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Improved Weld Strength in 2000 Series Aluminum Alloys

The use of coolants narrows the HAZ as well as the zones of eutectic and grain boundary melting, and also refines dendritic structure in weld beads

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SYNOPSIS. The use of coolants during the welding of 2000 series aluminum alloys was investigated in an attempt to improve the properties of fusion welds in these alloys. The general premises behind this experimentation were that cooling combined with minimal welding heat inputs should narrow the heat-affected zones and should increase the quenching rates in both the weld bead and heat-affected zone. It was believed that beneficial effects on weld properties might be obtained in this way.

A metallographic study of welds made with and without coolants indicated these postulates to be true. Weld heat-affected zones and zones of eutectic and grain boundary melting were narrowed, and dendritic structure in weld beads was refined when coolants were used. In addition, joint efficiencies of 90% or better were obtained for 2014-T6 sheet without solution treatment and both with and without artificial aging after welding. Joint efficiencies exceeding 85% were also obtained for 2024-T86 sheet without postweld solution treatment.

Introduction

The high strength, heat-treatable 2000 series aluminum alloys are among the most impressive materials for structural applications where high strength to density ratios are important. The use of these alloys has been hindered, however, because of the relatively poor mechanical properties achieved when the alloys are fusion welded. The yield and ultimate tensile strengths of as-welded joints generally do not exceed 65 to 70% of the respective strengths of the base metal. Elongation of thin welded sheet when measured in a 2 in. gage length is usually low, in the approximate range of 0.5 to 2.5%. Furthermore the best joint strengths are dependent on critical welding techniques and cannot be consistently obtained. Under relatively adverse conditions, including multipass welding of heavy sheet or plate, much lower properties often result. In most of the heat-treatable aluminum alloys, joint strengths can be improved somewhat by postweld natural or artificial aging. However, joint efficiencies still remain low, and there is frequently some sacrifice in the already marginal ductility.

Still further improvement in weld properties can be accomplished by full postweld heat treatment consisting of solution treatment followed by natural or artificial aging. The original base metal properties can be regained in some instances when this type of heat treatment is used after welding. Very often, however, even with this procedure, the original properties cannot be fully restored.[1, 2] In addition, full postweld heat treatment is usually difficult at best because of distortion and other heat-treating problems.

As a result of these various difficulties associated with welding, engineers must frequently sacrifice the savings in weight or the increased strength that might otherwise be gained through the use of the high strength aluminum alloys and turn to the more weldable 5000 series alloys. In an attempt to overcome some of these problems, a program was undertaken having as its goal, improvement of weld properties in the high strength, heat-treatable aluminum alloys.

Causes of Poor Properties

There are two principle factors that limit the strength and ductility of aged or as-welded weldments in the 2000 series aluminum alloys. First, with currently available filler metals, the weld metal without postweld solution heat treatment is not as strong per unit area as the base metal and usually lacks ductility. Second, eutectic and grain boundary melting in the heat-affected zone produce a zone of weakness immediately adjacent to the weld metal–base metal interface.

Fig. 1—Grain boundary melting in 2024-T4 base metal welded with 5556 filler metal. Keller's etch. × 300 (reduced 48% on reproduction)

Figure 1 illustrates such an area in 2024-T4. All of the high strength, heat-treatable aluminum alloys exhibit this behavior in varying degrees of severity. The location of failure in tensile tests depends somewhat on whether or not the weld reinforcement is retained. When retained, the weld deposit is strengthened in terms of the actual

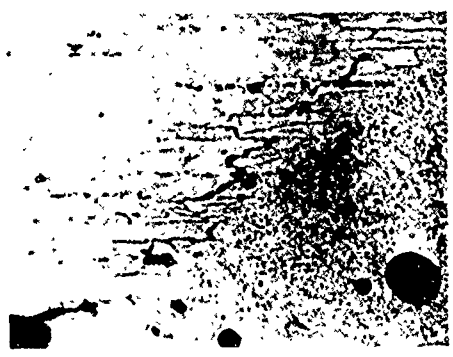

Fig. 2—Failure through zone of grain boundary melting in 2024-T4 base metal welded with 5556 filler metal. Keller's etch. × 150 (reduced 64% on reproduction)

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Table 1—Welding Conditions for Weldments Made with Various Degrees of Cooling, 2024-T4 Base Metal and 5556 Filler Metal

Coolant	Amp	Volts	Shielding gas flow rate, lpm	Travel speed, ipm	Energy input, joules/in
None	136	12.5	Al4, He3	26	3920
H_2O at 65° F	136	12	Al4, He3	26	3770
$CaCl_2$ Brine at −45° F	140	12.5	Al4, He3	26	4040
$CaCl_2$, Brine at −55° F	152	12	Al4, He3	26	4210

load that it will support because of its greater cross sectional area. The zone of eutectic melting then often becomes the weakest segment of the weld composite, particularly in thin materials which were of primary concern. Figure 2 illustrates the type of failure that is commonly observed under these circumstances.

