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Significance of Mechanical Properties in Design and Application

J. Gilbert Kaufman, Kaufman Associates

UNDERSTANDING THE MECHANICAL PROPERTIES of aluminum alloys is useful for the designer for choosing the best alloy and establishing appropriate allowable stress values, and for the aluminum producer to control the fabrication processes. While quality control is usually based on composition and room-temperature tensile properties, design specifications must include the full complement of allowable stress values, including values for compression, shear, and bearing loadings and for various loading profiles and environmental conditions. In tests of aluminum alloys to determine quality-control parameters and performance properties, the magnitude and significance of the values obtained also depend on the design of the specimen, its location in the product, and the testing procedure used (Ref 1–3).

Nature of Mechanical Property Data

Lot-to-lot variations in test results are to be expected, because no two production lots are exactly alike and evaluation of properties is affected by statistical variation. To obtain meaningful information for the quality control of aluminum alloy products, tests are made using ASTM International (Ref 4) and International Organization for Standardization (ISO) (Ref 5–7) standard methods and with specimens always taken from the same specified locations in successive production lots. Experience shows that such data obtained fall into relatively narrow bands and are amenable to statistical analysis. Based on such data, specification requirements are established usually calling for lot acceptance to be based on having properties that equal or exceed 99% limits with 95% confidence.

Other compilations of data from mechanical property tests are analyzed to determine average values for lots that exceed specified values, and these are usually referred to as typical properties. It is essential to recognize and differentiate between specification requirements and typical properties, because their applications are quite different. However, for both purposes, ASTM International or ISO standard test methods should be used and followed closely in accumulating data. Furthermore, sampling and testing procedures always should be reported in presentations of data.

Sampling for Testing

Because properties vary within any product (e.g., forging, extrusion, and plate), sampling procedures must define the location and orientation of test specimens. Generally, specifications for most aluminum alloy wrought products call for specimens taken with the longitudinal axis parallel to the direction of maximum flow during the metalworking process, that is, with grain or longitudinal specimens. However, for heat treated sheet and plate wider than 230 mm (9 in.), the specimen axis should be transverse to the direction of rolling and parallel to the rolled surface, that is, the long-transverse direction. For some thick products such as forgings, specimens are taken from all three principal directions, including normal to the major surface, the short-transverse direction. The locations within the thickness and width of the part from which specimens are to be taken are included in the specification.

For castings and die forgings, it may not be feasible to remove specimens from the manufactured part, and thus, alternate procedures are provided. Many casting specifications require separately cast test bars, which are test pieces that are either attached to the cast part or cast in the same casting lot. For forgings, test bars can be from separately forged coupons or machined from prolongations designed into the product for this purpose. Because amounts of working and rates of cooling in various locations within relatively large, complex castings and forgings can vary significantly, all portions of such products may not develop the same mechanical properties. For castings and forgings in which properties at certain regions are critical, the purchaser and producer should agree on the sampling and test procedures and the properties to be achieved.

Regardless of the alloy, temper, and product, testing of successive lots using standard methods to meet specification requirements ensures that composition, fabrication procedure, and heat treatment have been controlled within satisfactory limits.

Effects of Specimen Orientation

Compared with other metals, differences in properties associated with the direction of metal flow are usually small enough that aluminum alloys can be considered essentially isotropic. However, in thick plate, forgings, and extrusions, properties in the long-transverse and short-transverse directions can differ appreciably from those in the longitudinal direction, as shown in Table 1 (Ref 8). For these products, it may be necessary to consider anisotropy in the design of parts subjected to sustained high stress in the transverse directions.

Property variation through the cross section of a product is generally insignificant, but for structural members obtained by substantial machining of a product, it may be necessary to consider this variation. The critical section of a machined member could be at the point of minimum strength in the original product, which is typically near the center of the thickness in thick plate, forgings, and extrusions.

Design and Dimensions of Test Specimens

Whenever possible, tensile specimens described as standard (13 mm, or 0.5 in., diameter or width) are used. Sheet-type specimens can be taken from some products, but cylindrical specimens are often more practical and economical. For sheet-type and round specimens, there should be little or no difference in the values of tensile strength and tensile yield strength. Elongations of sheet-type specimens usually are lower than those of cylindrical specimens.

When it is necessary to test subsized tensile specimens, the largest specimen of proportionate dimensions should always be used. In measuring small dimensions and changes in the specimens, the size of the graduations of the measuring device could control the accuracy of the measurement; thus, it is undesirable to use specimens with a test section smaller than 6 mm (0.25 in.) in diameter or width. Also, greater care is required in machining smaller specimens to ensure that the machining technique (for example, tailstock pressure, depth of cut, finish, and heating) does not significantly influence the test results.

Design Values versus Specification Values

If a production lot meets specification requirements, the purchaser can be reasonably sure that it will behave in fabrication and in service in approximately the same manner as other lots that met the same specification. However, meeting these requirements does not imply that those properties were necessary for the application, nor does it ensure satisfactory performance in other applications. The purchase specification does not provide all the information needed to establish design values.

Stress-Strain Curves and Elastic Moduli

Stress-strain relationships (Fig. 1) provide considerable information for comparing alloys and for design. Stress-strain curves are commonly developed for axial tension, axial compression, and shear or torsion loadings and are continuous records of the relation between stress and strain from the initial application of load until the specimen fractures. In compression, the failure mode can be buckling. The curves are used to generate elastic and proportional limits and elastic moduli.

In the region of small plastic deformations, the departure of the stress-strain curve from the initial straight line usually is very gradual for most alloys and tempers. For a few alloys, particularly some of the 5*xxx* series in the annealed temper, the departure can be abrupt (Fig. 2). The magnitude of plastic strain developed before the stress again increases with increasing strain usually is less than 1%; for mild steel, it can be as much as 5%.

Elastic and Proportional Limits

Although the elastic and proportional limits within the low-strain portion of a stress-strain curve generally differ only slightly, if at all, their definitions are not the same. Elastic limit is the limit of elastic action and can be higher than the proportional limit, which is the limit of proportionality of stress to strain. Generally, the determination of either is impractical and unnecessary, because the shape of the curve in this region is highly affected by the sensitivity of both measuring and plotting the strains and representing the plotted points with a curve. In addition, the determination is affected by the scales used, as shown in Fig. 1, where two scales of abscissas are used

Table 1 Minimum tensile properties of aluminum alloy plate, hand forgings, and extrusions

	Plate(a)		Hand forgings(b)		Extrusions(c)	
Direction	7075-T651	7075-T7351	7075-T6	7075-T7351	7075-T6511	7075-T7351
Tensile strength, MPa (ksi)						
Longitudinal	496 (72)	448 (65)	503 (73)	455 (66)	559 (81)	545 (79)
Long-transverse	524 (76)	455 (66)	490 (71)	441 (64)	490 (71)	483 (70)
Short-transverse	483 (70)	428 (62)	476 (69)	421 (61)	462 (67)	...
Yield strength, MPa (ksi)						
Longitudinal	414 (60)	359 (52)	421 (61)	372 (54)	496 (72)	483 (70)
Long-transverse	441 (64)	359 (52)	407 (59)	359 (52)	421 (61)	428 (62)
Short-transverse	407 (59)	338 (49)	400 (58)	345 (50)	386 (56)	...
Elongation in 4*D*, %						
Longitudinal	...	...	9	7	7	8
Long-transverse	5	6	4	4	...	...
Short-transverse	...	...	3	3	...	...

