The Weldability and Grain Refinement of Al-2.2Li-2.7Cu

The key to reducing hot tearing may be in the control of the interdendritic second phase

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ABSTRACT. The basic weldability of the alloy Al-2.2Li-2.7Cu was investigated and compared with two common aluminum alloys: 2024 and 5083. The basic weldability was characterized by the susceptibility of the alloy to hot tearing as determined by the trans-Varestraint test. The hot tearing susceptibility was characterized through plots of total crack length and maximum crack length versus augmented strain. These data were correlated with thermal profiles taken of the weld to provide additional characterization through the use of the brittle temperature range and critical strain rate for temperature drop parameters. The second part of the investigation explored the effect of grain refiner additions upon enhancing the weldability of the alloy. The grain refiners explored were titanium and zirconium, and their effects upon the weldability were determined by the Varestraint test. The results of the study showed the Al-2.2Li-2.7Cu alloy to have a high susceptibility to hot tearing. Additions of titanium and zirconium were found to enhance weldability through refinement of the grain structure and alteration of the shape and distribution of the eutectic phase in the weld.

Introduction

The initiation of research into aluminum-base alloys containing lithium began in the 1920's in Germany. Primary concerns dealt with the age-hardening characteristics the lithium provided in strengthening aluminum. Early problems, however, with low ductility, fracture toughness, and lack of knowledge concerning the strengthening mechanisms, relegated the alloy to dormancy. Renewed interest in the alloy system came about again in the 1970's when escalating fuel cost prompted the reexamination of the alloy. The renewed interest primarily came from the aircraft industry where production of fuel-efficient aircraft is commonly achieved by using alloys that offer low density, high modulus, and high-strength properties in an effort to reduce aircraft weight. The aluminum-lithium alloys have the capability of providing these properties and therefore their development has become essential for not only the aircraft industry, but also for the many industries which utilize aluminum alloys.

An unfortunate consequence of the recent development of these alloys is research efforts have been mainly tailored to the needs of the aircraft industry where, most often, aluminum parts are joined by mechanical methods. As a result, very limited research and development has been performed on other means of joining these alloys, such as welding. Determination of the weldability of current aluminum-lithium alloys as well as production of weldable alloy variants is particularly necessary if their range of application is ever to be expanded beyond the aircraft industry.

The weldability of an aluminum alloy is often defined by its susceptibility to hot tearing since this weld defect is frequently encountered in these alloys. Hot tears will form during the welding process if the alloy possesses an inherent susceptibility, and sufficient strain exists in the weld to cause their formation. Several weldability tests have been designed to subject welds to an external strain during the welding process. These tests are able to induce hot tear formation under conditions that allow test repeatability and easy quantitative analysis of hot tearing susceptibility. Furthermore, two such tests, the trans-Varestraint and the Varestraint test, were utilized in this investigation (Refs. 1–3).

The goal of this study was to determine the basic weldability of the alloy Al-2.2Li-2.7Cu, and subsequently establish the effect of grain refiner additions on the weldability of this alloy. A trans-Varestraint test was used to determine the basic weldability of the alloy. Two aluminum alloys, 5083 and 2024, were tested in addition to the Al-2.2Li-2.7Cu alloy in order to provide a comparison between the aluminum-lithium alloy and an alloy exhibiting good weldability (Alloy 5083) and one exhibiting poor weldability (Alloy 2024). Moreover, the hot tearing susceptibility of each alloy was quantified in terms of maximum crack length, total crack length, minimum strain for cracking, and two additional parameters; the brittle temperature range and the critical strain rate for temperature drop (Refs. 4–6).

The second half of the study was an investigation of the effect of grain refiner additions on the weldability of the aluminum-lithium alloy. Research in the past few years has shown that hot tearing susceptibility of an aluminum alloy may be decreased through refinement of the weld metal grain structure (Refs. 7–11). One effective method available to produce this refinement is through the addition of innoculants into the weld. The two most common elements used to promote grain refinement in aluminum welds are titanium and zirconium. These elements form intermetallic compounds when combined with aluminum, and particles of these intermetallics will act as substrate for the heterogeneous nucle-

KEY WORDS

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Ti Grain Refiner
Zr Grain Refiner
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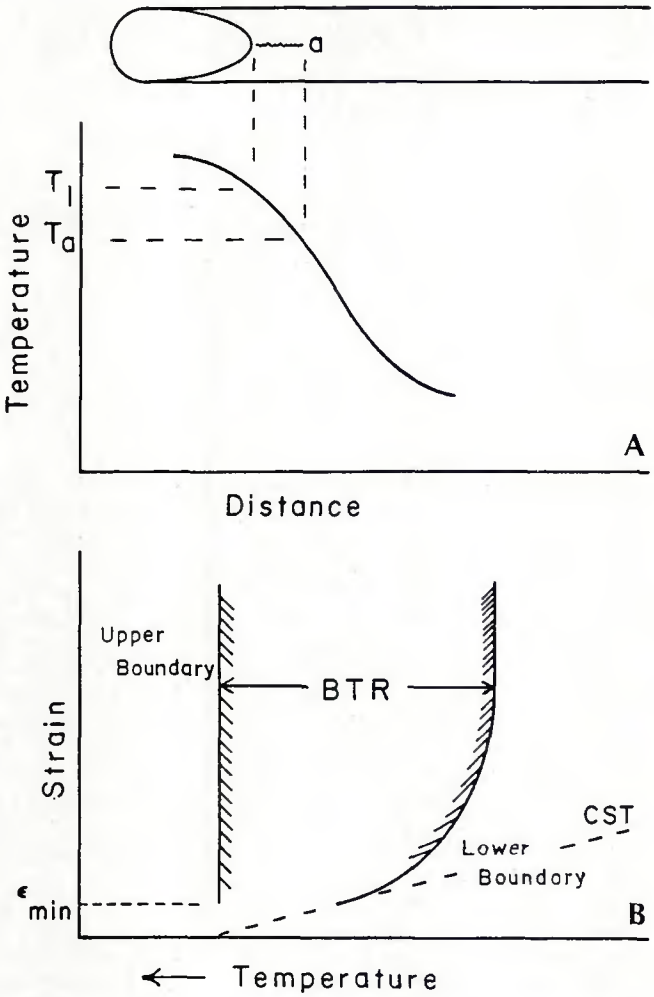

Fig. 1—Schematic representation showing how the solidification brittleness temperature range (BTR) and the critical strain rate for temperature drop (CST) of Senda, et al. is defined (Ref. 4). The maximum crack length is correlated with the A) weld thermal profile to generate the lower boundary of the B) BTR. The upper boundary represents the equilibrium liquidus temperature

ation of new grains during solidification. This leads to refinement of the grain structure and an overall enhancement in weld metal properties. The grain refiner additions were evaluated by testing specimens containing the titanium and zirconium additions with the Varestraint test. The analysis was performed by plotting total crack length versus concentration of each element. Macrostructural and microstructural analyses were performed on all of the weldments to ascertain the effect of the grain refiner elements on the weld structure.

