# Weldability Testing of Dissimilar Combinations of 5000- and 6000-Series Aluminum Alloys

*The Sigmajig weldability test was used to quantify the relative cracking susceptibility of dissimilar combinations of sheet alloys*

BY M. M. MOSSMAN AND J. C. LIPPOLD

ABSTRACT. The increased use of aluminum in the automotive industry has resulted in renewed interest in the weldability of 5000- and 6000-series alloys in dissimilar combinations. In this study, similar and dissimilar combinations of alloys 6111-T4, 6022-T4, 5182-H16, and 5754-O in sheet form were evaluated using gas tungsten arc welding in conjunction with the Sigmajig weldability test. Using this test, the relative cracking susceptibility of these alloys and their dissimilar combinations were determined.

Baseline testing of the individual alloys revealed 5182 had the highest resistance to cracking (highest threshold stress for cracking in the Sigmajig test), while 6022 was the most susceptible. For dissimilar combinations, 5182-6111 and 5754-5182 combinations exhibited the highest cracking resistance while all combinations with 6022 showed an increased susceptibility to cracking. Changing the relative dilution of each combination in the range from 25 to 75% had only a small effect on cracking susceptibility. When welded in combination with 5182 or 5754, 6022 showed a tendency to fail in the partially melted zone rather than the fusion zone.

## Introduction

Federal regulations have encouraged the automotive industry to produce automobiles that have increased fuel efficiency while maintaining structural integrity standards. One method to achieve this goal is to reduce the overall vehicle weight by substitution of aluminum for steel in body structural and panel components. A number of automobile producers are developing, or are currently producing, aluminum-intensive vehicles. The introduction of aluminum into automobile production has spurred interest in new alloys and the fabrication issues associated with these alloys. Of particular interest are the 5000-series alloys used for inner body panels, heat shields, and structural and weldable parts and the 6000-series alloys used for body components, outer and inner body panels, and structural and weldable parts (Ref. 1).

*M. M. MOSSMAN and J. C. LIPPOLD are with the Welding and Joining Metallurgy Group, The Ohio State University, Columbus, Ohio.*

It is clear dissimilar welds will be required between different aluminum alloys in a number of applications, including sheet-to-sheet, sheet-to-forgings, and sheet-to-castings. Currently, there is little information in the literature that addresses the issues of dissimilar aluminum joining or provides guidelines on weldability. A preliminary study of GTA welding evaluated heat input and travel speed effects on weld penetration, properties, and microstructure (Ref. 2). This study revealed a susceptibility to cracking under certain welding conditions and it was decided to use the Sigmajig test to quantify this behavior.

The purpose of this study was to evaluate the weld solidification and liquation cracking susceptibility of dissimilar sheet-to-sheet welds. The tests performed here were designed to evaluate the weldability of dissimilar combinations of interest to the automotive industry rather than develop or specify welding processes or procedures. The Sigmajig test provides a simple, straightforward technique for evaluating the cracking susceptibility of these alloys in sheet form.

**KEY WORDS**

Aluminum Welding
Dissimilar Welding
Solidification Cracking
Sigmajig Test
Liquation Cracking
Weldability Test

## Experimental Procedure

### Materials

The aluminum alloys selected for this study represent alloys currently under consideration, or in use, for automotive applications, including alloys 6111, 6022, 5754, and 5182. These alloys were supplied in a nominal sheet thickness of 1 mm (0.039 in.). Compositions, temper conditions, and actual sheet thicknesses are listed in Table 1. In addition to these materials, alloys 1100, 3003, and 5052 were used as control materials for the Sigmajig weldability test. These alloys are also listed in Table 1.

### Weldability Testing

Weldability testing of the sheet materials was conducted using the Sigmajig test. This test was developed by Goodwin (Ref. 3) to evaluate the solidification and liquation cracking susceptibility of sheet materials. The Sigmajig test setup is shown in Fig 1. A fixture holds a 50 x 50 mm (2 x 2 in.) square specimen between hardened steel grips while a transverse load is applied to the sample. The load is applied through a pair of strain-gauged bolts and maintained by stacks of Belleville washers in the load train. The washers provide an adjustable spring constant.

After loading, an autogenous gas tungsten arc weld (GTAW) is made along the centerline of the specimen. If no cracking is observed in the sample, the load is increased incrementally (approximately 50 lb or 0.5 ksi for 1-mm-thick material) in subsequent samples until cracking occurs. The minimum load (or stress) at which cracking occurs is defined as the threshold stress ($\sigma_{th}$). Multiple tests are run at loads slightly above and below ($\pm$10 lb) the threshold stress to verify $\sigma_{th}$. Figure 2 is a schematic representation of data collected from the Sigmajig test showing how $\sigma_{th}$ is determined.

