A Simple Test for Solidification Cracking Susceptibility and Filler Metal Effect

While Varestraint testing has long been the most widely used test, a simple, low-cost alternative is available to provide similar and valuable additional information.

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ABSTRACT

Solidification cracking is a serious weld defect, and it is essential to test the susceptibility to this defect. In Varestraint testing, the workpiece is bent suddenly during welding to induce cracking. This causes an unrealistically high deformation rate, and the global deformation rate of the workpiece cannot reveal the local deformation rate of the mushy zone that causes cracking. A simple new test was developed in the present study, where two pieces of materials were welded, while one piece moves normal to the welding direction at the speed \( V \). \( V \) is the lateral tensile deformation rate of the mushy zone that causes solidification cracking. As \( V \) was increased from zero, the transition from no crack propagation to full crack propagation occurred over a range of \( V \), called the transition range. The crack susceptibility is lower if the transition range is located at a higher \( V \) level because a faster deformation rate \( V \) is required to cause crack propagation. It was shown that the \( V \) level of the transition range increased, i.e., the crack susceptibility decreased, in the order of 6061 Al, 7075 Al, 2024 Al, 2014 Al, and 2219 Al, consistent with reported data. The crack susceptibility decreased when 6061 Al and 7075 Al were welded with filler 4043 Al, and 2014 Al and 2024 Al with filler 4145 Al. This is consistent with published filler metal guides and data. The repeatability of the present test and its several significant advantages over the Varestraint test, including the use of a filler metal, were discussed. Because the Varestraint test has long been the most widely used test for solidification cracking, the present test is particularly significant.

KEYWORDS

- Solidification Cracking
- Varestraint Test
- Mushy Zone
- Deformation Rate
- Aluminum Alloys
- Gas Metal Arc Welding (GMAW)
- Filler Metals

Introduction

Cracking inside the fusion zone during solidification is called solidification cracking (Ref. 1). The solidifying weld metal, called the mushy zone, is a weak, semisolid region located between the advancing weld pool and the completely solidified weld metal behind it. The mushy zone tends to shrink because liquid metal shrinks upon solidification due to solidifica tion shrinkage and thermal contraction. The former is caused by the higher density of the solid than the liquid, e.g., 6.6% in the case of Al (Refs. 2, 3), and the latter is associated with the thermal expansion coefficient of the solid metal. However, the mushy zone cannot shrink freely because it is connected to the workpiece. Thus, significant tension can be induced in the mushy zone to cause cracking. According to Novikov (Ref. 4), cracking during solidification is caused by obstructed shrinkage.

The mushy zone is a semisolid consisting of dendritic grains and interdendritic liquid. In welding, these dendritic grains are usually columnar unless the formation of equiaxed dendritic grains is promoted by grain refining. For the purpose of discussion, consider two columnar dendritic grains growing side by side in the welding direction along the centerline of the mushy zone. Tension induced in the transverse direction of the mushy zone is most likely to separate the grains from each other. Near the beginning of the mushy zone (close to the weld pool), grain separation is unlikely to cause cracking because there is plenty of liquid for feeding if the grains begin to separate.

However, near the end of the mushy zone (i.e., near the end of solidification), grain separation is likely to result in cracking because little liquid may be left to feed the grain boundary if it opens up. When cracking does occur, it happens along the grain boundary, and the fracture surface can appear dendritic because the grain boundary liquid is too thin to cover up the dendrite arms. An alloy that maintains a small fraction of liquid over a wide temperature range near the end of solidification is likely to form long, continuous thin liquid films along grain boundaries, making it susceptible to solidification cracking.

Models for Cracking during Solidification

Numerous models or criteria have been proposed for cracking during solidification in castings, including stress-based, strain-based, and strain rate-based models (Ref. 5). Essentially, stress-based models assume a semisolid will crack when tensile stresses exceed its strength. Strain-based models usually assume a semisolid will crack when tensile strains are sufficient to fracture the grain-boundary liquid.
films. It became clear more recently that the strain rate, instead of the actual strain, plays a critical role in solidification cracking. The existence of a critical strain rate above which solidification cracking occurs was confirmed experimentally by Matsuda et al. (Ref. 6) and more recently by Coniglio et al. (Refs. 7, 8).

