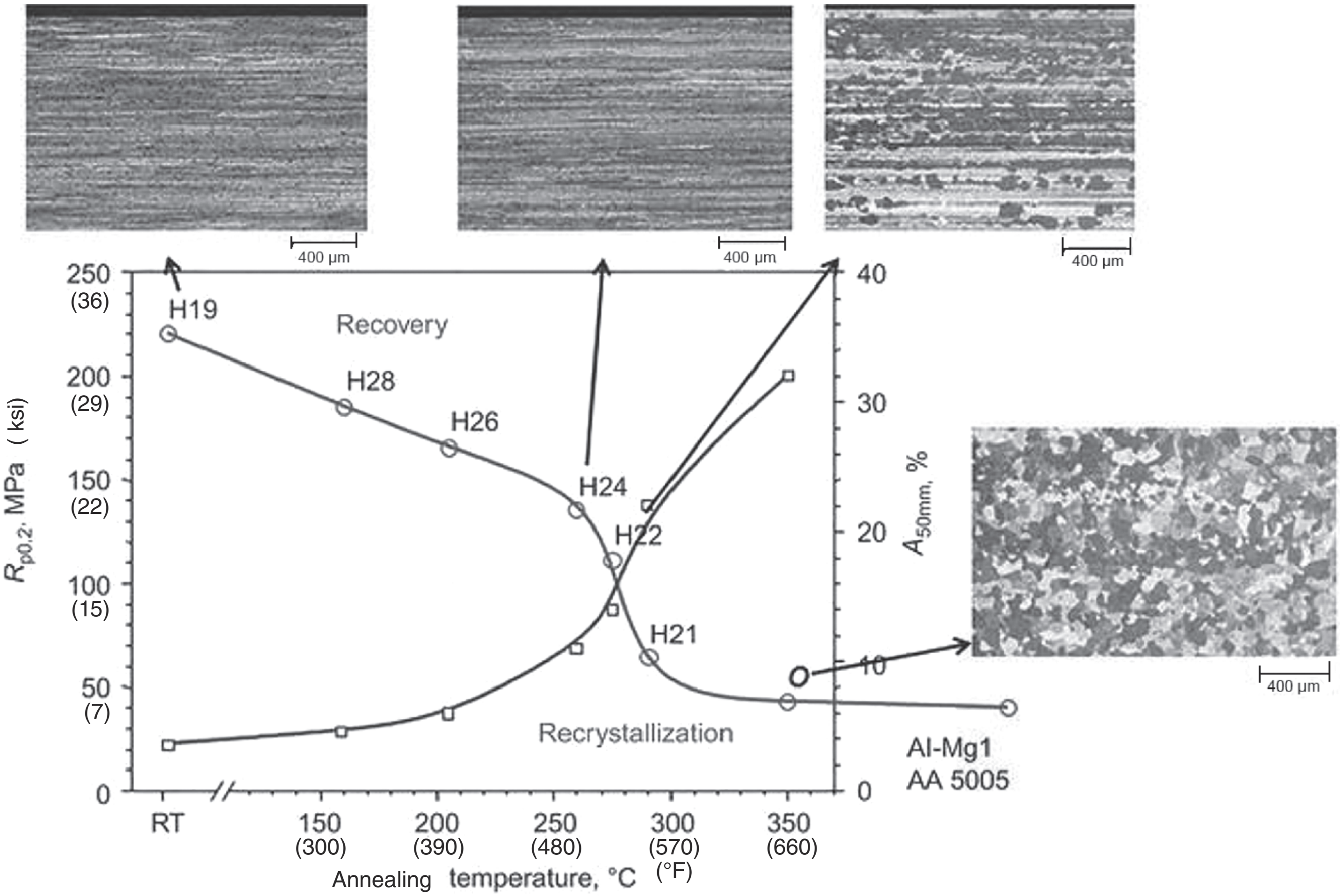

Fig. 1 Illustrates typical annealing curve, which shows the effect of temperature on tensile properties and grain structure. Above a certain temperature, which is dependent on alloy composition and strain energy conditions, the material recrystallizes to an essentially strain free state.

the increase in strength that accompanies cold work. This increase is obtained at the expense of ductility, as measured by the percentage of elongation in the tensile test and by reduced formability in operations such as bending and drawing. For this reason, the strain-hardened tempers are not usually used where high ductility and formability are required. Aluminum alloy beverage cans, readily formed by a unique drawing and ironing process using 3004-H19 as the starting material, are an exception.