Based on the work of Goodwin (Ref. 3), a teardrop-shaped weld pool is neces-

**Table 1 — Alloy Composition Ranges (wt-%) and Thickness (mm)**

| Alloy | Composition (wt-%) Cr | Cu | Fe | Mg | Mn | Si | Ti | Zn | Thickness (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1100-H14 | 0.06 | 0.03 | <0.01 | <0.01 | 0.20 | 0.11 | 0.089 | <0.01 | 1.25 |
| 3003-H14 | 0.06 | 0.14 | <0.01 | <0.01 | 1.31 | <0.01 | 0.109 | <0.01 | 1.00 |
| 5052-H34 | 0.20 | 0.03 | <0.01 | 2.45 | 0.21 | <0.01 | 0.080 | <0.01 | 1.58 |
| 5182-H16 | 0.10 | 0.08 | <0.01 | 4.05 | 0.52 | 0.03 | 0.088 | 0.04 | 1.02 |
| 5754-O | 0.06 | 0.03 | <0.01 | 2.94 | 0.45 | <0.01 | 0.087 | <0.01 | 1.07 |
| 6022-T4 | 0.06 | 0.08 | <0.01 | 0.46 | 0.26 | 1.21 | 0.104 | <0.01 | 1.04 |
| 6111-T4 | 0.11 | 0.72 | <0.01 | 0.57 | 0.41 | 0.78 | 0.156 | <0.01 | 0.97 |

**Table 2 — Combinations Evaluated with the Sigmajig Test**

| Alloy A | Alloy B |
|---|---|
| 6111 | 6022 |
| 6111 | 5182 |
| 6111 | 5754 |
| 5754 | 5182 |
| 5754 | 6022 |
| 6022 | 5182 |
| 6022 | 6022 |
| 6111 | 6111 |
| 5754 | 5754 |
| 5182 | 5182 |

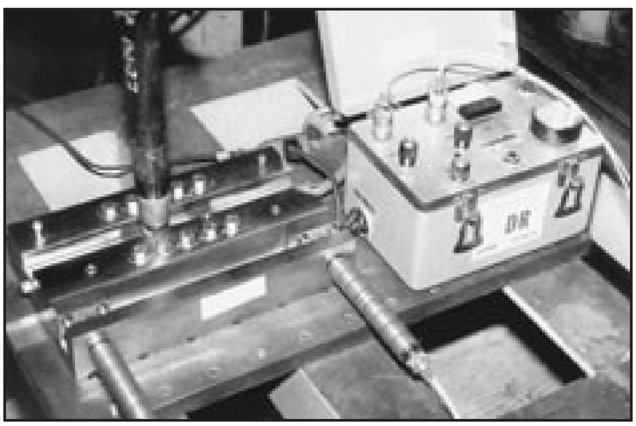


*Fig. 1 —The Sigmajig weldability test setup.*

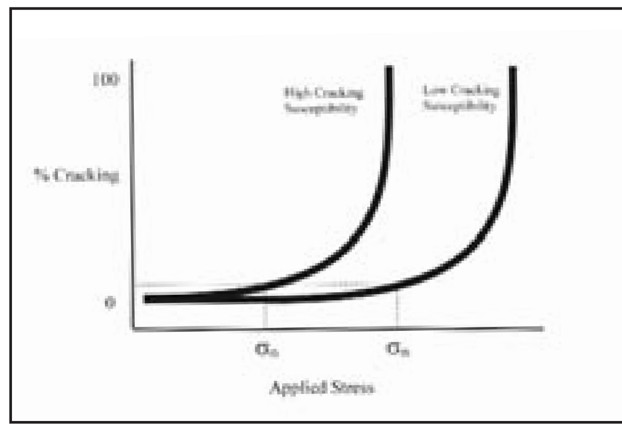



*Fig. 2 — Schematic of Sigmajig data plotted as percent cracking vs. threshold stress ($\sigma_{th}$) for a susceptible (low $\sigma_{th}$) and resistant (high $\sigma_{th}$) alloy.*

sary to accurately predict the cracking susceptibility using the Sigmajig test. This generally results in cracking along the weld centerline above the threshold stress. In order to achieve this pool shape, very high travel speeds may be necessary, which are not representative of what is used in production. Again, this test is not designed to reproduce actual manufacturing conditions. Rather, it is used to determine the relative weld cracking resistance of the materials of interest.

In order to produce the desired pool shape and full penetration with GTAW, the following parameters were used during testing: 50 A, 14 V DCEN, 55 in./min (23.3 mm/s), and helium shielding gas at 50 $ft^3/h$ (1415 L/h). These parameters were used for every combination tested. Since no cleaning action is provided by the DCEN GTAW process, the materials were chemically cleaned before welding in a sodium hydroxide bath followed by a nitric acid rinse(Ref. 4).

The matrix of similar and dissimilar combinations tested during this investigation is listed in Table 2. In order to test dissimilar combinations, coupons of the dissimilar pair nominally 25 x 50 mm (1 x 2 in.) were welded together along the 50-mm (2-in.) dimension using a 3-kW, Nd:YAG laser to form the standard 50 x 50 mm (2 x 2 in.) Sigmajig test sample. The size of the laser beam weld was controlled such that it would be completely consumed by the GTA weld during the Sigmajig test. To ensure the presence of the laser beam weld did not influence test results, similar combinations were prepared by laser welding and then tested using the Sigmajig test. These results were then compared to the standard bead-on-plate test technique for the given material.

For dissimilar combinations, three dilution levels were evaluated: 1) 25%–75%, 2) 50%–50%, and 3) 75%–25%. The dilution level was varied by moving the sample in the fixture so the GTAW electrode was offset to one side of the centerline of the sample, as shown in Figure 3. In all three cases, the laser weld used to form the dissimilar Sigmajig sample was completely consumed during the test.

