Welded Aluminum Highway Structures

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This paper discusses the applications of welded aluminum in highway structures from the standpoints of alloy recommendations and mechanical properties of the material, structural members, design features and specifications, welding processes, welder qualification, and precautions and methods in field welding.

•THE YEARS 1958, 1959, 1960, and 1961 are milestones in aluminum's long history. Old consumption records fell by the wayside and new total consumption marks were established in each of those years.

The building products industry was particularly outstanding. The official 1960 shipments of the aluminum industry to that field were 565,000 tons. Shipments to users in the building products industry were about 25 percent of total shipments, larger than any other industry. Official figures for 1961 are optimistically awaited. This growing industry fully expects to reach new heights in the year just beginning, 1962.

The use of aluminum in the highway field also made great strides from 1958 to 1961. In most of those years, the consumed tonnage doubled the figures for the previous year. The industry readily admits that the acceleration of the nations's highway programs on Federal, State, county, and city levels was a terrific force behind this upsurge. However, expanding recognition of aluminum's many natural advantages was undoubtedly influential in establishing the new records.

ADVANTAGES

Aluminum's advantages are threefold: (a) freedom from maintenance, (b) lightweight, and (c) versatility of form. These features will be fully explored to present a complete understanding of each.

Freedom from Maintenance

The natural formation of a tough, colorless oxide on the surface of the aluminum when exposed to air is the prime factor in aluminum's maintenance-free characteristics. This complex oxide layer protects the bulk of the metal from structural deterioration and rapidly seals itself if scratched. Of course, the degree of protection varies, depending on the alloy composition. It is important that specifications for structural aluminum alloys require the use of the more corrosion-resistant alloys or suitable protection for the less resistant alloys.

All the commercially weldable alloys and their recommended filler wires have a high degree of corrosion resistance and never need to be painted in highway applications. Generally speaking, these alloys are of the 3000, 4000, 5000, and 6000 series. Because they are not readily weldable, 2000 series alloys are frequently used in mechanically joined assemblies. Anodizing, cladding, and painting maintain the structural integrities of the 2000 series of alloys in corrosive environments.

Aluminum alloys that are recommended for welding never need painting. It is true that the structures will not maintain their "ribbon-cutting day" gleam indefinitely. The surfaces may become dirty in all but the purest environments, and self-limiting surface corrosion may occur in severe industrial and coastal atmospheres. Inspectors may assume, however, that these surfaces and those unseen to the eyes are not suffering any significant loss in their structural integrity.

Aluminum's corrosion resistance eliminates the maintenance crews' paint brushes and the related costs of the painting operation. The financial burden of completing the road-building job demands that limited funds must not be misdirected toward needless maintenance operations.

The safety of maintenance personnel and the motorists must be guaranteed. It is obvious that the removal of workmen and their necessary trucks, scaffolds, and ladders are instrumental in promoting this requirement. The public relations advantage can be readily appreciated, not to mention the hundreds of thousands of dollars saved in potential law suits.

No discussion would be comple without consideration of the compatibility of aluminum with other construction materials. Although aluminum alloy fasteners are recommended, stainless steel and zinc- or cadmium-plated steel fasteners are used with aluminum components without fear of galvanic corrosion in all but the most severe environments. Large faying surfaces between aluminum and any ferrous material should be protected. In these cases, the steel should be coated with red lead paint or iron oxide primer followed by an application of aluminum paint. The aluminum should be protected with a coating of zinc chromate primer. Aluminum in contact with wood or earth should receive a heavy coat of a chemical-resistant bituminous paint. More detailed information on these suggested paint systems is found elsewhere (1, Sec. I-6).

The Alcoa Research Laboratories (2) state that aluminum parts imbedded in structural concrete need not be painted to maintain their structural integrity.

Lightweight

The density of aluminum is one-third that of steel. However, the lower allowable stresses for aluminum dictate that the aluminum components shall have larger cross-sections than their steel counterparts. This means that the dead weight ratio of the two materials in the fabricated structure is about 2:1. This 50 percent weight reduction is significant for a number of reasons.

The most important benefit is the possibility of designing the structure for lighter dead loads. In extemely large bridges, where the dead weight is a large portion of the critical design load, this advantage can drastically affect the economics of the structure. Movable structures, such as bascule or lift spans, have been designed with lighter counter-balances because aluminum was used. Notable examples are the Hendon Dock Junction, Sunderland, England, bridge and the Victoria Dock, Aberdeen, Scotland, bridge. Both of these double-leaf trunnion bascule bridges used standard aluminum structural shapes and plate.

Larger shop-fabricated aluminum components are other benefits of the lightweight feature. Aluminum's lightweight encourages the use of large shop assemblies which are particularly well-adapted to joining by welding.

Expensive, and sometimes erratic, field fabrication is held to a minimum. A prime example of this feature is the 220-ft welded plate girder span erected in 1958 near Des Moines, Iowa (Fig. 1). Assemblies consisting of two girders and diaphragms were completely shop fabricated by Pullman Standard Company, Chicago, Ill., and shipped on flatcars and trailers to the erection site. Field erection was held to a few shear connections between diaphragms and girders and several girder splices.

Shipping and erection costs are held to a minimum with aluminum. Shipping expenses are drastically sliced because of the 50 percent weight saving. Many aluminum highway items, such as signs and traffic signal posts, are erected without need for mechanical lifting equipment (Figs. 2 and 3). Obviously, bridge components require mechanized equipment, but its capacity, and therefore its cost, is lowered (Fig. 4).

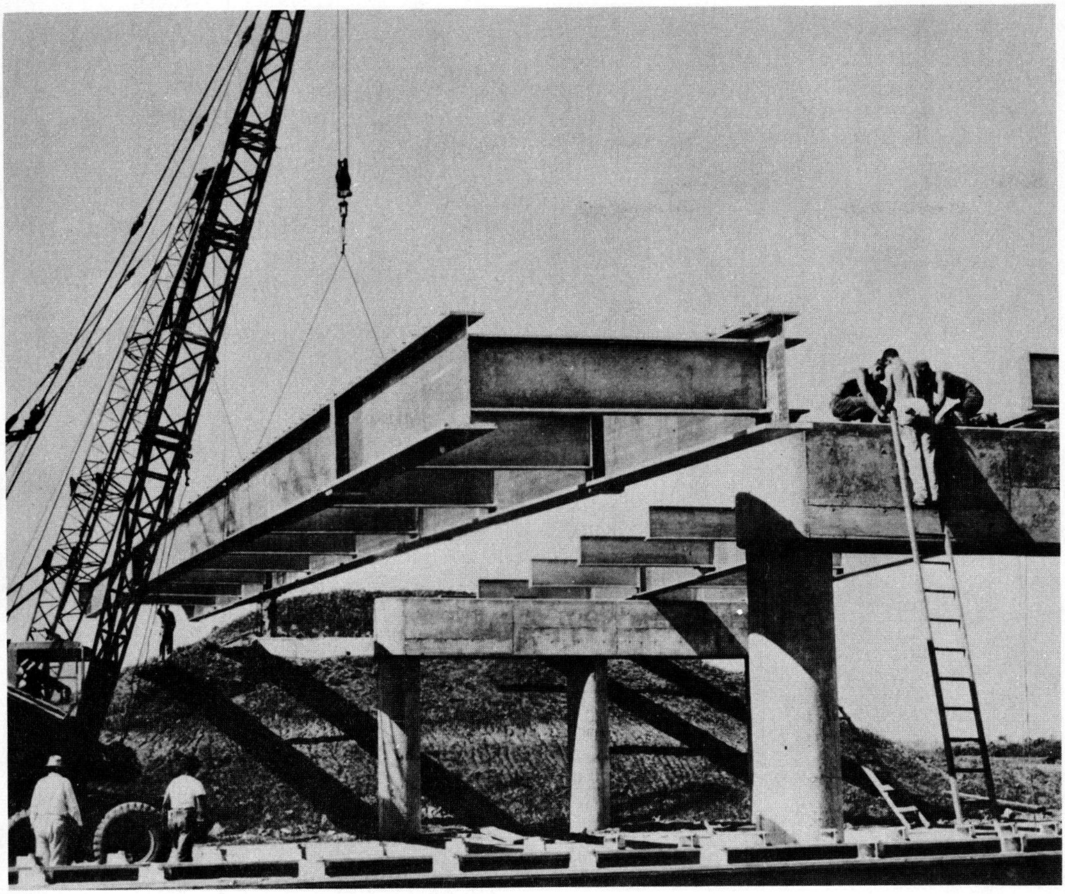


Figure 1. Giant subassembly of aluminum structural members elevated into position during construction of first aluminum girder-type highway bridge in the world, located near Des Moines, Iowa. Quick and easy field erection made possible by prefabrication of relatively lightweight members. Pioneering project jointly sponsored by Iowa State Highway Commission and Aluminum Company of America, Kaiser Aluminum and Chemical Corporation, and Reynolds Metals Company.

Versatility of Form

A vast array of aluminum products is available to the designer. Sheet and plate are available in thicknesses up to 3 in. and in widths up to 136 in. Lengths up to 45 ft are available in the common thicknesses of plate. Standard structural shapes are produced by rolling or extruding. Sizes up to 10- by 10- by ¼-in. angles, 12-in. I-beams, and 15-in. channels are available and the more common sizes are produced in lengths up to 85 ft.