The effects of increasing alloy content on the tensile properties and work-hardening characteristics of aluminum are also illustrated in Fig. 2. The two principal types of non-heat-treatable alloys are represented here: an alloy containing magnesium, which is largely in solid solution in aluminum; and an alloy containing manganese that is largely out of solution and distributed as a finely divided, dispersed aluminum-manganese constituent. Figure 2 shows that magnesium in solid solution hardens aluminum more effectively than an equal percentage of manganese as a dispersed second phase.

Cold working also increases shear strength, creep strength at low temperatures, and smooth-specimen fatigue strength. It has little effect on notch fatigue strength but increases notch tensile strength in approximately the same proportion as smooth-specimen tensile strength. The work-hardening characteristics of the annealed and T4 tempers of the heat treatable alloys are similar to those of the non-heat-treatable alloys. The work-hardening curve for the T4 temper of an Al-Mg-Si alloy (Fig. 3) is characterized by the same rapid, initial increase in yield strength shown by non-heat-treatable alloys (Fig. 2), followed by a more gradual increase in yield strength, roughly paralleling the change in tensile strength. In the artificially aged T6 temper (Fig. 3), the increase in yield strength and tensile strength with cold working is less than that for the T4 temper, except at very high strains.

Limited use is made of strain hardening to increase the strength of heat treatable alloys. The principal applications are in extruded and drawn products such as wire, rod, and tube. Heat treated Al-Mg-Si alloys are used extensively in such products, which are sometimes drawn after heat treatment to increase strength and improve surface finish. The low ductility and poor workability of other artificially aged, heat treatable alloys have restricted cold working as a procedure for obtaining higher strengths. In the aluminum-copper alloys, however, small amounts of cold work are used after solution heat treatment to obtain increased response during artificial aging.

Work-hardening curves for aluminum alloys, like most metals, when plotted as a function of true stress and true strain, are approximately parabolic and usually can be described by the Hollomon power relationship for hardening, such that:

$$\sigma = k\,\varepsilon^{n} \qquad \text{(Eq 1)}$$

where σ is the true stress, k is the stress at unit strain, ε is the true or logarithmic strain, and n is the strain-hardening exponent. A log-log plot of this relationship is shown in Fig. 4 for several annealed aluminum alloys.

As a close approximation, all of the alloys obey Eq 1 over the range of strains used here. The slopes of the lines may decrease as the initial strengths of the alloys increase, indicating a decrease in the value of n. At the same time, there is an increase in k. Measurements for the curves shown in Fig. 4 indicate that n decreases from 0.24 to 0.17 as k increases from 146 to 479 MPa (21 to 69 ksi). Examples of strain-hardening parameters are shown in Table 2.

Non-heat-treatable alloys initially in a cold-worked or hot-worked condition have rates of strain hardening substantially below those of material in the annealed temper. For the cold-worked tempers, this difference is caused by