## Results

### Preliminary Testing

Initial tests consisted of simple bead-on-plate welds on standard 50- x 50-mm (2- x 2-in.) coupons of each of the materials from Table 1. The threshold stress for cracking ($\sigma_{th}$) for these materials was compared to results provided by Goodwin (Ref. 5) for alloys 1100, 3003, and 5052, as shown in Fig. 4. The results showed $\sigma_{th}$ values measured in this investigation follow the same pattern as those of Goodwin (Ref. 5), but the absolute values of $\sigma_{th}$ for the individual alloys were approximately 2 ksi less. This variance may be due to the difference in composition, thickness of the alloys tested, or testing conditions. Of primary importance is the ranking of the alloys, and this is consistent with Goodwin's results.

Laser beam welds were used to join the dissimilar samples prior to Sigmajig testing. There was some concern the presence of the laser weld would alter the results relative to a normal bead-on-plate test technique due to residual stress, or other effects, from the laser beam welds. In order to evaluate this, each of the sheet materials was tested in both conditions. Results of these tests showed effectively no difference between samples containing a laser beam weld and those without. In all cases, the difference was 1 ksi or less and there was no systematic difference be-

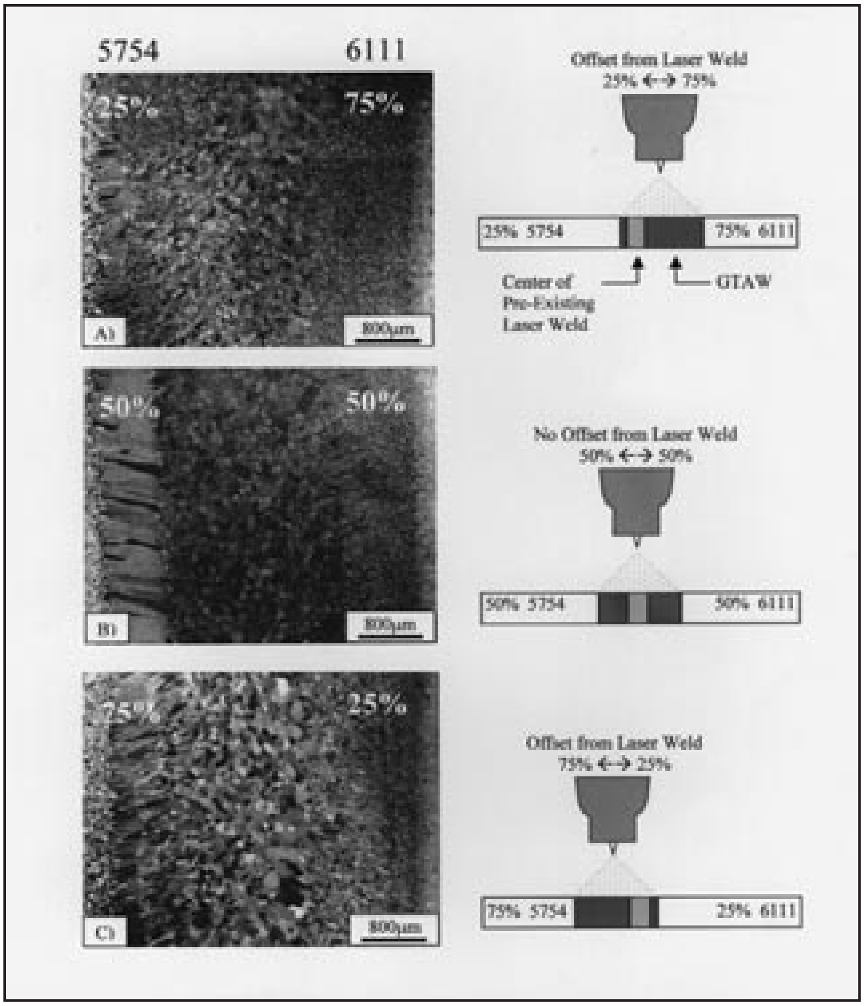



*Fig. 3 — Sigmajig weldability test specimens for combination 5754 to 6111 at varying dilution levels. A — 25% 5754 to 75% 6111; B — 50% 5754 to 50% 6111; C — 75% 5754 to 25% 6111 (Barker's reagent).*

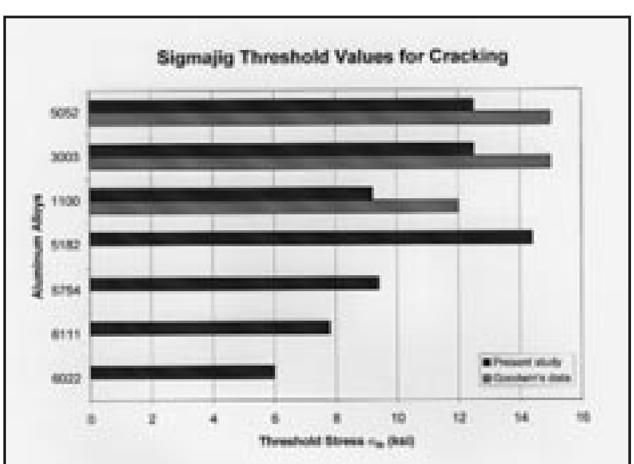



*Fig. 4 — Sigmajig threshold stress values for alloys evaluated in this study. Values for 1100, 3003, and 5052 are compared to previous work from Goodwin (Ref. 5).*

tween the two sample types. This ensured there was no effect of the laser weld on test results.