(a) Thickness, 50.79 to 63.45 mm (2.001 to 2.500 in.). (b) Thickness, 50.79 to 76.14 mm (2.001 to 3.000 in.); maximum cross-sectional area, 1652 cm^2 (256 $in.^2$). (c) Thickness, 38.07 to 76.12 mm (1.500 to 2.999 in.); maximum cross-sectional area, 129 cm^2 (20 $in.^2$). Source: Ref 8

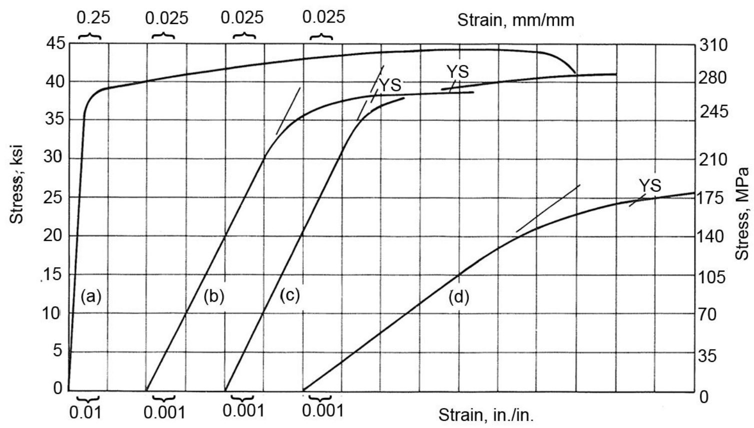

Fig. 1 Stress-strain curves for alloy 6061-T6 drawn tube. (a) Complete tensile curve, 200 mm (8 in.) gage length. (b) Expanded tensile curve, 200 mm (8 in.) gage length. (c) Compressive curve. (d) Shear curve. YS, yield strength

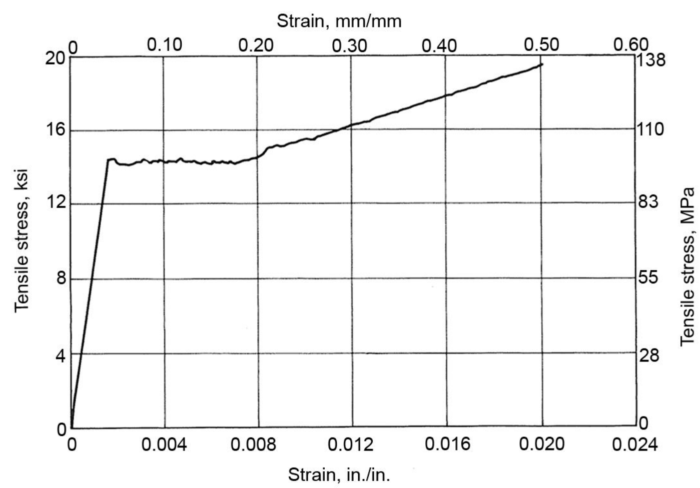

Fig. 2 Stress-strain curve for alloy 5052-O rod

for the tensile data. Also, attempts to measure these properties can be greatly influenced by the presence of internal residual stresses, which could bias the readings. For these reasons, the elastic and proportional limits are of little practical interest, and the yield strength is a more important property.

Modulus of Elasticity and Poisson's Ratio

The moduli of elasticity of aluminum alloys are dependent mainly on composition; they are virtually independent of temper, product, and direction of working. Although published values for modulus of a given alloy can vary considerably, the wide range is mainly the result of variations in accuracy and sensitivity of testing equipment, skill in testing, method used, and interpretation of results.

The elastic moduli of selected alloys under tensile and compressive loading (Young's modulus) and under shear loading (shear modulus or modulus of rigidity) are listed in Table 2. Moduli in compression are approximately 2% higher than in tension.

The moduli in tension and in shear are related by the expression:

$$G = \frac{E}{2(1+\mu)} \qquad \text{(Eq 1)}$$

where G is the elastic modulus in shear in MPa (or psi), E is the elastic modulus in tension in MPa (or psi), and μ is the Poisson's ratio.

For aluminum alloys, the value of Poisson's ratio is approximately 0.33. Therefore, the modulus of elasticity in shear is approximately 38% of the modulus of elasticity in tension.

The modulus of elasticity is used in equations for elastic deflection and elastic buckling strength of structures. For stresses above the elastic range, the tangent modulus and the secant modulus are sometimes used as the effective moduli, especially in buckling problems. Figure 3 shows how these two properties are determined from a stress-strain curve. Above the elastic range, they are stress dependent; in the elastic range, they are identical to the elastic modulus.

Stress-Strain Curves

For most applications, the most valuable part of the stress-strain curve extends to slightly beyond the yield strength (strains generally less than 1%). However, there are some uses for complete stress-strain curves (Fig. 1).

The application of stress-strain curves in design and alloy selection demands that the curves be representative of all lots of a specific product. Because of the variable nature of production lots, the stress-strain curve determined for a single lot may not be representative of other lots, and thus, typical and minimum stress-strain curves are used. The curves are developed from data from tests of many lots (Ref 8). Typical strengths and curves represent expected average behavior, while minimum strengths and curves show the level of behavior that all lots are expected to meet.

Nominal versus True Stress-Strain Curves

In developing stress-strain curves for mechanical property considerations, stresses usually are based on the original cross-sectional area, although the area actually changes as the test proceeds. Similarly, strains are based on the original gage length. Curves developed with these definitions usually are referred to as nominal or engineering stress-strain curves.

However, there are applications where it is advantageous to consider the deformation based on the instantaneous area and the strain based on the instantaneous gage length. Curves developed using these definitions are referred to as true stress-strain curves (Ref 9). Up to the point of necking (in the range of uniform elongation), the nominal and true curves are related algebraically, and one can be developed from the other.

For stresses in the range of elastic action and even up to the yield strength, there is no significant difference between the nominal and true stress-strain curves (Fig. 4). For stresses greater than the yield strength, the difference between the two curves gradually increases; it is greatest in the range of and beyond the point where the maximum load occurs.

In the nominal tensile stress-strain curve, the maximum load determines the maximum stress; that is, the tensile strength. For most aluminum alloys, fracture occurs at a subsequent smaller load; the amount of decrease after passing the maximum load also depends on the testing equipment and procedure.

In the true stress-strain curve, the maximum load determines only another point on the curve of increasing stress with increasing strain, and fracture occurs at a higher stress, the true fracture strength. These differences are associated with the fact that longitudinal strain and lateral contraction are nearly uniform along the gage length until the maximum load is developed and additional strain and contraction are concentrated within a short portion of the gage length, and a neck is formed.

Table 2 Moduli of elasticity of select aluminum alloys

	Modulus					
	Tension (E)		Tension (E_c)		Shear (G)	
Alloy	GPa	10^6 psi	GPa	10^6 psi	GPa	10^6 psi
1100	68.3	9.9	70	10	26.2	3.8
2020	76.6	11.1	78.6	11.4	29.0	4.2
2024	72.4	10.5	73.8	10.7	28	4
5052	69.7	10.1	70.3	10.2	26.2	3.8
6061	68.3	9.9	69.7	10.1	26.2	3.8
7075	71.0	10.3	72.4	10.5	26.9	3.9

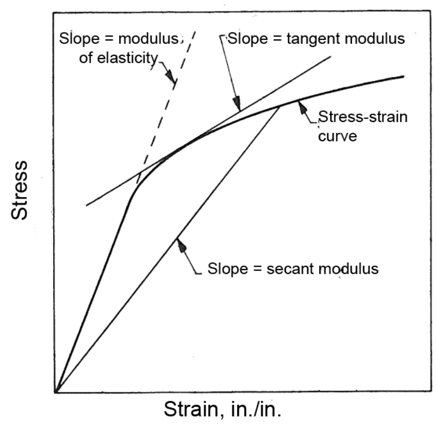

Fig. 3 Determination of tangent modulus and secant modulus from the stress-strain curve

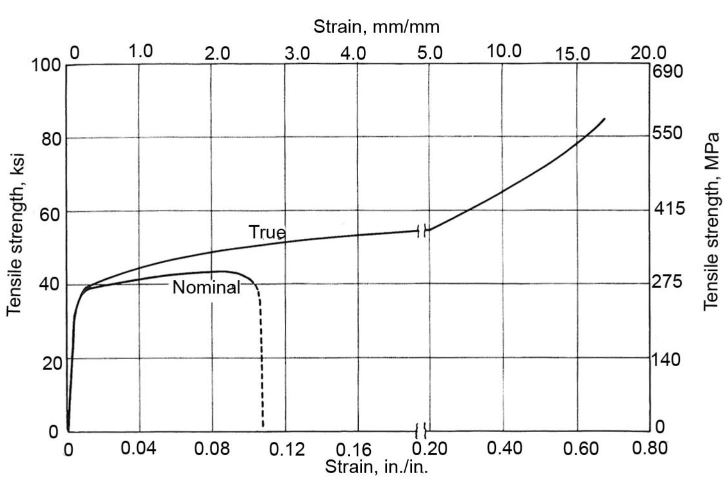

Fig. 4 Stress-strain curves for alloy 6061-T8 rod

Computations made in developing the nominal curve do not take nonuniform deformation into account, as is done in developing the true curve. Unless otherwise qualified, all references in this article are to nominal stresses and nominal strains.

Strain-Hardening Coefficient

On log-log coordinates, the portion of the true tensile stress-strain curve beyond the yield strength usually is a straight line represented by the equation:

$$\sigma_t = K(\varepsilon_t)^n \quad \text{(Eq 2)}$$

where σ_t is the true stress in MPa (or psi), K is the strength coefficient in MPa (or psi), ε_t is the true strain, and n is the strain-hardening exponent. The value of n generally approximates the true uniform strain, that is, the true strain at maximum load (Ref 8).