Deeper composite plate girders, employing moderate-strength alloy webs and high-strength alloy flanges, may be designed and fabricated. As an example, a welded plate girder may have a 6061-T6 web and 5456-H321 flanges. This configuration makes the most of the mechanical properties of aluminum alloys.

The versatile extrusion process allows the designer additional freedoms in developing an efficient aluminum structure. Intricate single shapes may be substituted for built-up assemblies and special projections or lugs may be integrated to facilitate special joining techniques. As an example in the welding field, integral back-up strips and bevels eliminate some joint preparation operations.

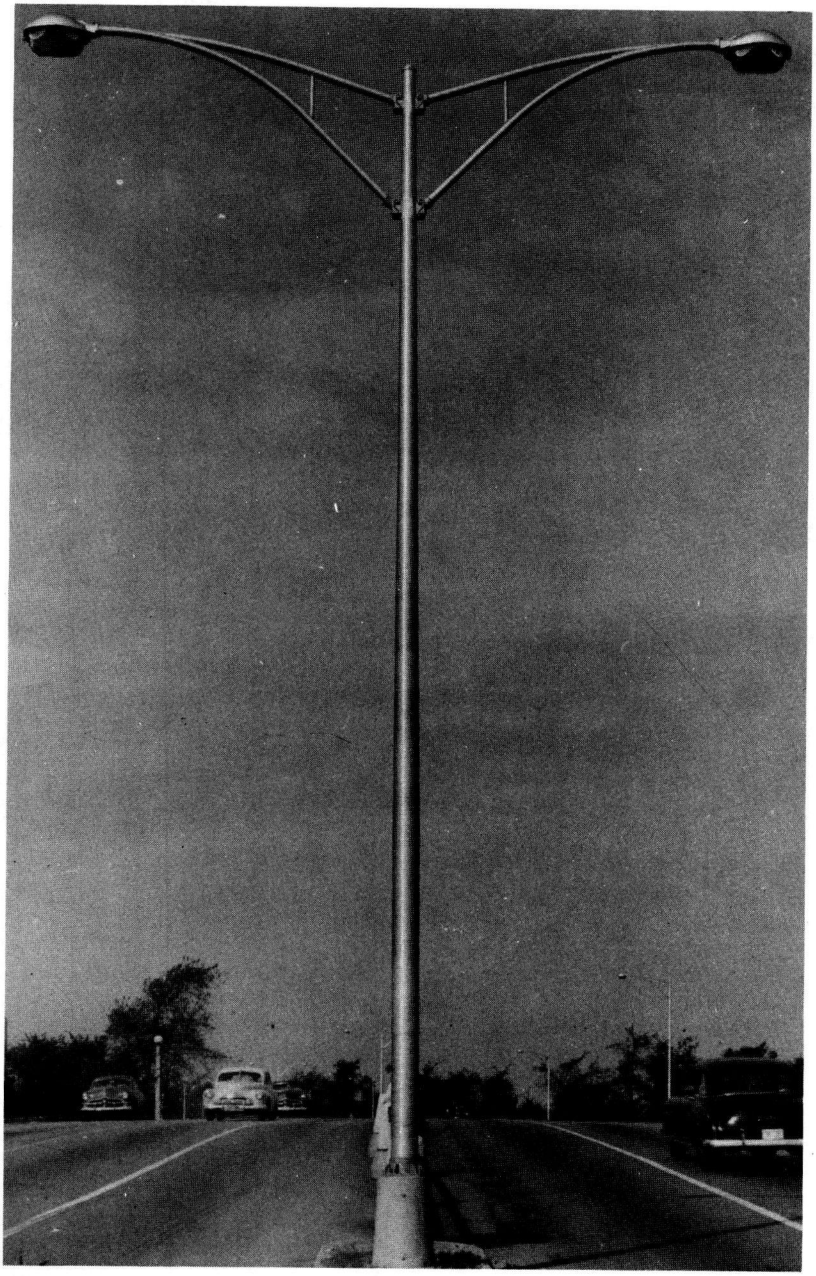


Figure 2. Tapered lighting standards with welded bases and bracket arms.

An extrusion press with the largest capacity in the United States, 14,000 tons, is owned and operated by Alcoa. This press is identical to one owned by the U. S. Government and operated by Alcoa which has produced huge extrusions for the government aircraft and missile programs for many years. This press is capable of producing extruded shapes up to 39 in. in width and up to 110 ft in length.

ALLOY RECOMMENDATIONS

The most common structural aluminum alloys are 6061-T6 and 6062-T6. These alloys are particularly well suited to mechanically joined structures, but welded fabrication is frequently employed. A minimum tensile strength of 24,000 psi across a butt joint is delivered by these alloys. Recognized design stresses for 6061-T6 and 6062-T6 are presented in ASCE Paper 970. When these alloys are used in sign structures, the working stresses shown in the AASHO Specifications for the Design and Construction of Structural Supports for Highway Signs (3) should be followed.

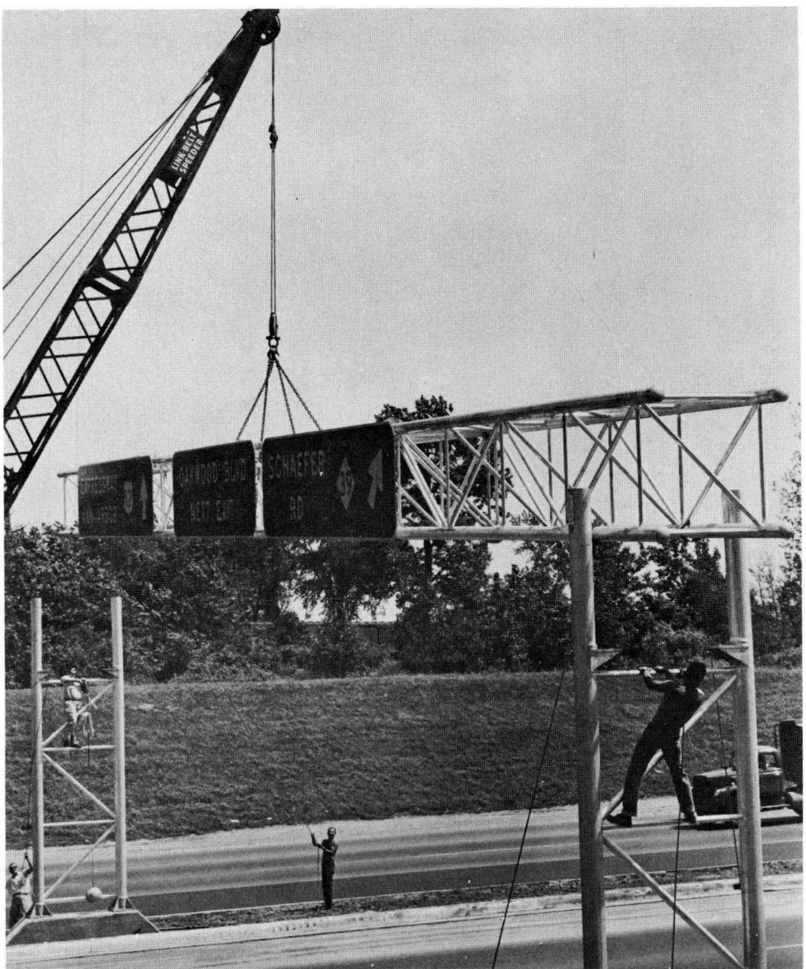


Figure 3. Welded tubular truss supporting overhead highway signs.

Alloy 5456 holds great promise for welded structural applications. Its use in highway structures has been limited to date, but its minimum tensile strength across a butt joint of 42,000 psi demands increased consideration. Working stresses are contained in ASCE Paper 2528 (4).

Alloy 6063-T6 is frequently used in low stress applications. Its 17,000-psi minimum tensile stress across a butt welded joint is often satisfactory in structures that are controlled by rigidity limitations. Design stresses for structural applications are anticipated from ASCE. The AASHO sign structure specifications (3) contain working stresses for alloy 6063-T6.

APPLICATIONS

Bridges

The history of aluminum bridges dates back to 1933 when the Smithfield Street Bridge in Pittsburgh, Pa., was refurbished with an aluminum deck. Riveting, the most popular joining method in that day, was used to assemble that structure.

Welding now has become established as a recognized joining technique. Bridge designers are urged to consider this technique for their modern structures.

Figure 4. Lightweight welded plate parapet for Fort Pitt Bridge, Pittsburgh, Pa.

A newsworthy application in recent years is the previously mentioned 220-ft welded plate girder span erected near Des Moines, Iowa, in 1958. This four-span continuous structure uses alloy 5083-H113 plate and alloy 5183 filler wire. These alloys are members of the aluminum-magnesium alloys family, which retain a great degree of their original strength after welding. The girders at the critical sections are composed of 36- by $1/2$-in. web plates, 12- by $3/4$-in. top flanges, and 12- by 1-in. bottom flanges. Eight-foot widths of the 8-in. reinforced concrete deck at each girder are depended on for composite action.

Ned L. Ashton of Iowa City, Iowa, was the consultant for the Iowa State Highway Commission and the aluminum components were fabricated by the Pullman Standard Company of Chicago, Ill. The bridge was designed for H20-S16 loading and carries a two-lane highway over a four-lane divided section of an Interstate highway.

