Wrought Aluminum Applications Guidelines—SAE J1434 JUN83

SAE Information Report
Approved June 1983

THIS IS A PREPRINT WHICH IS SUBJECT TO REVISIONS AND CORRECTIONS. THE FINAL VERSION WILL APPEAR IN THE 1984 EDITION OF THE SAE HANDBOOK.

SAE The Engineering Resource For Advancing Mobility

PREPRINT

Report of the Nonferrous Metals Committee, approved June 1983.

1. Scope—This report approaches the material selection process from the designer's viewpoint. Information is presented in a format designed to guide the user through a series of decision-making steps. "Applications criteria" along with engineering and manufacturing data are emphasized to enable the merits of aluminum for specific applications to be evaluated and the appropriate alloys and tempers to be chosen.

2. General Characteristics—In summary, aluminum is a suitable material for automotive applications. Its performance is a function of the degree to which its characteristics—which are different from steel—are recognized and taken into account in the design, fabrication, and assembly operations.

2.1 Strength—Typical property characteristics are illustrated in Figs. 1 and 2. Commercially pure aluminum has tensile yield and ultimate strengths of about 50 MPa (7 ksi) and 90 MPa (13 ksi). Values approaching 500 MPa (73 ksi) and 600 MPa (87 ksi) can be obtained with a combination of the following:

(a) Working the metal, as by cold rolling and forming.

(b) Alloying aluminum with small percentages of one or more other metals such as manganese, silicon, copper, magnesium, or zinc.

(c) Heat treatment and aging, as in the case of heat-treatable alloys. As a general rule, there is a reduction in elongation as yield and ultimate strengths of an aluminum alloy are increased by cold work or heat treatment. For alloys having a tensile yield strength of 500 MPa (73 ksi), elongations vary from 8–12%.

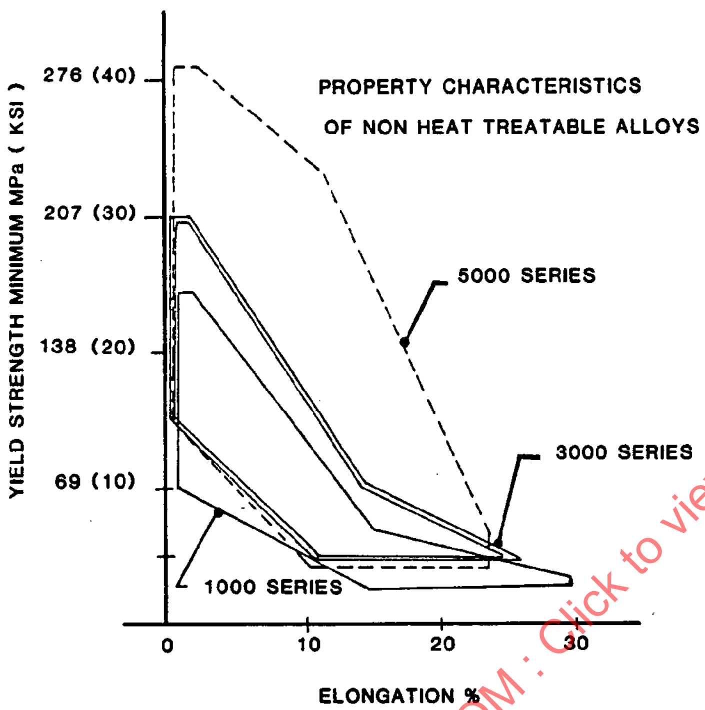


FIG. 1

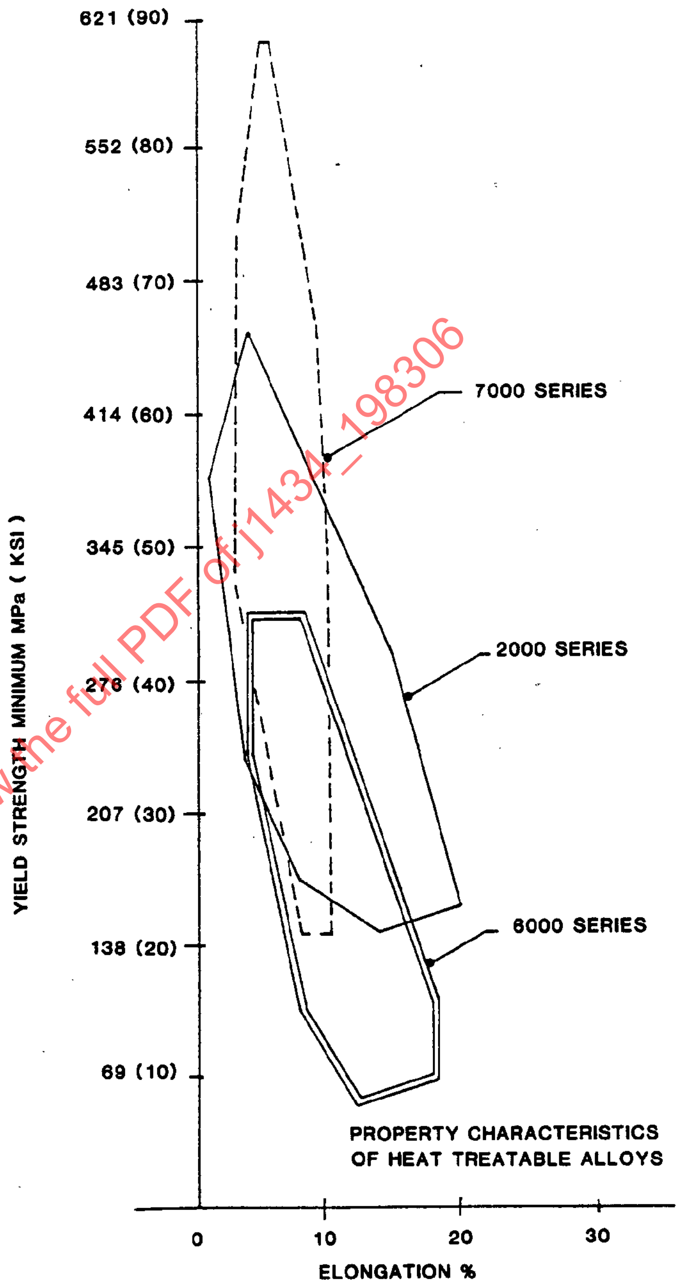


FIG. 2

The strength and modulus of aluminum and its alloys decrease at elevated temperatures, although some alloys retain good strength at temperatures up to 200–260°C (400–500°F). At sub-zero temperatures, however, their strength increases without loss of ductility so that aluminum is a particularly useful metal for low-temperature applications.

2.2 Fatigue—Components subjected to repeated loads should be carefully checked for the possibility of fatigue failure. Aluminum does not exhibit well-defined endurance limits. Typically, the endurance limits published for aluminum alloys are based on 500 million cycles. More data are being generated at 10 million cycles.

Limited strain control life data are also available. An S/N curve representing the design condition is required to take full advantage of an aluminum alloy when designing for fatigue. Connections, joints, holes, or other features that cause stress concentrations are areas subject to fatigue, especially with aluminum alloys. Careful design can reduce concentrations in highly stressed areas, thereby making the most efficient use of the material. All changes between different cross sections within a component should be gradual, as smooth transitions produce an improvement in the fatigue life of a component. In the assessment of fatigue, it is invaluable to compare available test data for joints similar to those of interest.

2.3 Corrosion Resistance—Aluminum alloys are known for their excellent atmospheric and road salt corrosion resistance, which results from the tightly adherent natural oxide film present on the surface. In many instances, aluminum alloys can be exposed to industrial and seacoast environment with no protection; others may require a protective coating at least on faying surfaces. In situations where crevices and pockets allow accumulation of mud and road salts and at junctions with dissimilar metals (galvanic couples), the corrosion protection of the natural oxide is insufficient and severe corrosion damage can occur. The former conditions should be avoided where possible in the design stage (for example, elimination of shelves, incorporation of drain holes, etc.). The elimination of the latter galvanic joints is extremely difficult or impossible in most ground transportation applications and various combinations of coatings and insulation techniques must be utilized.

Certain alloys, especially those containing over 3% magnesium and magnesium/zinc can be susceptible to stress corrosion cracking. This susceptibility must be considered in design and testing and care should be exercised in selecting appropriate alloys and tempers when designing structural members from these alloys.

2.4 Finishing—Aluminum needs no protective coatings for many applications. In many instances, the surface finish supplied is entirely adequate without further finishing. Where the plain aluminum surface does not suffice, or where decoration or additional protection is required, a wide variety of surface finishes such as chemical, electrochemical, and paint finishes may be applied.