The strain-hardening exponent is sometimes considered to be an index of the formability and toughness of a material, but these concepts have little practical use.

Tensile Properties

Standard procedures for tensile tests are given in ASTM E 8/E 8M, "Standard Test Methods for Tension Testing of Metallic Materials" (Ref 10). In this article, ASTM International definitions are implied unless test conditions are described as differing from the usual test conditions (plane stress).

For aluminum alloys, the yield strength is generally defined by an offset in the stress-strain curve equal to 0.2% plastic strain. For some purposes, and in some foreign countries, yield strength is defined by other values of offset, such as 0.1 and 0.01%, the latter being a close approximation of the elastic limit.

The designer must deduce allowable stress values from the values of tensile strength and yield strength determined by standard test procedures (Ref 10). For example, the "ASME Boiler and Pressure Vessel Code" (Ref 11) has four criteria for establishing the allowable stress value, two of which apply to tensile strength and yield strength. In these criteria, the allowable stress value shall not exceed 25% of the tensile strength or 67% (for nonferrous alloys) of the yield strength.

Elongation and reduction-of-area values are considered measures of ductility or workability. If the specimen necks substantially in fracturing, the elongation value depends strongly on gage length (Fig. 5). On the contrary, if the specimen fractures with insignificant necking, the elongation value is virtually independent of gage length. The data in Fig. 6 show the variation in elongation along a specimen. Elongation is nearly uniform except within approximately 2.5 cm (1 in.) of the fracture region of the neck. Elongation in zero gage length is computed from the reduction of area, with the assumption of constant volume.

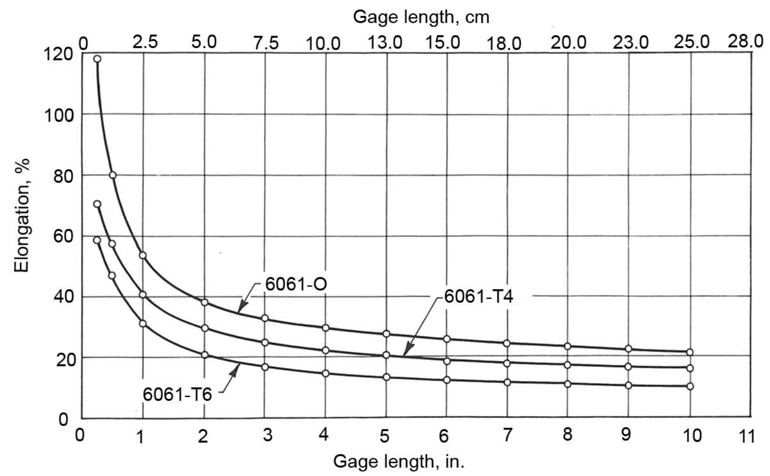

Fig. 5 Effect of gage length on elongation for different tempers of alloy 6061 rod

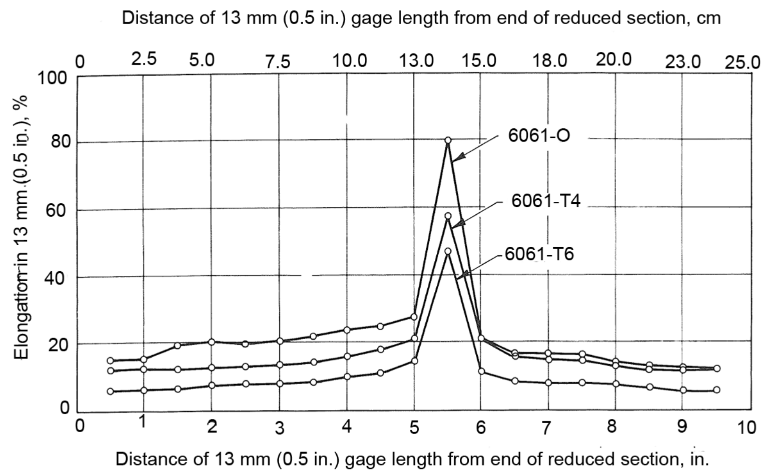

Fig. 6 Effect of temper on elongation of alloy 6061 rod

The aluminum industry relies heavily on tensile properties and makes tests on most production lots. Therefore, tensile property data are more abundant than for other properties, and they are used for quality-control purposes and analyzed statistically to determine the typical ranges of values.

The results of these continuing analyses are the basis for revising specification values and for establishing design values. Expected minimum values of other properties (for example, compressive, shear, and bearing) are derived from minimum tensile properties by applying empirical factors developed from specific interrelated tests.

Compressive Properties

Under compressive loading, aluminum alloys can fail due to one of four general types of behavior:

- Relatively short members (slenderness ratio less than approximately 10) of very ductile alloys deform by shortening continuously into a flat wafer, possibly with eventual development of edge cracks.
- Short members of very high-strength alloys can fail by shearing or splitting after considerable deformation.
- Members with thin webs or walls can fail by local structural instability.
- Long members can fail by lateral deflection.

Compression tests of small specimens provide valuable information for design to avert these types of failure. Significant properties usually determined are compressive modulus of elasticity and yield strength (stress at an offset of 0.2% plastic strain). Compressive stress-strain curves (Fig. 1) are used to develop curves of tangent and secant moduli as a function of stress (Fig. 3). For alloys with low capability of plastic deformation, compressive strength can also be obtained.

For most aluminum alloys and products, the compressive yield strength is approximately equal to, or slightly greater than, the tensile yield strength. Therefore, in lieu of compressive data, compressive yield strength generally is assumed to be equal to the tensile yield strength. Also, tensile and compressive stress-strain curves typically are assumed to be the same.

For aluminum alloys cold worked by stretching (for straightening and stress relieving), the tensile yield strength is higher, but the compressive yield strength in the direction of stretching can be reduced to a level lower than that of the tensile yield strength—an illustration of the Bauschinger effect. Compressive yield strengths in directions normal to the direction of stretching are increased slightly. For certain 2*xxx*-series alloys in the T3 and T4 temper (for example, 2024 and 2219), reductions in longitudinal compressive yield strength can be appreciable (alloy 2024-T3 in Fig. 7). In addition, if stretching is performed after artificial aging, the effect can be large, even for alloys not considered to be affected greatly by cold work (2014-T6 in Fig. 7). If stretching of heat treatable alloys is performed as an intermediate operation (between solution heat treatment and artificial aging, T*x*51 temper), most or all of the effects of stretching are removed by aging, directional differences are almost eliminated, and tensile and compressive yield strengths are usually equal within approximately ±3%.

To relieve internal stress, aluminum alloy forgings sometimes are cold worked by compressing (T*x*52 temper) instead of stretching, because compression is more practicable. (See the article "Properties of Pure Aluminum" in *Aluminum Science and Technology*, Volume 2A of *ASM Handbook*, 2018). The effects of compressive cold working on compressive yield strength are analogous to those of tensile cold working on tensile yield strength. That is, compressive cold working causes an increase in compressive yield strength and a decrease in tensile yield strength in the direction of working. Compressive yield strengths in directions normal to the direction of loading are reduced 3 to 5% by deformations of 1 to 3%.

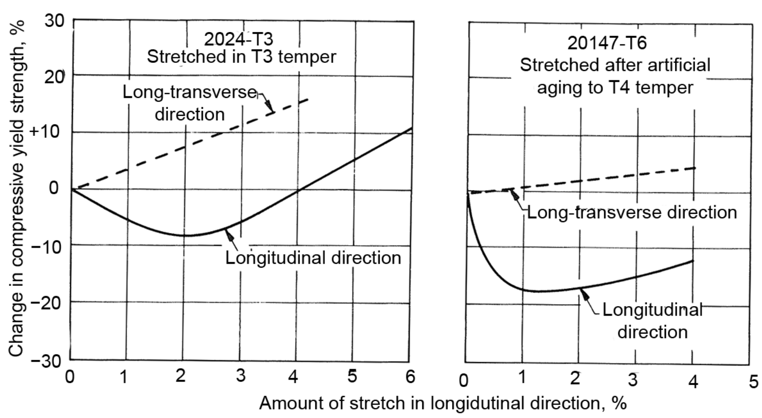

Fig. 7 Effect of stretching on compressive yield strength

Shear Properties

Shear strength is defined as the force required to shear cylindrical members on transverse sections, the force required to punch holes in plate and structural shapes, and the resistance to failure of members under torsional loads.