This investigation has therefore sought to provide basic information concerning the weldability of one aluminum-lithium alloy whose composition serves as a basis for a commercial alloy. The determination of basic weldability data is important for the establishment of a foundation upon which future welding research may take place.

The Welding of Aluminum Alloys

The weldability of an alloy is dependent upon many factors, but ultimately it is the ability to produce weldments free from defects. The weldability of an aluminum alloy has become synonymous with the alloy's susceptibility to hot tearing, since this weld defect is the most common defect for the aluminum alloys and has been shown to be primarily dependent on material composition. In order for hot tears to form, the material must exhibit a phase or group of phases that possesses a limited capacity to tolerate strain in a critical temperature range. Hot tears will form if the strain imposed upon the weldment resulting from the combination of internal (thermal) and external (restraint) stresses exceeds some maximum endurable limit. Evaluation of weldability from the hot tearing susceptibility standpoint has led to the formation of several weldability tests. These tests induce hot tear formation by instantaneously subjecting the weld to a severe strain during the welding process. Two such tests, the Varestraint and trans-Varestraint tests, were used in this investigation. In addition to the development of the weldability test, several models and parameters have been formulated to characterize hot tearing susceptibility. The model developed by the Japanese investigators Senda, Arata and Matsuda (Refs. 4–6) was used as a base foundation upon which the characterization of weldability was performed.

Hot Tearing Theory of Senda-Arata-Matsuda

The Japanese investigators who contributed to this model believed most alloys will pass through a low-ductility range during or immediately after solidification. Hot tear formation is speculated to occur in this range when the thermal and external strains acting on the weld exceed some maximum endurable limit. This low-ductility regime has been labeled the "solidification brittleness temperature range" or BTR. Determination of the BTR is considered to be important to the overall analysis of hot tearing susceptibility.

The weldability test chosen by these investigators was the trans-Varestraint test since it offered the most reliable method for determination of the BTR. The hot tearing susceptibility of the alloy tested was characterized by plotting both the maximum crack length (measured at the centerline) and the total crack length versus augmented strain. These characteristic curves along with the minimum strain for cracking (ϵ_{min}) are parameters available to analyze the susceptibility of each alloy.

The BTR is determined by correlating the maximum crack length for a given augmented strain with the centerline weld thermal profile—Fig. 1. This correlation allows the temperature at the far end of the crack tip to be determined. The augmented strain versus crack-tip temperature is plotted, thereby defining the lower boundary of the BTR (see Fig. 1). The upper boundary of the BTR is defined as the equilibrium liquidus temperature of the alloy measured from slowly cooled bulk samples. The temperature difference between the upper boundary and the lower boundary eventually becomes constant at the higher strain since the maximum crack length becomes saturated at higher strains and remains constant. This temperature difference is defined as the brittle temperature range of the alloy.

The Japanese investigators proposed a new index of hot tearing susceptibility referred to as the critical strain rate for temperature drop (CST). The CST is defined as the inclination of a straight line drawn from the liquidus temperature on the abscissa to the point of tangency on the lower boundary curve of the BTR. The CST may be easily converted to a critical deformation rate simply by realizing that the temperature drop incorporated in the CST corresponds to a time difference determined by the weld cooling curve. Therefore, a critical deformation rate exists for a particular alloy and set of welding conditions, above which hot tearing becomes possible. It is possible to experimentally determine the value of this rate by using a variable deformation rate test.

Table 1—List of Base Plate and Weld Metal Chemistries (wt-%)

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Zr	Li[a]
5083	0.10	0.29[a]	.06	0.41[a]	3.9[a]	0.07	–	0.05	0.01	–	–
2024	0.11	0.35	4.3[a]	0.64[a]	1.5[a]	0.01	–	0.11	0.04	–	–
2090	0.04	0.05	2.8[a]	–	–	–	0.01	0.01	0.01	0.05	2.1
Z1	0.03	0.04	2.3[a]	–	–	–	0.01	0.01	0.01	0.08	2.0
Z2	0.03	0.04	2.2[a]	–	–	–	0.01	0.01	0.01	0.12	2.1
Z3	0.03	0.05	2.2[a]	–	–	–	0.01	0.01	0.01	0.14	1.8
Z4	0.04	0.04	2.5[a]	–	–	–	0.02	0.01	0.01	0.20	2.1
Z5	0.04	0.05	2.4[a]	–	–	–	0.01	0.01	0.01	0.16	1.9
Z6	0.03	0.04	2.3[a]	–	–	–	0.01	0.01	0.01	0.14	2.2
T1	0.03	0.04	2.3[a]	–	–	–	0.01	0.01	0.03	0.04	1.8
T2	0.03	0.05	2.5[a]	–	–	–	0.01	0.01	0.04	0.03	2.1
T3	0.03	0.04	2.4[a]	–	–	–	0.01	0.01	0.12	0.03	1.9
T4	0.03	0.04	2.3[a]	–	–	–	0.01	0.01	0.10	0.04	2.0
T5	0.03	0.05	2.4[a]	–	–	–	0.01	0.01	0.19	0.03	2.0
T6	0.04	0.06	2.6[a]	–	–	–	0.01	0.01	0.25	0.03	2.1