The classic model of Prokhorov (Ref. 9) focused on the thermomechanical factor of cracking, assuming that cracking can occur if the rate of strain (ε) accumulation with temperature (T) drop, that is, dε/dT, exceeds a critical value during solidification. Matsuda et al. (Refs. 10–12) applied this model to solidification cracking in welds of Al alloys and stainless steels, but the critical dε/dT is difficult to determine accurately. The model of Feurer (Ref. 13), on the other hand, focused mainly on liquid feeding of the shrinking mushy zone. It is an empirical formula based on the assumption that cracking can occur if volumetric shrinkage exceeds volumetric feeding. Nasresfahani et al. (Ref. 14) revised Feurer’s model into another empirical formula by including a uniaxial contraction stress measured during casting.

The RDG criterion of Rappaz, Drezet, and Gremaud (Ref. 15) considered both uniaxial tensile deformation and solidification shrinkage. However, it did not consider the grain boundary, where cracking occurs. Instead, it treats the entire mushy zone as one piece and calculated the pressure distribution in it, assuming cracking (cavitation) can occur when the interdendritic liquid pressure falls below a certain level at the root of the dendrites.

Drezet et al. (Ref. 16), and Coniglio and Cross (Ref. 8) applied the RDG criterion (Ref. 16) to solidification cracking in Al welds. In fact, Coniglio and Cross (Ref. 8) proposed mechanisms for crack initiation and crack propagation. They pointed out that, according to Campbell (Ref. 3), a tensile hydrostatic fracture pressure about 3 × 10^4 atm is needed for homogeneous vapor pore nucleation and 2 × 10^4 atm for a heterogeneous one. Thus, it was concluded that liquid fracture by cavitation is unlikely. Instead, it was suggested that pores form from preexisting pore nuclei.

Kou (Refs. 17, 18) recently considered three factors at the boundary between two columnar dendritic grains growing side by side in the welding direction: 1) lateral separation of one grain from the other under welding-induced tension to cause cracking, 2) lateral growth of the grains toward each other to bond together to resist cracking, and 3) liquid feeding along the grain boundary to keep cracking from occurring. Considering the space in a volume element positioned between the two neighboring grains near the end of solidification, i.e., near (fS)1/2 = 1, Kou (Ref. 17) derived a criterion for cracking to occur during solidification. According to the criterion, if the rate of space increase, due to lateral grain growth, exceeds the rate of space decrease, due to grain separation under tension, minus the rate of space decrease, due to liquid feeding, a void can form in the volume element, that is, a crack can form at the grain boundary. This can occur if crack initiation sites, such as microporosity, folded oxide films, or external surfaces (Ref. 8), are available.

Kou found a simple index to predict the susceptibility to cracking, that is, the steepness |dT/d(fS)1/2| of the curve of T vs. (fS)1/2 near (fS)1/2 = 1, where T is the temperature and fS the fraction solid (Ref. 18). He showed that a high |dT/d(fS)1/2| near (fS)1/2 = 1 causes the following: 1) slow growth of the grains toward each other to bond together to resist cracking, 2) a long liquid channel along the grain boundary to hinder liquid feeding (Ref. 19), and 3) a long liquid channel between the grains to act as a sharp notch to promote crack initiation.

Because the maximum steepness occurs near (fS)1/2 = 1, an option is to use the maximum |dT/d(fS)1/2| as the index for the susceptibility to solidification cracking (Ref. 19). For binary alloys, simple analytical equations describing fS as a function of T can be used to plot the T–(fS)1/2 curve (Refs. 20–23). For multicomponent alloys, several commercial thermodynamics software package and databases are available to do it. The steepness |dT/d(fS)1/2| is the absolute value of the slope dT/d(fS)1/2. It was shown that the index works well for Al alloys, consistent with the crack-susceptibility ranking of commercial Al alloys, the published Al filler-metal guides, and the crack susceptibility curves of binary Al alloys (Refs. 17, 18, 24).