### Similar Combinations

The $\sigma_{th}$ data for similar combinations of alloys 5182, 5754, 6111, and 6022 is plotted in Fig. 4 and listed in Table 3, along with the bead-on-plate values for the control alloys used in this investigation. In Table 3, the alloys are ranked in order of resistance to cracking, as determined by $\sigma_{th}$. When ranked in this manner, alloy 5182 exhibits the highest resistance to cracking, while alloys 6111 and 6022 are the worst. Note there are differences in the thickness of alloys 1100 and 5052 tested in this study as compared to Goodwin's work and this has been shown previously (Ref. 6) to increase $\sigma_{th}$ as thickness increases. Thus, for the 2 mm thickness tested by Goodwin, the $\sigma_{th}$ values for alloys 1100 and 5052 might be expected to be slightly higher than those values achieved in this study with slightly thinner specimens.

**Table 3 — Sigmajig Threshold Stress Values (ksi) for Similar Combinations**

| Alloy | $\sigma_{threshold}$ |
|---|---|
| 5182-H16 | 13.2 |
| 3003-H14(a) | 12.5 |
| 5052-H34(a) | 12.4 |
| 5754-O | 9.3 |
| 1100-H14(a) | 9.3 |
| 6111-T4 | 8.2 |
| 6022-T4 | 7.1 |

(a) Reference alloys used in this study.

### Dissimilar Combinations

Two Sigmajig test specimens of the combination 5754/6111 are shown in Fig. 5A. Sample 1 was tested below the threshold stress level and therefore no cracking was present. Sample 2 was tested slightly above the threshold level and, as is shown, cracking was present both along the fusion boundary and at the weld centerline.

### Fusion Zone Mixing Characteristics.

A transverse section of the dissimilar weld between 5754 and 6111 is shown in Fig. 5B. Nonuniform mixing is evident in this section and this was the characteristic of all dissimilar combinations between the 5000- and 6000-series alloys tested in this study. This nonuniform mixing was attributed to high travel speed resulting in rapid solidification rates and the differences in viscosity and surface tension of 5000- and 6000-series alloys.

Travel speeds approaching those used here would be at the extreme of what would be used in the automotive industry during high-speed arc welding of aluminum alloys, but it is conceivable such nonuniform mixing, as shown in Fig. 5B, is possible at lower travel speeds and could occur during manufacturing. No experiments were run to determine the travel speed ranges over which this would occur.

As shown in Fig. 6, surface tension decreases with increasing alloying content of magnesium (Ref. 7). It can be assumed the 5000-series alloys will have a lower surface tension than the 6000-series alloys due to their higher magnesium content. Viscosity, as shown in Fig. 7B, also decreases

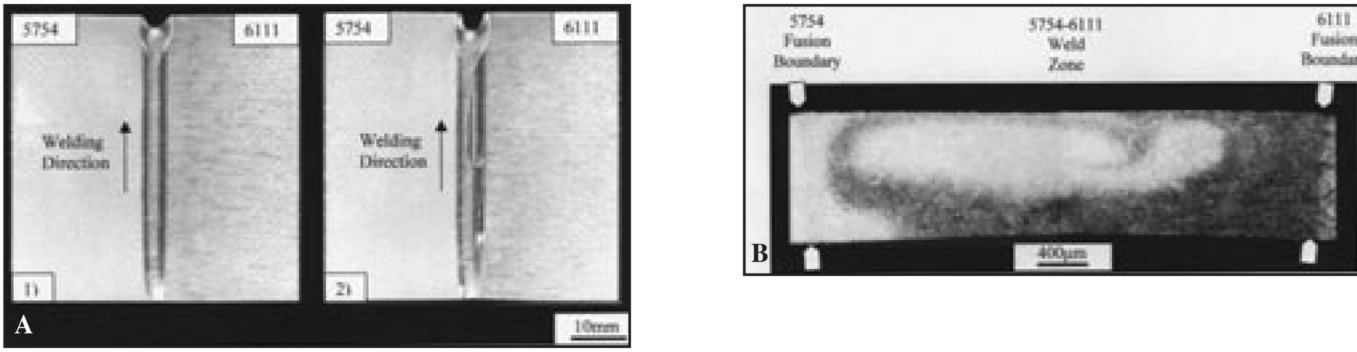



*Fig. 5 — Sigmajig test samples. A — 5754/6111 combination illustrates a sample (No. 1) tested just below $\sigma_{th}$ and a sample (No. 2) tested just above $\sigma_{th}$; B — Transverse section showing inhomogeneous mixing in the 5754/6111 combination at a 50/50 dilution level (Keller's reagent).*

with increasing magnesium. It is concluded the combination of travel speed, viscosity, and surface tension differences result in nonuniform mixing.