(a) Approximate compositions

Experimental Outline and Procedure

The experiments undertaken during the course of this study were designed to provide weldability data on the Al-2.2Li-2.7Cu alloy. A trans-Varestraint test device was used to determine the basic weldability of the aluminum-lithium alloy and compare these results with two other aluminum alloys, 5083 and 2024, which were tested under identical conditions. A conventional gas tungsten arc welding (GTAW) process employing direct current and electrode-negative polarity was used to make the welds during the investigation. The weld parameters were held constant throughout the investigation and are as follows: 100 A welding current, 16 V welding voltage, 0.42 cm/s (10 in./min) travel speed, and helium shielding gas at a flow rate of 23 L/min (50 ft^3/h). The trans-Varestraint test equipment used was capable of testing 6.35-mm (0.25-in.) thick plate specimens under five different augmented strains of 0.1, 0.3, 0.5, 1.0, and 2.0%. Test samples were prepared by lightly sanding the top surface followed by degreasing with acetone prior to testing. Samples containing the hot-tear region of the test weld were lightly sanded and polished to a 0.05-micron surface finish and viewed through a stereomicroscope under oblique lighting for optimum crack detection and measurement. Weld metal cooling profiles were obtained by placing a 0.25-mm chromel-alumel thermocouple assembly into a hole drilled from the underside of the plate specimen. The welds were made directly over the thermocouple, which was placed within 1 mm of the top surface, and the thermal profile was gathered using a chart recorder.

Evaluation of the effect of grain refiner additions on improving the weldability of the aluminum-lithium alloy was performed using the Varestraint test due to the economy of test specimen size. Additions of the titanium and zirconium grain refining elements were achieved by placing alloy insert strips into slots machined in the base metal test specimens. The alloy inserts were made to have the same base composition of the Al-2.2Li-2.7 Cu alloy being tested with the addition of either titanium or zirconium. The compositional range investigated for the grain refiner additions was from 0.05 to 0.30 wt-% in increments of 0.05 wt-%. The list of base plate and weld metal chemistry investigated are shown in Table 1. The inserts were welded over once prior to testing to ensure complete mixing of the insert and the base plate. The test specimens were lightly sanded and degreased with acetone prior to each weld sequence. The Varestraint test samples were tested under a constant 4% augmented strain and samples of the hot tear regions were viewed in the same manner as samples for the trans-Varestraint test. Metallographic samples for evaluation of the weld metal structure were prepared and etched using a solution having 60 parts HCl, 40 parts HF, and 360 parts water (by volume).

Experimental Results and Discussion

Relative Weldability of Al-2.2Li-2.7Cu

The trans-Varestraint test used in this investigation provided a range of data useful for characterizing susceptibility to hot tearing. The hot tears generated by this test are predominately intergranular and extend over several grains as shown in Fig. 2. The cracks usually form close to the centerline for small applied strains, while for larger strains, additional tears are observed to radiate out toward the edge of the weld.

The hot tearing generated in the test specimens may be quantified by plotting the total length of the hot tears versus the applied strain—Fig. 3. The relative position of the curves for the Al-2.2Li-2.7Cu, 2024 and 5083 alloys shows the aluminum-lithium alloy to have a much higher susceptibility for the formation of hot tears than either of the two other aluminum alloys tested under the same conditions. The other important parameter revealed in this plot is the minimum strain required for the initiation of hot tear formation (ϵ_{min}). The ϵ_{min} range was < 0.1% for the Al-2.2Li-2.7Cu alloy, 0.1–0.3% for the 2024, and 0.3–0.5% for the 5083. These data reveal that the formation of hot tears will occur very readily and without much strain in this particular aluminum-lithium alloy.

The brittle temperature range (BTR) and the critical strain rate for temperature drop (CST) parameters were determined by correlating maximum crack length data (Fig. 4) provided by the trans-Varestraint test with the individual weld thermal profiles for each alloy. Figure 5 plots augmented strain versus temperature with the BTR shown for each alloy. The upper boundary of the BTR for each alloy is shown to be the same, since the cooling curves for the bulk samples showed approximately the same liquidus temperature for all three alloys. Figure 5 shows the Al-2.2Li-2.7Cu alloy to have a brittle temperature range that lies between the 5083 and 2024 alloys. This may be partially explained by looking at the solidification range for each binary alloy. The aluminum-magnesium system has the smallest solidification range, followed by the aluminum-lithium and aluminum-copper binary systems. Therefore, it should be expected for the order of the BTR to be as observed. The BTR range, or even the relative positions of the lower boundaries, however, cannot be solely predicted from the solidification range, since the lower boundary of the BTR is often below the equilibrium solidus temperature. The position of the lower boundary curve may result from the non-

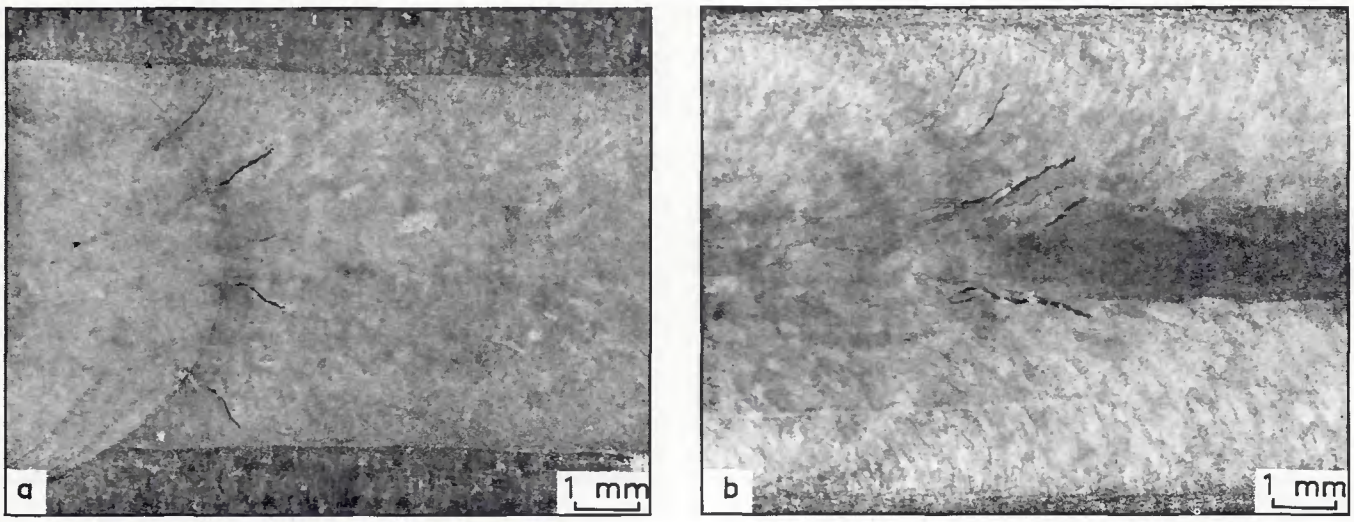

Fig. 2 — Top view of the trans-Varestraint test coupons for: A — 5083 alloy; B) — Al-2.2Li-2.7Cu alloy tested with a 2% augmented strain