Tests for Solidification Cracking Susceptibility

Numerous tests have been developed to evaluate solidification cracking (Ref. 25). Essentially, three different types of test have been developed to evaluate the susceptibility of welds to solidification cracking. In the first type of test, strain is self-induced; for example, the Houldcroft test (Ref. 26), circular-patch test (Refs. 27–31), ring-casting test (Refs. 11, 32, 33), and cast-pin test (Refs. 34, 35). They can serve as a useful tool for assessing the crack susceptibility, but they do not provide quantitative information, such as the deformation (or strain) or deformation rate (or strain rate) needed to cause cracking.

In the second type of test, deformation (or strain) is applied, before welding starts, to the workpiece normal (Refs. 36–39) or parallel (Ref. 40) to the expected welding direction. In the third type of test, deformation (or strain) is applied to the workpiece during welding. For example, in the Varestraint test (Refs. 41–43), the workpiece is bent suddenly during welding. In the programmable deformation rate (PVR) test (Ref. 44), the workpiece is stretched along the welding direction at an increasing rate. In the variable deformation rate (VDR) test (Ref. 6), the mushy zone is deformed under tension normal to the welding direction. In the controlled tensile weldability (CTW) test (Refs. 7, 8), the workpiece is pulled normal to the welding direction.

The Varestraint test, originally developed by Savage and Lundin (Ref. 41), is shown in Fig. 1. It has been the most widely used test for evaluating the susceptibility to solidification cracking. Welding is conducted by the gas tungsten arc welding (GTAW) process without a filler metal. The standard Al specimen is 203 mm long, 102 mm wide, and 12.7 mm thick. With the use of a pneumatic system, an augmented strain is applied in the welding direction by bending the workpiece suddenly against a curved mandrel during welding. A transverse version of the Varestraint test was subsequently developed by Senda et al.
then removed the weld reinforcement by gas metal arc welding (GMAW), and posited the filler metal in the groove a groove 2 mm deep and 16 mm wide.

Spot welding has also been conducted to evaluate the effect of filler metal on the susceptibility to solidification cracking. The workpiece, usually 12.7 mm thick, is bent suddenly during welding to cause cracking. The workpiece, usually 12.7 mm thick, is bent suddenly during welding to cause cracking. The workpiece, usually 12.7 mm thick, is bent suddenly during welding to cause cracking.

To evaluate the effect of filler metals on the susceptibility of an alloy to solidification cracking, a multistep procedure is required. For example, Lippold et al. (Ref. 45) first machined a groove 2 mm deep and 16 mm wide in a 304 stainless steel plate, then deposited the filler metal in the groove by gas metal arc welding (GMAW), and then removed the weld reinforcement by machining. The specimen prepared by this three-step procedure was then used for Varestraint testing, with GTAW restricted to within the weld made previously by GMAW.

Regarding the Varestraint test, Coniglio (Ref. 46) indicated that the applied strain is global in the workpiece rather than local within the mushy zone and the strain rate is very high. He pointed out measurements revealed actual strain rates in the weld up to 130%/s, far exceeding both the strain rates in real-world welding conditions (less than 8%/s) and the critical strain rate to form a crack (less than 5%/s in arc welded aluminum alloys). He further pointed out in Varestraint testing the weld metal shows significantly higher strains (more than 2%) and strain rates (more than 100%/s) than the applied strain (0.5%) and strain rate (40%/s) calculated based on $\varepsilon = \frac{H}{2R + H} \times 100\%$. Nakata et al. (Ref. 11) subsequently lowered the strain rate, called the slow-bending Varestraint test. The bending speed had to be carefully controlled. However, according to Coniglio (Ref. 46), the global strain in the weld metal still does not represent the local strain in the mushy zone that causes solidification cracking.

Matsuda et al. (Ref. 6) developed the variable deformation rate (VDR) test. A flat plate (160 mm wide, 320 mm long, and 10–15 mm thick) was rotated at a constant angular speed $\omega$ while being welded by GMAW to a vertical plate (60 mm wide, 330–450 mm long, and 10–15 mm thick) on the top to cause solidification cracking. The local deformation rate in the mushy zone $dD/dt = L\omega$, where $D$ was the deformation, $t$ time, and $L$ the distance from the gun to the axis of rotation. $dD/dt$ decreases continually as the welding gun advances and eventually brings the crack to a stop.