Chemical conversion coatings are available for additional corrosion protection. They also provide an excellent base for paint. Electroplating procedures have been developed to give aluminum an attractive, durable finish. Anodic coatings are used for both decorative and functional applications. Hardcoat anodized aluminum surfaces can provide wear resistance similar to case-hardened steel. Vitreous enamels have also been developed for aluminum.

2.5 Fabrication—Aluminum can be cast, stamped, drawn, extruded, forged, spun, roll formed, and cold impacted. Typical aluminum body-sheet alloys are not as formable as low-carbon steel, but are comparable to high-strength low-alloy steels. Aluminum can be fabricated on conventional press lines with modifications in tooling, lubrication, and handling. Formability considerations should be taken into account in the initial design phase.

2.6 Machinability—The high speed with which many aluminum alloys may be machined is an important factor in determining the manufacturing cost of aluminum parts. Aluminum may be turned, milled, bored, or machined at the maximum speeds of which most machines are capable. An example of this is aluminum rod and bar employed in the high speed manufacture of parts by automatic screw machines.

2.7 Joining—Aluminum may be resistance welded, arc welded, brazed, soldered, and adhesive bonded. It may also be joined by mechanical systems such as hemming, riveting, clinching, pierce riveting, bolting, and stitching. Resistance welding, clinching, and riveting may be combined with adhesives for improved strength and fatigue life. Resistance spot welding, for high speed production applications, is in the developmental phase.

2.8 Electrical Conductivity—Electrical conductor grades of aluminum have 62% of the current carrying capacity of copper in equal volumes. These grades of aluminum have equal current carrying capacity at ½ the weight of copper. The high electrical conductivity property has led to the widespread use of aluminum in electromagnetic radiation shielding.

2.9 Magnetic Properties—Aluminum is non-magnetic if sufficiently free from paramagnetic impurities such as iron. This property has led to the use of aluminum in sensitive mechanical and electronic devices.

2.10 Thermal Conductivity—The high thermal conductivity of aluminum has led to its extensive use in radiators, heat exchangers, heat sinks, and other devices that involve the transfer of thermal energy.

2.11 Reflectivity—Aluminum is an excellent reflector of radiant energy through the entire range of wavelengths, from ultraviolet through the visible spectrum and infrared heat waves. It is used for heat shields. It also reflects electromagnetic wavelengths in the radio and radar range. Aluminum has a light reflectivity of over 80% which has led to its wide use in automotive trim, reflectors, and in lighting fixtures.

3. Alloy and Temper Designation Systems

3.1 The Metallurgy of Aluminum—This section is intended to give the automotive designer a brief overview of the different types of alloys available and an indication of the effects of alloying elements. The numerical alloy designation system adopted by the aluminum industry is based on the principal alloying elements in each class of alloy.

In high-purity form, aluminum is soft and ductile. Most automotive uses, however, require greater strength than pure aluminum offers. This is achieved in aluminum first by the addition of other elements which singly, or in combination, impart strength to the metal to produce various alloys. Further strengthening is possible by heat treatment and cold work.

3.1.1 NON-HEAT-TREATABLE ALLOYS—The initial strength of alloys in this group depends upon the hardening effect provided by manganese, silicon, iron, and magnesium, singly, or in various combinations. The non-heat-treatable alloys are usually designated as the 1000, 3000, 4000, or 5000 series. Further, strengthening is achieved by various degrees of cold working, denoted by the "H" series of tempers. Alloys containing appreciable amounts of magnesium, when supplied in strain-hardened tempers, are usually given a final elevated-temperature treatment called stabilizing to insure stability of properties.

3.1.2 HEAT-TREATABLE ALLOYS—The initial strength of alloys in this group is enhanced by the addition of alloying elements such as copper, magnesium, zinc, and silicon. These alloys are designated as the 2000, 6000, or 7000 series.

It is possible to subject them to thermal treatments which will impart pronounced strengthening, denoted by the "T" series of tempers.

The first step, called heat treatment or solution heat treatment, is an elevated-temperature process designed to put the soluble element or elements in solid solution. This is followed by rapid quenching, usually in water.

At room or elevated temperature, the alloys are not stable after quenching and precipitation of the constituents from the super-saturated solution begins. After a period of several days at room temperature, termed aging or room-temperature precipitation, the alloy is considerably stronger. Many alloys approach a stable condition at room temperature, but some alloys, particularly those containing zinc magnesium or zinc with magnesium and copper, continue to age harden for long periods of time at room temperature.

By heating for a controlled time at slightly elevated temperatures, further strengthening is possible and properties are stabilized. This process is called artificial aging or precipitation hardening. By the proper combination of solution heat treatment, quenching, cold working, and artificial aging, the highest strengths are obtained.

3.1.3 ANNEALING CHARACTERISTICS—All wrought aluminum alloys are available in annealed form. In addition, it may be desirable to anneal an alloy from any other initial temper, after working, or between successive stages of working such as in deep drawing.

3.2 Alloy Designation System and Effect of Alloying Elements

3.2.1 1000 SERIES—Aluminum of 99% or higher purity. This series has many applications especially in the electrical and chemical fields and is characterized by excellent corrosion resistance, high thermal and electrical conductivity, low mechanical properties, and excellent workability. Moderate increases in strength may be obtained by strain hardening. Iron and silicon are the major impurities.

3.2.2 2000 SERIES—Copper is the principal alloying element in this group. These alloys require solution heat treatment to obtain optimum properties. The heat-treated condition has mechanical properties that are similar to, and sometimes exceed, those of mild steel. In some instances, artificial aging is employed to further increase the mechanical properties. This treatment increases yield strength, with attendant loss in elongation; its effect on ultimate tensile strength is not as great.

3.2.3 3000 SERIES—Manganese up to 1.5% is the major alloying element in this group of work-hardenable alloys. One of these is the alloy 3003 which is widely used as a general-purpose alloy for low to moderate strength applications requiring good workability.

3.2.4 4000 SERIES—The major alloying element of this group is silicon, which can be added in sufficient quantities to cause substantial lowering of the melting point without producing brittleness in the resulting alloys. For this reason, aluminum-silicon alloys are used in welding wire and as brazing alloys where a lower melting point than that of the parent metal is required. Alloys in this series are non-heat-treatable. When used in welding heat-treatable alloys, they will pick up some of the alloying constituents of the latter and so respond to heat treatment to a limited extent.

3.2.5 5000 SERIES—Magnesium is one of the most effective and widely used alloying elements for aluminum. When it is used as the major alloying element or with manganese, the result is a moderate to high strength non-heat-treatable alloy. Alloys in this series possess good welding and low temperature characteristics and good resistance to corrosion in marine atmosphere. Certain limitations should be placed on the amount of cold work and service temperatures for the higher magnesium content alloys (alloys with over 3% magnesium) to avoid susceptibility to intergranular forms of corrosion.

3.2.6 6000 SERIES—Alloys in this group contain silicon and magnesium and are heat-treatable.

The magnesium-silicon (magnesium-silicide) alloys possess good formability and corrosion resistance, with medium strength. Alloys in this heat-treatable group may be formed in the solution heat-treated condition and then artificially aged to attain optimum properties.

3.2.7 7000 Series—Zinc is the major alloying element in this group which is usually coupled with a smaller percentage of magnesium resulting in heat-treatable alloys of very high strength. Usually other elements such as copper and chromium can be added in small quantities.

3.2.8 8000 Series—This series is used for wrought alloys where the principal alloying element is not covered within the preceding series. Thus, a number of different and generally very specialized alloys are included in the series. The series includes alloys where iron is the principal alloying addition, which are general purpose and high strength fin stock alloys.

3.3 Temper Designation System—The temper designation system is used for all forms of wrought and cast aluminum alloys except ingot. It is based on the sequences of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, the two being separated by a hyphen. Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as signficantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

3.3.1 Basic Temper Designation

F–as fabricated—Applies to the products of shaping processes in which no special control over thermal conditions or strain hardening is employed. For wrought products, there are no mechanical property limits.

O–annealed—Applies to wrought products which are annealed to obtain the lowest strength temper, and to cast products which are annealed to improve ductility and dimensional stability. The O may be followed by a digit other than zero.

H–strain-hardened (wrought products only)—Applies to products which have their own strength increased by strain hardening with or without supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits.

W–solution heat-treated—An unstable temper, applicable only to alloys which spontaneously age at room temperature after solution heat treatment. This designation is specific only when the period of natural aging is indicated; for example: W ½ h.

T–thermally treated to produce stable tempers other than F, O, or H—Applies to products which are thermally treated, with or without supplementary strain hardening, to produce stable tempers. The T is always followed by one or more digits.