equilibrium conditions that exist in the weld or the amount and distribution of eutectic phases present. The Japanese investigators have shown the BTR to increase with increasing alloy additions, and the lower boundary of the BTR will approach the eutectic temperature for the alloy with increasing amounts of the phase present in the weld (Ref. 5). Since this parameter is still relatively new, all of the factors which ultimately determine the BTR are still not known. The BTR only has secondary importance in assigning order of hot tearing susceptibility, since the alloy with the larger BTR will not always exhibit the higher hot tearing susceptibility.

The last parameter available for the characterization of weldability is the CST. The CST parameter takes into account both the ϵ_{min} and the BTR, which is useful since this may be converted to a critical deformation rate under a given set of welding conditions. The larger the CST value, the harder it will be for hot tears to form in the weld. The CST, ϵ_{min} and BTR values are listed in Table 2 for each alloy. The CST value also shows the aluminum-lithium alloy as being the most susceptible to hot tear formation of the three alloys tested.

The data gathered from the trans-Varestraint test were analyzed and reviewed to determine which parameters were the most reliable for assigning order of hot tearing susceptibility. The plot of total crack length versus strain, the parameters of ϵ_{min} and the CST were considered to have primary importance, with secondary importance being on the BTR for assigning hot tearing susceptibility. With the review of the parameters used to describe susceptibility to hot

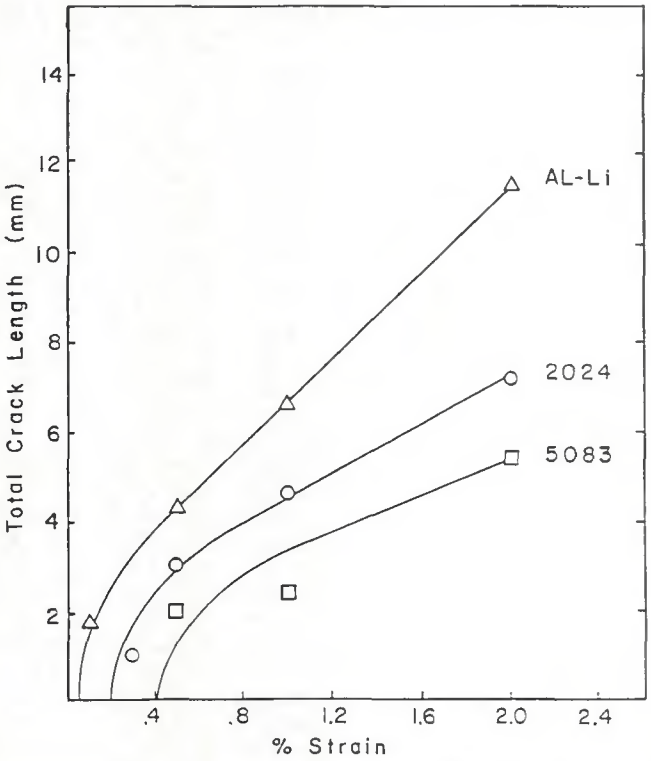

Fig. 3 — Comparison of the total crack length generated at various applied strains for the Al-2.2Li-2.7Cu, 2024, and 5083 alloys tested in the trans-Varestraint test

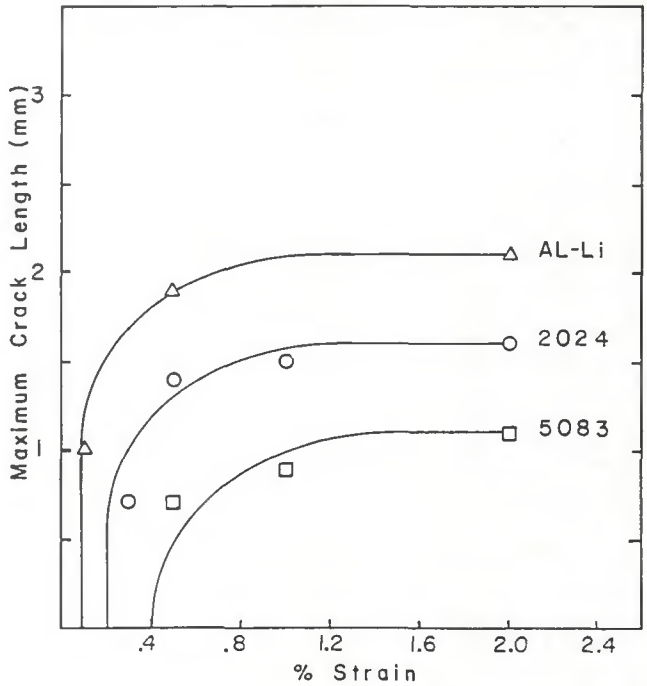

Fig. 4 — Comparison of the maximum crack length generated at various applied strains for the Al-2.2Li-2.7Cu, 2024 and 5083 alloys tested in the trans-Varestraint test

Table 2—Comparison of the Values for the ϵ_{min}, BTR, and CST Parameters

Alloy	ϵ_{min} (%)	BTR (°C)	CST (1/°C)
Al-Li	0.0–0.1	73	13×10^{-5}
2024	0.1–0.3	80	47×10^{-5}
5083	0.3–0.5	68	84×10^{-5}

tearing completed, the final analysis of the relative weldability of the alloy Al-2.2Li-2.7Cu concludes that the alloy has an extremely high inherent susceptibility for the formation of hot tears.