### Cracking Susceptibility

The threshold stress values for each dissimilar combination at the three dilution levels are listed in Table 4. This data shows some interesting variations as a function of dilution. For example, the dilution of 5182 by 5754 results in a slight decrease in cracking resistance, while dilution of 6111 by 5182 improves resistance to cracking. Dilution has essentially no effect on the cracking resistance of the 6111/5754 combination. Unfortunately, dilution effects in dissimilar welds made with alloy 6022 could not be determined since almost all the Sigmajig samples failed in the partially melted zone (PMZ) adjacent to the fusion boundary. As a result, the $\sigma_{th}$ values for the 5754, 5182, and 6111 combinations with 6022 all fall in the range from approximately 5.5 to 6.5 ksi. This precludes determination of the actual fusion zone $\sigma_{th}$ values for these combinations and only indicates the threshold stresses exceed about 6.5 ksi.

An order ranking of both similar and dissimilar combinations is provided in Table 5. In general, dissimilar combinations between 5182 and 5754 were more resistant to cracking than 5000/6000 combinations, or the 6022/6111 combination. Again, because combinations with 6022 failed in the PMZ of the 6022, these combinations were the lowest ranking.

**Table 4 — Effect of Dilution on Sigmajig Threshold Stress Values (ksi) for Dissimilar Combinations**

| | Percent Dilution | | | | |
|---|---|---|---|---|---|
| Alloy Combination | 0/100 | 25/75 | 50/50 | 75/25 | 100/0 |
| 5754/5182 | 13.2 | 9.47 | 9.47 | 10.53 | 9.3 |
| 5182/6111 | 8.2 | 9.21 | 10.26 | 9.47 | 13.2 |
| 5754/6111 | 8.2 | 8.68 | 8.42 | 7.63 | 9.3 |
| 5754/6022 | 7.1 | 6.97(a) | 6.18(a) | 5.26(a) | 9.3 |
| 6022/5182 | 13.2 | 5.53(a) | 5.79(a) | 6.32(a) | 7.1 |
| 6022/6111 | 8.2 | 5.26(a) | 6.05(a) | 6.05(a) | 7.1 |

(a) Sample failed in the PMZ of alloy 6022.

**Table 5 — Order Ranking of Similar and Dissimilar Combinations**

| Alloy Combination | Dilution | $\sigma_{threshold}$ (ksi) | Failure Location(a) |
|---|---|---|---|
| 5182/5182 | — | 13.2 | CL |
| 5754/5182 | 75/25 | 10.53 | CL |
| 5182/6111 | 50/50 | 10.26 | PMZ/FZ of 6111 |
| 5754/5182 | 25/75 | 9.47 | CL |
| 5754/5182 | 50/50 | 9.47 | CL |
| 5754/5754 | — | 9.30 | CL |
| 5182/6111 | 25/75 | 9.21 | PMZ of 6111 |
| 5754/6111 | 25/75 | 8.68 | CL |
| 5754/6111 | 50/50 | 8.42 | PMZ of 6111 |
| 6111/6111 | — | 8.20 | CL |
| 5754/6111 | 75/25 | 7.63 | PMZ of 6111 |
| 6022/6022 | — | 7.10 | PMZ |
| 5754/6022 | 25/75 | 6.97 | PMZ of 6022 |
| 6022/6111 | 50/50 | 6.05 | CL |
| 6022/6111 | 75/25 | 6.05 | CL |
| 6022/5182 | 50/50 | 5.79 | PMZ of 6022 |
| 6022/5182 | 25/75 | 5.53 | PMZ of 6022 |
| 5754/6111 | 75/25 | 5.26 | PMZ of 6111 |
| 6022/6111 | 25/75 | 5.26 | PMZ of 6022 |

(a) CL = centerline of fusion zone. PMZ = partially melted zone in HAZ.

### Effect of Composition

Based on results listed in Tables 3 and 4, there is clearly an effect of fusion zone composition on cracking susceptibility. This can be explained in part by variation in the concentration of Si and Mg as a function of dilution. From data originally published by Dowd (Ref. 8) and Singer *et al.* (Ref. 9), for binary Al-Mg and Al-Si alloys, cracking susceptibility reaches a peak at approximately 1.3% wt-% Mg and 0.8 wt-% Si based on nonequilibrium solidification conditions. Pumphrey and West (Ref. 10) have also proposed a cracking susceptibility diagram for aluminum alloys that predicts the highest susceptibility in the range from 0–2.5 wt-% Mg and 0–1.5 wt-% Si, as shown in Fig. 7. The compositions of the dissimilar combinations evaluated in this study have been superimposed on this diagram.

Note 6111 (0.57 wt-% Mg, 0.78 wt-% Si) and 6022 (0.46 wt-% Mg, 1.21 wt-% Si) both lie in the "high" susceptibility range of the diagram while 5754 (2.94 wt-% mg, 0.01 wt-% Si) and 5182 (4.05 wt-% Mg, 0.03 wt-% Si) fall within the "medium"