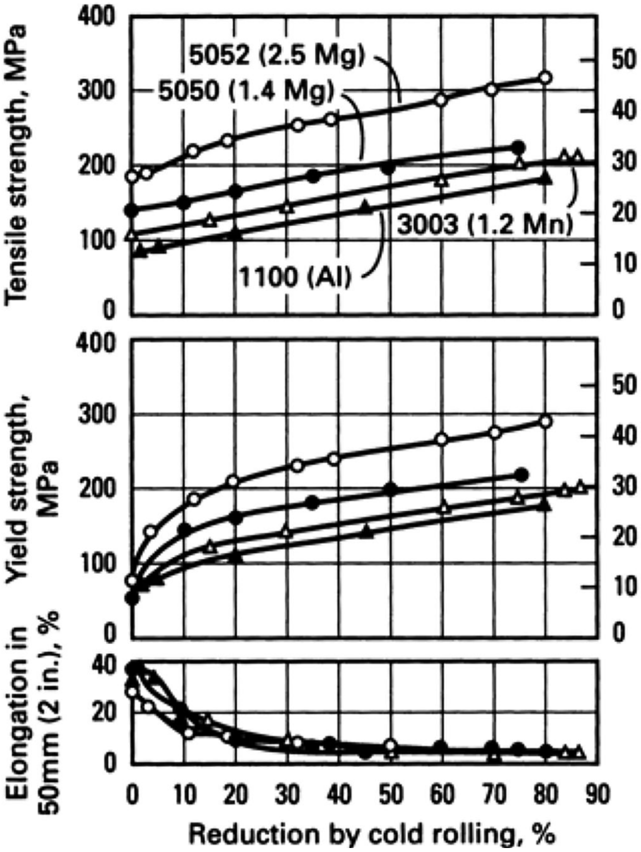

Fig. 2 Strain-hardening curves for aluminum (1100), aluminum-manganese (3003) alloys, and aluminum-magnesium (5050 and 5052) alloys

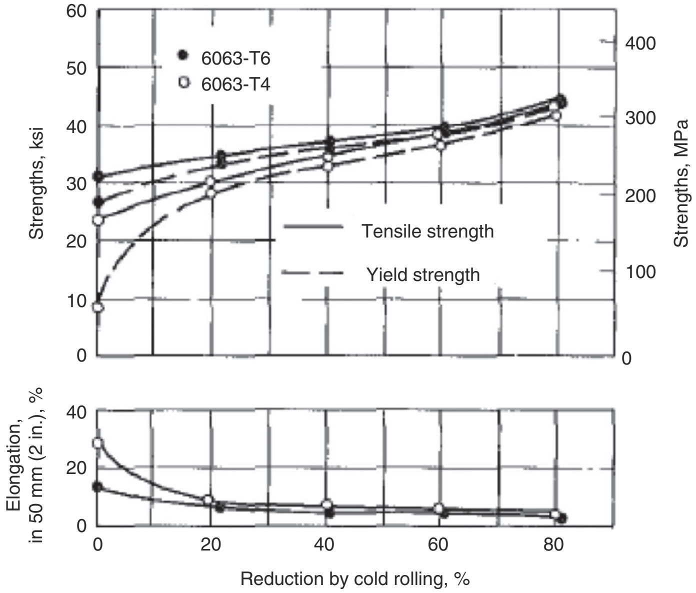

Fig. 3 Work-hardening curves for 6063-T4 and 6063-T6 sheet

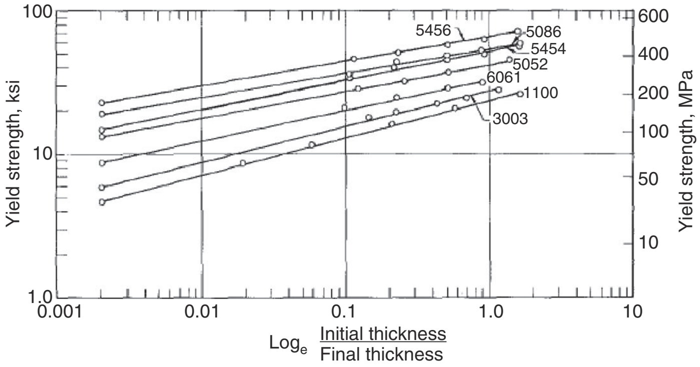

Fig. 4 Strain-hardening curves for annealed aluminum alloys plotted according to the relation in Eq 1 and substituting yield strength for true stress

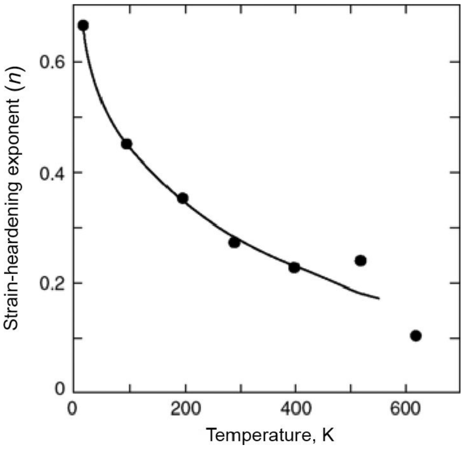

Fig. 5 Decrease of the strain-hardening exponent, *n*, of pure aluminum with temperature. Adapted from Ref 3

Table 2 Strain-hardening parameters of selected aluminum alloys at room temperature