Effect of Grain Refiners on Weldability

The first part of the investigation determined the relative weldability of the Al-2.2Li-2.7Cu alloy and subsequently showed the alloy to have a high susceptibility to hot tearing. The second part of the study therefore focused on improving the weldability of the alloy through refinement of the weld metal grain structure. The results of the test are shown in Figs. 6 and 7. In addition to these samples, the base metal specimens containing no additions were tested and the results on these specimens revealed an average total crack length of 25 mm (1 in.).

The weldability was found to be greatly enhanced with both additions of titanium and zirconium and a marked enhancement was observed to occur even at very-low concentrations. Comparison of the two elements shows the zirconium improves weldability more than the titanium for concentrations less than 0.30 wt-%. The zirconium has an additional advantage over the titanium since the base commercial aluminum-lithium alloys contain zirconium as a dispersoid-forming element for controlling grain size during recrystallization. The zirconium addition is therefore recommended as the grain refiner addition to be used with the aluminum-lithium alloys, since it is already included in the commercial alloys and only small additional amounts would have to be added to boost this amount in order to achieve the desired weldability. Titanium additions are not recommended since it has been shown by others that combinations of titanium and zirconium produce less refinement and enhancement of weldability as compared to additions containing only one element (Refs. 7, 8). This is believed to occur due to the formation of a less effective heterogeneous nuclei

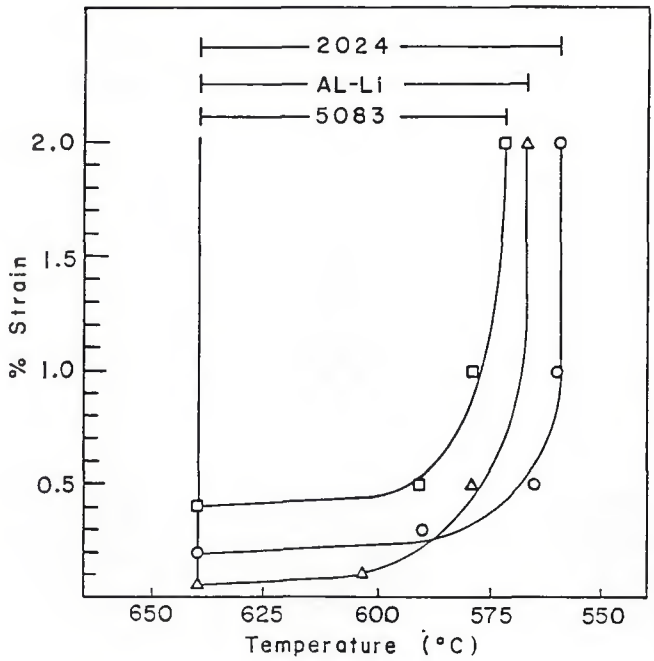

Fig. 5—Plot of strain versus temperature showing the BTR for the Al-2.2Li-2.7Cu, 2024 and 5083 alloys

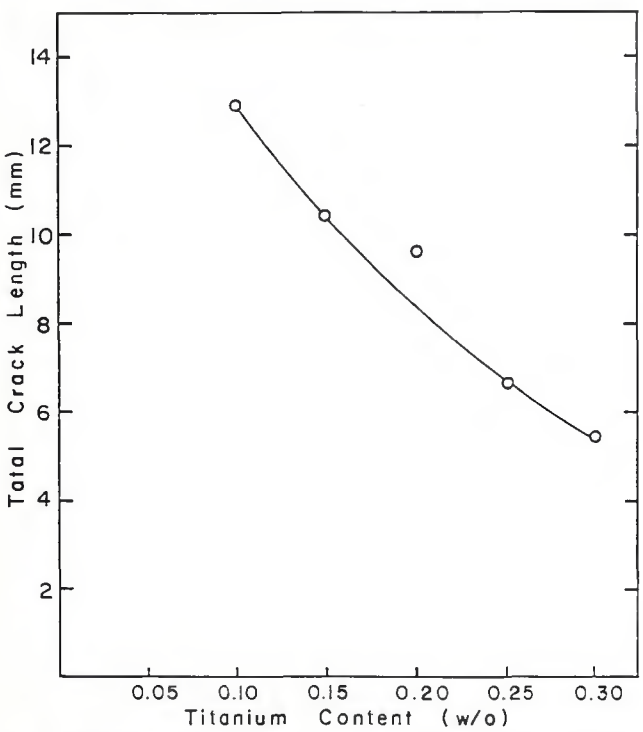

Fig. 6—Plot of total crack length versus concentration of titanium in the Al-2.2Li-2.7Cu alloy welds

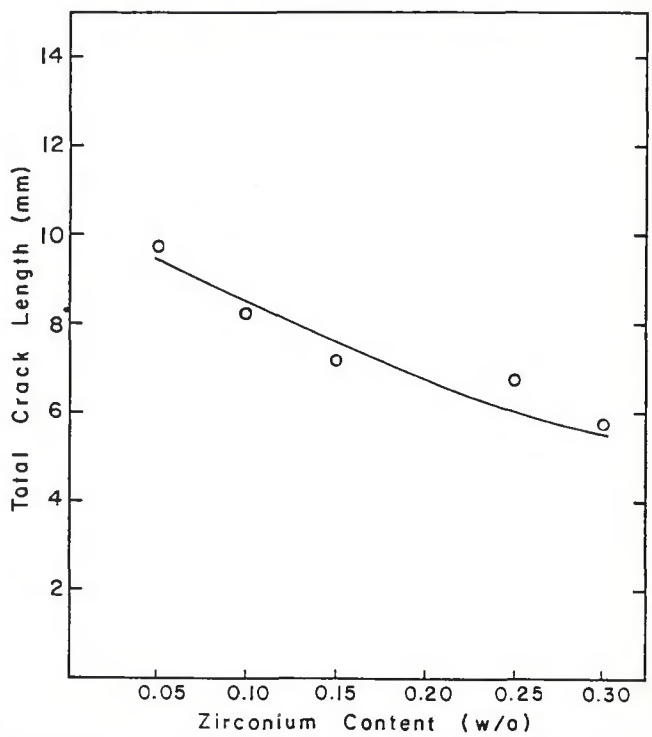

Fig. 7—Plot of total crack length versus concentration of zirconium in the Al-2.2Li-2.7Cu alloy welds