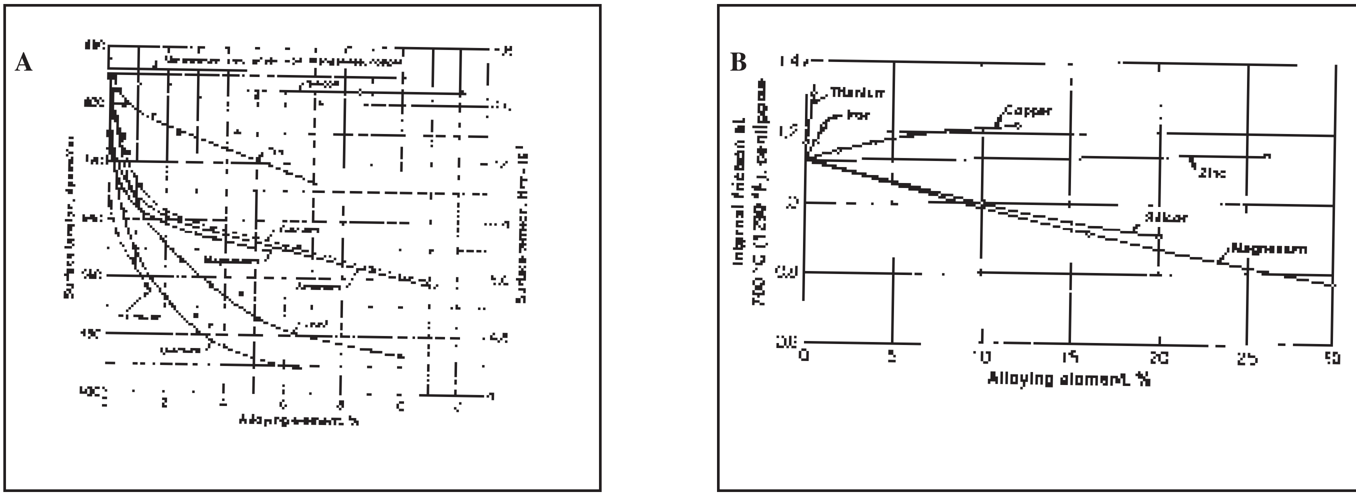



*Fig. 6 — A — Effects of alloy content on the surface tension of aluminum at 700°C in argon (Ref. 7); B — effect of alloy addition on the viscosity of aluminum (Ref. 7).*

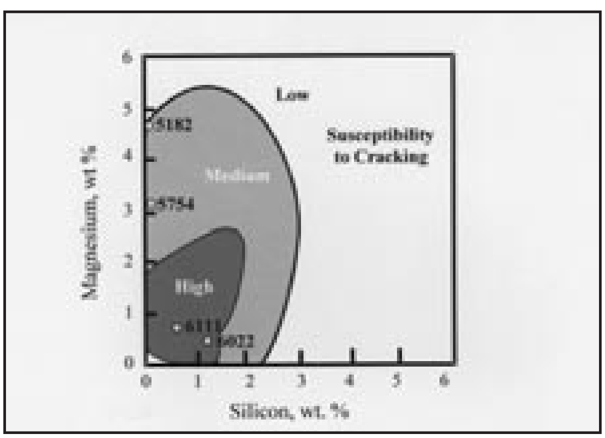



*Fig. 7 — Cracking susceptibility of aluminum alloys containing Mg and Si, with alloys used in this study superimposed (Ref. 10).*

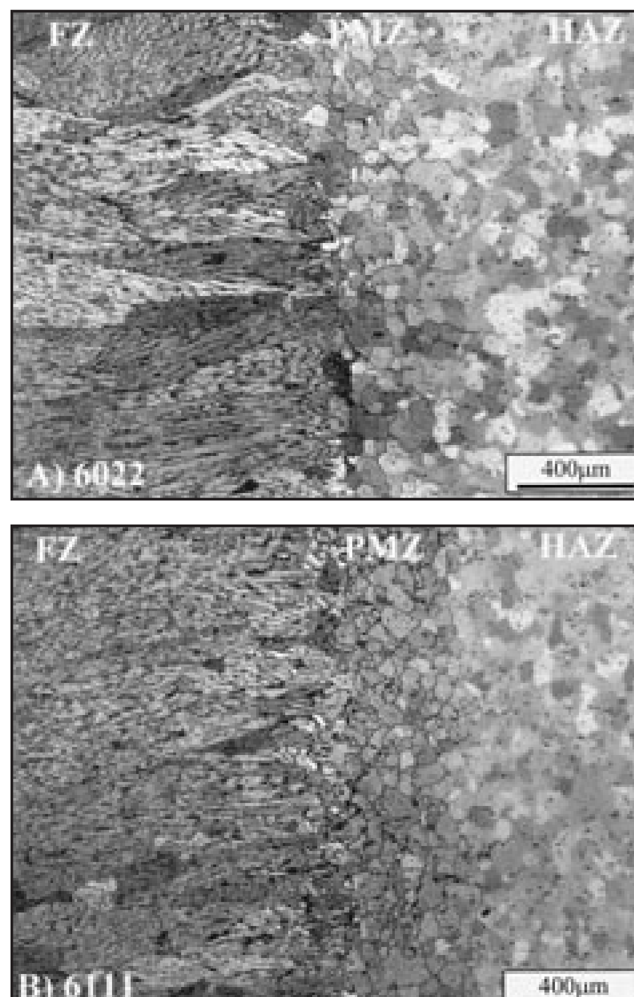



*Fig. 8 — Micrographs showing the PMZ grain size difference between A — 6022; and B — 6111 (Barker's reagent).*

susceptibility. The results of this study support the general behavior predicted by Fig. 7. Combinations of 5754 and 5182 show the lowest susceptibility to cracking, and dilution of 6111 by either 5754 or 5182 tends to improve weld cracking resistance.