The bridge used only 75,000 lb of aluminum alloys, and the aluminum items were bid at $1.00 per lb fabricated and erected.

Overhead Sign Structures

Proper signing increases the efficiency of modern highways. The most effective location to mount these vital signs is above the highway on overhead sign structures. Aluminum is enjoying great usage in this application.

The Michigan State Highway Department was the leader in this aluminum development. Many other State highway departments and city and county agencies now recognize aluminum's advantages and accept it as a standard construction material. Hundreds of tons of aluminum are used annually in this application.

Most of these structures are fabricated from alloy 6062-T6 extruded tubes which are welded into three- or four-chord trusses with alloy 4043, 5356, or 5556 welding filler wire. The widths of these trusses range from 2 to 7 ft and the depths are in the 3- to 12-ft range. Lengths of 100 ft are common and many of the newer spans cover 160 ft. The trusses are fabricated in 25- to 50-ft long modules which are bolted together at the erection site. Two chord posts are fabricated in single units about 25 ft long. Typical chords are 4- to 6-in. OD-extruded 6062-T6 tubes, and the web struts are normally about $2\frac{1}{2}$-in. OD-extruded tubes.

Recent AASHO Specifications for the Design and Construction of Structural Supports for Highway Signs (3) cover the design of aluminum overhead sign structures. The aluminum industry welcomes this standardization and anticipates that it will begin a new era of even greater acceptance of this material.

Roadside Sign Structures

Roadside signing supplements the larger overhead mounted signs. Aluminum also is recognized in this application.

Straight and tapered round tubes are favorite types of poles because of their appearance and torsional strength advantages over structural shapes. The bases of these alloy 6062-T6 or 6063-T6 tubes, which are normally about 8 in. OD, are welded to alloy 356 castings or 6061-T6 plates. These bases are bolted to aluminum or galvanized steel anchor bolts which are imbedded in concrete pedestals.

Signs

Aluminum's corrosion resistance makes it a natural for directional and informational signs. Most of these signs are bolted assemblies of special extruded channel-shaped sections or flat 0.125-in. sheet. An exception is a recently developed panel which is a resistance-welded assembly of extrusions and sheet.

These new panels are available in 12- to 36-in. widths which help to reduce the number of joints between panels. The facing sheet is alloy 3003-H18 in an 0.080-in. thickness. Alloy 6063-T6 extrusions with 2-in. depths and integrally extruded bolt head slots are welded to the facing sheet for additional strength and rigidity. The intermittent seam welding process is used for making these joints. The dimples on the facing sheet are slight and do not adversely affect the performance of any reflective surface or paint coating. Special hardware makes attachment to post flanges a simple job.

Lighting Standards

All lighting standards of aluminum depend on welding for their strength and rigidity.
Specially curved bracket arms of alloy 6063-T6 extruded tubes are normally shop welded to brackets that are field bolted to the poles. These poles are either spun-tapered alloy 6063-T6 round tubes, alloy 5052 flat sheet formed into round shafts and then longitudinally seam welded, or brake-formed alloy 6061-T6 hexagonal shafts. The shafts are slipped inside cast bases and alloy 4043 or 5556 continuous fillet welds are placed between the two.

There is no need for engineers to be concerned about originating special lighting standard designs for each project. A number of well-qualified fabricators have a myriad of pre-engineered designs. Their engineers are willing to work with highway engineers to develop special designs if needed.

Traffic Signal Pedestals

The construction of these items is similar to that used for lighting standards. Alloy 6063-T6 spun-tapered tubes are fillet welded to alloy 356 bases.

These poles have been used by New York City and other municipalities for a number of years. The principal advantage of aluminum is its lightweight. Initial installation and replacement costs are drastically reduced because of this feature.

Bridge Railing

Many wrought bridge railings are assembled by shop welding. Common-welded joints in these assemblies are between the balusters and rails and between the posts and base plates.

The balusters are solid bars of alloy 6061-T6 or extruded tubes of 6061-T6 or 6063-T6. Rails and posts are normally 6061-T6 or 6063-T6 extruded shapes or tubes. Filler wires are alloy 4043 of 5556.

SUMMARY

Welded aluminum highway structures have good service records and their popularity is increasing. Engineers are acknowledging aluminum's advantages: (a) freedom from maintenance, (b) lightweight, and (c) versatility of form. Bridges, overhead sign structures, roadside sign structures, signs, lighting standards, traffic signal pedestals, and bridge railings make frequent use of welding.

DESIGN

Effect of Welding on Mechanical Properties

Most of the structural aluminum alloys attain their strength by heat treatment or strain hardening. The heat of welding removes part of the effect of the prior heat treatment or strain hardening in the vicinity of the weld, causing this heat-affected material to be weaker than the unaffected metal. The resulting effect on mechanical properties in the vicinity of a weld is illustrated by the typical distribution of yield strength shown in Figure 5. The distance b_h in the figure designates the extent of the "heat-affected zone," measured from the center of the weld.

In evaluating the effect of a weld on the strength of a member, it is convenient to consider that the material in the vicinity of a weld has only two strength levels, as indicated by the dotted line. The material in the "reduced strength zone," whose extent is indicated by b_r, is considered to have minimum properties, and the material outside this zone is considered to have the properties of unaffected parent metal. The width of the zone is adjusted so that conservative values of the strength of members with longitudinal welds can be calculated as the sum of the strength of the material within the reduced strength zone and the strength of the unaffected metal outside this region (4).

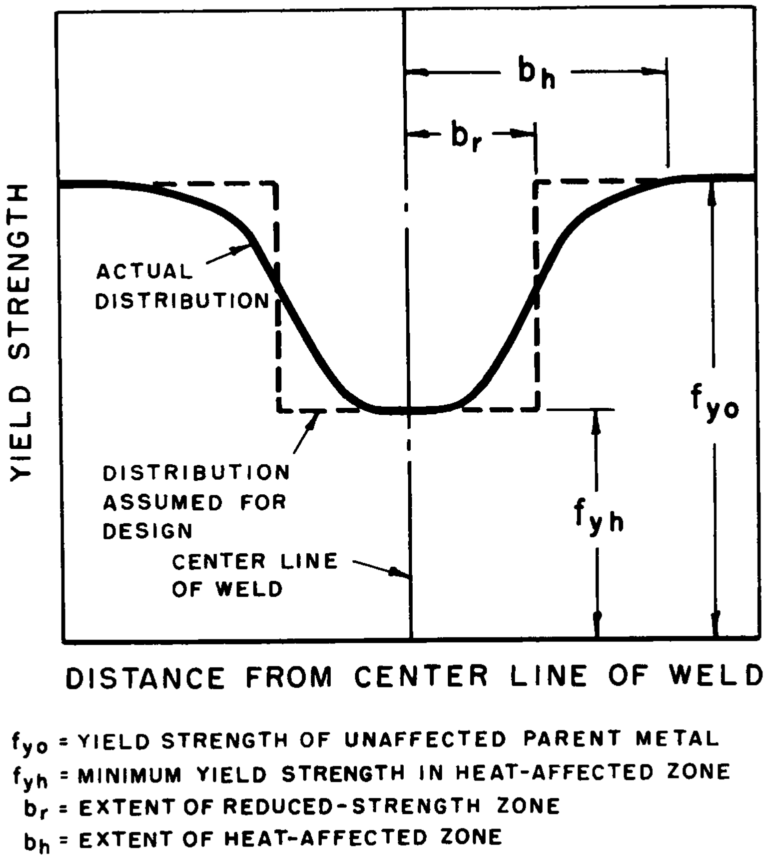


Figure 5. Typical distribution of yield strength values in vicinity of weld.

The reduced strength zone is considered to extend an equal distance in all directions from the center of a butt weld or the heel or a fillet weld. When the welding procedure is carefully controlled to minimize the heating of the material in the vicinity of the weld, the extent of the reduced-strength zone may be very small, approaching zero in some cases. These small values can be used for design in cases where they have been well established by hardness surveys or tension tests. However, for general design purposes in cases where it is not practical to determine the actual extent of reduced-strength zone, a value of 1 in. can be used for b_r.

Strength of Butt Welds

In the strain-hardened alloys, tensile strengths across butt welds equivalent to the strength of annealed material are developed (7, 8, 9). This strength is the basis for the weld qualification test requirements in the ASME Boiler and Pressure Vessel Code (6). In the case of heat-treatable alloys not heat treated after welding, weld strengths are intermediate between the strength of annealed material and the strength of the unaffected parent metal. The ASME welding qualification test requirements are 24,000 psi for 6061-T6 and 17,000 psi for 6063-T5 and -T6.