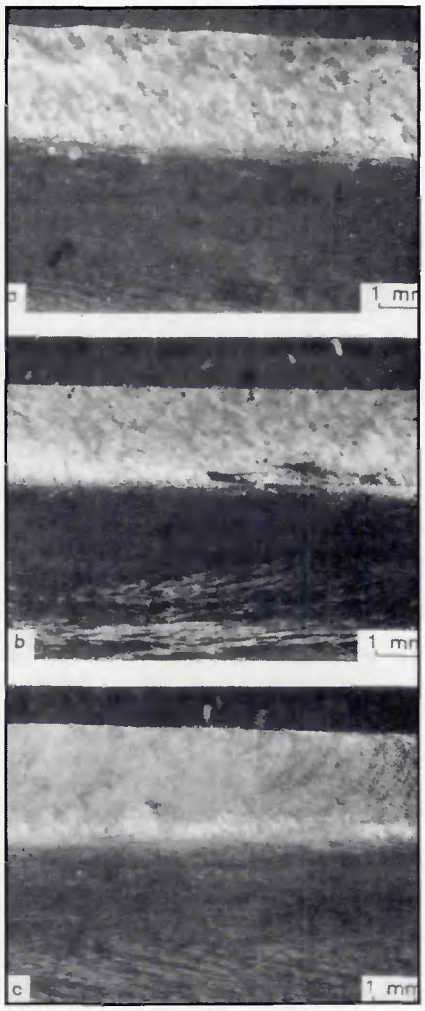

Fig. 8 — Longitudinal cross-section showing the weld metal grain structure for the Al-2.2Li-2.7Cu alloy welds containing: A — 0.0 wt-%; B — 0.10 wt-%; C — 0.20 wt-% titanium

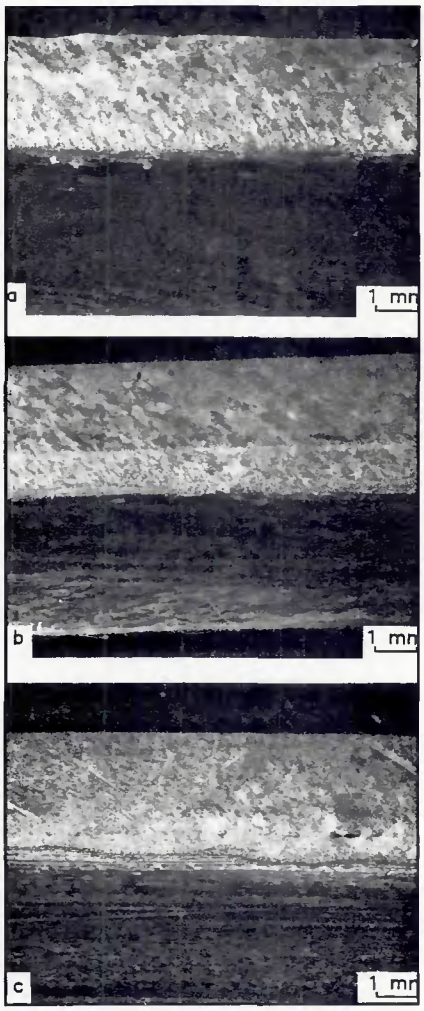

Fig. 9 — Longitudinal cross-section showing the weld metal grain structure for the Al-2.2Li-2.7Cu alloy welds containing: A — 0.0 wt-%; B — 0.10 wt-%; C — 0.20 wt-% zirconium.

when the two elements are combined. The critical amount of zirconium cannot be recommended since the weldability still had room for improvement with additions greater than 0.30 wt-%, and specimens for determination of mechanical properties could not be machined from the small weldments. It is recommended, however, that the strength and ductility of weldments containing the various additions be analyzed in order to determine the optimum amount of grain refiner addition that provides a combination of adequate weldability and sufficient ductility in the weld.

Weld Metal Macrostructure

The weld metal grain structure for the aluminum-lithium alloy is compared with the structure observed for the welds containing titanium and zirconium in Figs. 8 and 9. In the absence of any grain refiner additions, the base alloy exhibits a very refined structure with the grains bordering upon being equiaxed. The intrinsic grain refinement was also reported to occur in the Al-Li binary alloys (Refs. 12, 13). Low concentrations of grain refiners added to the weld show no significant increase in refinement of the weld structure. The higher concentrations of the additions do show refinement of the structure, and eventually the individual grains become fine enough that they cannot be resolved.

The general trend observed in the macrostructure can be quantified by plotting the mean grain width measured at the center of the weld longitudinal cross-section versus the amount of titanium or zirconium. Figure 10 shows that for the low amounts of additions of titanium and zirconium there is not significant refinement of the structure. Refinement of the weld metal grain structure does occur, though, at the higher concentrations of the grain refiner additions. These data confirm the observation made by several previous investigations that a decrease in weld metal grain size will decrease an alloy's susceptibility to hot tearing (Refs. 9, 11, 23). The data taken also show the zirconium addition to be more effective in refining the weld metal grain structure. This may also serve to explain why the zirconium addition was also found to enhance the weldability more than the titanium additions. The smaller grain size found in the zirconium-containing welds would allow for the strain in the weld to be distributed among more grains and across their boundaries, thereby giving the greater improvement in weldability over the titanium additions until higher concentrations are reached that have the grain size approximately the same. Therefore, the observed grain refinement provides an increase in weldability and also shows why there is an observed difference in the weldability between the zirconium and titanium additions for the intermediate concentrations.

Origin of Heterogeneous Nuclei

During the past few years, there have been several disputed theories concerning the origin and formation of the particles of the intermetallic compounds ($TiAl_3$ and $ZrAl_3$) used to provide heterogeneous nuclei for the refinement of the weld metal grain structure in aluminum alloys. The following investigation was undertaken in an effort to provide data or evidence to support one of the theories concerning the origin of these heterogeneous nuclei.