3.3.1.1 *Subdivision of H Temper: Strain-Hardened*—The first digit following the H indicates the specific combination of basic operations, as follows:

H1–Strain-hardened only. Applies to products which are strain-hardened to obtain the desired strength without supplementary thermal treatment. The number following this designation indicates the degree of strain hardening.

H2–Strain-hardened and partially-annealed. Applies to products which are strained-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. For alloys that age soften at room temperature, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H3 tempers. For other alloys, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H1 tempers and slightly higher elongation. The number following this designation indicates the degree of strain hardening remaining after the product has been partially-annealed.

H3–Strain-hardened and stabilized. Applies to products which are strain-hardened and whose mechanical properties are stabilized by a low temperature thermal treatment which results in slightly lowered tensile strength and improved ductility. This designation is applicable only to those alloys which, unless stabilized, gradually age soften at room temperature. The number following this designation indicates the degree of strain hardening after the stabilization treatment.

The digit following the designation H1, H2, and H3 indicates the degree of strain hardening. Numeral 8 has been assigned to indicate tempers having an ultimate tensile strength equivalent to that achieved by a cold reduction [temperature during reduction not to exceed 93°C (120°F)] of approximately 75% following a full anneal. Tempers between 0 (annealed) and 8 are designated by numerals 1–7. Material having an ultimate tensile strength about midway between that of the 0 temper and that of the 8 temper is designated by the numeral 4; about midway between 0 and 4 tempers by the numeral 2; and about midway between 4 and 8 tempers by the numeral 6. Numeral 9 designates tempers whose minimum ultimate tensile strength exceeds that of the 8 temper by 14 MPa (2.0 ksi) or more. For two-digit H tempers whose second digit is odd, the standard limits for ultimate tensile strength are exactly midway between those of the adjacent two digit H tempers whose second digits are even.

Note: For alloys which cannot be cold reduced an amount sufficient to establish an ultimate tensile strength applicable to the 8 temper (75% cold reduction after full anneal), the 6 temper tensile strength may be established by a cold reduction of approximately 55% following a full anneal, or the 4 temper tensile strength may be established by a cold reduction of approximately 35% after a full anneal.

The third digit,[1] when used, indicates a variation of a two-digit temper. It is used when the degree of control of temper or the mechanical properties are different from, but close to, those for the two-digit H temper designation to which it is added, or when some other characteristic is significantly affected. (See Footnote 1 for three-digit H tempers.)

Note: The minimum ultimate tensile strength of a three-digit H temper is at least as close to that of the corresponding two-digit H temper as it is to the adjacent two-digit H tempers.

3.3.1.2 *Subdivision of T Temper: Thermally-Treated*—Numerals 1–10 following the T indicate specific sequences of basic treatments, as follows:[2]

T1–Cooled from an elevated-temperature shaping process and naturally-aged to a substantially stable condition. Applies to products which are not cold-worked after cooling from an elevated-temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T2–Cooled from an elevated-temperature shaping process, cold-worked, and naturally-aged to a substantially stable condition. Applies to products which are cold-worked to improve strength after cooling from an elevated-temperature shaping process, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T3–Solution heat-treated,[3] cold-worked, and naturally-aged to a substantially stable condition. Applies to products which are cold-worked to improve strength after solution heat-treatment, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T4–Solution heat-treated[3] and naturally-aged to a substantially stable condition. Applies to products which are not cold-worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T5–Cooled from an elevated-temperature shaping process and then artificially-aged. Applies to products which are not cold-worked after cooling from an elevated-temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T6–Solution heat-treated[3] and then artifically-aged. Applies to products which are not cold-worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T7–Solution heat-treated[3] and overaged/stabilized. Applies to wrought products which are artifically aged after solution heat treatment

[1] Numerals 1–9 may be arbitrarily assigned as the third digit and registered with The Aluminum Association for an alloy and product to indicate a variation of a two-digit H temper provided: (1) the temper is used or is available for use by more than one user, (2) mechanical property limits are registered, (3) the characteristics of the temper are significantly different from those of all other tempers which have the same sequence of basic treatments and for which designations already have been assigned for the same alloy and product and (4) the following are also registered if characteristics other than mechanical properties are considered significant: (a) test methods and limits for the characteristics or (b) the specific practices used to produce the temper. Zero has been assigned to indicate variations negotiated between the manufacturer and purchaser which are not used widely enough to justify registration.

[2] A period of natural aging at room temperature may occur between or after the operations listed for the T tempers. Control of this period is exercised when it is metallurgically important.

[3] Solution heat treatment is achieved by heating cast or wrought products to a suitable temperature, holding at that temperature long enough to allow constituents to enter into solid solution, and cooling rapidly enough to hold the constituents in solution. Some 6000 series alloys attain the same specified mechanical properties whether furnace solution heat-treated or cooled from an elevated-temperature shaping process at a rate rapid enough to hold constituents in solution. In such cases the temper designations T3, T4, T6, T7, T8, and T9 are used to apply to either process and are appropriate designations.

to carry them beyond the point of maximum strength to provide control of some special characteristic.

T8—Solution heat-treated,[3] cold-worked, and then artifically-aged. Applies to products which are cold-worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T9—Solution heat-treated,[3] artifically-aged, and then cold-worked. Applies to products which are cold-worked to improve strength.

T10—Cooled from an elevated-temperature shaping process, cold-worked, and then artifically-aged. Applies to products which are cold-worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

Additional digits,[4] the first of which shall not be zero, may be added to designations T1–T10 to indicate a variation in treatment which significantly alters the characteristics of the product. (See Footnote 4 for specific additional digits for T tempers.)

3.3.1.3 *Variations of O Temper: Annealed*—A digit following the O, when used, indicates a product in the annealed condition having special characteristics.

4. ***Relative Features of Various Product Forms***

4.1 Aluminum Sheet and Plate—Sheet is a rolled product having a thickness between 0.15 and 6.30 mm and is available in widths to approximately 2600 mm in coil or cut length form. It may be clad with other aluminum alloys for special finishes, corrosion protection, or brazing.

A variety of surface textures and patterns are available. Plate is a product thicker than 6.30 mm and is available in widths over 5 m. Some forms of plate may be cast rather than rolled as in tool and jig plate.

4.2 Foil—Foil is a rolled product less than 0.15 mm in thickness. It may be made in a variety of alloys for purposes such as electronic capacitors, fin stock for heat exchangers (some fin alloys are available which are anodic to the tubing used, giving corrosion protection), laminated packaging materials, reflective insulation, and plastic encapsulated foil trim.

4.3 Wire, Rod, and Bar—Wire, rod, and bar products are made by a sequence of rolling and drawing operations or less commonly by the extrusion process. Wire can be round, square, hexagonal, or rectangular in cross section. It is, by definition, 10 mm or less in diameter or the greatest perpendicular distance between parallel faces.

Rod is any round section over 10 mm in diameter. Bar is any section other than round with the greatest perpendicular distance between parallel faces being over 10 mm. Screw machine stock is rod, bar, or wire supplied in solid or hollow form and chamfered on the ends for automatic screw machines. A greater range of tempers in the non-heat-treatable alloys is available by rolling and drawing.

4.4 Extrusions—Extruded products are produced by forcing (hot, but not molten) metal through an orifice having a shape of the desired cross section. Complex structural shapes and beams having wide, thick flanges, and thin webs for efficient material utilization can be extruded. Irregular shapes having channels or slots for mating parts can be produced.

Sizes can range from rails for model railroads to aircraft wing spars weighing 100 kg/m of length.

Designers have found that the advantages of closer dimensional control and elimination of subsequent machining operations have warranted the use of extrusions in their designs.

4.5 Tube and Pipe—Tube and pipe are produced by extrusion, welding, or cold drawing. Round, square, rectangular, and oval shapes are available. Selection of the process is based on tolerance and straightness requirements. Tubing can be supplied in coils or straight lengths.

4.6 Forgings—Aluminum alloy forgings are produced on conventional hammer equipment and on hydraulic and mechanical presses. Forgings are applicable for brackets, support members, and connectors to other structural members where high strength, fatigue life, and good ductility are required. Die forgings are made in sizes from air-conditioning compressor connecting rods to parts covering over 4 m^2 and weighing 1500 kg.

4.7 Impact Extrusions—The primary advantage of an impact extrusion is that it can be made into a closed-end tube or cylinder. The tube section may have a variety of shapes, one or both ends open, internal web, a heavy end with bosses suitable for further machining.

Impact extrusions are made from cast, blanked, or sawn slugs. Examples include: electronic condensor cans, air-conditioning receivers/dehydrator, and accumulator bodies.