The location of failure is, of course, subject to variation with other welding parameters such as filler metal choice, joint preparation (which affects dilution and thus strength) bead size, heat input and fixturing. However, it is true that the properties of the weld bead and/or the zone of eutectic melting are the determinants of weldment properties, and the mechanisms outlined above are commonly observed.[2]

Approach

The applications under consideration at the initiation of this program were for thin sheet and permitted the retention of weld beads. It was decided, therefore, that the zone of eutectic melting should receive initial attention as the weakest segment of the weld composite under consideration. This zone is a direct result of overheating of the base metal by the welding arc as the weld is deposited. It was reasoned that it should be possible to minimize the extent of this zone by limiting heat input to minimum practical values and by cooling the base metal during the welding operation.[3] If this zone could be reduced sufficiently in thickness, the properties of the weldment might be improved by biaxial restraint of the relatively weak material. Such phenomena have been widely observed in brazed and diffusion-bonded joints wherein the strength of the joint increases as the thickness of the joint decreases. In brazed joints, the tensile strength of the brazement often exceeds the tensile strength of the filler metal.

The use of cooling during welding also seemed promising for other reasons. Since the base metal is overheated in the zone of eutectic melting, it is probable that it is at least partially solution treated. If so, a more rapid quench of this zone produced by cooling and minimized heat input during welding should aid in retention of solid solutions and should make this zone more amenable to natural or artificial aging. It is recognized that the heat-treatable aluminum alloys are quench rate sensitive and that slow cooling from solution treating temperatures has a detrimental effect on properties.

Similar considerations seemed applicable to the weld metal. The weld metal, particularly in unbeveled butt joints, consists of appreciable percentages of melted base metal alloyed with the filler metal used. Thus, the weld metal will contain elements which will make it susceptible to solution treatment and aging even if no such elements are contained in the filler metal, although some commercial filler wires do contain such elements. If the weld metal is rapidly cooled during and after solidification, greater amounts of solute should likewise be retained in solid solution and the weld metal should also be more amenable to natural or artificial aging. It was also believed that beneficial effects might be obtained with respect to refinement of dendritic structure and finer dispersion of high melting phases with more rapid cooling.[4]

In addition to these considerations, numerous investigators have observed the need for adequate fixturing in welding sheet thickness not only for alignment purposes but also for cooling during the welding of heat-treatable alloys. Chill in these instances has generally been provided by copper hold-down shoes and backing bar.

Exploratory Experiments

The various considerations set forth above seemed worthy of experimentation. To facilitate the study, a special specimen was designed with integral cooling passages so that a coolant could be passed through it prior to and during welding. The design of the specimen is illustrated in Fig. 3. The aluminum alloy 2024 in the T4 temper was selected as the material for this specimen, because it is particularly susceptible to grain boundary melting. Specimens of the type shown were welded using no liquid coolant,