The critical deformation rate was $(dD/dt)_{c} = L\omega$, where $L$ was the distance at which the crack stops. Alloys that were more crack resistant showed higher $(dD/dt)_{c}$ values. This suggests that the local deformation (strain) rate played a critical role in solidification cracking. Liquidation cracking was not expected because the partially melted zone is not under tension. Unfortunately, the VDR apparatus is very complicated and seldom used.

More recently, Coniglio and Cross (Ref. 8) developed the controlled tensile weldability (CTW) test. The specimen consists of a smaller sheet (120 mm long, 40 mm wide, and 4 mm, thick) for welding, and two larger plates (each 150 mm long, 300 mm wide, and 8 mm thick) needed to connect the smaller sheet to a horizontal tensile testing machine to pull it normal to the welding direction during GMAW. To measure the deformation (or displacement) and hence transverse strain across the weld, an extensometer was attached underneath the weld at a gauge length of 10.5 mm.

The test was repeated at various crosshead speeds to determine the minimum speed needed to cause solidification cracking, that is, the critical deformation rate, which can be divided by the gauge length (10.5 mm) to become the critical strain rate. 6061 Al was welded with and without filler metal 4043 Al (~Al-5Si). It was shown that the critical strain rate increased with increasing 4043 Al in the weld, which is consistent with the practice of using filler metal 4043 Al to reduce solidification cracking in 6061 Al. The critical strain rate was used to develop models for solidification cracking.

Because an alloy melts over a temperature range, the material in the weld pool was completely melted and the material in the region immediately next to the weld pool was partially melted, with liquid formation (called liquation) along grain boundaries. This region, called the partially melted zone, can crack under tension (called liquation cracking). Except for the ring-casting, cast-pin, and VDR tests, liquation cracking can occur and interfere with solidification cracking. When liquation cracking occurs, the tension is relaxed and solidification cracking can stop. This has been observed, for instance, in the circular-patch test (Ref. 29). As compared to the Varestraint test (Ref. 41), the transverse Varestraint test (Ref. 43) tends to show much less liquation cracking but liquation cracks can still occur (Ref. 42).

In the present study, an attempt was made to develop a simple, low-cost test (requiring no pneumatic system and bending blocks, or a tensile...
testing machine) that could: 1) apply a slow deformation rate during welding to evaluate the susceptibility to solidification cracking, and 2) use filler metals to test their effect on the crack susceptibility. It was intended to apply a local deformation to the mushy zone alone (instead of a global deformation to the entire workpiece) at a slow rate close to that in welding practice (instead of a much higher deformation rate). It was also intended to keep cracking within the mushy zone, without liquation cracking occurring in the adjacent partially melted zone to interfere with the solidification cracking being tested.

**Experimental Procedure**

A new test was developed here. Instead of welding one single piece of material and bending it during welding to induce tension in the solidifying part of the material (as in Varestraint testing), it was decided to weld two pieces of materials while one piece moves in a straight line normal to the welding direction. One such example is welding a lap joint and another is welding a T-joint. In both cases, either one of the two members being joined can move normal to the welding direction.

Figure 2A is a schematic sketch of welding a lap joint between two sheets. During welding, the upper sheet is stationary while the lower sheet moves at speed $V$ normal to the welding direction. This can induce a transverse tensile deformation rate $V = dD/dt$, where $D$ is deformation in the mushy zone.

Figure 2B shows how the lap welding in Fig. 2A can be implemented. The photo shows the arrangement of the workpiece and the gun for GMAW. In order to not block the view of the lap joint, the gun is shown near its ending position instead of starting. The upper sheet was 3.2 mm thick, 152 mm wide, and 51 mm long. The lower sheet was 3.2 mm thick, 102 mm wide, and 127 mm long. In the case of 2014 Al, the thin pure Al cladding on the top and bottom surfaces were milled off to keep them from changing the weld composition.

A steel bar and two steel tabs were used to help prevent distortion of the workpiece during welding as shown in Fig. 2C. Initially, the lower sheet
stuck out of the upper sheet by 19 mm (0.75 in.). The lower sheet, positioned between two Al guide sheets of the same thickness, was moved normal to the welding direction by a 12.7-mm-thick Al plate.