4.8 Electrical Conductors—Aluminum conductors are available in a variety of forms, from wire to large bus bars. The natural oxide film on aluminum is a dielectric. Special joining techniques are required.

4.9 Roll-Bond—The product form "roll-bond" is aluminum sheets or plates containing continuous passages through which gases or liquids can flow. It is made by metallurgically bonding two sheet panels together after first silk-screening a specific pattern of non-bonding ink onto one of the adjoining surfaces. After roll-bonding the two sheets together, the non-bonded inked pattern is inflated to become the desired tube circuit. The most common application of roll-bond sheet panels is for household refrigerator evaporators but it can be used in many other heat exchanger applications such as condensers, tube circuits, accumulators, or in other fields where patterned, hollow plate sections are desired.

5. ***Influence of Aluminum Properties on Part Design and Fabrication***—The analytical basis and procedure used in the design of an aluminum structural component are no different from those used for any other material. An engineer must recognize that the selection of aluminum requires an understanding of the material's physical and mechanical properties, as well as its fabrication characteristics. This will lead to an optimum design for a given set of loading and performance conditions, that is, the lightest weight structural component that is cost and performance effective.

5.1 Mechanical Properties

5.1.1 Modulus—Young's modulus for aluminum, which varies slightly with alloy composition, is 69 000 MPa (10 × 10^6 psi). The shear or torsional modulus is 26 000 MPa (3.8 × 10^6 psi).

These values are approximately one-third of those for steel.

For a given design, modulus of elasticity determines the stiffness of a component. The modulus of aluminum (as compared to steel) may require that, where stiffness is important, a component be designed so that its geometric properties (moment of inertia, section modulus, end constraint, etc.) compensate for aluminum's lower modulus.

The elastic moduli must be considered when designing structures in which stiffness or deflection is important. The stiffness can be increased by a combination of increased thicknesses and sections, decreased spans, and improved joining techniques. For a simple beam loaded at its midpoint, the stiffness is proportional to the elastic modulus and moment of inertia and inversely proportional to the cube of the span.

TABLE 1—MODULUS OF ELASTICITY OF SELECTED METALS

	Modulus of Elasticity	
Material	**MPa**	**psi × 10^6**
Magnesium	45 000	6.5
Aluminum	69 000	10
Copper	110 000	16
Carbon Steel	200 000	30

$$\text{Stiffness} = \frac{\text{Load}}{\text{Deflection}} = \frac{\text{constant} \times \text{elastic modulus} \times \text{moment of inertia}}{(\text{span})^3}$$

The most efficient method for increasing stiffness is by decreasing the span. Equal stiffness can be obtained with an aluminum span 70% that of a steel span. This is particularly applicable to outer panels, because inner panel structures can be designed to maintain the desired stiffness of an outer panel. As an example, in the original design of a steel hood, a large portion in the center of the outer panel may not have been reinforced, resulting in excessive deflection when using aluminum. However, a shallow web may be provided in the inner panel to contact the outer, which, coupled with adhesives, can effectively increase the stiffness of this section by several orders of magnitude; thereby reducing deflections to less than those for the original steel hood.

[4] Additional digits may be arbitrarily assigned and registered with the Aluminum Association for an alloy and product to indicate a variation of tempers T1–T10 provided: (1) the temper is used or is available for use by more than one user, (2) mechanical property limits are registered, (3) the characteristics of the temper are significantly different from those of all other tempers which have the same sequence of basic treatments and for which designations already have been assigned for the same alloy and product, and (4) the following are also registered if characteristics other than mechanical properties are considered significant: (a) test methods and limits for the characteristics, or (b) the specific practices used to produce the temper. Variations in treatment which do not alter the characteristics of the product are considered alternate treatments for which additional digits are not assigned.

The deflection of an aluminum panel that has been substituted thickness-for-thickness for the steel panel, may be reduced by a factor of 2.8 by shortening the effective beam length by 50%. Flat fender panels often are reinforced with internal channel shapes. The use of an adhesive at the midpoint can effectively cut the "beam" length by a factor of two.

The next most efficient technique is to increase the depth of a section. For equal resistance to deflection of flat sheet panels, the thickness of the aluminum would need to be nearly 44% greater than a steel part, but the aluminum panel would weigh about 50% that of the steel panel. For structural shapes, such as channels and I-beams, increased resistance to deflection can be achieved most effectively by increasing the depth and the area of the flanges.

Lastly, if both span and depth changes are limited, the section shape can be modified. Increasing the width of the section, or the use of extrusions to redistribute material to the flanges as much as possible, improves stiffness without adding metal or increasing weight. Extrusion permits the use of thick flanges and thin webs for maximum strength and minimum deflection for a beam in a given space.

A designer should critically study the need for imposing stiffness limitations on parts because there will be a weight penalty when designing for stiffness rather than strength. In conclusion, where clearances permit and dies are designed for aluminum panels, equivalent deflection performance may be achieved in formed sheet members. For flat external panels, undesirable deflections may be greatly reduced by using an adhesive between the panel and existing reinforcements or by permitting metal to remain in large openings in inner panels so that additional spots of adhesive may be applied. Aluminum may then be used in thicknesses equal to steel, for a maximum weight saving at a minimum cost.

The natural frequency of vibration (flutter) of a part is a function of its mass-to-modulus ratio, and is therefore the same for aluminum and steel parts of the same geometry and thickness.

5.1.2 TENSILE—Structural aluminum alloys have yield strengths ranging from 35–500 MPa (5–73 ksi). Automotive aluminum alloys have yield strengths from 125–380 MPa (18–55 ksi) and ultimate tensile strengths from 205–410 MPa (30–60 ksi). In many cases, the alloys are formed in a low-strength temper and then artificially aged to maximum properties.

The high strength-to-weight ratio of the medium- to high-strength aluminum alloys makes them very efficient in crash energy management systems.

5.1.3 FATIGUE—Aluminum alloys do not exhibit a fatigue limit or stress level below which the fatigue life becomes essentially unlimited. Accordingly, their fatigue strengths must be specified for a certain number of cycles, commonly 10^6, 10^7, or rotation bending fatigue data, 5×10^8 cycles.

Typical values for automotive alloys tested in bending are in the range 110–165 MPa (16–24 ksi) at 10^6 cycles and 95–145 MPa (14–21 ksi) at 5×10^8 cycles.

These fatigue properties are slightly lower than those for low-carbon steel, which has a fatigue limit of 140–175 MPa (20–25 ksi). Particular care must therefore be taken in designing aluminum structures subject to fatigue stresses to avoid stress raisers such as notches, sudden changes in section, and heavy machining marks or other manufacturing or service damage and to ensure that good joining practices are used.

5.1.4 ELONGATION—Aluminum automotive alloys have elongations prior to forming of 20–25%, in comparison with about 40% for draw quality steel. This limits the depths of draw, sharpness of bend, and draw radii and other forming characteristics of aluminum and also the amount of service deformation it can withstand. Elongation is an important characteristic but many other properties must also be determined for a complete analysis of formability.

5.2 Physical Properties

5.2.1 DENSITY—A property of aluminum that makes it attractive to the designer is its light weight. It has a density of $2.65–2.85 \times 10^3$ kg/m³ (0.096–0.103 lb/in³), resulting in a high strength-to-weight ratio. For example, weight savings of 50–75% have been achieved in bumpers, hoods, and rear deck lids with strength performance equivalent to steel. The values are approximately one-third of those for steel.

The use of a single kilogram (pound) of aluminum in an auto part produces a primary (direct) weight saving of one to two kilograms (pounds) on the average, depending on product form and application, when substituted for traditional ferrous automotive materials. In addition, this weight saving encourages redesign, allowing use of a lighter supporting structure and reduced power requirements for comparable performance, saving at least an additional 50–100% of the direct or primary weight savings in the form of secondary savings.

5.2.2 THERMAL CONDUCTIVITY—Aluminum has a high thermal conductivity. Alloy 1100, for example, has a value of 222 W/(m · K) [128 Btu/(h)(ft²)(°F/ft)]. See Table 3. Aluminum, therefore, is used to transfer thermal energy from one medium to another for either heating or cooling. Examples include tubing and sheet for heat exchangers in automotive air conditioning systems and aluminum radiators. Brazing alloys have the same thermal conductivity as the sheet and tubing being joined. Underhood heat sensitive electronic components are often housed in extruded housings with integral heat dissipating fins. Aluminum's high thermal conductivity combined with its high electrical conductivity also affects the welding procedures used for aluminum compared with those used for steel. (See paragraph 2.8, Electrical Conductivity.)