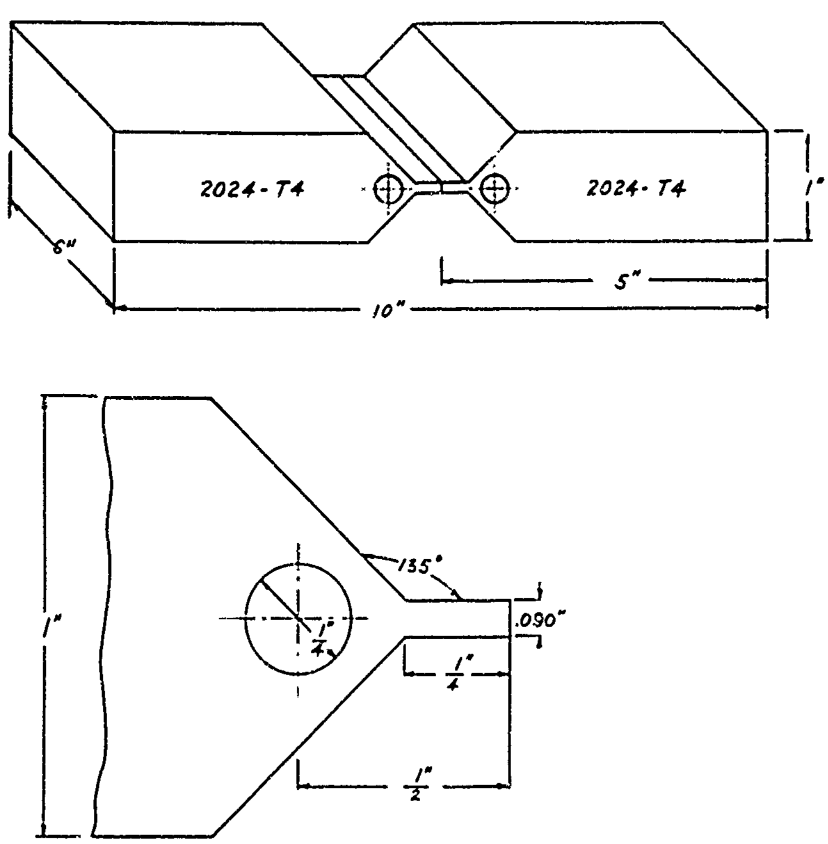

Fig. 3—Weld specimen used to investigate effects of cooling on weld strength

Table 2—Composition Limits[a] of Alloys Used in Study

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others— Each	Others— Total	Al
2014	0.50–1.2	1.0	3.9–5.0	0.40–1.2	0.20–0.8	0.10	0.25	0.15	0.05	0.15	Rem
2024	0.50	0.50	3.8–4.9	0.30–0.9	1.2–1.8	0.10	0.25	.....	0.05	0.15	Rem
4145	9.3–10.7	0.8	3.3–4.7	0.15	0.15	0.15	0.20	.....	0.05	0.15	Rem
5556	(0.40 Si + Fe)		0.10	0.50–1.0	4.7–5.5	0.05–0.20	0.25	0.05–0.20	0.05[b]	0.15	Rem

[a] Values are percent maximum where not shown as a range.
[b] Except Be which is 0.008 maximum for welding wire.

Table 3—Effects of Cooling on Width of Zone of Grain Boundary Melting in 2024-T4 Base Metal Welded with 5556 Filler Metal

Coolant	Thickness of zone of grain boundary melting, in.
None	0.015
H_2O at 65° F	0.012
$CaCl_2$ Brine at −45° F	0.006

Table 4—Results of Tensile Tests of Base Metal and Weldments Made with Various Degrees of Cooling, 2024-T4 Base Metal and 5556 Filler Metal

Coolant	Yield strength, 0.2% offset, psi	Tensile strength, psi	Elongation in 0.450 in., %	Natural aging time, days	No. specimens tested
Weldments					
None	30,100	40,800	1.9	27	6
Water at 65° F	31,600	43,600	2.3	27	6
Brine, −45° F	32,800	50,300	4.3	34	5
Base metal					
...	47,200	66,400	22.9	...	6

water at 65° F and calcium chloride brine at approximately −45° F.

A stainless steel backing bar was fitted to the underside of the specimen. The flow of the coolant was initiated a few seconds before the initiation of the arc and continued during welding. It would have been preferable to allow flow of the coolants for some appreciable period of time before initiation of the arc in order to approach equilibrium. However, a recirculatory cooling system was not available, and the condensation of atmospheric water vapor proved to be a serious problem if coolants were permitted to flow for long periods of time.

Welding procedures and energy inputs were similar for all conditions of the test and are shown in Table 1. Gas metal-arc welding with a short circuiting arc was used because of the low heat input possible with this technique. The filler alloy was 0.035 in. diameter 5556. Table 2 shows the composition of the materials used in these experiments.

After the welds were completed, they were X-rayed and a section was removed for metallographic examination. The remainder of the specimen was used to make 1/2 in. wide tensile specimens to permit evaluation of the effects of cooling on mechanical properties.

X-ray examination revealed considerable porosity in the brine cooled welds. It was believed that this was caused primarily by condensation of atmospheric water vapor on the workpieces as welding progressed. However, it was not present to such a degree as to make tensile testing impractical.

Metallographic examination gave indications that the zone of grain boundary melting was reduced in thickness by the use of coolants as had been postulated. An attempt was made to arrive at some quantitative evaluation of this reduction by measuring the distance from the weld metal–base metal interface to the end of the liquated grain boundaries on photomicrographs at 150 magnifications. The technique is not precise, because it is difficult to determine exactly where grain boundary liquation stops. However, a line was sketched in on the photomicrographs at what was judged to be the limit of this zone. Measurement of the distance between this line and the weld metal base metal interface and division of this measurement by 150 yielded the results shown in Table 3.

Figure 4 shows the zones of eutectic melting in the specimen welded with no coolant compared to a similar zone in the specimen cooled with brine at −45° F.

The results of tensile tests of the 1/2 in. wide specimens are shown in Table 4. Because of the specimen configuration, it was necessary to use a 0.450 in. gage length so that some degree of caution should be observed in attempting to compare the elongations shown with those usually obtained for 2 in. gage lengths. It can be seen that ultimate strength and ductility improved substantially with the introduction of coolants. Yield strengths did not respond as well, but there does appear to be some improvement.