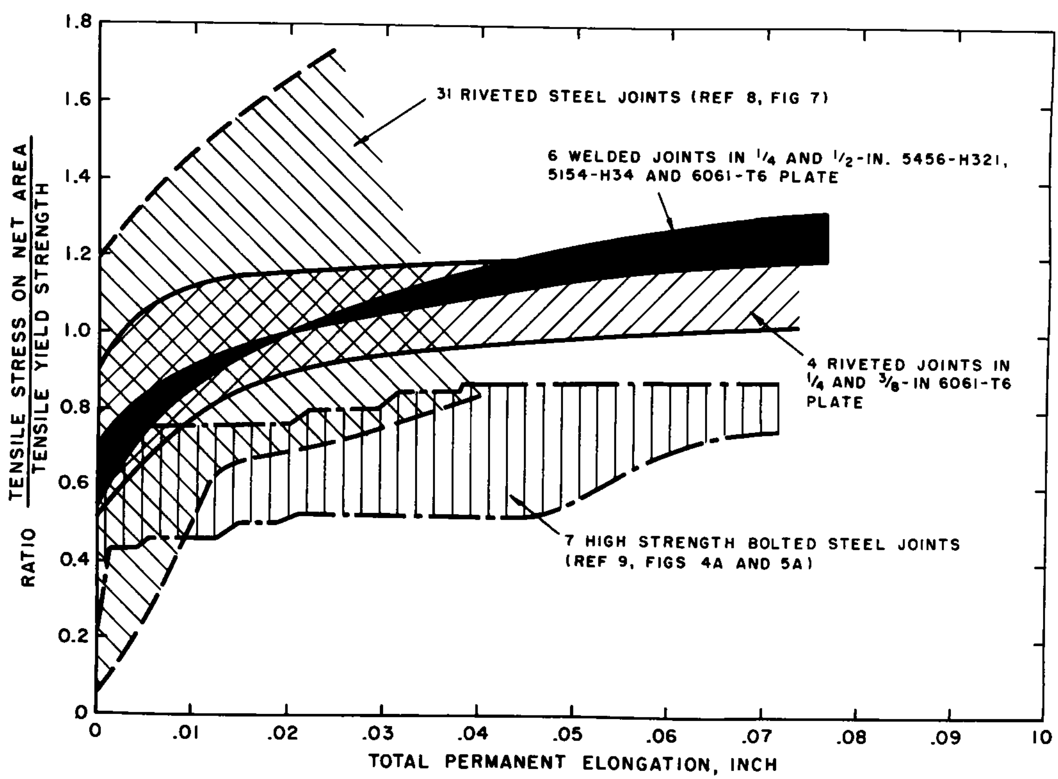
For welds that receive only visual inspection, it is recommended that a weld strength equal to 90 percent of the weld qualification test requirement value be used as the minimum expected weld strength for the purpose of selecting allowable stresses. In determining allowable stresses, this minimum expected weld strength should be divided by the same factor of safety that is applied to the ultimate tensile strength of the material in structures without welds. For welds stressed longitudinally, the minimum expected strength of the material in the reduced strength zone should be considered to be the same as the minimum expected transverse weld strength.

Because of heat-of-welding effects, the yield strength across butt welds made in strain-hardened or heat-treated aluminum alloys depends on the gage length used. The yield strength value corresponding to 0.2 percent offset on a 10-in. gage length is considered to be applicable to the design of welded structures (4). This offset represents a permanent deformation across a joint of 0.02 in., which, as shown in Figure 6, is typical of the deformation in riveted or bolted joints at loads that cause an average net section stress equal to the yield strength (12, 13, 14).

Values of minimum tensile strength and yield strength across butt welds for a number of weldable alloys are given in Table 1. Also, the table gives values of minimum tensile strength and yield strength for the weakest material in the reduced strength zone. Yield-strength values in this case were determined from specimens stressed parallel to the weld, so that gage length does not influence the yield strength.

Strength of Fillet Welds

It is recommended that the minimum shear strength of fillet welds for design purposes be taken as 75 percent of the average value determined from tests (7, 8). Values of minimum shear strength of fillet welds determined in this way are given in Table 1. The minimum expected tensile strength of the material immediately adjacent to the



NOTE: TENSILE YIELD STRENGTH IS STRESS AT 0.2 PER CENT OFFSET ON 10-IN. GAGE LENGTH ACROSS WELDED BUTT JOINTS AND YIELD STRENGTH OF MAIN PLATE MATERIAL FOR RIVETED AND BOLTED DOUBLE STRAP BUTT JOINTS

Figure 6. Permanent elongation of welded, riveted, and bolted joints.

TABLE 1

MINIMUM[1] STRENGTH DATA FOR WELDED JOINTS (TIG or MIG welding with no post weld heat treatment)

Parent Material(2)	Filler Wire (3)	Across Butt Weld: Tensile Strength, psi	Across Butt Weld: Yield Strength,(4) psi	In Reduced Strength Zone: Tensile Strength, psi	In Reduced Strength Zone: Yield Strength, f_{yh}, psi	Shear Strength of Fillet Welds(5), psi: Longitudinal	Shear Strength of Fillet Welds(5), psi: Transverse(6)
3003	1100(7)(8)	14 000	7 000	14 000	5 000	8 000	9 500
3004	4043(7)(8)	23 000	11 000	23 000	8 500	11 500	16 000
5052	5652(7)(8)	25 000	13 000	25 000	9 500	13 500	19 000
5154	5254(7)(8)	30 000	15 000	30 000	11 000	16 000	23 000
5454	5554(7)(8)	31 000	16 000	31 000	12 000	16 000	23 000
5086	5356(7)(8)	35 000	19 000	35 000	14 000	17 000	26 000
5083	5556	40 000	24 000	40 000	18 000	20 000	30 000
5456	5556	42 000	26 000	42 000	19 000	20 000	30 000
6061-T6, 6062-T6	5556	24 000	20 000	24 000	15 000	20 000	21 000(10)
6061-T6, 6062-T6	5356	24 000	20 000	24 000	15 000	17 000	21 000(10)
6061-T6, 6062-T6	4043(7)(8)	24 000	15 000	24 000	11 000	11 500	16 000
6063-T5, -T6, -T83, -T831, -T832	4043(7)(9)	17 000	11 000	17 000	8 000	11 500	15 000(10)

(1) These are minimum expected strength values to be used as basis for design. Typical or average strength values are appreciably higher.

(2) Strength values apply to all tempers of nonheat-treatable alloys except as noted under note (4).

(3) Filler wires listed are commonly used. They do not necessarily represent recommended filler wires for all applications.

(4) Yield strength across a butt weld corresponds to 0.2 per cent set on a 10-in. gage length. Values listed for nonheat-treatable alloys are for tempers quarter hard or harder. For annealed temper, this value will be the same as yield strength in the reduced strength zone.

(5) Applicable to throat area of fillet.

(6) For transverse shear in unsymmetrical joints, such as single lap joints, use values for "Longitudinal Shear "

(7) Greater strengths, particularly in fillet welds, can be obtained with higher strength filler alloys.

(8) 5556 filler metal recommended for greatest strength.

(9) 5356 or 5556 filler metal recommended for greatest strength.

(10) Strength controlled by shear strength of parent metal adjacent to weld

welds should be considered to be the same as the minimum expected transverse strength of butt welds.

Fatigue Strength of Welds

Fatigue strength data have been reported for a wide variety of aluminum alloy joints (10, 11). Figure 7 shows typical values of fatigue strength determined in tests of butt welds at zero stress ratio. The effect of variation in stress ratio (that is, the ratio of minimum to maximum stress in a loading cycle) on fatigue strength is shown in Figure 8. These results illustrate the increase in fatigue strengths attributable to higher stress ratios often encountered in cyclic loading of structures. The curves shown in both Figures 7 and 8 represent the average test results for ⅜-in. thick plate specimens which were obtained from butt-welded panels prepared by welding, back-chipping, and filling the back-chipped groove. The panels were tested with the weld

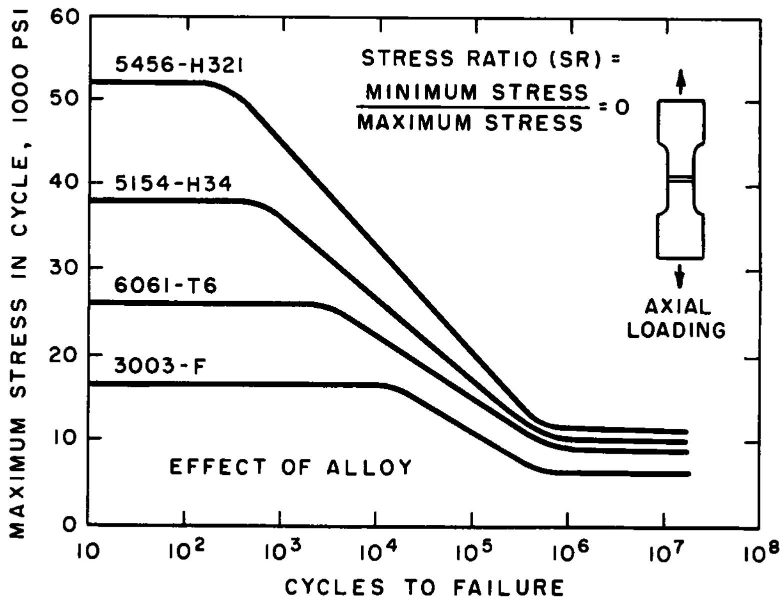


Figure 7. Direct stress fatigue test results for welded aluminum butt joints for inert-gas arc welds.