Methods used to determine shear strengths of metals include shearing the material on one plane (single shear) or two planes (double shear), punching a hole (punching shear or blanking shear), or applying torsional loads. While these methods provide useful data, values may not be identical, because loading conditions do not always represent pure shear. Tests should be conducted to avoid stresses other than shear stresses so that the specimens actually fail in shear. In single-shear tests, these conditions commonly do not prevail because of the eccentricity of loading and the resulting rotation of the member into a position to better accommodate loading.

In double-shear tests and in blanking-shear tests of sheet, only the ultimate shear strength is determined. However, in torsional tests of circular tubes, it is feasible to measure shear strains, plot the shear stress-strain curve, and determine the shear yield strength at 0.2% plastic strain offset. Shear stress-strain curves (Fig. 1) have many characteristics of tensile and compressive stress-strain curves.

The value of ultimate shear strength is a function of test specimen or member dimensions. In double-shear tests, values obtained depend on the spacing of the shear planes and the stiffness of the tool (Ref 12). Values obtained using a rigid tool with relatively large spacing between planes average approximately 10% higher than those obtained using rivet-testing devices with less rigidity and in which shear planes are only one diameter apart. In torsion tests, strain is not uniform across the section, and a meaningful value of shear strength cannot be determined by inserting the maximum torque into the equation for elastic stress. The error is less in tests of tubing than in tests of solid rods, because stress is relatively more uniform over the cross section; the error decreases with wall thickness until buckling is encountered.

Shear strengths of aluminum alloys average approximately 60% of the tensile strengths; the range is approximately 55 to 80%. The lower percentages are applicable to high-strength wrought alloys, especially in extrusions, and the higher percentages to annealed and low-strength wrought alloys and some casting alloys.

Shear strengths of some aluminum alloy products also vary with the plane of shear and direction of loading. For example, in plate, shear strengths on planes parallel to the surface average approximately 15% lower than those on planes normal to the surface. For planes normal to the surface, the shear strengths are approximately 10% higher when loads are applied parallel to the surface than when applied normal to the surface.

Hardness

Hardness is of little direct value to the designer, but sometimes hardness values are useful for quality control, particularly during fabrication of semifinished parts. Hardness values for a number of common heat treated aluminum alloy/temper combinations are given in Table 3 (Ref 13). Hardness tests of aluminum alloys are much less informative than tension tests. They can indicate tensile strength, although hardness numbers can actually be misleading in this respect. There are no useful relationships with yield strength and ductility. Caution is recommended in direct use of hardness measurements as the mechanical property test for quality-assurance purposes, because the relationship between hardness and tensile strength for aluminum alloys has a relatively wide band (Fig. 8) (Ref 14). Thus, tensile testing often is specified as the mechanical property test for heat treated aluminum products, because the correlation between hardness and either tensile strength or yield strength of aluminum alloy is not as good as it is for steels.

With careful interpretation and if the composition is known, hardness tests of aluminum alloys can be used to indicate whether the metal is in the annealed or heat treated condition, to indicate within acceptable limits whether certain heat treating operations have

Table 3 Typical hardness values for wrought aluminum alloys

Alloy and temper	Product form(a)	Hardness HRB	Hardness HRE	Hardness HRH	Hardness HRIST
2014-T3, -T4, -T42	All	65–70	87–95	···	···
2014-T6, -T62, -T65	Sheet(b)	80–90	103–110	···	···
	All others	81–90	104–110	···	···
2014-T61	All	···	100–109	···	···
2024-T3	Not clad(c)	69–83	97–106	111–118	82.5–87.5
	Clad, ≤1.60 mm (0.063 in.)	52–71	91–100	109–116	80–84.5
	Clad, >1.60 mm (0.063 in.)	52–71	93–102	109–116	···
2024-T36	All	76–90	100–110	···	85–90
2024-T4, -T42(d)	Not clad	69–83	97–106	111–118	82.5–87.5
	Clad, ≤1.60 mm (0.063 in.)	52–71	91–100	109–116	80–84.5
	Clad, >1.60 mm (0.063 in.)	52–71	93–102	109–116	···
2024-T6, -T62	All	74.5–83.5	99–106	···	84–88
2024-T81	Not clad	74.5–83.5	99–106	···	84–88
	Clad	···	99–106	···	···
2024-T86	All	83–90	105–110	···	87.5–90
6053-T6	All	···	79–87	···	74.5–78.5
6061-T4(d)	Sheet	···	60–75	88–100	64–75
	Extrusions; bar	···	70–81	82–103	67–78
6061-T6	Not clad, 0.41 mm (0.016 in.)	···	···	···	75–84
	Not clad, ≥0.51 mm (0.020 in.)	47–72	85–97	···	78–84
	Clad	···	84–96	···	···
6063-T5	All	···	55–70	89–97	62.5–70
6063-T6	All	···	70–85	···	···
6151-T6	All	···	91–102	···	···
7075-T6, -T65	Not clad(e)	85–94	106–114	···	87.5–92
	Clad:				
	≤0.91 mm (0.036 in.)	···	102–110	···	86–90
	>0.91 ≤ 1.27 mm (>0.036 ≤ 0.050 in.)	78–90	104–110	···	···
	>1.27 ≤ 1.57 mm (>0.050 ≤ 0.062 in.)	76–90	104–110	···	···
	>1.57 ≤ 1.78 mm (>0.062 ≤ 0.070 in.)	76–90	102–110	···	···
	>1.78 mm (0.070 in.)	73–90	102–110	···	···
7079-T6, -T65	All(e)	81–93	104–114	···	87.5–92
7178-T6	Not clad(f)	85 min	105 min	···	88 min
	Clad:				
	≤0.91 mm (0.036 in.)	···	102 min	···	86 min
	>0.91 ≤ 1.57 mm (>0.036 ≤0.062 in.)	85 min	···	···	···
	>1.57 mm (0.062 in.)	88 min	···	···	···

(a) Minimum hardness values shown for clad products are valid for thicknesses up to and including 2.31 mm (0.091 in.); for heavier-gage material, cladding should be locally removed for hardness testing or test should he performed on edge of sheet. (b) 126 to 158 HB (10 mm ball, 500 kg load). (c) 100 to 130 HB (10 mm ball, 500 kg load). (d) Alloys 2024-T4, 2024-T42, and 6061-T4 should not be rejected for low hardness until they have remained at room temperature for at least three days following solution treatment. (e) 136 to 164 HB (10 mm ball, 500 kg load). (f) 136 HB min (10 mm ball, 500 kg load)

been performed properly, and to separate mixed lots of alloys having sufficiently different compositions and tempers.

The use of hardness measurements in the quality assurance of heat treated aluminum products is most effective when used in conjunction with the measurement of surface electrical conductivity. The extent of solute precipitation in a given alloy has a direct influence on electrical conductivity, and therefore, the temper of aluminum alloys can be identified on the curve of hardness and conductivity measurements (Fig. 9) (Ref 15). Because there can be two different hardness values for a given conductivity measurement, hardness can be used effectively to assess temper condition when combined with eddy-current measurements of electrical conductivity. A summary of typical values is given in Table 4 (Ref 14). Various industry specifications, such as Aerospace Materials Specification 2658 (Ref 16), use hardness and conductivity measurements for inspection and condition assessment.

The hardness of aluminum alloys generally is measured using tests such as Brinell, Rockwell, and Vickers. Less common tests are the Knoop indentation, Shore scleroscope rebound, and scratch hardness tests.

In Brinell tests, a standard combination of load and ball (500 kg load on a 10 mm tungsten carbide ball, or an equivalent) must be used. Otherwise, different values may be obtained, and the differences are not the same for all alloys (Fig. 10). Hardness values for certain other metals, such as steels, are not comparable with those for aluminum alloys. When the Brinell hardness test is properly performed, hardness values for different wrought aluminum alloys and tempers are comparable, and there is a broadly defined, linear relationship between hardness and tensile strength (Fig. 11).

The Rockwell test is also used frequently and advantageously for process-control testing. However, there are no linear relationships with other mechanical properties, and no single Rockwell scale can be used for all alloys or, in some cases, for all tempers of the same alloy. Figure 12 shows approximate relationships between tensile strength and Rockwell E values for different tempers. Figure 13 shows the approximate Brinell-Rockwell relationship for several Rockwell scales.