Failure in all specimens occurred through the zone of eutectic melting except in instances where weld metal porosity induced failure through

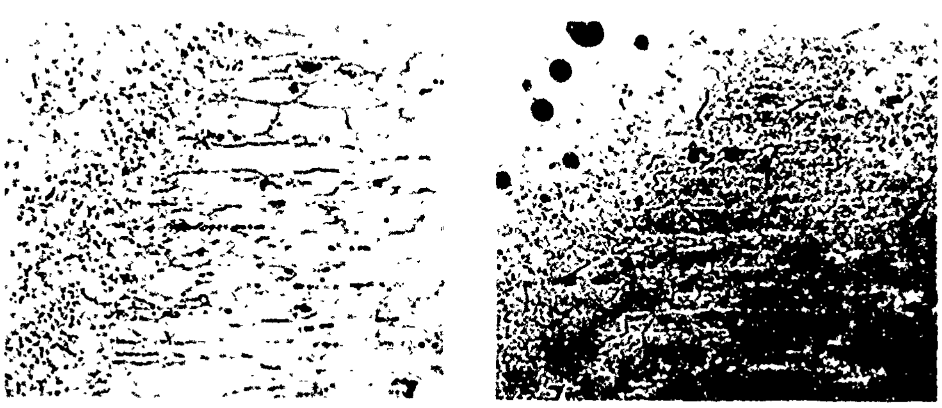

Fig. 4—Depth of grain boundary melting in weldments made with and without artificial cooling. A (left)—no cooling, 0.015 in. depth of melting, B (right)—cooled with brine at −45° F, 0.006 in. depth of melting. Keller's etch. × 150 (reduced 28% on reproduction)

Table 5—Welding Conditions for 0.090 in. Thick 2000 Series Aluminum Alloys Using 4145 Filler Metal

Base metal	Fixture	Amp	Volts	Travel speed, ipm	Shielding gas flow rate, lpm A	He	Coolant temp, °F	Backing bar temp, °F	Hold-down shoe temp, °F	Energy input, joules in.
2014-T6	a	160–165	19–20	70	42	3	None	75	75	2600–2800
2014-T6	b	150–160	23–25	55	12	22	−55	−25	−35	3800–4400
2014-T6	c	170	25	55	12	22	None	82	82	4700
2024-T86	b	150–160	23–24	55	12	22	−55	−25	−35	3800–4200
2024-T86	c	170	25	55	12	22	None	85	85	4700

[a] Aluminum bronze hold-down shoes, stainless steel backing bar, no coolant.
[b] Aluminum bronze hold-down shoes, copper backing bar, shoes and backing bar cooled with $CaCl_2$ brine.
[c] Aluminum bronze hold-down shoes, copper backing bar, no coolant.

that area. It was concluded that the strength and perhaps the ductility of the zone of eutectic melting had been improved.

Cooling and Sheet Thicknesses

The results of the experimentation described above seemed sufficiently promising to warrant further investigation. It was decided that this subsequent work should be applied to more realistic and practical applications i.e., thin sheet of the 2000 series alloys and tempers. Accordingly, it was necessary to construct a suitable hold-down fixture which would permit the flow of coolants during welding. Figure 5 illustrates the essential elements of the fixture. Only one hold-down shoe is shown for the sake of clarity. The hold-down shoes were constructed of aluminum bronze with copper tubing coolant passages soldered to the tops as shown.

Backing bars of the type shown were constructed of both copper and stainless steel. The two coolant passages can be seen at the end of the backing bar.

In order to overcome the problem of condensation of atmospheric water vapor and thereby prevent porosity in the weld, a polyethylene bag was constructed which enveloped the welding fixture, welding head and sheets being welded as shown in Fig. 6. The bag, being flexible, permitted sufficient linear movement of the welding head to complete the weld. It was found that by alternately inflating and deflating this bag with very dry shielding gases (mixtures of argon and helium), it was possible to remove the majority of air and water vapor. The fixture and sheets being welded could then be cooled without condensation.

The cooling medium for the fixture was calcium chloride brine which had a freezing point of about −60° F. The brine was circulated by a centrifugal pump and returned to an insulated tank for recirculation. Dry ice was used to cool the brine to the desired temperatures.

Thermocouples were attached to the hold-down shoes and the backing bar and brine tank to determine the temperature of the fixture and coolant. In all welding experimentation with sheet, efforts were made to weld at maximum travel speeds and at minimum amperage and voltage.