Finally, the coefficient of linear expansion for aluminum is approximately twice that of steel. Coefficients 100 K^{-1} (in/in/100°F) are shown in Table 4. It should be noted that, if fully restrained, the stress resulting

TABLE 2—APPROXIMATE DENSITY OF SELECTED METALS

Material	Density	
	kg/m³	lb/in³
Magnesium	1700	0.06
Aluminum	2700	0.10
Zinc	7100	0.26
Carbon Steel	7900	0.28
Copper	9000	0.32

TABLE 3—THERMAL CONDUCTIVITY

Material	Btu/(h)(ft²)(°F/ft)	W/(m · K)
Aluminum	128	222
Brass	87	151
Bronze	17	29.4
Cast Iron	27.6	47.8
Copper	227	393
Steel	26.2	45.3
Zinc	65	112.5

TABLE 4—COEFFICIENT OF LINEAR EXPANSION

Material	in/in/100°F	100 K⁻¹
Aluminum	0.00128	0.002304
Copper	0.00093	0.001674
Iron	0.00059	0.001062
Steel	0.00067	0.001206

from thermal expansion in an aluminum component is less than the stress in a ferrous component, because the modulus of elasticity of aluminum is only one-third that of steel.

5.2.3 ELECTRICAL—Aluminum is one of the two common metals having electrical conductivity high enough for use as an electric conductor. The conductivity of electrical conductor grade aluminum (SAE-UNS A1350) is about 62% of the International Annealed Copper Standard. However, because aluminum has less than one-third the specific gravity of copper, an aluminum conductor of equivalent conductivity will weigh approximately one-half that of a copper conductor. Special treatment is required at joining surfaces because the natural oxide on aluminum is a non-conductor.

The high conductivity of aluminum means that spot welding equipment—along with power generation, distribution, and control—designed to join steel automotive components and assemblies—must be revised or redesigned to suit aluminum. This has been done successfully to produce low-volume automotive body applications, such as truck cabs. Work is still underway to develop processes to join consistently high volume passenger car assemblies by spot welding.

5.2.4 EMISSIVITY—The capacity of a material to emit radiant energy can be expressed by its emissivity ratio. This is the ratio of emissive power to that of a black body at the same temperature. Emissivity ratios for various materials are given in Table 5.

To be most effective, exposed metal surfaces of aluminum must face an air space to be in the bare condition and have no applied coating.

5.2.5 Reflectivity—Aluminum reflects radiant energy through the entire range of wavelengths—from ultraviolet through the visable spectrum to infrared and heat waves. It also reflects electromagnetic wavelengths in the radio and radar range.

Because aluminum has a light reflectivity value of over 80%, several wrought alloys are used in auto trim and lighting fixtures.

5.2.6 Magnetic—Aluminum is non-magnetic. This property makes aluminum useful in electronic applications where various components must be shielded from electromagnetic disturbances that would upset their operation.

This property also means that in warehousing, transport, fabrication, and assembly operations, magnetic devices employed to handle ferrous materials will require modification.

5.2.7 Acoustic Properties—The influence of aluminum on the acoustical characteristics of a vehicle is governed by the design and shape of the component or assembly, rather than the material used. In terms of noise resulting from vibration, theoretically there should be no difference between identical aluminum and steel components, since the frequency of vibration is the same. On the other hand, if shielding governs, the component made from the metal with the lesser mass should allow more noise penetration. Nevertheless, because design is the key, passenger cars employing aluminum extensively for such items as body panels and engines are as quiet or quieter than their ferrous counterparts.

5.2.8 Melting Range—The melting range for aluminum and its alloys is from 657°C (1215°F) for 99.5% pure aluminum to 477°C (890°F) for an Al-Zn-Mg alloy (AA7075). The melting range for various automotive materials is shown in Table 6.

TABLE 5—EMISSIVITY RATIOS[a]

Aluminum (alloy 1100)	0.09 0.20	(commercial sheet) (heavily oxidized)
Copper (electrolytic)	0.072	(commercial shiny)
Iron (cast) (wrought)	0.435 0.94	(freshly turned) (heavily oxidized)
Steel (mild)	0.12	(cleaned)
Zinc (cast) (galvanized)	0.05 0.23	(polished) (fairly bright)
Paints (white enamel) (flat black lacquer) (aluminum lacquer)	0.91 0.96 0.39	(on rough plate) (on rough plate)

[a] Source: ASHRAE Handbook of Fundamentals.

TABLE 6—MELTING RANGE COMPARISON

Al (99.5% purity)	657°C (1215°F)
Al-Zn-Mg (AA7075)	477°C (890°F)
Mg alloys	490–610°C (914–1130°F)
Cu alloys	880–1180°C (1616–2156°F)
Zn alloys	380–442°C (716–828°F)
Steel	1400–1540°C (2250–2800°F)

5.3 Corrosion

5.3 Corrosion—Aluminum alloys currently specified for automotive applications have moderate to excellent resistance to corrosion. Because there are differences in corrosion resistance, the properties of the individual alloys should be considered for each application. Corrosion will usually not undercut protective and decorative coatings on aluminum even when the paint is scratched. If bright-finished products are required, anodizing enhances corrosion resistance.

Designs that provide crevices and "shelves" that could collect mud and debris that will form a poultice should be avoided, particularly where galvanic corrosion may occur.

Galvanic corrosion may be encountered where aluminum is coupled to steel or other dissimilar metals in the presence of an electrolyte. Corrosion of this type usually can be reduced or eliminated by taking the following precautions:

1. Keep electrolyte out of the joint. Sealants can be placed in hemmed joints or bolted connections.
2. Apply protective or inhibitive coatings of metallic or inorganic materials on the cathodic member or both of the materials prior to joining.
3. Provide some other satisfactory barrier between the two materials.
4. Proper design, such as avoiding crevices, can minimize corrosion in most cases.
5. Replace bare steel with galvanized or aluminized steel. Stress corrosion cracking and exfoliation corrosion can be encountered in certain alloys, especially the heat-treatable Al-Zn-Mg alloys. However these effects can be overcome by the proper control of microstructure and heat-treatment practice. Al-Mg alloys with magnesium levels about 3% can also be susceptible to stress corrosion but this can be controlled by appropriate thermal-mechanical practice.

5.4 Fabrication

5.4.1 General—Aluminum sheet alloys can be successfully formed into automotive components on a high-volume basis utilizing existing press line equipment. High-volume production has been accomplished by understanding and properly managing the effects which material characteristics, tool design, tool finish, part shape, lubrication, and press setup have upon the overall forming process.

Key differences in the forming characteristics of drawing quality steel and aluminum are:

1. Strain distribution capabilities for aluminum are lower; intermediate forming steps may be required.
2. Forming limit diagram values and limiting strains are lower for aluminum.
3. Total elongation is lower for aluminum.
4. Drawing of typical shallow drawn auto body panels will be equal if tools are made using aluminum design guidelines.
5. Stretchability is less for aluminum.
6. Spring back is greater for aluminum, but overcrown can be built into the initial draw die to compensate for the difference.
7. Bending and hemming capabilities are less for the aluminum outer panel alloys, that is, 2036-T4, 6010-T4; therefore, rope hemming is recommended to prevent cracking.
8. Aluminum heat-treated body sheet may be supplied dry and has a natural thin oxide film. Light overall lubrication on both sides of the blank to be formed is preferred and supplemental binder lubrication may be required.

For successful volume production forming of aluminum sheet components:

1. Design the part to be compatible with the forming limitations of the specified alloy.
2. Design the draw tools to control metal flow into the die while minimizing stretch.
3. Apply a good lubricant evenly to both sides of the blank.
4. Use grid strain analysis techniques in conjunction with forming limit diagrams for the alloys involved during development of aluminum components and the production tools.

5.4.2 Formability Testing—A large number of testing techniques are being used in an effort to predict the formability of sheet materials. Each technique has its advantages, but none correlate completely between the laboratory and press shop performance.

A description of an alloy's forming characteristics includes; the measurement of tensile and yield strength, uniform and total elongation, reduction in area, the strain hardening exponent "n," the plastic strain ratio "r," the strain rate sensitivity exponent "m," cup testing, tensile/yield ratio, and the development of forming limit diagrams and strain distribution capabilities.

The plastic strain ratio "r" is a measure of a metal's resistance to thinning. Higher "r" values indicate greater formability in a drawing operation. The values may vary with rolling direction and are generally lower for aluminum sheet than for steel.

The strain hardening exponent "n" reflects how well the metal distributes strain. It establishes relative performance in a stretching process. A high "n" value is desirable and values for aluminum and steel body sheet are similar.