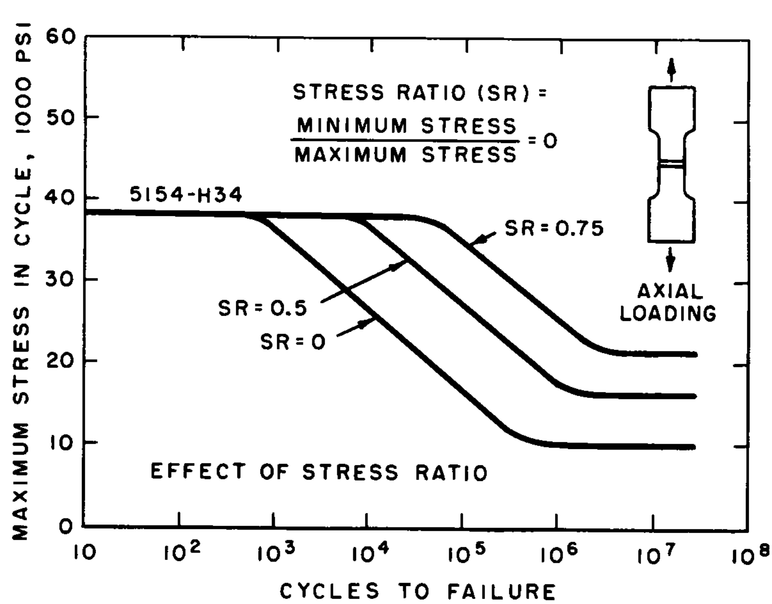


Figure 8. Direct stress fatigue test results for welded aluminum butt joints for inert-gas arc welds.

bead in the as-welded condition. The following additional observations are based on experience in fatigue-testing aluminum alloy joints:

1. The fatigue strengths of butt-welded joints generally equal or exceed those of a well-designed riveted joint of equal static strength.

2. Spatter adjacent to the weld bead can cause a more serious stress raiser than the weld bead geometry and should be avoided.
3. Integral back-up strips should be avoided for fatigue applications.
4. The fatigue strengths of longitudinal welded butt joints are at least equal to those of transverse butt joints.
5. The use of unsymmetrical joints should be avoided for fatigue applications.
6. The effect of secondary flexing on the fatigue strength of unsymmetrical joints can be partially overcome by the use of stiffeners.
7. Butt-welded joints have higher fatigue strengths than fillet-welded joints.
8. Continuous fillet welds are superior to intermittent fillet welds for fatigue applications.
9. The fatigue strengths of plate specimens with fillet-welded attachments are about equal to those of butt-welded joints.

Residual Stresses Caused by Welding

Tests (15, 16) have shown that welding of aluminum alloys produces residual stresses whose maximum value is about equal to the minimum yield strength in the heat-affected zone. Figure 9 shows a typical distribution of residual stress parallel to the weld in a wide welded plate of 5456-H321. The dotted lines in the figure show how the residual stresses were reduced by cutting a 4-in. wide strip containing the weld out of the original 36-in. wide welded plate.

Tests of members under static loading, including column tests and falling-weight impact tests and falling-weight impact tests of plates, have shown that these residual welding stresses have no significant effect on structural behavior (15). Nor do these stresses introduce a susceptibility to stress corrosion cracking, according to results of tests on 5456-H321 plate (15).

Under conditions of cyclic loading, involving variations in applied stress from compression to tension, or from no stress to a tensile value, the residual tensile stresses in the weld region can have a significantly detrimental effect on fatigue strength at large numbers of cycles, as shown in Figure 10. Residual welding stresses can also

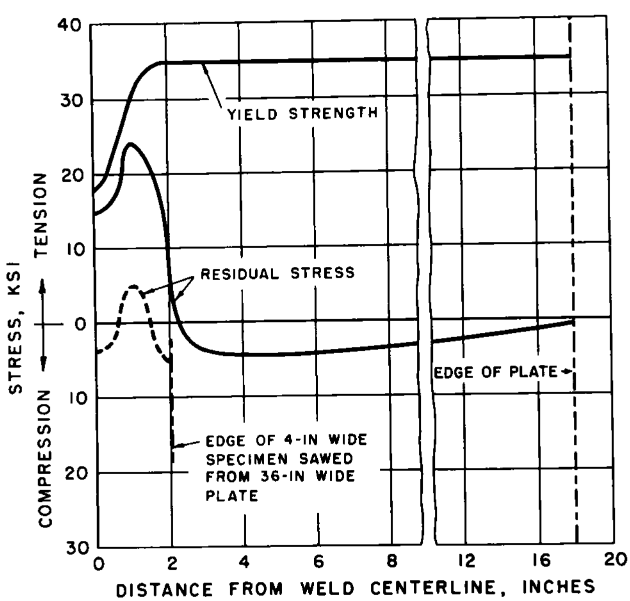


Figure 9. Distribution of yield strength and residual stresses in a 36-in. wide longitudinally welded plate, 5456-H321 plate, $\frac{1}{2}$ in. thick—5556 electrode.

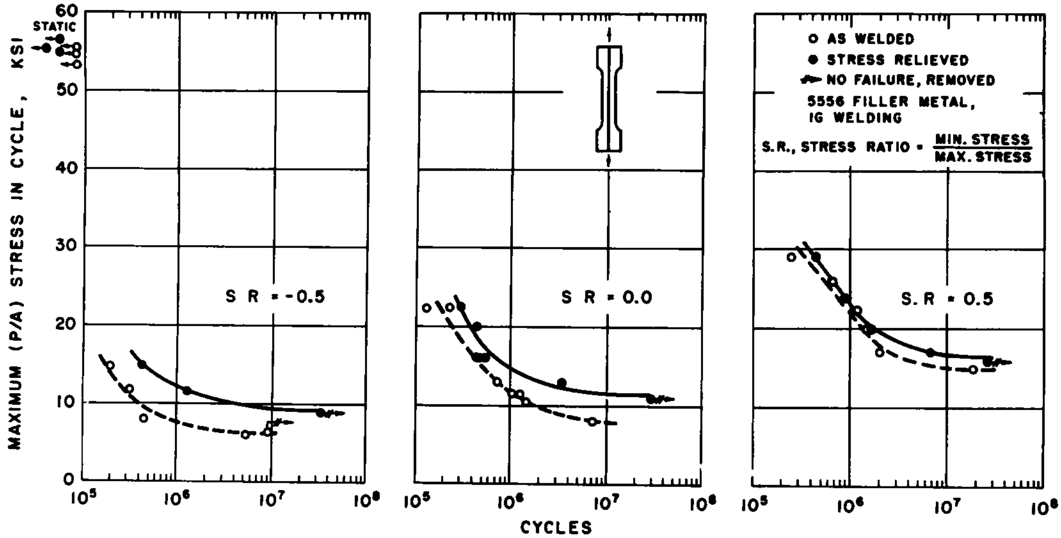


Figure 10. Effect of stress relief on fatigue strength of 5456-H321 longitudinal butt welds.

be undesirable if a weldment is to be machined after welding. Machining may disturb the residual stress balance, which will result in warping of the part.

Residual welding stresses in nonheat-treatable aluminum alloys can be reduced appreciably by a thermal treatment, with little sacrifice in strength. Tests on welded 5456-H321 plate indicate that holding weldments in this alloy at 525 F for about 15 min will reduce the residual welding stresses about 75 percent with no significant loss in tensile strength and less than 10 percent reduction in yield strength of the base material (15). The minimum yield strength in the heat affected zone may actually be increased slightly.

Design of Welded Tension Members

Tension members with transverse butt welds are designed on the basis of the minimum values of tensile strength and tensile yield strength across butt welds, which were discussed earlier. For highway structures, it is recommended that basic allowable tensile stresses be determined by applying a factor of safety of 2.2 to the minimum tensile strength and a factor of safety of 1.85 to the minimum tensile yield strength. The allowable stress is the lower of the two resulting values. As previously discussed, it is recommended that for weldments that receive only visual inspection the minimum tensile strength for design purposes be taken as 90 percent of the values given in Table 1

Frequently welds in tension members are so located that less than the entire cross-sections is affected by the heat of welding. In this case the allowable stress need not be as low as it would be if the entire cross-section were welded. Figure 11 shows the result of tension tests on specimens of ½-in. plate with longitudinal welds. As the width of the specimen was increased, so that a smaller portion of the cross-section was affected by the heat of welding, the experimental values of tensile and yield strength approached the strength of the unaffected parent metal. The curves in the figure represent strength values calculated from

$$f_{pw} = f_n - \frac{A_w}{A}(f_n - f_w) \qquad (1)$$

in which

f_{pw} = strength* of member with only part of cross section affected by heat of welding.

f_n = strength* of unaffected parent metal.
f_W = strength* of material in reduced-strength sone.
A = area of cross-section.
A_W = area within area A that lies within reduced-strength zone.

The extent of the reduced-strength zone for the test specimens in Figure 11 was about 0.55 in. on either side of the weld, as determined by hardness surveys.

Eq. 1 is derived by assuming that the strength of the entire member is equal to the weighted average of the strength of the material in the reduced-strength zone and the strength of the unaffected parent metal outside this zone. Eq. 1 can be used for design purposes if the strength values are replaced by allowable stresses.