Dilution of 6000-series alloys by 5000-series alloys will reduce Si content of the fusion zone and should improve resistance to cracking. This dilution also increases Mg content past the point of the "critical" region as defined by Dowd and Singer. This variation in Mg concentration in the weld zone as a function of dilution with a 5000-series alloy can be shown by drawing a tie line between the two alloys in Fig. 7 and, depending on the dilution, the new relative cracking susceptibility can be predicted for the 5754 and 5182 combinations with 6111. Note in both cases, there is a net improvement in cracking resistance as the Mg content increases (and Si decreases).

As discussed previously, the behavior of 6022 dictated the threshold stress levels in any dissimilar combination. This was attributed to the fact 6022 cracked both in the PMZ and the fusion zone. PMZ cracking can be explained by three factors that contribute to the partial melting of the grain boundaries in the heat-affected zone (HAZ), namely composition, grain size, and solute segregation. As the alloying addition increases, the amount of solute segregation can increase and, therefore, the potential for liquid film formation

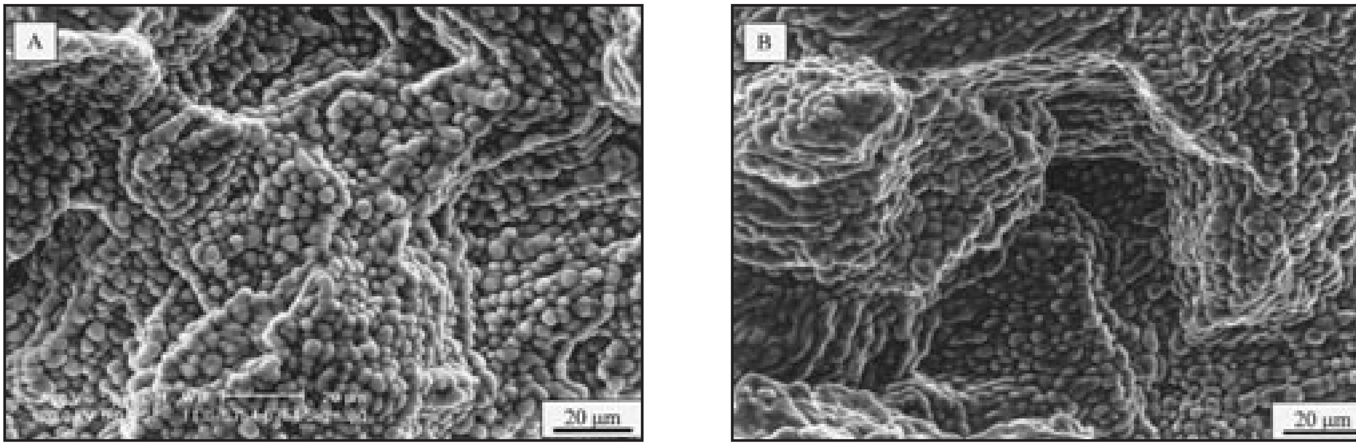
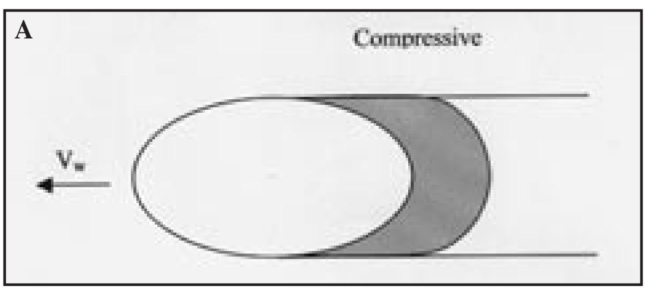



*Fig. 9 — Fracture surface morphology of weld centerline cracking in combinations. A — 5754/6111; B — 5754/5754.*