Preweld cleaning procedures for the sheets consisted of degreasing in alcohol followed by a caustic soda dip, water rinse, nitric acid dip, water rinse and air dry. The edges of the sheets to be welded were then scraped clean of oxide for approximately 1/4 in. top and bottom and the butting surfaces were draw filed. The spray transfer

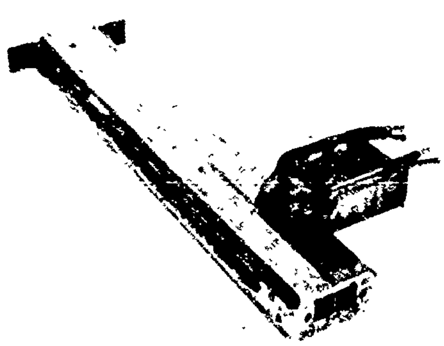
Fig. 5—Backing bar and hold-down shoe with coolant passages


Fig. 6—Welding set-up with refrigerated fixture

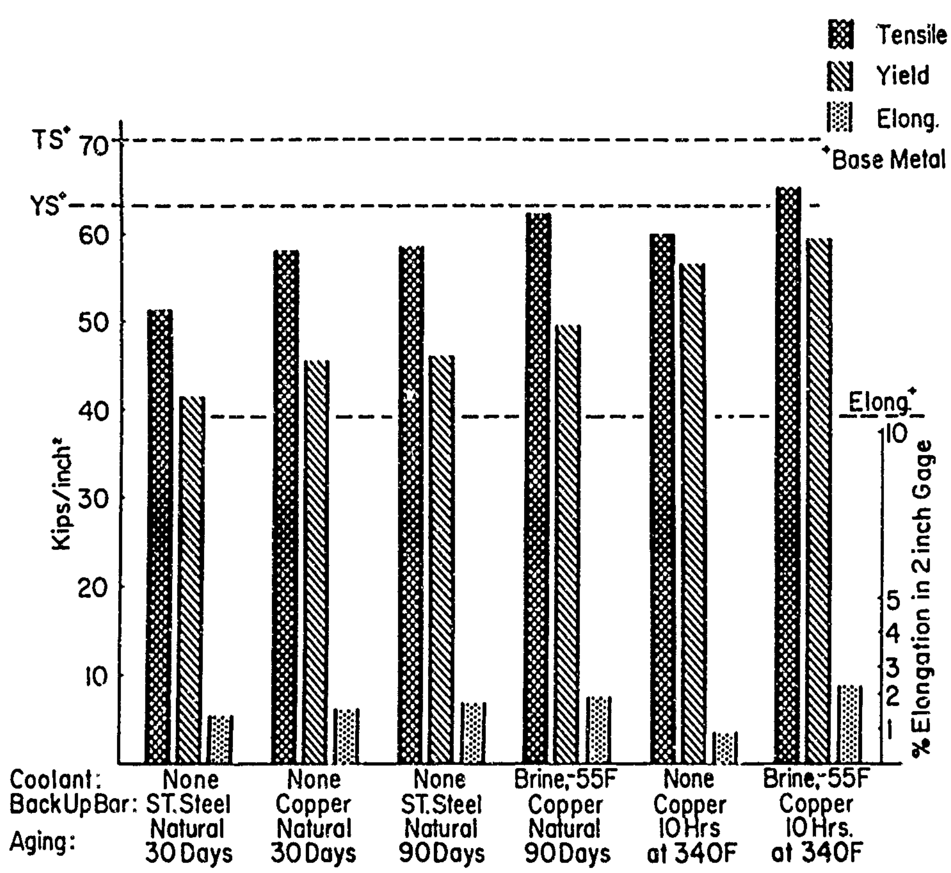

Fig. 7—Tensile properties of 2014-T6/4145 weldments

technique was used in conjunction with the gas metal-arc process because the short circuiting arc technique appeared to be marginal with respect to penetration. Reverse polarity direct current was used.

The tensile specimens used for testing the weldments were the $^1/_2$ in. wide sheet type F2 of Federal Test Method Standard No. 151A. Weld beads were left intact for all tests. All welds tested met X-ray quality standards of Class II or better in accordance with Army Ballistic Missile Agency Purchase Description ABMA-PD-R-27A.

2014-T6 Sheet

An alloy of primary interest in this investigation was 2014 in the T6 condition. Typical tensile properties for this alloy are 70 ksi ultimate strength, 60 ksi yield strength and 10% elongation in a 2 in. gage length. Sheets of 2014-T6, 0.090 in. thick, were welded using the stainless steel backing bar, the copper backing bar, and the copper backing bar with brine cooling. The joint design was square butt, and the filler wire was 0.035 in. diam 4145 aluminum alloy. Composition limits of these materials are shown in Table 2. When the brine coolants were used, it was possible to permit the coolant to flow until equilibrium was closely approached because the dry inert gas filled enclosure prevented condensation problems. Welding conditions and procedures are shown in Table 5.

After welding the sheets were aged naturally for 30 or 90 days or artificially for 10 hr at 340° F. These postweld aging treatments have little or no deleterious effects on the properties of the base metal in the T6 temper, the worst situation being the artificial aging treatment which results in losses of 1 to 2 ksi in yield and tensile strength and some slight loss in elongation. The natural aging treatments do not affect the base metal at all. After aging, tensile specimens were prepared and tested.