As shown in Fig. 3, the moving plate was mounted on a lead-screw assembly driven by a motor. Because the mushy zone was semisolid, it had little strength. Thus, a small ordinary motor sufficed. For programming purposes, however, a servomotor was used. The control unit was hooked to a computer for both control of the moving speed and data acquisition.

The compositions of the workpiece and filler metals used in the present study are shown in Table 1. Gas metal arc welding was used to lap weld the upper sheet to the lower sheet (other processes might work, as well). This allowed the effect of the filler metal on the crack susceptibility to be evaluated. The welding conditions were as follows: Ar shielding at $3.54 \times 10^{-4}$ m$^3$/s (45 ft$^3$/h), DCEP polarity (direct current electrode positive), 23 V welding voltage, 5.1 mm/s (12 in./min) gun travel speed, 1.2 mm filler metal diameter, 93 mm/s (220 in./min) wire feed speed (except for 7075 wire at 116 mm/s or 275 in./min), and the corresponding welding current was (124–133 A). The gun was tilted 10 deg toward the joint and 10 deg backward (dragging).

To avoid filler metal piling up at the start of the weld, the gun started travelling not after but before arc initiation. The lower sheet also started moving before arc initiation. The servomotor was programmed to move the lower sheet at 1.5 mm/s for a distance up to about 25 mm before making a step change to a lower predetermined constant speed, e.g., 0.4 mm/s. The servomotor was set at a maximum torque of 1 Nm (Newton meter). Crack initiation always occurred at 1.5 mm/s. The servomotor automatically stopped when crack propagation stopped.

During the present study, the servomotor was also programmed such that the pushing speed of the lower sheet decreased from 1.5 mm/s step by step, for instance, 0.6, 0.4, and 0.2 mm/s during one welding experiment. It was anticipated that this would determine the critical deformation rate in one single experiment. However, the critical deformation rate determined by this multispeed procedure was not always consistent. Thus, the simple, two-speed procedure was adopted in the present study. If the crack initiated at the beginning failed to propagate, the moving speed of the lower sheet was raised to a higher level in the following experiment.

After welding, the fracture surface of the fusion zone was examined to confirm its dendritic feature characteristic of solidification cracking. Welds made with nonmatching filler metals were cut in the transverse cross section, polished, and etched with Keller’s etching solution (5 mL HNO$_3$, 3 mL HCl, 2 mL HF, and 190 mL distilled water) to reveal the fusion boundary. The composition of the weld metal was calculated based on the transverse cross section of the weld and the compositions of the workpiece and the filler metals. Let $A_U$, $A_L$, and $A_F$ be the areas in the weld transverse cross section that represent the contributions to the weld metal from the melted upper sheet, lower sheet, and filler metal. The so-called dilution $D$, that is, the volume fraction of the melted base metal in the weld metal, is as follows:

$$D = \frac{(A_U + A_L)}{(A_U + A_L + A_F)}$$ (1)
Assuming complete mixing in the weld pool as an approximation, the composition of the weld was calculated using the following equation (Ref. 1):

\[ (\text{wt-% E})_{\text{weld}} = D \times (\text{wt-% E})_{\text{work}} + (1 - D) \times (\text{wt-% E})_{\text{filler}} \]  

where \((\text{wt-% E})_{\text{weld}}\), \((\text{wt-% E})_{\text{work}}\), and \((\text{wt-% E})_{\text{filler}}\) are the wt-% of element E in the weld metal, workpiece, and filler metal, respectively.

**Results and Discussion**

Figure 4 shows an example of the overview of the workpiece after testing. It shows 6061 Al welded at the travel speed of 5 mm/s with filler metal 4043 Al and the lower sheet moving at 0.55 mm/s. As shown, the crack is wider in the initial 25 mm of the weld because, as already mentioned, the lower sheet moved at 1.5 mm/s in the initial 25 mm weld length to ensure crack initiation. No significant distortion was observed in this or any other workpiece after welding.