Following the work of Kou and Le (Ref. 14), several of the doped welds were rewelded such that the secondary passes were contained within a slightly larger first pass. These investigators proposed this method to determine the origin of the heterogeneous nuclei responsible for the refinement of the weld metal. Kou and Le believe the origin of the nuclei to be carried over from the master alloy ingots, whereas Yunjia, *et al.* (Ref. 11) surmises that the particles are formed in the weld itself due to constitutional supercooling, allowing for the homogeneous nucleation of the particles. It is thought that the particles provided by the additions of titanium and zirconium could be resolutionized if multiple welds were made over the same weld bead. If the particles are carried in from the master alloy and can be resolutionized, then a decrease in refinement should be observed when compared to a single pass weld containing the additions. On the other hand, if no decrease in grain refinement is observed, homogeneous nucleation of the particle may be taking place as a result of constitutional supercooling or some other mechanism is responsible for the refinement (*i.e.*, dendrite fragmentation or disrupted solidification). The results of this multiple-pass weld test are shown in Fig. 11.

The longitudinal cross-sections of the

welds show, for the low concentration titanium weld, that upon the second pass the grain structure was converted from a refined structure shown in the single-pass weld to a structure consisting of large epitaxial grains that grow across the deposit with only a few new grains being formed. This behavior was only observed to occur for very low concentrations of titanium and zirconium and did not occur in the multipass welds made upon the base alloy. This change in grain structure shows that the heterogeneous nuclei were not present in the second weld. The multiple-pass welds are believed to solutionize the particles and subsequently the high cooling rate during solidification of the weld metal suppresses the particles from reforming. The results of this test support the theory that the $TiAl_3$ and $ZrAl_3$ particles are carried in from the master alloy ingots. This behavior probably does not occur at the higher concentrations of grain refiners since the kinetics of dissolution will be much slower as the concentration of the titanium or zirconium is increased. Further support for the origin of the nuclei may be seen in an investigation performed by H. W. Kerr, *et al.* concerning the equilibrium and nonequilibrium peritectic transformations in the aluminum-titanium alloy system (Ref. 15).

The results obtained are very significant since they point out that the heterogeneous nuclei must exist prior to being added to the weld because the solidification conditions found in the weld will not allow for their formation. The importance of this from an engineering standpoint is that the ingots used to make weld wire or the alloy inserts must be cooled slow enough to allow for the formation of beta-phase particles. In addition to the importance of the processing procedure, the amount of the grain refiner added to the weld becomes a significant variable since the dissolution kinetics will be directly affected by the amount of the titanium or zirconium in the weld. The conclusion being that a weld should contain a larger amount of the grain refiner than needed in order to offset the encountered dissolution of some of the particles during the welding process.

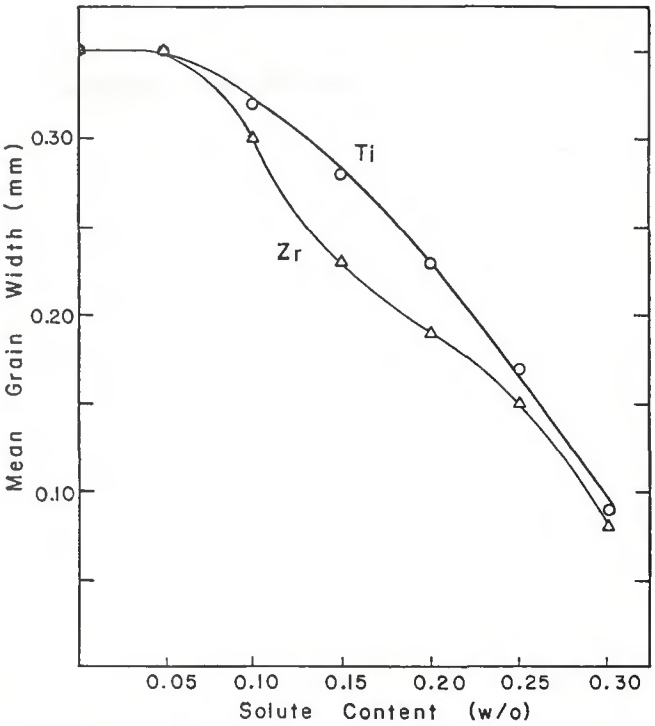

Fig. 10—Plot of mean grain width measured at the center of the weld longitudinal cross-section versus concentration of titanium and zirconium in the weld

Microstructural Characterization of Weld Metal

Weld metal microstructures representative of the aluminum-lithium base alloy and the welds containing the grain refiner additions are shown in Fig. 12. The microstructure of the welds consists of primary dendrites with an interdendritic second phase. The welds differ in the distribution and shape of the second phase.

The microstructure for the base aluminum-lithium alloy weld shows the second phase to be elongated and distributed in a fairly semicontinuous fashion around the primary dendrites. As soon as small amounts of titanium or zirconium are added to the weld, the morphology of the second phase changes. The photomicrograph of the weld containing 0.10 wt-% titanium reveals the second phase has become more spherical in shape and most of the semicontinuous network has been broken up. The semicontinuous distribution is not found in welds containing higher additions of the grain refiner elements.

The microstructural observations made above may explain why the Al-2.2Li-2.7Cu alloy exhibits a high susceptibility

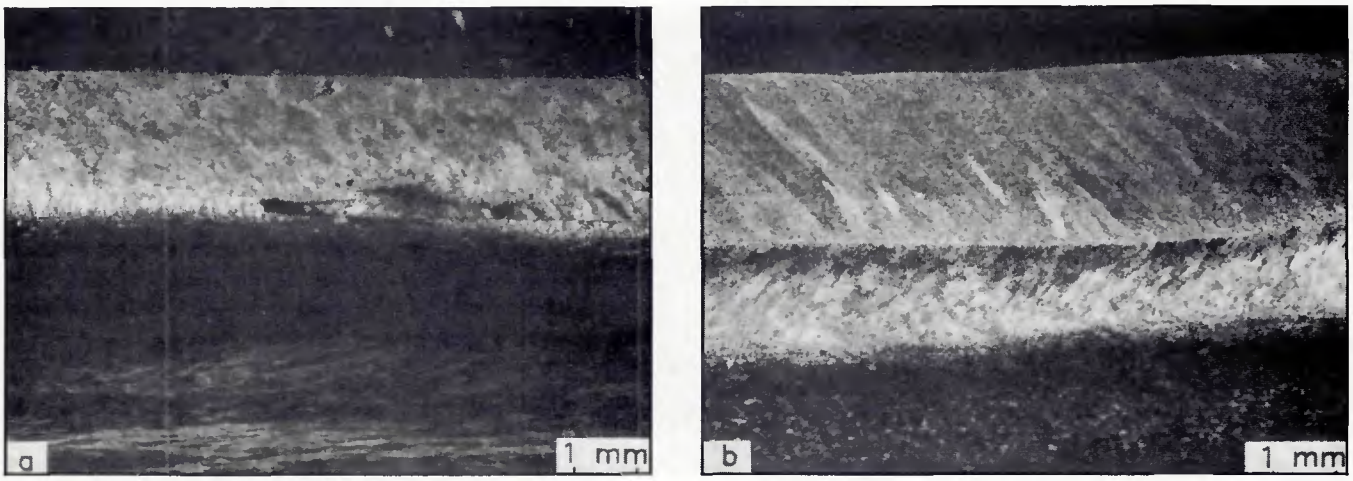

Fig. 11—Comparison of the weld metal grain structure for: A—A single-pass weld; B—a two-pass weld made on a Al-2.2Li-2.7Cu alloy specimen containing 0.10 wt-% titanium