		Stress at unit strain (k)	
Alloy	Strain-hardening exponent (n)	MPa	ksi
1100-0	0.242	146	21.1
3003-0	0.242	188	27.2
6061-0	0.209	224	32.5
5052-0	0.198	281	40.7
5454-0	0.189	340	49.3
5086-0	0.193	368	53.3
5456-0	0.178	479	69.4

Source: Aluminum Company of America

the strain necessary to produce the temper. If this strain equals ε_0, then the equation for strain hardening becomes:

$$\sigma = k(\varepsilon_0 + \varepsilon)^n \quad \text{(Eq 2)}$$

A similar situation exists for products initially in the hot-worked condition. The strain hardening resulting from hot working or forming is assumed to be equivalent to that achieved by a certain amount of cold work. From the tensile properties of the hot-worked product, the amount of equivalent cold work can be estimated, using the work-hardening curve for the annealed temper. By such procedures, it is usually possible to calculate work-hardening curves for hot-worked products that are in reasonable agreement with those for annealed products.

The work-hardening characteristics of aluminum alloys vary considerably with temperature. At elevated temperatures, the rate of strain hardening falls rapidly in most metals with an increase in temperature, as shown in Fig. 5 for aluminum and Fig. 6 for various aluminum alloys at typical warm forming temperatures. The flow stress and tensile strength, measured at constant strain and strain rate, also drop with increasing temperature. However,

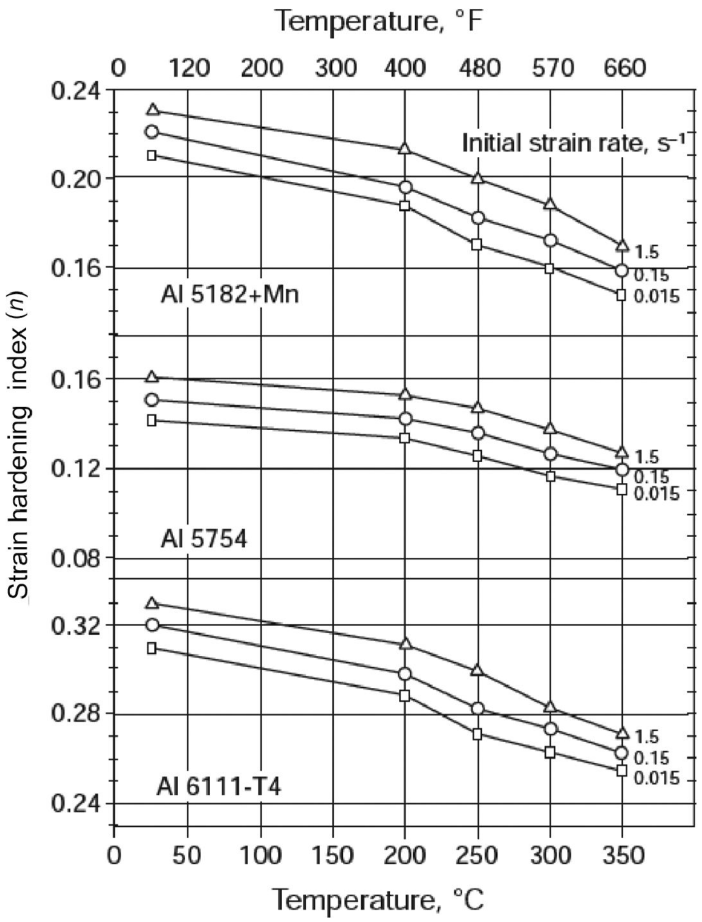

Fig. 6 Effect of typical warm forming temperatures on strain-hardening exponent of various aluminum alloys. Source: Ref 4