Design of Welded Compression Members

The most common type of welded compression member is a column supported at both ends with welds at the points of support. Tests and analyses have demonstrated that the welds have little effect on the column strength of such a member in the range of slenderness ratios where allowable stresses are controlled by column buckling rather than by yielding, provided that the ends are simply supported (16). Therefore, simply-supported compression members with welds at the ends can be designed on the basis of column formulas applicable to the unaffected parent metal, with a cut-off at an allowable stress based on the yield strength across butt welds. The strength of aluminum columns is given by the Euler column formula in the elastic stress range

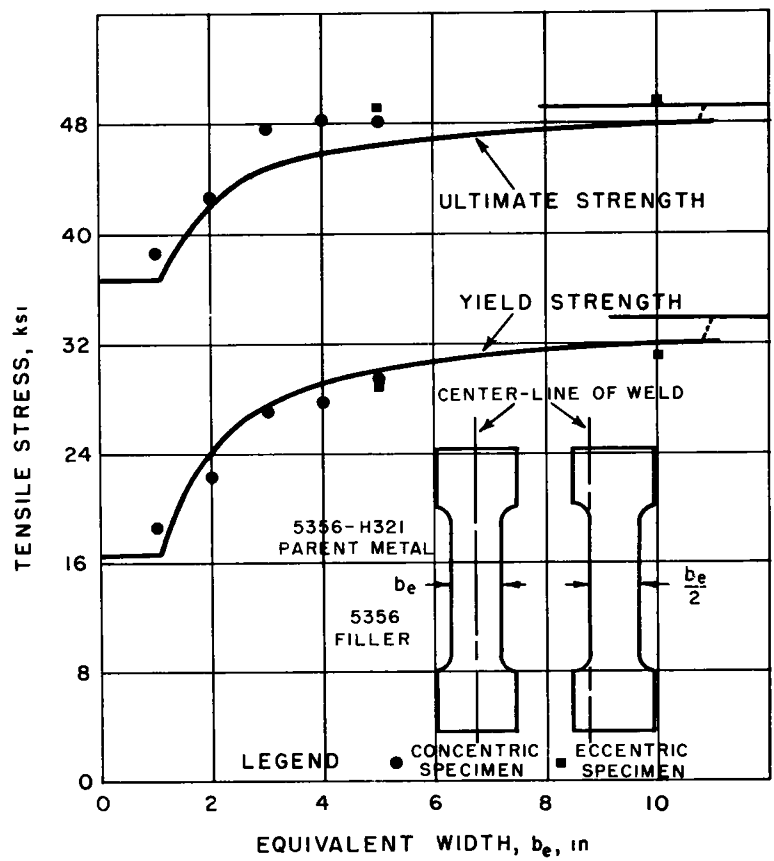


Figure 11. Results of tension tests of longitudinally welded members.

and a straight line approximation to the tangent modulus column formula in the inelastic stress range (17). Column formulas for the various commercial alloys are published in the Alcoa Structural Handbook (18).

If a column supported at both ends has welds at locations other than the ends (say, farther than 0.05L from the ends, where L is the distance between supports), the welding may have an appreciable effect on the column strength. The following equations may be applied to such members:

For $KL/r \le C_1$

$$f_c = 6.5\, f_y\,(1 - 0.04\sqrt{f_{yh}})\,/\,\sqrt{KL/r} \tag{2}$$

For $KL/r > C_1$

$$f_c = \pi^2 E/(KL/r)^2 \tag{3}$$

in which

f_c = column strength, ksi.
f_{yh} = compressive yield strength in reduced strength zone (considered to be equal to tensile yield strength in the reduced-strength zone), ksi.
K = end fixity coefficient, equal to 1.0 for columns simply supported at both ends and 2.0 for cantilever columns.
L = length of column, in.
r = least radius of gyration of column, in.
E = modulus of elasticity, ksi.

$$C_1 = \left\{\pi^2 E/[6.5\, f_{yh}\,(1 - 0.04\sqrt{f_{yh}})]\right\}^{2/3}$$

For columns with welds at locations other than the ends but with less than the full cross-section affected by the heat of welding, the column strength for design purposes can be determined by using Eq. 1 to interpolate between the allowable column strength for a member without welds and the column strength given by Eq. 2 for a member with the entire cross-section affected by the heat of welding.

In the case of cantilever columns, a weld at the end affects the column strength as much or more than a weld at any other location. Therefore, Eqs. 2 and 3 should be used to design such members, regardless of the weld location.

Local buckling of thin plate elements in the presence of welds can be calculated from the following equations:

For $k'b/t \le C_2$

$$f_{cr} = 7.5\, f_y\,(1 - 0.04\sqrt{f_{yh}})/\sqrt{k'b/t} \tag{4}$$

For $k'b/t > C_2$

$$f_{cr} = \pi^2 E/(k'b/t)^2 \tag{5}$$

in which

f_{cr} = local buckling stress.
b = width of plate element, in.
t = thickness of plate element, in.
k' = coefficient as given in Alcoa Structural Handbook (18, pp. 131-133).

$$C_2 = \left\{\pi^2 E\,[7.5\, f_{yh}\,(1 - 0.04\sqrt{f_{yh}})]\right\}^{2/3}$$

f_{yh} = and E as previously defined.

Local buckling of elements not affected by heat of welding can be calculated from the column formulas as indicated in the Alcoa Structural Handbook (18, pp. 130-137).

Allowable stresses for compression members are determined by applying the factor of safety on yielding (a value of 1.85 is recommended) to the compressive yield strength and the factor of safety on ultimate strength (a value of 2.20 is recommended) to the column-buckling strength and using the smaller of the two resulting allowable stresses.

Design of Welded Beams

Allowable tensile stresses in beams are affected by welding in the same way as allowable tensile stresses in other tension members. Similarly, allowable compressive stresses in beams are affected by welding in the same way as are allowable compressive stresses in columns. In other words, welds at the points of lateral support have little effect on the lateral buckling strength of a beam, although the lateral buckling strength may be reduced by welds at other locations. The lateral buckling strength of single web beams, either with or without welds, can be determined from the formulas for column strength by substituting the following value of equivalent slenderness ratio for KL/r in the column-buckling formulas:

$$\frac{KL}{r} = \frac{L_b}{1.2\, r_y} \qquad (6)$$

in which

L_b = length of beam between points of lateral support, in.

r_y = radius of gyration of beam about axis parallel to web (for a beam unsymmetrical about horizontal axis, r_y is calculated as though both flanges were the same as compression flange), in.

Use of the preceding values of equivalent slenderness ratio in the column formulas represents a conservative approximation, especially for values of L_b/r_y greater than about 50. For such beams, the designer may wish to compute a more precise value of equivalent slenderness ratio from the formulas in the Alcoa Structural Handbook (18, pp. 118-129).

Application of these principles to the design of beams in which the strength is controlled by yielding or fracture rather than by lateral buckling and comparisons with test results are illustrated elsewhere (19).

Design Specifications

The design principles discussed in this section were used as a basis for the allowable stresses in aluminum alloys quoted in recent specifications adopted by the American Association of State Highway Officials (20). These are the most up-to-date specifications for welded aluminum alloy structures that have been officially adopted by any code-writing body.

WELDING

Welded aluminum construction as presently used on American highway structures utilizes almost all of the commercial welding processes. This includes arc welding, resistance welding, gas welding, arc cutting, some brazing, and a little soldering. The following discussion, however, is limited to arc welding and, more specifically, to the inert gas welding processes.

Welded structures made from the ferrous metals are almost universally welded with a flux-coated metal electrode. Welding equipment, trained personnel, and procedure are widely available. It would be a tremendous advantage if aluminum alloy structures could also be welded with this process, but so far no generally acceptable coated welding electrode has appeared.

There seems to be little chance that coated electrode welding will displace the inert gas methods in the foreseeable future even though development work is continuing. The Norwegian marine industry, for instance, has developed an electrode for shipyard use, and several British and American electrodes are commercially available.

All of these electrodes are coated with fluxes made from chlorides and fluorides, and residual fluxes in the presence of moisture may attack the metal. Although this condition seldom affects the structural integrity of a part, it does produce an undesirable appearance. Painting a flux-contaminated surface results in blistered paint at the joints, and many cases it is not feasible to remove welding flux, particularly on field-welded structures.

The inert gas arc welding processes, performed with either consumable electrode (mig welding) or with tungsten arc (tig welding), are used almost universally for either field- or shop-welding aluminum structures. Both processes make superior joints from the standpoint of consistent weld soundness and contours, both can be used for welding in any position, and neither require post-weld cleaning. These processes do require special equipment and operator training, but such factors are no longer limitations because of the wide distribution of suitable equipment and the availability of training schools and other opportunities for self-training.

Tungsten Arc (Tig) Welding Equipment

Tig welding is most suitable for welding metal from 0.050 up to 0.5 in. thick. In most cases, welding is done with an alternating current generator or transformer that can be adjusted to the capacity needed to melt and weld a particular joint. A shield of argon or helium or a mixture of these gases flows through a gas cup positioned around a tungsten electrode.

An almost universally used appurtenance to provide an ionization path for the welding current is superimposed high frequency current on the secondary or welding arc circuit. This makes arc starting easier and re-establishes an arc that is extinguished accidentally.

Welding with direct current is widely used when welding the ferrous materials, but is seldom used in welding aluminum. An exception is automatic shop welding to make tube and pipe where DC with straight polarity is used.

Many publications, some of which are listed in the references show machine settings and other operating factors, but such data is not repeated here (21).

Tig welding has been used for a great deal of field welding, particularly on cross-country pipe line. Welds of excellent soundness are more easily achieved with this process. There is a substantial sacrifice in welding speed if this factor is measured in the pounds of metal that are laid down per unit of time when comparing speed of mig welding. This often is no disadvantage in field welding where the relatively slow rate of metal deposition makes it possible to get better control without exact joint fit or positioning the work. When welding decorative parts, tig welding will frequently make the best appearing joints.