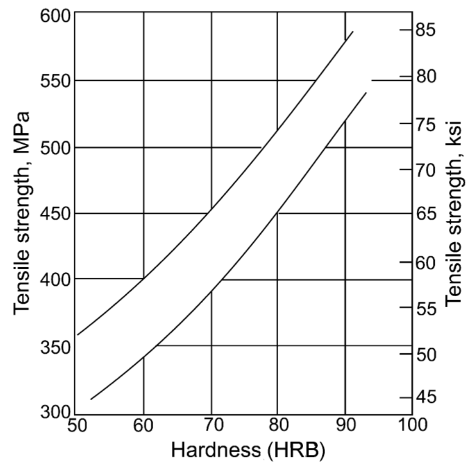

Fig. 8 Wide correlation band between hardness and tensile strength of aluminum alloys. Source: Ref 14

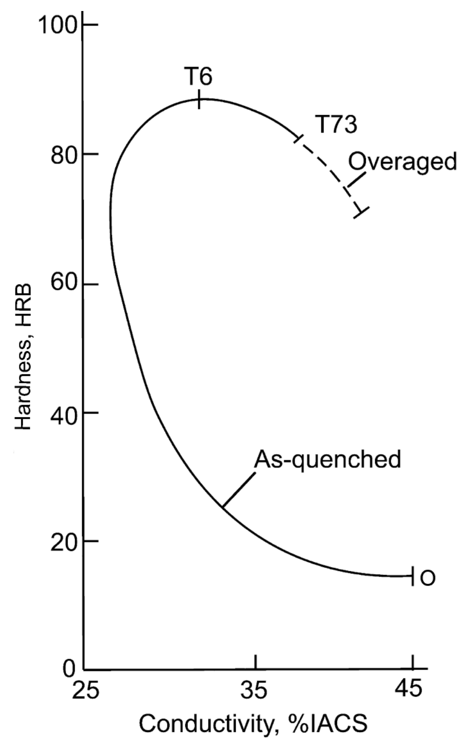

Fig. 9 Hardness vs. electrical conductivity of 7075 aluminum alloy. Typical values only; not for use in acceptance or rejection. IACS, International Annealed Copper Standard. Source: Ref 15

Hardness tests of coated and clad aluminum alloys are generally of little or no value, because the test measures the average hardness of only a relatively small volume of metal near the surface. Clad coatings usually are much softer than the core material, and the actual thickness of coating varies with the total thickness. For example, hardness values of alclad 2024-T3 0.8 mm (0.032 in.) sheet and 6 mm (0.250 in.) plate are 98 and 55 HB, respectively, whereas the typical

Table 4 Typical examples of hardness and conductivity values for various aluminum alloy tempers

Alloy	Temper	Brinell hardness	Rockwell hardness B	Rockwell hardness E	Rockwell hardness H	Rockwell hardness 15T	Typical conductivity, %IACS
Bare alloys							
2014	O	···	22 max	70 max	95 max	···	43.5–51.5
	T3	100	65	95	···	82	31.5–35
	T4	100	65	95	···	82	31.5–34.5
	T6	125	78	102	···	86	35.5–41.5
2024	O	···	22 max	70 max	95 max	···	46–51
	T3	110	69	94	···	82	28.5–32.5
	T4	100	63	94	···	82	28.5–34
	T6	118	72	98	···	84	36.5–40.5
	T8	120	74	99	···	85	35–42.5
2124	T3	110	69	97	···	···	28.5–32.5
	T8	120	74	99	···	···	35.0–42.5
2219	O	···	22 max	95	···	···	44–49
	T3	98	60	92	···	79	26.0–31.0
	T37	99	62	93	···	81	27.0–31
	T4	96	58	90	···	78	28.0–32
	T6	99	62	93	···	81	32.0–35.0
	T8	116	71	98	···	83	31.0–35
	T87	124	75	100	···	84	31.0–35
6061	O	40 max	···	···	75 max	···	42.0–49
	T4	50	···	70	···	64	35.5–43.0
	T6	80	42	85	···	78	40.0–47.0
6063	O	···	···	···	70 max	···	57.0–65.0
	T1	···	···	37	···	53	48.0–58.0
	T4	···	···	40	···	54	48.0–58.0
	T5	···	···	44	···	57	50.0–60.0
	T6	60	···	70	···	68	50.0–60.0
6066	O	···	···	40 max	···	···	42.0–47.0
	T4	···	···	85	···	76	34.0–41.0
	T6	102	65	95	···	82	38.0–50.0
7049	O	···	22 max	70 max	95 max	···	44.0–50.0
	T73	134	81	104	···	85	40.0–44.0
	T76	142	84	106	···	87	38.0–44.0
7050	O	···	22 max	70 max	95 max	···	44.0–50.0
	T73	134	81	104	···	85	40.0–44.0
	T736	140	82	105	···	86	40.0–44.0
	T76	142	84	106	···	87	39.0–44.0
7075	O	···	22 max	70 max	95 max	···	44.0–48.0
	T6	142	84	106	···	87	30.5–36.0
	T73	129	78	102	···	85	40.0–43.0
	T76	136	82	104	···	86	38.0–42.0
Alclad alloys							
2014	T6	···	76	102	···	85	35.5–44.0
2024	T3	···	57	91	···	79	28.5–35.0
	T4	···	57	91	···	79	28.5–35.0
	T6	···	60	93	···	81	35.0–45.0
	T8	···	65	97	···	82	35.0–45.0
2219	T6	···	61	92	···	80	32.0–37.0
	T8	···	64	96	···	82	31.0–37.0
6061	T6	···	84	74	···	···	40.0–53.0
7075	T6	···	78	103	···	86	30.5–36.0
7178	T6	···	76	104	···	86	29.0–34.0

hardness for nonclad 2024-T3 is 120 HB. Anodic coatings are harder and more brittle than the base material; therefore, they could have the effect of artificially raising the measured hardness. For example, Vickers hardness numbers (5 kg load) of 89 and 105 HV5 were obtained on bare and coated sheet, respectively.

Bearing Properties

Bearing properties of aluminum alloys are used in the design of riveted, bolted, and pinned joints, or where edgewise loads are applied by pins and rods. They are established as the resistance of specimens to crushing against a round, hardened steel pin tightly fitted in a hole in the specimen and loaded in the plane of the specimen.

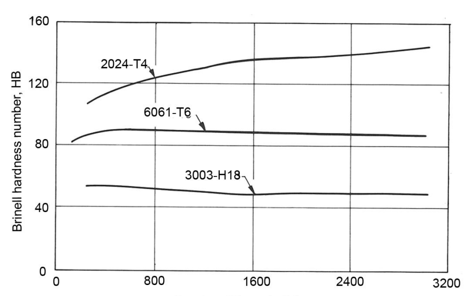

Fig. 10 Effect of load on Brinell hardness (10 mm ball)

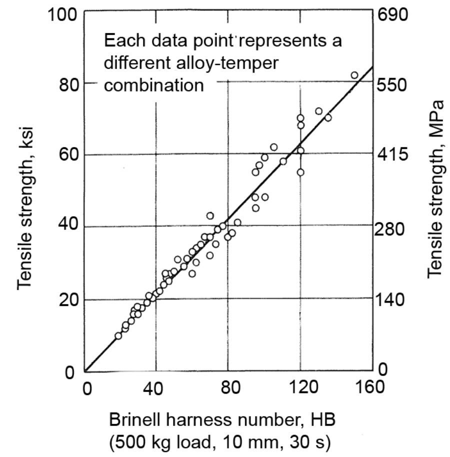

Fig. 11 Correlation of tensile strength with Brinell hardness of wrought aluminum alloys

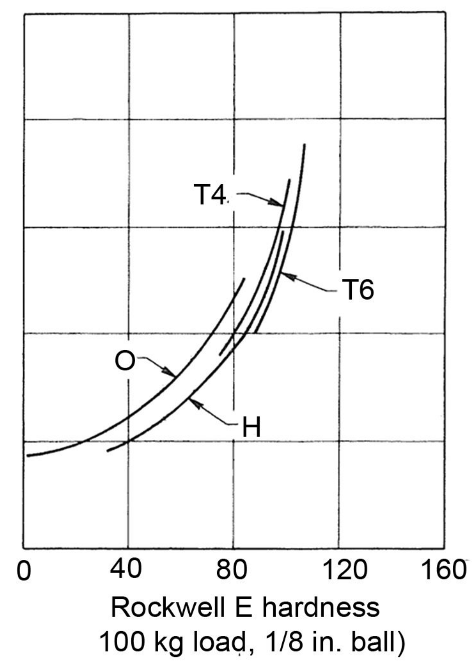

Fig. 12 Tensile strength vs. Rockwell E hardness of aluminum alloy sheet

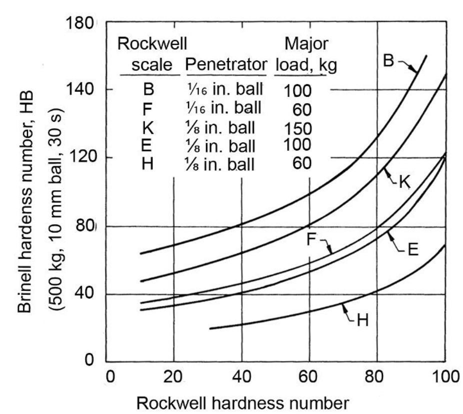

Fig. 13 Approximate correlation between Brinell and Rockwell hardnesses of wrought aluminum alloys