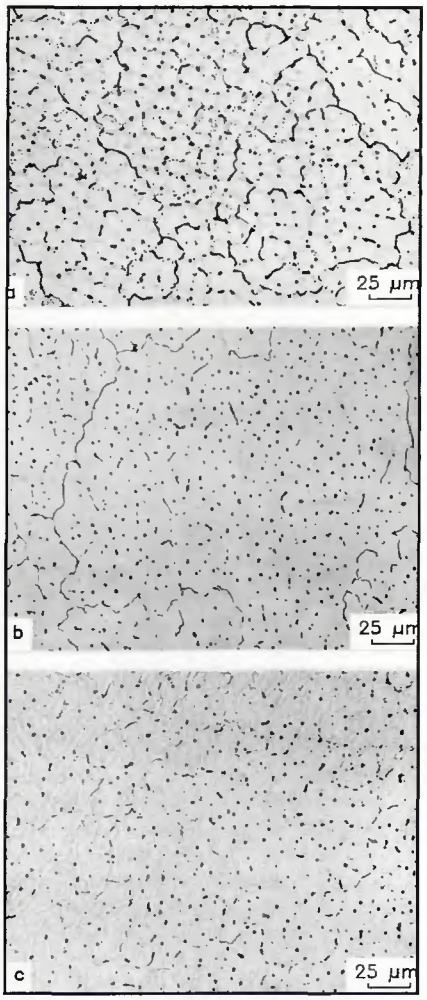

Fig. 12 — Weld metal microstructure for the Al-2.2Li-2.7Cu alloy welds containing: A — 0.0 wt-%; B — 0.10 wt-%; C — 0.20 wt-% titanium (section taken normal to growth direction)

to hot tearing in spite of having an inherent refined weld grain structure. Since hot tearing involves the separation of liquid films, the observed semicontinuous network of low melting point second phase should be very detrimental to the weldability of the alloy in spite of the refined grain structure. This distribution of the second phase may be the controlling factor in this alloy for determining hot tearing susceptibility. If this is the case, then improvement of weldability would depend upon either changing the shape and distribution of the second phase or providing sufficient grain boundary area to spread the second phase such that it is no longer continuous. The grain refiner additions were seen to improve the weldability of the alloy even at low concentrations where the decrease in grain size was not very significant. The observed enhancement of weldability is therefore thought to have come about partially as a result of the change in the shape and distribution of the second phase as seen in the microstructure of the welds containing the additions. The increase in grain boundary area for the higher concentration of grain refiner elements may also help to break up the network.

Conclusions

1) The Al-2.2Li-2.7Cu alloy was found to be the least weldable followed by the 2024, with Alloy 5083 being the most weldable. In the absence of the zirconium addition usually contained in the aluminum-lithium alloys, the Al-2.2Li-2.7Cu alloy showed a significantly high susceptibility to hot tearing in spite of the refined weld metal grain structure inherent in the base alloy welds. The high susceptibility to hot tearing may arise from the shape and distribution of the eutectic phase in the weld.

2) The additions of titanium and zirconium were found to enhance the weldability of the Al-2.2Li-2.7Cu alloy. The zirconium addition was found to increase the weldability more than the titanium addition up to 0.30 wt-%. Zirconium is the recommended grain refiner addition for the alloy since the base aluminum-lithium alloys contain zirconium as a dispersoid-forming element for controlling grain size. A specific concentration of zirconium, however, cannot be recommended here since the weldability and grain refinement data did not reach an optimum within the concentrations explored.

3) The base Al-2.2Li-2.7Cu alloy weldments were found to have a refined grain structure with the grains bordering upon being equiaxed. The intrinsic refinement is thought to occur as a result of the homogeneous nucleation of new grains resulting from supercooling ahead of the solid-liquid interface. The supercooling is thought to be present as a result of the cellular solidification mode exhibited by the alloy (Ref. 12).

4) The additions of titanium and zirconium refined the weld metal grain structure of the base Al-2.2Li-2.7Cu alloy. The zirconium addition decreased the weld metal grain size more than the titanium addition for intermediate concentrations, but at higher levels, the two additions showed approximately the same amount of refinement. The additions of titanium and zirconium are also thought to change the shape and distribution of the eutectic phase, thereby improving weldability even at low concentrations where grain refinement was negligible.

5) The multiple pass weld test revealed the origin of the heterogeneous nuclei to be from the master alloy used to make the grain refiner additions. The formation of the particles of $TiAl_3$ or $ZrAl_3$ during solidification or the reprecipitation of these particles is unlikely due to the high cooling rates experienced in the weld. The significance of these results is that the particles must exist prior to being placed in the weld and a high concentration of the particles is needed since a certain amount will be resolutionized during the welding process.

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WRC Bulletin 332
April 1988

This Bulletin contains two reports that characterize the mechanical properties of two different structural shapes of constructional steels used in the pressure vessel industry.

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By J. M. Barsom and B. G. Reisdorf

This report presents information concerning the chemical, microstructural and mechanical (including fracture toughness) properties for heavyweight wide-flange structural shapes of A36, A572 Grade 50 and A588 Grade A steels.

(2) Data Survey on Mechanical Property Characterization of A588 Steel Plates and Weldments
By A. W. Pense

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WRC Bulletin 341
February 1989

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By J. H. Bickford, K. Hayashi, A. T. Chang and J. R. Winter

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