The strain rate hardening exponent "m" may be positive or negative. Metals with positive values, such as steel, exhibit an increasing ability to strain harden as the strain rate increases. Those materials with negative values (many aluminum alloys) have a greater tendency towards localized necking as the strain rate increases. Metals with similar "n" values but differently directed "m" values, may demonstrate different results in stretching operations.

Uniform elongation is the limit of plastic strain which precedes localized necking. Total elongation is the strain to fracture and is related to gauge length. Elongation alone is not a reliable indicator of actual forming characteristics.

5.4.3 Application of Grid Strain Analysis—Grid strain analysis is a technique for effectively identifying, evaluating, and solving forming difficulties. The technique provides a record of the strains introduced during forming by the deformation of preprinted circles on the blank surface. The major and minor strains for deformed circles of interest may then be plotted on the forming limit diagram of the alloy involved (Schematic Forming Limit Diagram, Fig. 3). Three features are important in a complete grid strain analysis. The first two are the strain state and the limiting strain. The third is the distribution of strain around the area where the peak strains occur. The peak strain levels provide a measure of total forming severity while strain distribution evaluates the efficiency of the forming operation. Since there is little control over the shape or level of the Forming Limit Diagram for a given material, a study of the strain distribution offers the only opportunity for controlling the process. The shape of the deformed circles identifies the specific forming process (strain state, Fig. 4a) active at a failure location. Plotting the major and minor strains for circles on the selected strain path on the strain distribution plot (Fig. 4b) establishes the critically strained regions and the maximum allowable strain level for a given location. Changes in material, tooling or part design, and lubrication can be made to lower peak strains or modify the strain distribution.

5.4.4 Part and Tool Design Guidelines—The design of tooling to form sheet metal parts is covered extensively in the literature.[5] There are unique guidelines to insure satisfactory parts and shape control for aluminum. When followed for aluminum, they may enable the tooling

[5] 780141—*Forming High Strength Bumpers from Aluminum Sheet*—Manufacturing sequences, part and tooling guidelines for forming bumpers are discussed.

780392—*Interrelation Between Part and Die Design for Aluminum Auto Body Panels*—Guidelines for forming aluminum auto body panels have been developed for use by part and forming tool designers. Full size proof die and production die tryout programs were conducted to establish part design, forming, tool, and process parameters.

800931—*Reducing the Cost of Aluminum Body Panels*—The design of parts to control stiffness and deflection while maintaining shape control in high visibility parts is discussed.

810122—*Aluminum Sheet Bumpers*—Alloy selection, relative weight, design, forming, finishing, and corrosion are discussed.

SCHEMATIC FORMING LIMIT DIAGRAM

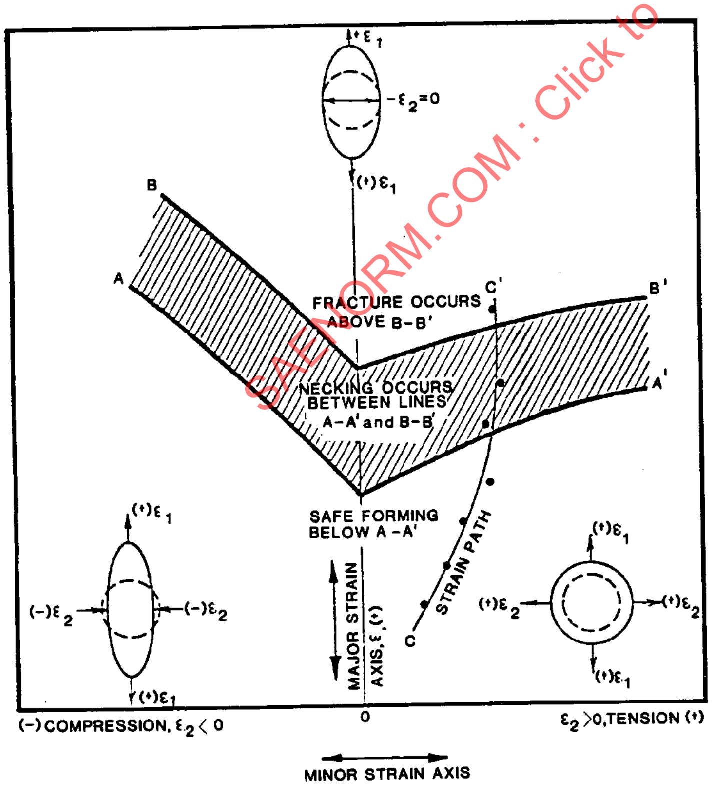


FIG. 3

FORMING LIMIT DIAGRAM

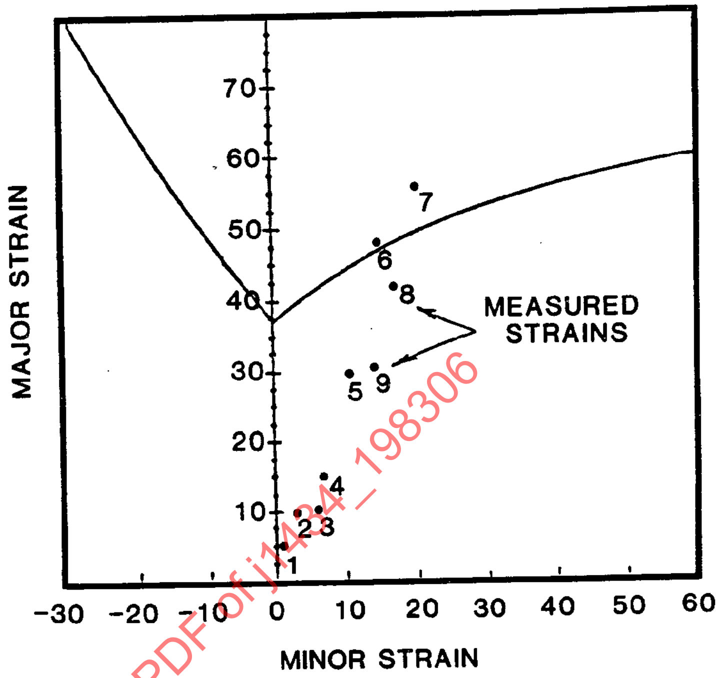
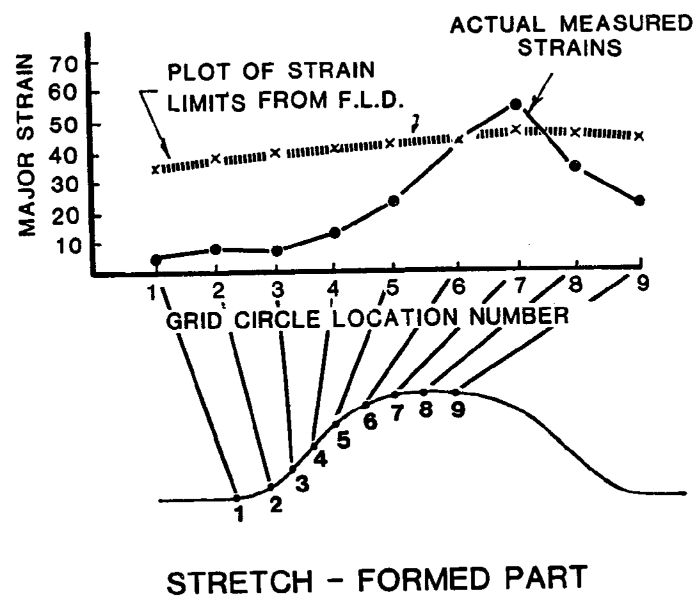


FIG. 4A

STRAIN DISTRIBUTION PLOT



STRAIN DISTRIBUTION SURVEY OF STRETCH - FORMED PART

FIG. 4B

to make excellent steel parts, but the reverse, is often not true.

5.4.5 Process Considerations

5.4.5.1 *Tool Materials*—A combination of hardened-steel tools with highly-polished forming surfaces and fully-lubricated blanks permit satisfactory production of aluminum panels with a minimum of tool maintenance. Excessive heat buildup or metal pickup can be avoided by using the proper die material, adequate maintenance, and suitable lubricants. Table 7 lists some of the die materials being used.

Experience has shown that the finish of hardened-tool surfaces in sliding contact with aluminum, such as panel and die radii and binderline surfaces, should be polished and maintained to a 4–8 μin (rms) finish. Hardened and polished tool steel inserts should be used in key locations in cast iron drawn tools to improve wear resistance and minimize metal pickup.