The relation between the load and the deformation of the hole has many of the characteristics of a tensile stress-strain curve. Bearing yield strength is the stress at a permanent set equal to 2.0% of the pin diameter. The maximum load before fracture defines the bearing strength. Both bearing strength and yield strength are based on the area of the projection of the contact surface (diameter of pin multiplied by thickness of specimen). Bearing values depend on the test conditions and the proportions of the specimens (Ref 17). To obtain uniform results, bearing specimens and fixtures should be cleaned thoroughly (e.g., ultrasonically), and care should be taken to avoid touching the bearing surfaces before the test is performed (Ref 18).

Formability

The term *formability* is commonly used to describe the ability of a sheet metal to maintain its structural integrity while undergoing plastic deformation into a shape. Failure can occur by tearing, buckling, wrinkling, and excessive thinning (Ref 19). Aluminum is among the most workable common metals and can be formed by processes involving tensile, compressive, shearing, and bending forces, or combinations of these. However, there are no universally accepted measures of formability, and various types of tests are used. Some examples are given subsequently. A test is applicable only when it closely simulates a specific forming operation.

Elongation from Tensile Tests Elongation from tensile tests is one of the most commonly used measures of formability. However, the value obtained represents a composite of characteristics dependent to some extent on the size, shape, and gage length of the test section. The value is governed by two factors: the uniform elongation, which is independent of gage length, and the localized elongation in the vicinity of the fracture, which is dependent on the extent of necking. Uniform elongation is representative of the characteristics needed in stretching operations, whereas localized elongation represents those needed in severe bending or forging. These two types of elongation may rate materials differently (Table 5). For example, experience shows that 2024-T4 is better than 2024-O for forming by stretching, whereas 2024-O is better for forming by bending.

Table 5 Indexes of formability from tensile tests of several wrought aluminum alloys

Alloy and temper	Ratio of yield strength to tensile strength	Elongation(a), % In 0.5*D*	In 4*D*	Uniform	Reduction of area, %
1100-O	0.39	147	53	35	88
1100-H12	0.89	130	25	12	76
1100-H18	0.92	···	23	9	73
2024-O	0.36	50	22	13	43
2024-T36	0.84	45	17	12	17
2024-T4	0.62	46	23	14	34
2024-T6	0.8	35	15	7	26
2024-T86	0.95	53	9	3	25
6061-O	0.36	118	38	20	75
6061-T4	0.67	70	30	13	54
6061-T6	0.87	58	21	8	49
6061-T91	1	35	9	0.2	34
7075-O	0.45	···	20	10	40
7075-W(b)	0.48	48	26	19	37
7075-T6	0.86	···	19	8	31

(a) 13 mm (0.5 in.) diameter specimens. (b) Tested 4 h after quenching

Reduction of area and ratio of yield strength to tensile strength, also obtained from the tensile test, are sometimes used as measures of formability. Reduction of area is closely related to localized elongation. Workability is typically greater for alloys having low ratios of yield to tensile strength.

Bend Tests Bend tests are used to evaluate formability and are of value in establishing limits of shop practices. One such test reveals the smallest radius over which a metal can be bent without fracture; the values vary, not only with alloy and temper but also with thickness and diameter. Guided and wrap-around bend tests with prescribed radii are used to establish the quality of welds and thus the qualifications of welding procedures and welders.

Cupping Tests Cupping tests, such as the Olsen and Erichsen, Swift, and Fukui tests, are used to evaluate the formability of sheet. The Olsen and Erichsen cup tests and the hemispherical dome tests measure stretching, while the Swift cup test measures drawing. The Swift round-bottomed test and the Fukui conical cup tests are involved with combined stretch and drawing. The Mullen test is often applied to foil, and the hydrostatic pressure is the index of formability. After trial runs of a particular forming operation have shown that a specific alloy and temper are satisfactory, these cupping tests may be useful supplementary tests for quality control.

Another form of cupping test is made to determine the degree of draw possible with a certain value of hold-down pressure, type of lubrication, forming pressure, and punch-and-die clearance. Experience is required to correlate data with plant practices.

Forming Limit Diagram

Perhaps the most widely used indicator of formability in use today (2019) is the forming limit diagram (FLD). The FLD was established for sheet metals by subjecting the sheet to various ratios of major to minor in-plane strains and plotting the locus of strain ratios for which local thinning (necking) and failure occur (Fig. 14). The surface of the sheet is covered with a grid of circles produced by electrochemical marking. When the sheet is

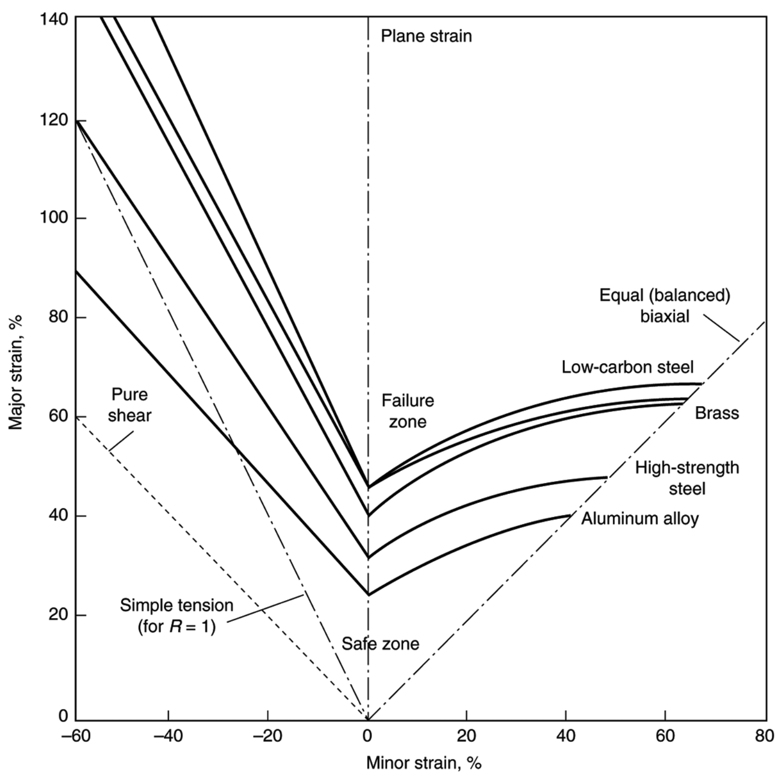

Fig. 14 Typical forming limit diagrams for different sheet metals. To use the diagram, locate the position on the chart for the major strain (always positive) and minor strain that is the most critical combination in the part to be formed. Failure will occur if the point is above the forming limit diagram for the sheet metal. Source: Ref 20

deformed, the grid of circles distorts and the ratio of major to minor strain can be determined at critical points. These strains are plotted in Fig. 14 to determine how close the material is to failure (Ref 20). Strain conditions on the left side of the diagram, where circles distort to ellipses, represent drawing conditions, while the right side, where circles distort to larger circles, corresponds to stretch conditions. When the minor strain is 0, a plane-strain condition is developed.

An FLD for a sheet metal can be used in conjunction with a trial run of the part to determine how close the material is to failure and how lubrication or die parameters should be adjusted to take the material away from a failure condition. Forming limit diagrams are dependent on bulk material properties, geometry of deformation, strain history (or strain path), sheet thickness, and the characteristics of the tool-sheet interface. Therefore, FLDs serve only as an indicator of formability and are not regarded as a material property.

This topic is discussed more completely in the article "Forming of Aluminum Alloys" in *Aluminum Science and Technology*, Volume 2A of the *ASM Handbook*, 2018.

Creep and Creep-Rupture Properties

In the preceding discussions of tensile, compressive, and shear properties, it is implied that the stress is increased continuously, and that the accompanying strains are independent of time under any specific stress. However, if a stress less than the ultimate strength is maintained for a period of time, the strain increases continuously (Fig. 15). If the stress is high enough or held long enough, the specimen eventually fails in the mode that would occur under continuously increasing loading. In this respect, the behavior of aluminum is like that of other metals.