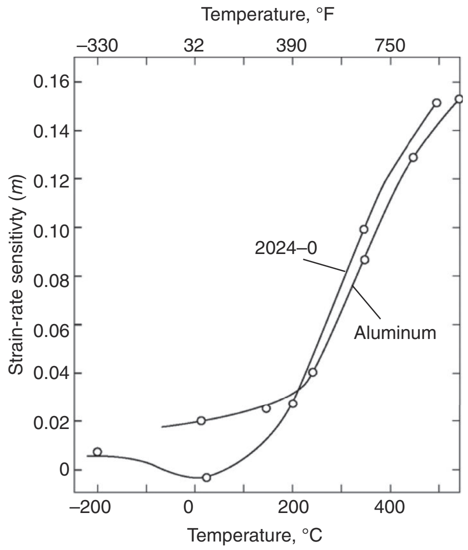

Fig. 7 Temperature dependence of the strain-rate sensitivities of 2024 and pure aluminum. Source: Ref 5

the drop is not always continuous; often, there is a temperature range over which the flow stress is only slightly temperature dependent or, in some cases, even increases slightly with temperature. The temperature dependence of flow stress is closely related to its strain-rate dependence, as discussed in the following section.

Strain-Rate Sensitivity. Work hardening and strength usually increase as strain rates increase. The effect typically is not large for deformation at room temperature, but it can be more significant at higher temperatures associated with hot working. The effect at constant strain of strain rate ($\dot{\varepsilon}$) on flow stress (σ) can be approximated by:

$$\sigma = C\dot{\varepsilon}^m \qquad \text{(Eq 3)}$$

where C is a strength constant that depends on strain, temperature, and material; and m is the strain-rate sensitivity of the flow stress at constant strain. For most metals at room temperature, the magnitude of m is quite low—between 0 and 0.03, as is the case for aluminum (Fig. 7). For example, if $m = 0.01$, increasing the strain rate by a factor of 10 would raise the flow stress by only 0.01×2.3, or approximately 2%, which illustrates why rate effects are often ignored. However, rate effects can be important in certain cases. If, for example, one wishes to predict forming loads in wire drawing or sheet rolling (where the strain rates may be as high as 10^4/s) from data obtained in a laboratory tension test, in which the strain rates may be as low as 10^{-4}/s, the flow stress should be corrected unless m is very small.

The value of m typically increases between 0.10 and 0.20 at higher temperatures associated with hot working or warm forming (Fig. 7, 8). Strain-rate sensitivity of aluminum at hot working has important implications for hot working operations. For example, Fig. 9 illustrates this behavior for alloy 1050 for typical extrusion temperatures and strain rates. At hot working temperatures, the flow stress of metals is dependent on both temperature and strain rate (the rate of deformation), while any dependence on strain (the amount of deformation) is generally ignored.

Constitutive Equations. A number of constitutive equations have been used to correlate flow stress (σ), strain rate ($\dot{\varepsilon}$), and temperature (T) of hot working operations such as creep, torsion, extrusion, and rolling (Ref 7). The three popular constitutive relations are the power relation, the logarithmic relation, and the hyperbolic sine relation (Ref 8, 9). Constitutive relations appear to represent the flow-stress behavior of relatively simple aluminum alloys; they are less adaptable to complex heat treatable alloys, which have extremely temperature-dependent microstructures and solubility relationships. The effects of any metallurgical or microstructural change (i.e., grain size, second-phase particle size and distribution, etc.) should be considered, if not negligible.

All constitutive equations include the Zener-Hollomon parameter (Z), which is a temperature-compensated strain rate ($\dot{\varepsilon}$) such that:

$$Z = \dot{\varepsilon}\, e^{[Q/RT]}$$

where Q is an activation energy, T is absolute temperature, and R is the gas constant. The Zener-Hollomon parameter is based on the idea that plastic straining can be treated as a rate process using the Arrhenius rate law. Flow stress can then simply be quantified as a function of Z, which accounts for strain rate and temperature in a single parameter, as illustrated in the example in Fig. 10 for 1050 aluminum. Experimentally determined values for some typical aluminum extrusions are described in a procedure set forth by Wright et al. (Ref 6).

The power-relation constitutive equation is expressed as:

$$\sigma = A_1 Z^n$$

or

$$\ln \sigma = A_1' + n \ln(\dot{\varepsilon}) + n\, Q/RT$$

where both A_1 and n are parameters. This relation works well in the low-stress range (creep), but at high stresses, both A_1 and n are variable. Figure 11 illustrates the shape of the stress-Z curve, as determined for commercial-purity aluminum (Ref 1).

The logarithmic-relation constitutive relation is expressed as:

$$\sigma = A_2 + b \ln Z$$

or

$$\sigma = A_2' + b \ln \varepsilon + b\, Q/RT$$