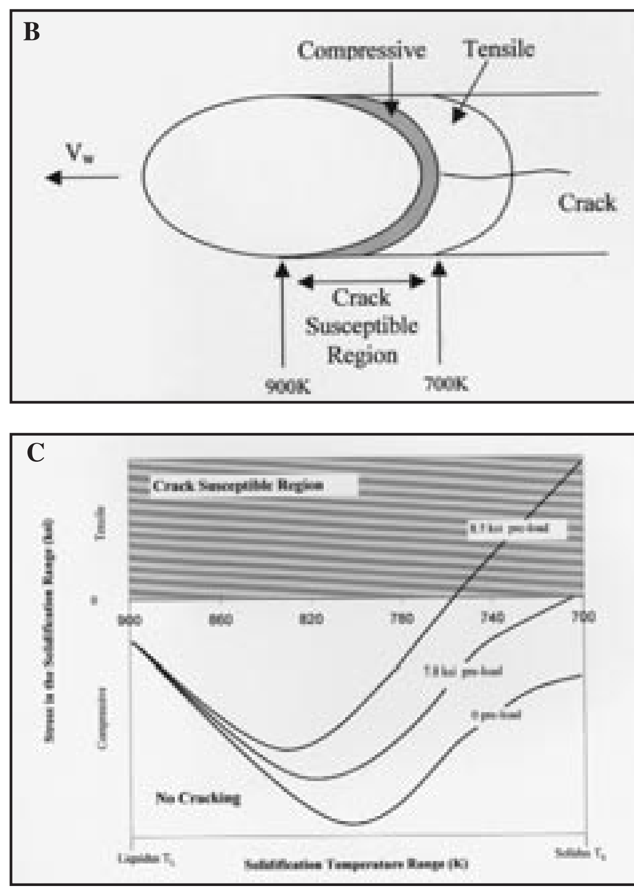




*Fig. 10 — Schematic of stress distribution in Sigmajig samples of aluminum alloy 6111 prestressed at different loads. A — 7.8 ksi prestressed weld that resulted in no cracking; B — 8.5 ksi prestressed weld that resulted in cracking; C — characterization of the stress behind the weld pool for different stress levels applied with the sigmajig.*

increases (Ref. 11). However, the HAZ grain size can have an effect on the amount of liquation along these grain boundaries. It has been proposed (Ref. 11) that for alloys with the same base metal composition but different grain sizes in the HAZ, failure will preferentially occur in the alloy that has the larger grain size. This is due to the fact that less grain boundary area is available when larger grains are present, and the solute segregation of these boundaries can become more concentrated with more liquid film development. Therefore, a base metal with coarser grains is expected to be more susceptible to crack formation in the PMZ.

This is believed to be contributory to preferential PMZ failures in alloy 6022. Using a linear intercept method, the PMZ grain size was determined for both 6111 and 6022. Based on this analysis, alloy 6022 had an average grain diameter of 0.05 mm (~ASTM 5.5), while alloy 6111 had an average grain diameter of 0.03 mm (~ASTM 7).

Figure 8 shows this difference in grain size between the two alloys. The higher silicon content of 6022 relative to 6111 also contributes to the preferential PMZ failures, since silicon segregation to the grain boundaries promotes a local depression in the melting temperature. It should be noted 6111 was not immune from PMZ cracking, as shown in Table 5.

## Fractography

The fracture surfaces of both similar and dissimilar combinations were examined using a scanning electron microscope (SEM). Representative fracture surfaces are shown in Fig. 9. Note both the 5754-5754 and 5754-6111 combinations, and all other combinations that failed in the fusion zone, exhibited a characteristic dendritic fracture morphology typical of weld solidification cracking.

## Practical Implications

This study has clearly shown a composition has a strong effect on the weld solidification cracking susceptibility of dissimilar combinations of aluminum sheet alloys for automotive applications. While the weldability of dissimilar combinations of 5182 and 5754, at all dilution levels, was generally good, it is also significant the cracking resistance of some of the dissimilar 5000- and 6000-series alloys was also good. In general, material combinations and dilutions that pushed composition levels of Mg and Si above the peak for maximum cracking (Fig. 7) had a high resistance to cracking. It would be beneficial to study the compositions of the alloys selected for dissimilar joining to achieve the best weldability based on composition alone.

A complicating factor in the straightforward assessment and quantification of weld cracking susceptibility in these alloys was the tendency for HAZ liquation cracking in the PMZ of the 6000-series alloys. This precluded direct measurement of the weld solidification cracking threshold stress, but identified an issue that is a potential problem when these alloys are welded under moderate restraint conditions.

Another interesting aspect of this study was the behavior of alloy 6111 when welded under "no load" vs. Sigmajig loading conditions. In the "no load" condition, where autogenous, full penetration welds were made at travel speeds of 30 and 55 in./min (12.7 and 23.3 mm/s), centerline solidification cracking would always occur.

However, when the sample was secured in the Sigmajig fixture and loaded below 8.2 ksi, cracking did not occur. Based on the work of Feng *et al.* (Ref. 12), who studied the stress field surrounding the weld pool during Sigmajig testing of Ni-alloys, it appears small tensile loads applied to the sample can alter stresses around the weld pool such that the crack-susceptible region at the trailing edge of the weld pool sees a compressive stress rather than a tensile stress until the preload stresses reach 8.2 ksi. This implies the tensile load normally seen behind the weld pool has been shifted to a compressive stress thus eliminating the initiation of the solidification crack. Using the approach of Feng (Ref. 12), the schematic in Fig. 10 can be used to show this phenomenon.

Although these results seem counterintuitive, they suggest that in certain situations, rigid fixturing and small preloads may actually be beneficial with respect to avoiding weld solidification cracking. More work in this area is needed, but it appears plausible managing the stress fields around solidifying welds through controlled fixturing may be a possible solution to solidification cracking in full penetration welds in sheet materials.

## Conclusions

1. The similar combination of 5182-H16 exhibited the best weld cracking resistance and 6022-T4 the worst using the Sigmajig weldability test.

2. Dissimilar combinations 5182/5754 and 5182/6111 exhibited the best resistance to weld solidification cracking.

3. For a given dissimilar combination, dilution within the range from 25 to 75% did not significantly affect the weld cracking susceptibility.

4. All combinations with 6022 had a low resistance to weld cracking due to preferential failure in the PMZ of the 6022.

5. Nonuniform mixing was observed in the fusion zone of the 6000- to 5000-series alloys resulting from a combination of high travel speeds and differences in viscosity and surface tension.

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