Tungsten Arc DC Welding

Although most tig welding is done with AC, there is some use of DC either with direct or reverse polarity. These procedures deserve attention in view of their potential use for maintenance and repair and for welding the high-strength heat-treatable alloys.

Direct-current reverse polarity (electrode positive) can be used with almost any general purpose DC welding power supply and is characterized by shallow penetration, very easy arc-control, and exceptional "arc-cleaning." It has been found useful for repair operations on parts made from sheet and tubing. It is almost always used with argon gas because this provides the most easily controlled arc. In view of the wide availability of DC power sources, this method has the desirable quality of very low equipment cost.

Direct current straight polarity tig welding is used only for mechanized welding. The greatest welding heat is generated at the work surface, as contrasted to AC or reverse polarity. This results in a cool tungsten electrode and the ability to attain highest welding speeds because maximum current can be delivered to the joint. There is little or no cleaning action, and the arc must be operated at such short arc length as to require automatic torch positioning and traverse mechanisms.

The narrow weld zone is advantageous for welding the high-strength heat-treatable alloys. Best strength is obtained with a narrow cast weld and transition zone on such materials.

Consumable Electrode (Mig) Welding Equipment

Most structual welding on aluminim alloy is done on metal where the thickness is suitable for consumable electrode welding, and this process is preferred for most work. Metal from 1/16 in. up to any desired thickness can be welded. Welded sections up to 2 in. thick are common, and metal up to 4 in. or more in thickness has been welded.

Filler metal is fed thru a jet of inert gas. Control of the arc length and rate of weld deposition is achieved by a high rate of electrode feed. Thus a high welding rate is inherent in the mig process.

There has been a multiplicity of types of equipment used for generating welding current, with some confusion on the part of fabricators as to what was best for their work. This situation is now welll stabilized on the use of direct current power source with reverse polarity for welding almost all aluminum. Generators delivering welding current with a drooping volt-ampere curve are widely available in industry. Such generators are driven by electric motors for shop work or by automotive engines for field work. This equipment is most economical in first cost, and is probably the most versatile in handling the multiplicity of geometries that must be welded in structural parts.

Constant arc voltage machines with control of slope to deliver either rising or drooping volt-ampere characteristics are finding wider use and, though more expensive, can be more universally used. The normal production variations such as joint fit, nonuniform section thickness, or varying surface conditions require somewhat less adjustment on the welders part with this type of apparatus. Electrode "stubbing" or "burn back" are more easily controllable.

Machine settings, joint design, and other welding variables are well-established for a wide range of work. This information is available elsewhere (21).

Arc Spot Welding

An adaption of the mig welding process to make spot welds has been developed. Joints are made by melting thru the top section into the lower part or along the edges of a piece making a localized fillet joint.

The process is useful for attaching stiffening members to sheet construction and for repair and maintenance operations. Equipment is portable so that either field or shop welding is feasible. In view of the low capital investment, the ability to weld when only one side is accessible, and the mobility of the equipment, the process should find increasing use.

Automatic timing equipment enables the operator to set welding time for the metal thickness concerned, and subsequent welding is then a matter of positioning the welding gun. Manual skill or a long training period is not required.

Best results are obtained with metal thicknesses below 1/4 in. Joints are designed so that top member is about 25 percent thinner than the bottom part. This design is particularly desirable when the weld melts through on the face side and produces an undesirable appearance. Joints can be expected to have equal performance to electric resistance spot welds. Table 2 gives machine-setting data that are useful for design.

Choice of electrode alloy is the same as that normally recommended for the parent alloys used in the joint, although 4043 electrode finds wide use as a general purpose material.

Welding Characteristics of Structural Alloys

The first of this paper stated that alloys 6061-T6 and 6062-T6 are the most common structural alloys and that 5456 holds great promise for future development. It is not possible to express the weldability of these materials in single or even several criteria. Some important weldability factors are described here. A more detailed

TABLE 2

ARC SPOT WELDING CONTROL SETTING GUIDE[1]

Overlap Joints, .064 in. Sheet, 3/64 in. Diameter Electrode

Open Circuit Voltage: 32
Weld Time: Non-penetrating welds - 22 cycles
Penetrating welds - 30 cycles

Non-penetrating Welds	Wire Feed, in/min Filler Alloy			
Sheet Alloy	1100	4043	5554	5556
1100	475	400		550
3003	450	400		560
5154		400	440	475
6061		390	420	475
Penetrating Welds[2]				
All Alloys	550	500	550	600

1. Figures shown only for normally compatible sheet and filler alloy combinations. Each alloy listed representative of a family of alloys.

2. Against a copper backup plate.

analysis will depend on consideration of specific applications as there are perhaps as many aluminum alloys to fill specific needs as there are in the ferrous materials.

There are two factors in welding these alloys; namely, mechanical performance and weld soundness, that should be understood in using these materials. In alloys 6061 and 6062, mechanical strength is achieved by solution and precipitation heat treatment. Arc welding lowers the strength. This was described in the second section and the strength across a weld shown in Table 1. The minimum tensil strength of a butt weld in these alloys is 24,000 psi, chosen on the basis of many thousands of tests. This might be exceeded by judicious choice of welding practice to minimize the effect of welding heat. In practical use, however, such procedure control is seldom attempted.

Alloy 5456-H321 is a strain-hardened alloy which in the annealed or soft temper has a strength of 42,000 psi. This is also the strength in the "reduced strength zone" and consequently the minimum strength of a weld.

Another factor is ductility in the weld and the heat-affected zone. There are several ways to measure this factor so that one might choose a "free bend" test that measures in percent the elongation across a weld bead when it is bent until the metal fails. Joints in 6061-T6 or 6062-T6 show a ductility of 15 percent when welded with 4043 filler and 20 percent when welded with 5556 filler. Arc-welded joints in 5456 alloy have an elongation of 25 percent in this test.

Thus weldability, as measured by mechanical performance of a weld, static strength, and ductility, shows the superiority of 5456 alloy.

The alloy previously mentioned are representative of alloy groups each of which has parallel performance. The heat-treated alloy 6063 in a variety of tempers has a weld strength of 17,000 psi. Similarly, there are a series of nonheat-treatable alloys with lesser amounts of alloying constituents in which the minimum weld strength is the strength of the annealed temper, and the ductility of the joint is equal to or higher than that for welds in 5456. These alloys are generally called the 5000 series alloys and are usually chosen where the lower strength is adequate because the metal cost is lower

Weld soundness, the other major factor to be considered in judging weld quality, can be determined by detection of internal discontinuities in the weld or transition zone and of cracking when the weld cools. Internal discontinuities are defects in welds such as porosity, oxide film inclusions, contamination from other metals, poor fusion, or entrapped dirt. These conditions are the same for all aluminum alloys and are a function of welding technique. Correcting conditions that cause these defects cannot be accomplished by changing from a heat-treated alloy to a 5000 series alloy or vice versa.

Cracking, on the other hand, is a condition in which the alloy being welded has an important effect. During welding, cracks may occur in the deposited weld metal, in the transition zone, or at the end of a weld bead where a shrink or crater appears when the metal solidifies. The sensitivity to cracking in the weld zone has been measured quantitatively (23). The results can be summarized by stating that 5456 and other 5000 series alloys are much less sensitive to this condition that the heat treatable alloys.

This does not mean that welds in 6061 or 6062 are likely to have joint defects of this type. It does mean that more searching inspection is needed to control this condition, that weld procedure and tooling must be devised to put less restraint in the joints while cooling after welding. These precautions in general add to welding cost and thus may be undesirable.

Crater cracks at the end of a weld are controlled by welding technique and should not occur if the operator has been properly instructed.

There is general agreement in all specifications that cracks are not acceptable. In the aluminum alloys, elimination of cracks is accomplished by chipping or machining away the cracked area and then rewelding. Welding over a crack without removing it seldom eliminates the crack.

Qualification of Procedure and Operations

Welding codes and specifications for arc welding the aluminum alloys have been developed for a wide range of work, although no specific code for welding highway structures has been adopted. Probably the most widely used code, both in direct application, and as a model for new codes and specifications, is the Non-Ferrous Section IX "Welding" of the ASME Boiler and Pressure Vessel Code. The general system outlined in the code is much the same as that used on the ferrous materials.

In this code, a fabricator welds a test plate with the process and procedure he proposes to use on the structure, and the weld must meet minimum requirements in strength and soundness. In addition, each operator demonstrates his ability to make a weld, meeting minimum soundness requirements by welding a test plate. This is about all a welding code can accomplish in control of fabricating by welding. The requirement of code compliance before production is particularly useful for fabricators who are breaking into the field or are reactivating a department to weld aluminum structures.

Specific code requirements may be varied to suit particular problems. The following suggestions are offered for general use as an outline for code requirements. Details to meet specific jobs may then be developed.

Welding procedure is examined by making a butt joint in a metal thickness at least one-half that of the maximum thickness of the production parts with the welding process to be used in production. Strength is measured on two reduced section tensile specimens. Strength requirements are the minimum values shown in Table 1 for the alloy being welded.