Figure 7 and Table 6 show the tensile properties obtained under various cooling conditions for the welds and with various aging treatments. Some interesting comparisons can be made with this data. One, which is believed to be important, is that for any given aging treatment the weldment made with the greater degree of cooling shows the better properties. Thus, when welds were aged for approximately 30 days, a weldment made on a copper backing bar (which has greater conductivity than a stainless steel bar) showed superior tensile properties.

Similarly, welds aged for 90 days naturally or artificially for 10 hr at 340° F showed superior properties where the greater degree of cooling capacity was provided. Welds made with a brine cooled copper bar yielded superior properties to those made on a stainless steel bar when aged for 90 days. Welds made on a brine cooled copper bar also yielded superior properties to those made with an uncooled copper bar when aged for 10 hr at 340° F.

It is also interesting to note the effects of the artificial aging treatment which appears to improve yield strengths more than any other tensile property. This can be seen most readily by comparing welds made under similar conditions where only the aging treatment is varied, such as the 2014 welds made using the brine cooled copper backing or those made using the copper backing without coolants. In both instances, yield strength has been improved about 10 ksi with the artificial aging treatment over that obtained with natural aging.

Perhaps the most interesting observations that can be made with this data are the high joint strengths and efficiencies that were obtained with the brine cooled copper backing bar. The best properties were obtained with artificial aging. Both yield and tensile strengths of these weldments achieved levels of 94% of the respective base metal property. Natural aging produced a tensile strength of 90% of base metal tensile strength and a yield strength of 79% of the base metal yield strength. It was believed that these were the best properties ever achieved for welds in 2014-T6 sheet with natural and artificial aging. Elongation, unfortunately, remained low for all weldments although it appeared to be best for the brine cooled welds.

Fig. 8—2014-T6/4145 weldments. A (top)—weldment made on stainless steel backing bar without coolants; B (bottom)—weldment made on copper backing bar with brine cooling. Keller's etch. × 10 (reduced 50% on reproduction)

The predominant type of failure noted for the tensile specimens was weld metal failure except for the brine cooled specimens aged naturally for 90 days. These failed partially through the base metal and partially through the weld metal–base metal interface. Most of the observed elongation in the tensile specimens took place in the weld heat-affected zones. Weld beads, the major location of failure, showed very little deformation or elongation around the fracture. Metallographic examination of the welds revealed that many of the effects that had been postulated for the use of coolants were indeed apparent.

Figures 8 through 10 compare different areas of a weldment made on the stainless steel backing bar with similar areas of a weldment made on the copper bar with brine cooling. The welds were similar otherwise except that the brine

Table 6—Tensile Properties of Welds in 0.090 in. Thick 2000 Series Aluminum Alloys Welded with 4145 Filler Metal

Base metal	Fixture	Aging treatment	Yield strength, ksi	Efficiency, %	Tensile strength, ksi	Efficiency, %	Elongation in 2 in., %
2014-T6	a	30 days nat	41.7	66	51.5	74	1.5
2014-T6	c	31 days nat	45.5	72	58.4	84	1.5
2014-T6	a	90 days nat	45.9	73	58.5	84	1.8
2014-T6	b	90 days nat	49.7	79	62.6	90	1.9
2014-T6	c	10 hr at 340° F	56.4	90	59.8	86	0.8
2014-T6	b	10 hr at 340° F	59.2	94	65.1	94	2.3
2024-T86	c	31 days nat	54.3	77	60.7	80	1.5
2024-T86	b	90 days nat	56.8	80	66.4	87	1.9
2024-T86	c	8 hr at 375° F	60.5	86	62.2	82	0.8
2024-T86	b	8 hr at 375° F	63.8	90	66.5	88	1.0

[a] Aluminum bronze hold-down shoes, stainless steel backing bar, no coolant.

[b] Aluminum bronze hold-down shoes, copper backing bar, cooled with $CaCl_2$ brine at -55° F.

[c] Aluminum bronze hold-down shoes, copper backing bar, no coolant.

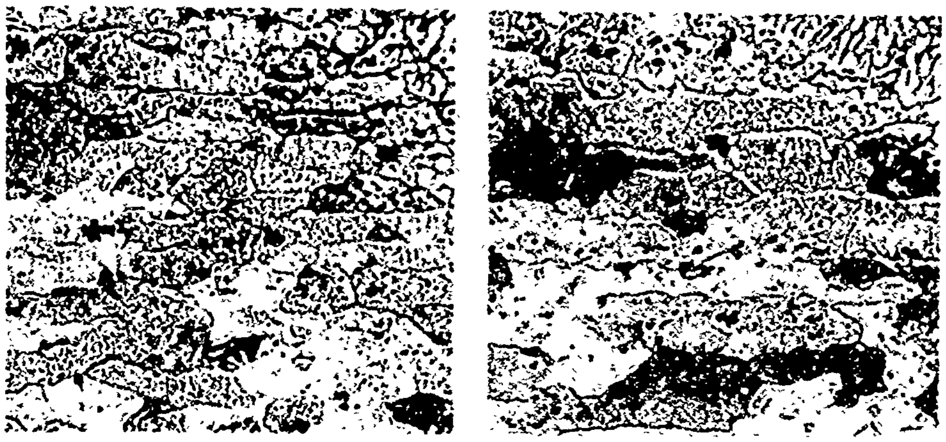

Fig. 9—Zones of grain boundary and eutectic melting in 2014-T6/4145 weldments. Weld metal is at upper right hand corner of both photomicrographs. Left—weldment made on stainless steel backing bar without coolants; right—weldment made on copper backing bar with brine cooling. Keller's etch. X 500 (reduced 52% on reproduction)