Figure 5 shows the fracture surface of the fusion zone of a weld made by lap welding 6061 Al with 6061 Al as the filler metal. The location of the fracture surface in the weld is shown in Fig. 5A. As shown by the SEM images in Fig. 5B and C, dendrites are visible on the fracture surface. This confirms cracking occurred during solidification, that is, solidification cracking.

**Matching Filler Metals**

Figure 6 shows the test results of 6061 Al welded with 6061 Al as the filler metal. The normalized crack length is plotted against the deformation rate of the mushy zone. Because the welds were close to each other in length but not identical, it is more convenient to discuss the experimental results based on the normalized crack length than the crack length itself. As illustrated in Fig. 4B, the normalized crack length is \( L_{\text{crack}} / L_{\text{weld}} \), where \( L_{\text{crack}} \) and \( L_{\text{weld}} \) are, respectively, the crack length and weld length corresponding to the deformation rate.

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<th>Table 1 — Compositions of Materials</th>
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<td>Si</td>
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at which crack propagation was tested.

A blue curve is drawn to best fit the data points in Fig. 6. As shown, the normalized crack length increases from 0 at about \( V = 0.06 \text{ mm/s} \) to 1.0 at \( V = 0.21 \text{ mm/s} \). Hereinafter, the range of \( V \) over which the normalized crack length increases from 0 to 1.0 will be called the transition range. Thus, for 6061 Al welded with 6061 Al as filler, the transition range is 0.06–0.21 mm/s under the welding conditions involved here.

Similar test results are shown in Figs. 7–10 for alloys 7075 Al, 2024 Al, 2014 Al, and 2219 Al. It should be pointed out that filler 2319 Al is known as a matching filler metal of alloy 2219 Al, similar in composition except for a slightly higher Ti content of about 0.15 wt-% intended for grain refining (which can reduce the susceptibility to solidification cracking).

Figure 11A summarizes the transition ranges of the five Al alloys shown in Figs. 6–10. As shown, the level of the deformation rate \( V \) required for the transition from no crack propagation to full crack propagation to occur increases in the order of 6061 Al, 7075 Al, 2024 Al, 2014 Al, and 2219 Al. This means the difficulty for the transition to occur increases in the same order. Thus, the crack susceptibility should decrease in
the same order. This order is consistent with the author's data (Ref. 47) and the data reported by previous investigators shown in Fig. 11B (Refs. 48, 49).

Alloy 2219 Al appears to have a significantly lower crack susceptibility than other alloys. This difference can be seen in both Fig. 11A and B but is clearer in the former. One possible explanation for this difference is that the relatively high Ti content of filler metal 2319 Al can make grains smaller to reduce the crack susceptibility (Refs. 1–3). More microstructural analysis is needed to confirm it. It is worth mentioning that the present test has also been conducted successfully with autogenous GTAW (Ref. 47), and the results are similar to those in Fig. 11A, but the difference between 2219 and other alloys is significantly less than that in Fig. 11A. This smaller difference supports the effect of high Ti in 2319 Al.

Before moving on from this section, it is worth pointing out that Matsuda et al. (Refs. 10, 11) observed a strain rate of 0.6–5.3% per second across the weld width in GTAW of Al sheets. The deformation rate in Figs. 6–10 ranges from 0.0 to 1.0 mm/s. This range of the deformation rate can be divided by the width of the weld, which is on the order of 10 mm, to obtain a range of strain rate from 0.00 to 0.10 per second or 0 to 10% per second. Thus, unlike Varestraint testing, the proposed test for the susceptibility to solidification cracking can cover the realistic range of deformation or strain rate realistic in actual welding.

It is also worth pointing out that the results in Figs. 6–10 demonstrate clearly the importance of deformation or strain rate. Below a critical rate, cracking cannot even propagate. This is consistent with the criterion for solidification cracking proposed by Kou (Ref. 17). That is, two neighboring columnar dendritic grains growing side by side can grow toward each other and bond together to resist cracking if they are being separated from each other by tension too slowly.