Soundness is established by making face- and root-guided bend tests. Most aluminum alloy joints are bent to a 2T radius, except joints in 5456 alloy which are bent to a $3\frac{1}{3}$T radius, and joints in 6061 which are bent to an 8T radius. Transverse guided bend tests are sometimes difficult to control because the parent metal, the heat affected zone and the cast weld zone have different bending properties. In this case, a longitudinal bend is made in which the specimen is made with the weld zone on the centerline and parallel to the sides.

Operator qualification may or may not be a requirement on the basis that inspection of the finished joints is essential to establish weld quality. Qualification does not insure good welds in the production parts.

In the event operator qualification is a requirement, it can be accomplished by welding a test plate to the same specifications as the procedure qualification plate. The major interest in the case of an operator is weld soundness; therefore (2), guided bend specimens are prepared and tested.

There is little difference in welding the various aluminum alloys discussed previously. This leads to the recommendation that operator qualification on any aluminum alloy is adequate for welding any of the other alloys in Table 1.

Filler Metal

The commonly used filler metals for inert gas arc welding are given in Table 1. These are available from distributors' stocks on short notice. The choice given here is suitable for most structural welding that is exposed to normal atmospheric service.

Occasionally, special exposure conditions are met with, and sometimes dissimilar alloy combinations must be welded. Table 3 gives a recommendation for six classifications of service requirements for welding an alloy to itself or to compatible alloys that might be used in combination.

Joint Preparation, Pre- and Post-Weld Cleaning

Joint preparation in welded structures is based on the amount of weld metal required to meet the strength and service conditions on the joint. Therefore, the aluminum alloys, the entire cross-section usually must be welded in butt joints, and a specified fillet size must be achieved in fillet joints.

In butt joints, the joint must be opened by a V, J, or U type of edge preparation to permit the weld to be made by melting to abutting edges and flowing in separate filler metal. In manual welding, and particularly in the fusion of a butt joint by heat alone, there is a greater likelihood of oxide film entrapment, cracking, or lack of complete fusion of the cross-section.

In welding aluminum alloys with the inert gas arc welding procedures, fusion to, but not beyond the root of a fillet weld, is attained. In a butt joint, fusion will occur not more than 1/8 in. deeper than the root of the edge preparation. This is somewhat different than is experienced with the ferrous metals and, if understood, will lead to making sound joints that will meet the standard X-ray soundness requirements and have good static and fatigue strength.

Whether pre-cleaning of the aluminum surface is done before welding with the inert gas arc welding processes depends on the type of contamination present. The only two factors of importance in pre-cleaning are the natural oxide film and the presence of hydrocarbons such as oil, grease, or dirt.

Aluminum products as received from the mill have a very thin, uniform oxide film on the surface and, in the majority of cases, require no pre-cleaning to remove the film. Sometimes, however, there are cases where the metal has been stored outdoors under such conditions that water stain occurs, where several heat treatments or anneals have been applied to a part to form it, or where a part has required repair welding after having been in service. In such cases, pre-cleaning is easily done with a manual or rotary wire brush to clean the area in the joint and perhaps an inch or so to each side.

The other type of contamination, caused by oils, grease, or dirt, should be removed by solvent cleaning before welding. The inert gas arc welding processes are not very tolerant of such contamination. It is difficult to make sound welds if any hydrocarbons are present.

Post-weld cleaning is not essential to improve weld performance. The consumable electrode process leaves a dust deposit on the weld surface that is composed mostly of aluminum oxide. If the deposit is objectionable from the standpoint of appearance, it can be removed by a brushing or wiping operation. In most cases, however, it is left until the normal weathering washes it away.

TABLE 3

CHOICE OF FILLER ALLOY FOR WELDING HIGHWAY STRUCTURES

TO WELD THIS ↓	TO THIS ↓	EASE OF WELDING						① STRENGTH OF WELDED JOINT "AS WELDED"						② CORROSION RESISTANCE						⑤ SERVICE AT SUSTAINED TEMPERATURE						COLOR MATCH AFTER ANODIZING						③ DUCTILITY					
	FILLER ALLOYS	1100	4043	5254	5554	5356	5556	1100	4043	5254	5554	5356	5556	1100	4043	5254	5554	5356	5556	1100	4043	5254	5554	5356	5556	1100	4043	5254	5554	5356	5556	1100	4043	5254	5554	5356	5556
5456	1100																																				
5456	3003		A			A	A		B			A	A		B			A	A											A	A		C			A	B
5456	ALCLAD 3003		A			A	A		B			A	A		B			A	A											A	A		C			A	B
5456	3004		A			A	A		C			B	A		B			A	A											A	A		C			A	B
5456	ALCLAD 3004		A			A	A		C			B	A		B			A	A											A	A		C			A	B
5456	5005 - 5050		A			A	A		B			A	A		B			A	A											A	A		C			A	B
5456	5052					A	A					B	A					A	A											A	A					A	B
5456	5154			B	B	A	A			C	C	B	A			A	A	A	A									B	A	A	A			A	A	A	B
5456	5454				B	A	A				C	B	A				A	B	B										A	A	A				A	A	B
5456	5086 5356					A	A					B	A					A	A											A	A					A	B
5456	5083 5456					A	A						A					A	A											A	A					A	B
5456	6063 2EC ④		A	B	B	A	A		B	B	B	A	A		A	A	A	A	A									B	A	A	A		C	A	A	A	B
5456	6061 ④		A	B	B	A	A		C	C	C	B	A		A	A	A	A	A									B	A	A	A		C	A	A	A	B
5456	6062 ④		A	B	B	A	A		C	C	C	B	A		A	A	A	A	A									B	A	A	A		C	A	A	A	B
6061	1100		A			B	B		A			A	A		A						A									A	A		C			A	B
6061	3003		A			B	B		B			A	A		A						A									A	A		C			A	B
6061	ALCLAD 3003		A			B	B		B			A	A		A			B	B		A									A	A		C			A	B
6061	3004		A			B	B		C			B	A		A						A									A	A		C			A	B
6061	ALCLAD 3004		A			B	B		C			B	A		A			B	B		A									A	A		C			A	B
6061	5005 - 5050		A			B	B		B			A	A		A						A									A	A		C			A	B
6061	5052		A	C	C	B	B		C	C	C	B	A		A	B	B				A		A					A	B	A	B		C	A	A	A	B
6061	5154		A	C	C	B	B		C	C	C	B	A		A	B	B											A	B	A	B		C	A	A	A	B
6061	5454		A	C	C	B	B		C	C	C	B	A		B	B	A				A		A					B	A	A	A		C	A	A	A	B
6061	5086 5356		A	B	B	A	A		C	C	C	B	A		A	A	A	A	A									B	A	A	A		C	A	A	A	B
6061	5083 5456		A	B	B	A	A		C																			B	A	A	A		C	A	A	A	B
6061	6063 2EC ④		A	C	C	B	B		B																			B	A	A	A		C	A	A	A	B
6061	6061 ④		A	C	C	B	B		C																			B	B	A	B		C	A	A	A	B
6061	6062 ④		A	C	C	B	B		C																			B	A	A	A		C	A	A	A	B
6061																																	C	A	A	A	B
6062	1100		A			B	B		A			A	A		A						A									A	A		C			A	B
6062	3003		A			B	B		B			A	A		A						A									A	A		C			A	B
6062	ALCLAD 3003		A			B	B		B			A	A		A			B	B		A									A	A		C			A	B
6062	3004		A			B	B		C			B	A		A						A									A	A		C			A	B
6062	ALCLAD 3004		A			B	B		C			B	A		A			B	B		A									A	A		C			A	B
6062	5005 - 5050		A			B	B		B			A	A		A						A									A	A		C			A	B
6062	5052		A	C	C	B	B		C	C	C	B	A		A	B	B				A		A					B	A	A	A		C	A	A	A	B
6062	5154		A	C	C	B	B		C	C	C	B	A		A	B	B											B	A	A	A		C	A	A	A	B
6062	5454		A	C	C	B	B		C	C	C	B	A		B	B	A				A		A					B	A	A	A		C	A	A	A	B
6062	5086 5356		A	B	B	A	A		C	C	C	B	A		A	A	A	A	A									B	A	A	A		C	A	A	A	B
6062	5083 5456		A	B	B	A	A		C	C	C	B	A		A	A	A	A	A									B	A	A	A		C	A	A	A	B
6062	6063 2EC ④		A	C	C	B	B		B	B	B	A	A		A	B	B	C	C		A		B					B	A	A	A		C	A	A	A	B
6062	6061 ④		A	C	C	B	B		C	C	C	B	A		A	B	B	C	C		A		B					B	A	A	A		C	A	A	A	B
6062	6062 ④		A	C	C	B	B		C	C	C	B	A		A	B	B	C	C		A		B					B	A	A	A		C	A	A	A	B

1. RATING APPLIES PARTICULARLY TO FILLET WELDS. ALL FILLER ALLOYS RATED WILL DEVELOP PRESENTLY SPECIFIED MINIMUM STRENGTHS IN BUTT WELDS
2. RATING BASED ON CONTINUOUS OR ALTERNATE IMMERSION IN FRESH OR SALT WATER.
3. RATING BASED ON FREE BEND ELONGATION OF THE WELD
4. RATING DOES NOT COVER THESE ALLOYS WHEN HEAT-TREATED AFTER WELDING.
5. ABOVE 150° F.

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