TABLE 7—A PARTIAL LIST OF SUGGESTED DIE MATERIALS

Application	Part Produced	Die Material	Die Hardness "C"
Blanking dies	Up to 2.29 mm (0.090 in) thick	SAE 1060	58–60
	Over 2.29 mm (0.090 in)	Type S7 tool steel	58–60
Draw dies	Most parts	Chromium-molybdenum alloy cast iron with D2, D5, or D7 tool steel inserts	60–65
Trim dies	Most parts	Composite sections: SAE 1020 base and SAE 1060 cutting edges	58–60
Flanging dies	From 0.58–1.91 mm (0.023–0.075 in) thick with straight flanges up to 25.4 mm (1 in) each	Type O tool steel	59–60
	Same gauge range but with curved flanges, flanges over 25.4 mm (1 in) wide	Type D7 tool steel	64–65
	All parts over 1.91 mm (0.075 in) thick	Type T15 tool steel	64–66
Hemming dies	All parts	Type W110 tool steel, D2	60–63

5.4.5.2 *Blanking and Shearing*—A clean-cut blank edge free of burrs and slivers is essential to damage free forming. Suggested punch clearances for the aluminum body sheet alloys are shown in Table 8. The ordinary shearing forces encountered in blanking operations can be estimated by multiplying the area to be cut (thickness × perimeter) by the shear strength of the material. The ultimate shear strength of aluminum alloys is approximately equal to 60% of the ultimate tensile strength.

TABLE 8—SUGGESTED BLANKING/PIERCING AND SHEARING CLEARANCES[a]

Alloy/Temper	Blank/Pierce	Shear
5182-O, 6009-T4, 6010-T4, 2036-T4	8–12% × t[b]/Side	8–12% × t/Side
7021-O, 7029-O, 7129-F-O	15–20% × t/Side	20–25% × t/Side
7029-F	15–20% × t/Side	15% × t/Side
5454-O	7–10% × t/Side	7–10% × t/Side

[a] Assumes sharp tooling.
[b] t = Metal thickness.

5.4.5.3 *Lubrication*—The use of good lubrication is important in all aluminum forming operations. The lubricant must maintain film strength under high pressure at the draw radius, be non-toxic, non-staining, easily removed, and be compatible with welding, adhesive bonding, and paint pre-cleaning operations to follow.

Aluminum sheet is normally supplied without lubricant in contrast to conventional steel. Good results are being obtained in production by roller coating lubricant to both sides of the sheet before forming. Occasionally, additional lubricants may have to be added at secondary operations.

5.4.5.4 *Stretch Stamping*—Stretch stamping is a sheet forming sequence in which the blank is clamped in lock bead tooling, prestretched over a punch to establish positive strains, and, finally, embossed to achieve part contours in mating tools. This process has the advantage of reducing blank size, maintaining shape control, reducing surface damage (visible surface up), and eliminating forming marks by reducing buckles and skid lines.

5.4.5.5 *Hemming/Bending/Downflanging*—The 90 deg bending and downflanging characteristics and the 180 deg hemming capabilities of the aluminum body sheet alloys are summarized in Table 9. In some instances, the inside radius for 90 deg bends for a straight downflange are sharper than the inside bend radius recommended for downflanges that will be formed into hemmed joints. The higher strength body sheet alloys require a roped hem. Schematic tool design for the rope hem is shown in Fig. 5a.

5.4.5.6 *Hole Flanging/Stretch Flanging*—Hole flanging capabilities of aluminum body sheet are signficantly influenced by tooling design and edge preparation. Flange lengths comparable to those obtained with steel can be produced through the use of specially designed pressure backup tooling. Splits occur in flanges when conventional piercing and flanging tools are used. Schematic representation of the tooling and its sequential operation are shown in Figs. 6 and 6a. Hole flange guidelines using pressure backup tooling are shown in Table 10.

5.5 **Joining**—Aluminum can be joined by most of the processes used to join steel such as resistance welding, fusion welding, mechanical fastening, adhesive bonding, and weldbonding.

5.5.1 Resistance Welding—Most series of aluminum alloys can be resistance welded. The 7000 series is an exception because many alloys of this series develop inferior mechanical properties and resistance to corrosion in the weld zone and should not be resistance- or fusion-welded.

The inherent characteristics of aluminum and its alloys require procedures which differ from the conventional methods used for carbon and stainless steels. The shear and peel strength and fatigue life of resistance spot welds in aluminum are approximately 50% of those of the same nugget size in low-carbon steel of the same gage.

Aluminum combines instantaneously with oxygen in the atmosphere to produce an aluminum oxide coating, this shortens the tip life of electrodes through pick-up of aluminum oxide resulting in a considerably shorter life than for electrodes used in spot welding steel.

In addition, the oxide has a rather high and occasionally erratic electrical resistance which, in turn, affects the amount of heat produced during resistance welding. This can result in a wide variation in weld strength. Improved resistance welding results can be achieved by chemical cleaning and by mechanical abrasion to produce uniform low-resistance oxide surfaces.

TABLE 9—RELATIVE FORMABILITY CHARACTERISTICS—BODY SHEET ALLOYS

Alloy	Gauge (mm)	Bend Radii				Stretchability			
		90 deg Downflange		180 deg Hem		Plane Strain		Biaxial Strain	
		As Received	cw[a]	DF[b]	Type	Strain (%)	Depth (mm)	Strain (%)	Depth (mm)
5182-O	0.7–1.2	1/2t[c]	1/2t	1t	Flat	20/5	23	40/35	33
6009-T4	0.7–1.2	1/2t	1/2t	1t	Flat	20/5	20	30/30	30
2036-T4	0.7–1.2	1t	1t	1-1/2t	Roped	20/5	21	25/25	30
6010-T4	0.7–1.2	1t	1t	1-1/2t	Roped	20/5	20	30/25	29
6009-T4	1.6		3/4t	—	—	25/5	29	35/35	37
	3.1		1-1/4t	—	—	25/5	30	40/40	38
6010-T4	1.6		1-1/2t	—	—	25/5	29	30/30	30
	3.1		2t	—	—	25/5	30	30/30	32

[a] Cold-worked (cw) from forming operation.
[b] Downflange (DF) radii.
[c] Metal thickness (t).

Since aluminum has high electrical and thermal conductivity, about two to three times the amount of current and about one-quarter the welding time are needed compared to steel spot welding.

Welds should not be too closely spaced. While the amount of the current that is shunted depends on material thickness and the surface resistance of the faying surface, weld spacing is the principal controlling factor. Poor part fitup and the effects of too little overlap and edge distance, reduce weld strength and electrode life. For example, welds made on the edge or very close to the edge, have reduced strength and may cause a weld blowout, which normally requires an electrode change. Poor fitup conditions reduce effective weld pressure also leading to excessive weld heat and possible blowouts.

5.5.2 Flash Welding—Advantages and Limitations—Flash welding of aluminum is a high-volume production process that is suitable for making butt and miter joints between two workpieces of similar cross-sectional shape. Most aluminum alloys can be welded and no filler metal