cooled weld was made with a somewhat higher energy input than the weld made on the stainless steel backing bar (approximately 4000 joules per in. as opposed to approximately 2700 joules per in.). Figure 8 shows macrosections of the two welds. It is immediately apparent that the weld made on the brine cooled copper backing bar has a substantially narrower heat-affected zone. Figure 9 compares the zone of eutectic melting found in the two welds. The weld made on the brine cooled copper backing bar shows a narrower zone of eutectic and grain boundary melting than the weld made on the uncooled stainless steel backing bar.

Figure 10 illustrates the dendrite structure found in the weld beads of the two welds. The weld made on the brine cooled copper backing bar shows the finer dendrite structure that would be expected of a more rapidly cooled weld.

2024-T86 Sheet

Experimentation similar to that described for the 2014-T6 alloy was also carried out with 0.090 in. thick 2024-T86, an alloy having typical mechanical properties of 71 ksi yield strength and 75 ksi ultimate strength with 6% elongation. Joint preparation was again square butt and the filler metal was 4145. Composition limits of the materials used are shown in Table 2. Weldments were prepared using the copper backing bar with and without brine coolants. Welding procedures and conditions which were used are shown in Table 5. After welding, the panels were aged naturally for 30 or 90 days or artificially for 8 hr at 375° F.

Figure 11 and Table 6 show the properties that were obtained when these weldments were tensile tested. Once again as in the case of 2014-T6, specimens welded on the cooled backing bar show superior properties to the welds made without coolants. However, in the naturally aged specimens, the weld made with the coolants was aged for a longer period of time. In addition, it can be seen that the brine cooled welds exhibit the highest tensile strengths regardless of the aging treatment used.

The effects of artificial aging as compared to natural aging are somewhat similar to those previously observed for 2014-T6. This can best be seen by comparing the welds where the same fixture was used and the only variable is aging. In both cases (with and without cooling), yield strength is increased about 6 ksi by artificial aging. This is accompanied by a decrease in elongation as is often observed when postweld artificial aging treatments are used.

Other observations that can be made from this data are the high tensile efficiencies achieved in the brine cooled welds. The weldments aged naturally for 90 days achieved

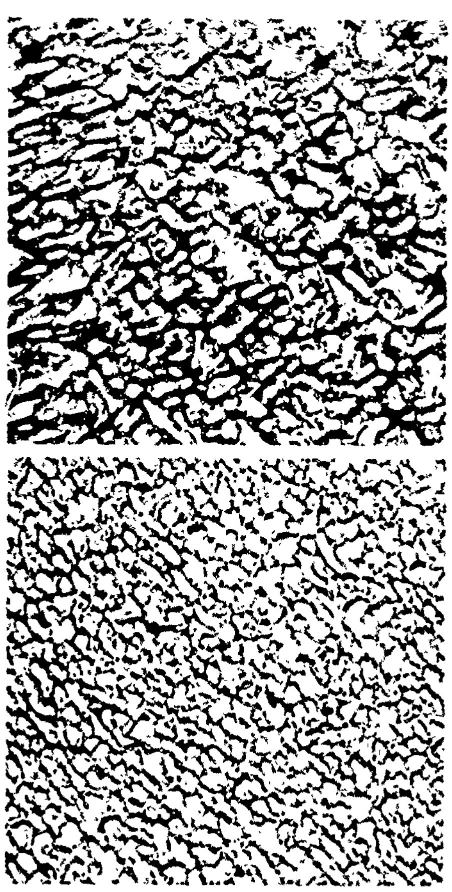

Fig. 10—Dendrite structure in weld beads of 2014-T6/4145 weldments. A (top)—weldment made on stainless steel backing bar without coolants; B (bottom)—weldment made on copper backing bar with brine cooling. Keller's etch. × 500.