Creep or rupture strengths cannot be expressed by a single number but must be related to time, amount of deformation, and temperature. Similarly, creep-rupture strength must be related to time and temperature. Strengths are lower for longer times and higher temperatures (Fig. 16).

At stresses less than approximately the yield strength, the amount of creep at room temperature is very small. Thus, room-temperature creep is seldom used to establish working stresses. However, at elevated temperatures, the amount of creep within the anticipated life of a structure or machine part can be significant; the creep strength corresponding to the tolerable amount of deformation therefore must be considered an upper limit of the working stress. For example, Section VIII of the "ASME Boiler and Pressure Vessel Code" (Ref 11) sets the creep strength associated with a minimum creep rate of 0.1% in 10,000 h as one limit on the allowable stress value. However, criteria of this type neglect much of the primary creep and imply that a certain amount of deformation is tolerable. Another approach to the consideration of creep in design is to specify the total creep and the associated time as a criterion for establishing the allowable stress.

Similarly, creep-rupture strength can be considered in establishing allowable stress values by specifying the time to fracture. For example, another criterion of the ASME code is the stress to produce rupture in 100,000 h. However, designers of rockets may be concerned with rupture lives of only a few minutes.

The use of allowable stress values derived from the creep and creep-rupture strengths in design led to the misconception that creep occurs only at temperatures in the creep range. Using other fractions of the tensile and yield strengths or other conditions to determine creep and stress-rupture strengths may lead to another range of temperature in which the creep characteristics control the allowable stress values, thus to a different creep range.

Because it generally is impractical to continue creep and creep-rupture tests beyond a few thousand hours, it is necessary to determine strengths for longer periods by extrapolating available data. Several procedures have been suggested for making such extrapolations, notably those by White, Clark, and Wilson (Ref 21), Larson and Miller (Ref 22), Manson and Haferd (Ref 23), and Orr, Sherby, and Dorn (Ref 24). Experience shows that for aluminum alloys, the Larson-Miller parameter is the easiest to use and provides the most reliable information, provided

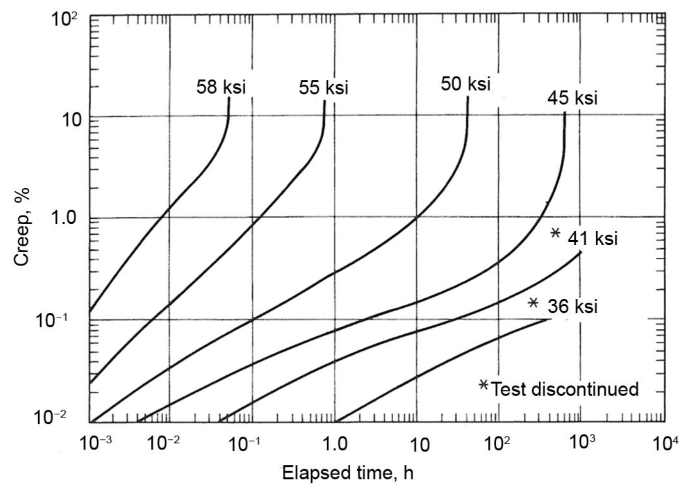

Fig. 15 Creep-time curves for 22 mm (0.875 in.) thick alloy 2024-T851 plate at 150 °C (300 °F) in the longitudinal direction

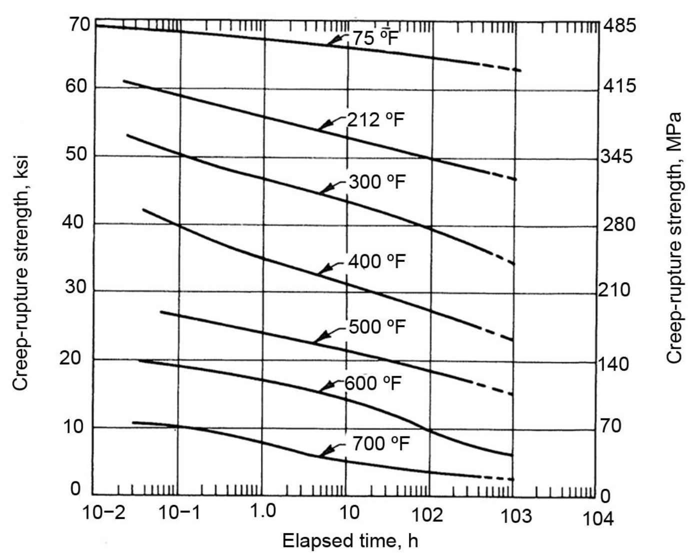

Fig. 16 Creep-rupture strengths at various temperatures of 25 mm (1 in.) alloy 2219-T851 plate in the longitudinal direction

that care is taken to determine the constants that best characterize the data.

Effects of Prior Creep

Creep strains could be accompanied by changes in the grain structure and in the subsequent mechanical properties. Test results given in Fig. 17 indicate that creep developed in 1060-H19 over long exposure times causes a greater loss in strength than the same amount of deformation developed at the same temperature over a shorter period but at a higher stress (Ref 25). Creep at higher temperatures causes a greater loss in strength than the same deformation at lower temperatures; in fact, creep at room temperature, like cold work, has a strengthening effect (Ref 26). As seen in Fig. 17, the decrease in strength associated with creep strains of 0.2% (the offset used to define yield strength) is not more than 2%.

Creep strains in alloys 2020, 2024, and 2219 also are associated with some decrease in tensile strength, but the decreases are less than 5% for strains as great as 0.5%.

Relaxation

In contrast to creep, which is the time-dependent strain resulting from stress, relaxation is the time-dependent decrease in stress under conditions of constraint. Relaxation is a complex interaction of creep strain, the accompanying direct relief of the stress, and the indirect relief of load through relief of elastic stress in adjacent members. Design for relaxation is difficult due to problems in obtaining suitable information on relaxation characteristics; this arises because of the need for extremely sensitive automatic feedback mechanisms with rapid response and the strong dependence of relaxation phenomena on the characteristics of the testing equipment. Freudenthal (Ref 27) suggested that relaxation curves for aluminum alloys could be based on the stress-rate effects on inelastic straining, which have been determined in tests with linearly increasing or decreasing stresses.

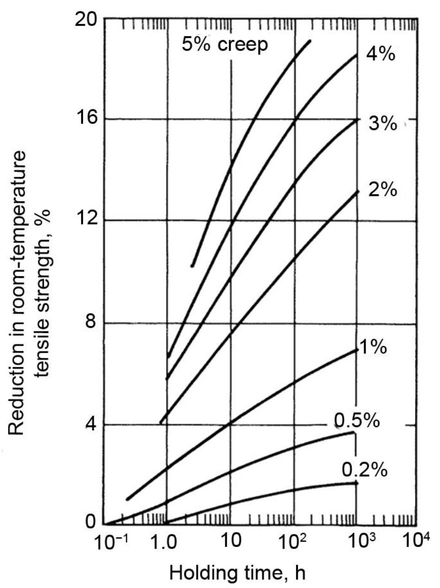

Fig. 17 Effect of holding time on percent of creep damage for alloy 1060-H19 for various creep strains at 150 °C (300 °F)

Damping Capacity

The damping capacity of a material is its ability to absorb vibrational energy and thus to dampen or resist the development of vibrations. It is sometimes referred to as internal friction. Damping capacity can be measured by a variety of tests; the results depend on the test method and the magnitude of the maximum stresses developed. Consequently, damping capacity is expressed in various ways, and the measured values are not readily converted from one unit to another. Furthermore, the data seldom are applicable directly to the design of a structure but are usually of value only to merit rate the alloys.

A common method used to evaluate relative damping capacity is to determine the rate at which free vibrations decay in free-free (simple) beam or fixed-free (cantilever) beam specimens. Log decrement (δ) is the simplest measure of damping capacity from this test. Specific damping capacity, based on the percentage of total potential or kinetic energy in the system dissipated in each cycle of vibration, may be estimated as 200 δ for values of δ less than 0.1. The damping capacity increases with the maximum stress during the cycle of vibration; the rate of increase is much greater for stresses above the elastic limit of the metal. For this reason, the lower-strength aluminum alloys and those with soft alclad coatings have much higher damping capacities than the high-strength bare alloys.

It is important to recognize that the vibration characteristics of most structures are less dependent on the damping capacity of the alloy than on features in the design, particularly the joints.