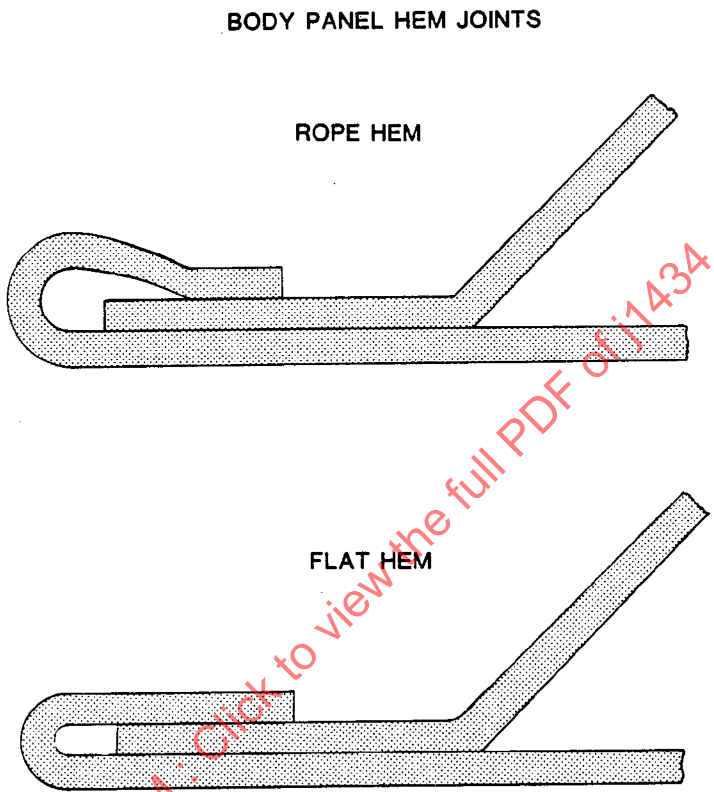


FIG. 5

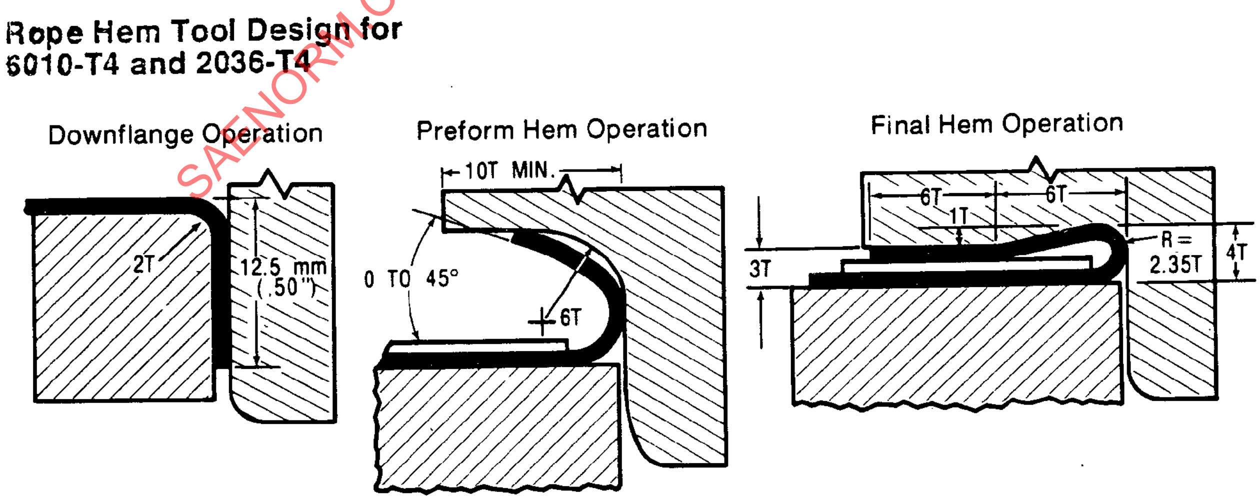


FIG. 5A

is required. The process is capable of producing welds that have strength equal to the base metal in some alloys. Flash welding can be used to produce assemblies that otherwise would require more costly forgings or castings. Dissimilar metals can also be welded using this process.

Cross sections up to 127 mm² (5 in²) of aluminum can be joined by flash welding. Aluminum thicknesses below 12.7 mm (0.050 in) are difficult to flash weld and should be avoided. Machines for flash welding aluminum require much larger transformer capacity than is needed for steel. They also require a more precise control, a faster upset velocity, and good alignment of surfaces to be joined.

5.5.3 Stud Welding—Stud welding is a specialized type of flash welding in which an aluminum stud is attached endwise to an aluminum surface. The stud can be a bolt, screw, rivet, rod, or similar device. Two different systems are used for stud welding.

1. Capacitor discharge which is a very rapid flash weld. With this system, studs can be welded to sheet as thin as 0.5 mm (0.020 in) when proper backups are used.

2. DC shielded arc stud welding which is similar to gas metal arc welding (GMAW).

The minimum aluminum thickness limitation is 2.0 mm (0.080 in) when proper backups are used.

5.5.4 Arc Welding

5.5.4.1 *GTAW Welding*—This is a joining method where an electric arc is maintained between a non-consumable, tungsten type electrode and the workpiece in an atmosphere of inert gas. The most popular uses for this process are for weld joints requiring a good appearance, thin gauge welding, and for joints where abrupt changes of weld direction occur.

The GTAW process is readily automated. Its greatest deterrent is the slow weld progression when compared to Gas Metal Arc Welding (GMAW).

5.5.4.2 *GMAW Welding*—The GMAW process utilizes an electric arc maintained between a consumable electrode (filler wire) and the workpiece in an atmosphere of inert gas. The GMAW process is faster and more economical than the GTAW process. The process is readily automated, and used extensively. Materials 1.1 mm (0.045 in) thick and greater can be welded automatically. Semi-automatic welding is generally limited to 1.5 mm (0.060 in) material thicknesses and greater. Minimum thickness for manual welding is 0.9 mm (0.035 in).

5.5.4.3 *Butt Welding*—Butt welds have good appearance, better fatigue life than lap or fillet welds, use less base material, and are easy to design. They require more accurate alignment, fitup, and either tacking or fixturing. In material 4.8 mm (0.19 in) or thicker, edge preparation or back chipping may be required. A weld pass may be required on the root side of plate.

5.5.4.4 *Fillet Welding*—Fillet welds generally do not require any edge preparation of the weld joint. Continuous fillet welds have better fatigue life than do intermittent fillet welds and often cost less to produce due to the labor involved in stopping and restarting the arc. Continuous welds are easier to automate than intermittent welds. The shear strength of fillet welds depends on the filler metal alloy rather than the base material.

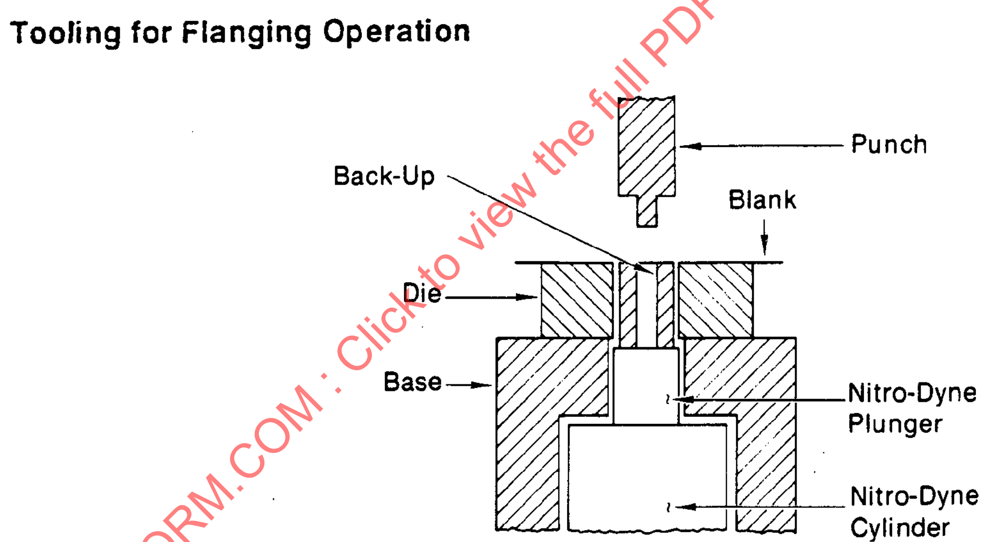


FIG. 6

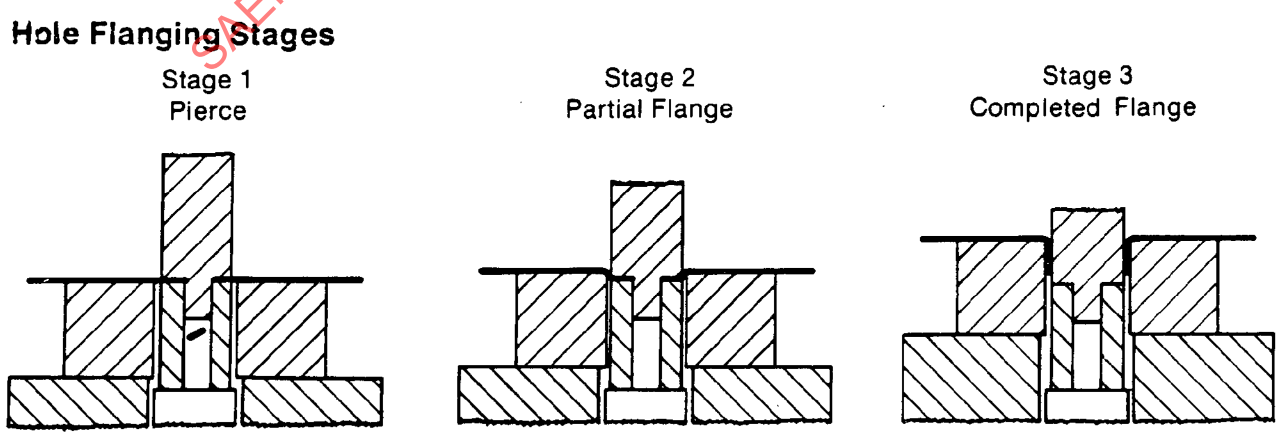


FIG. 6A