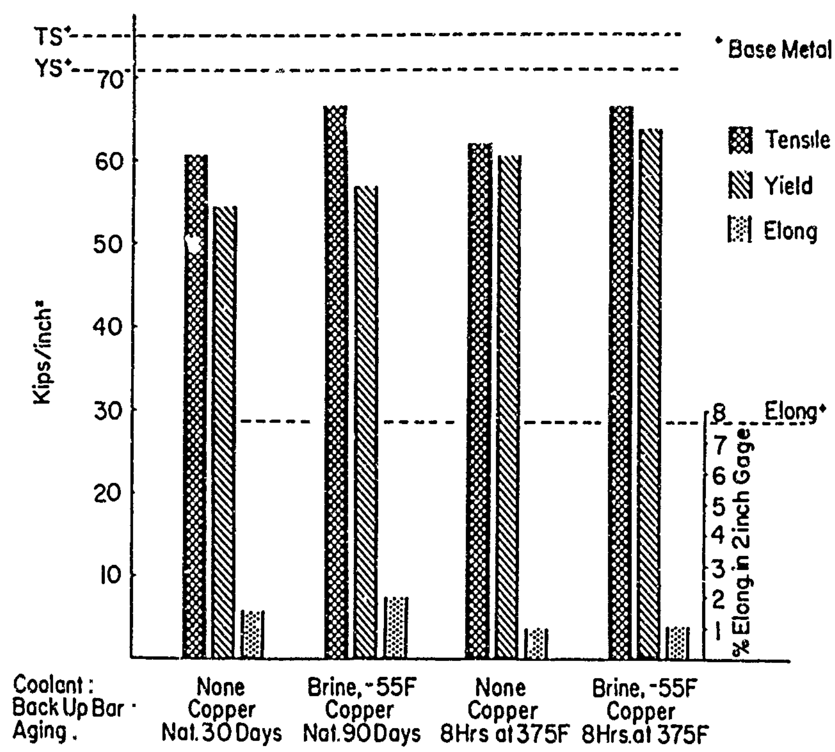

Fig. 11—Tensile properties of 2024-T86/4145 weldments

a yield strength of 80% of the base metal yield strength and a tensile strength of 87% of that of the base metal. The artificially aged brine cooled welds achieved a yield strength efficiency of 90% and a tensile efficiency of 88%. Elongation, however, was low regardless of welding conditions.

The primary mode of failure for all of these weldments was weld metal failure suggesting that the deleterious effects of overheating in the heat-affected zone had been minimized. Metallographic observation tended to bear this out, the zone immediately adjacent to the weld metal–base metal interface showing a minimum of enlargement of the grain boundaries and only slight depletion of alloying elements around the surfaces of the grains as shown in Fig. 12. Weld metal microstructure once again revealed the very fine dendritic structure that would be expected of rapidly solidified weld metal.

Fig. 12—Zone of grain boundary melting in 2024-T86/4145 weldment made on copper backing bar with brine cooling. Keller's etch. X 500 (reduced 64% on reproduction)

Additional Observations

Weld quality was not a problem when welding at the low temperatures (approximately −30° F) achieved in the brine cooled welding fixture. It was found that porosity free welds could be made consistently at subzero temperatures and that no special problems were encountered with respect to weld cracking. Except for occasional crater cracks, welds could be made that were crack-free in the 2014 and 2024 alloys with 4145 filler metal.

In addition to the experiments previously described, the welding fixture was later modified so that liquid nitrogen could be used as a refrigerant. With this equipment, the welding fixture and work could be cooled to temperatures below −300° F at which point (approximately −303° F) condensation of argon from the shielding gases became a problem. Such drastic cooling had been avoided in early experiments, because it was believed that the condensation of water vapor from the shielding gases, which in the grades used have dew points ranging from around −70 to −100° F, would be a serious problem. However, experimentation showed that even at temperatures approaching −300° F, there was no apparent condensation of water vapor on parts enclosed in a helium or argon filled chamber.

A number of welds were made in the 2014 and 2024 alloys at temperatures around −250° F with this equipment. Welding procedures were very similar to those already described with very little change necessary in energy input. Once again, no particular difficulty was experienced in producing welds of excellent quality which were crack-free and exhibited little or no porosity. However, the tensile properties of these welds were very similar to the properties which were obtained with the brine cooled welds and are, therefore, not reported here. Mention is made of these experiments because of the possibility of interest of a general nature in the fact that welds can be successfully made by the gas metal-arc process in materials at extreme subzero temperatures.

Conclusions

1. For 0.090 in. 2014-T6 alloy, yield and tensile strength efficiencies of 93–95% can be obtained through the use of the gas metal-arc welding process, refrigerated welding fixtures and artificial aging.

2. For 0.090 in. 2024-T86 alloy, yield and tensile strength efficiencies of 88–90% can be obtained through the use of gas metal-arc welding, refrigerated welding fixtures and artificial aging.

3. Welding at subzero temperatures does not appear to introduce any special welding problems for aluminum alloys other than the potential for condensation of ambient water vapor. This can be overcome by surrounding the weldment with suitably dried shielding gases.

4. The use of coolants appears to be helpful in improving tensile and yield strengths; however, it does not appear to be especially helpful in improving the elongation of weldments as measured in tensile tests.

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