Effects of Strain Rate

Tensile tests for purposes of material qualification and evaluation are usually made at strain rates in the range from 0.001 to 0.1 mm/mm/min (0.1 to 10% per minute), so fracture occurs within 1 to 3 min after the beginning of loading. Although this range is considered as standard or static, it represents only a narrow band in a wide range of strain rates that are encountered, extending from those in relatively long stress-rupture tests, where fracture may develop after hundreds of thousands of hours, to those in explosive fractures that develop in milliseconds. Although this may be considered as a continuous range, the effects of strain rate can be discussed as the effects of rates less than and higher than those typically used in conventional tensile tests, respectively.

Low Strain Rates In tensile tests at room temperature, aluminum alloys are considered insensitive to strain rates less than 0.01 mm/mm/min (1% per minute). As the strain rate is reduced below the practical limit of a tensile test, the condition approaches that in which the load on the specimen remains constant and the creep rate becomes the strain rate. Therefore, the subject merges with that of creep and creep rupture.

High Strain Rates The term *impact*, as applied to strain rate, is not clearly defined; in fact, a test made at an impact rate actually is made at a specific strain rate represented by some point in the spectrum of rates. For aluminum, a high rate generally increases both ultimate and yield strengths and ductility. However, for strain rates up to approximately 0.01 mm/mm/min (1% per minute), the effects are small and can be ignored. At higher rates, the effects are increasingly significant. Although the amount of the increase dependent on strain rate appears to differ with alloy and temper, the overall effect is essentially the same. Data are insufficient to establish the variations in the trends for specific alloys or tempers.

The increases in properties of aluminum alloys with increases in strain rate are more pronounced at elevated temperatures than at room temperature; in general, the effects increase with temperature.

Because the strengths of aluminum alloys at high strain rates are at least as high as those in static tensile tests, the use of the static test values in design represents a conservative approach for high strain-rate applications. Few attempts are made to take advantage of the higher strengths at the higher strain rates.

Effects of Environment

Most material specifications are concerned with room-temperature and normal atmosphere conditions. However, many service applications involve deviations from these conditions, and thus, it is necessary to know the effects of variations in environment on properties.

The most significant environmental factor is temperature. Room temperature represents only one point (or a small range) in the scale between absolute zero and the melting range of a metal, so the properties of the metal at room temperature represent points on smooth curves covering the entire range, as illustrated in Fig. 18. Nevertheless, it is convenient to discuss the effect of temperature by subdividing temperature into those ranges below and above room temperature.

Temperatures below Room Temperature

Aluminum alloy strength increases with decreasing temperature. Increases at −45 or −75 °C (−50 or −100 °F) are almost negligible, but at lower temperatures, they become increasingly significant. The tensile strengths and tensile yield strengths of most aluminum alloys at −195 °C (−320 °F) average approximately 30 and 20%, respectively, higher than those at room temperature; at −250 °C (−420 °F), they average approximately 50 and 35% higher, respectively. Actual differences vary appreciably with composition and temper. Aluminum alloy strength at low temperatures is not influenced by time of exposure at those temperatures, with the exception of a few alloys in the freshly quenched temper that age harden at room temperature. Refrigeration retards aging of these alloys but does not completely prevent the process. Aluminum alloy strength at room temperature after exposure to low temperatures is not influenced by the exposure.

Elongations of most alloys increase with reduction in temperature, at least to −195 °C (−320 °F). With further decrease in temperature, elongations of some alloys decrease slightly but usually not below room-temperature values. For a few high-strength heat treated alloys (notably the 7*xxx* series), elongations remain approximately the same or decrease gradually with temperature.

The shear and fatigue strengths of aluminum alloys increase with decrease in temperature. The amounts of the increases are of the same order as those in tensile strengths, and the ratios of the properties remain virtually constant.

Elastic moduli in uniaxial tension and compression and in shear also increase with decreasing temperature at a nearly linear rate, as shown in Fig. 19. This indicates that Poisson's ratio is essentially the same as at room temperature.

The toughness or fracture characteristics of many aluminum alloys, as measured by the results of tear tests (unit propagation energy) or notch-tensile tests (notch-yield ratio), remain approximately the same or improve with decreasing temperature, as shown by representative data in Fig. 20 and 21. However, for the high-strength 7*xxx*-series alloys, there is a gradual decrease in toughness with decreasing temperature, the extent of which varies with composition and temper (Fig. 21). This indicates that care should be exercised to avoid severe stress raisers in these alloys in cryogenic applications.

Temperatures above Room Temperature

Aluminum alloy strength generally decreases with increasing temperature above room temperature, except that in some cases, the effects of age hardening offset other effects of exposure within narrow temperature ranges for various holding times. The length of exposure is important in the case of cold-worked and heat treated alloys (Fig. 22), but it has little or no effect on the properties of annealed alloys. The time-temperature dependence of strength requires that the properties over the entire exposure time be considered in selecting the alloy, in establishing allowable stress values, and in determining section sizes.

Shear, bearing, and fatigue strengths vary with temperature in a similar way as tensile strengths; ratios of these strengths to tensile strength generally can be considered constant. Similarly, ratios of tensile and compressive yield strengths are approximately the same at elevated temperatures as at room temperature. As a result, it is possible for designers to deduce compressive, shear, bearing, and fatigue design properties at elevated temperatures based on the ratios of the properties at room temperature and the tensile properties at elevated temperatures.

The ductility of aluminum alloys, measured by elongation and reduction of area, generally increases with increasing temperature and with exposure time at temperature. Exceptions to these trends parallel those with respect to strength. The ductility of heat treatable alloys exposed after solution heat treatment decreases until the maximum strength is attained and then increases with overaging. The ductility of annealed alloys is not affected by exposure time.

Toughness, as indicated by tear resistance, notch toughness, or fracture toughness, follows the same general trends as ductility with respect to temperature, as measured by elongation and reduction of area. Changes in toughness are usually more pronounced. For the designer, if toughness of fully age-hardened aluminum alloys is satisfactory at room temperature, elevated-temperature exposure should not be a problem. However, for alloys that artificially age harden, toughness in the

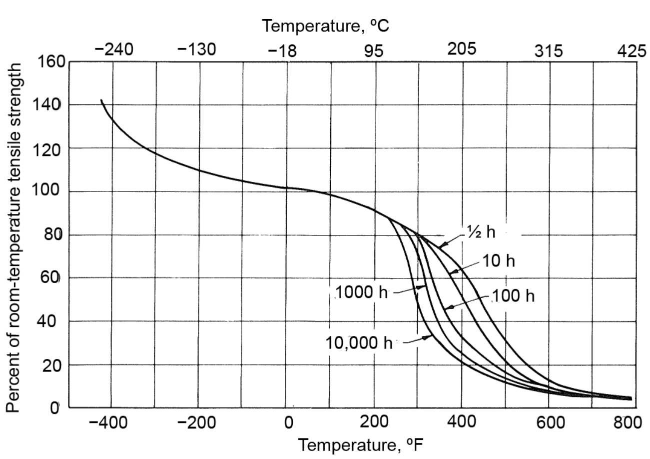

Fig. 18 Effect of temperature on tensile strength of 2014-T6

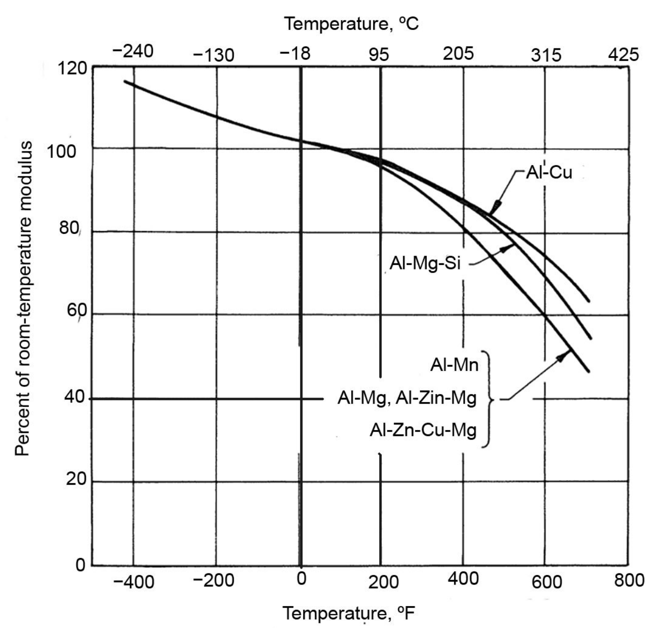

Fig. 19 Effect of temperature on modulus of elasticity of aluminum alloys