Nonmatching Filler Metals

Figure 12 shows the transverse cross section of the weld shown previously in Fig. 4. The transverse macrograph was taken near the end of the crack. The areas denoted by $A_o$, $A_c$, and $A_p$ represent, respectively, contributions to the weld metal from the upper sheet, lower sheet, and filler metal that were melted and mixed thoroughly to form the weld. These areas can be calculated using commercial computer software. The small areas occupied by cracks are not included in the areas. As shown in Eq. 1, areas $A_o$, $A_c$, and $A_p$ can be used to de-
termine the dilution of the filler metal by the melted workpiece, \( D \). The composition of the weld metal can be calculated based on \( D \) and the compositions of the workpiece and the filler metal using Eq. 2. Using the weld in Fig. 12 as an example, the dilution is 47.8%. Based on this dilution and the compositions of the workpiece and the filler metal, the weld metal composition was calculated using Eq. 2 and is shown in Table 2.

Figure 13 shows the test results of welding 6061 Al with 4043 Al as a nonmatching filler metal, which is a commonly used commercial filler metal. The normalized crack length is plotted against the deformation rate \( V \), and the data points are best fitted with the blue curve. The highlighted range of the deformation rate \( V \) is the transition range. The transition is from no crack propagation at \( V = 0.43 \text{ mm/s} \) to full crack propagation at \( V = 0.60 \text{ mm/s} \). Similar results are shown in Fig. 14 for welding 7075 Al with filler metal 4043 Al, Fig. 15 for welding 2024 Al with filler metal 4145 Al, and Fig. 16 for welding 2014 Al with filler metal 4145 Al.

The test results in Figs. 13–16 for welds made with nonmatching filler metals are summarized in Fig. 17. For comparison, the test results of welds made with matching filler metals are also included. As shown, the transition range is at a significantly higher level of \( V \) in welding 6061 Al with 4043 Al as the filler metal than with 6061 Al. In other words, with filler metal 4043 Al, the deformation rate \( V \) has to be raised significantly before crack propagation can occur, that is, the crack susceptibility of 6061 Al is reduced significantly by filler metal 4043. This is consistent with filler metal guides, which recommend 4043 Al for reducing solidification cracking in welding 6061 Al (Refs. 48, 49).

The transition range is also at a significantly higher \( V \) level in welding 2014 Al with 4145 Al as the filler metal.
than it is with 2014 Al. Thus, the crack susceptibility of 2014 Al is reduced significantly by filler metal 4145 Al. This is consistent with filler metal guides, which recommend 4145 Al for reducing solidification cracking in welding 2014 Al (Refs. 48, 49). The effect of filler metal 4145 Al on 2024 Al is similar.

As also shown in Fig. 17, in welding 7075 Al, the transition range is at a higher V level with 4043 Al as the filler metal than with 7075 Al though the difference is not as much as in the case of 6061 Al. The reduction of the crack susceptibility of 7075 Al by filler metal 4043 Al is consistent with the data reported by previous investigators (Refs. 50, 51).

**Effect of Travel Speed**

Figure 18 shows the results of welding 6061 Al with a matching filler met-
al at the gun travel speed of 10 mm/s. The transition range of 0.20–0.30 mm/s here is higher than that of 0.06–0.21 mm/s at the gun travel speed of 5 mm/s (see Fig. 6). This indicates that the crack susceptibility is lower at 10 mm/s than at 5 mm/s. Because the heat input was not changed, the mushy zone became smaller at 10 mm/s travel speed than 5 mm/s. This can explain the lower crack susceptibility at 10 mm/s than at 5 mm/s. However, the experiments were not conducted by increasing the gun travel speed alone, which could also change the deformation rate of the mushy zone. Instead, the deformation rate \( V \) was still imposed on the mushy zone when the travel speed was doubled. This allows the effect of travel speed to be compared under the same deformation rate and hence explained based on Kou’s criterion for cracking during solidification (Ref. 17). Consider two neighboring columnar grains growing along the centerline of the mushy zone.

Three key factors need to be considered: 1) lateral deformation rate separating the grains to cause cracking, 2) lateral growth rate of grains toward each other to bond together and resist cracking, and 3) liquid feeding rate of the grain boundary. Under the same tensile deformation rate \( V \), increasing the travel speed would increase the cooling rate (and reduce the mushy zone) to help grains bond together earlier to resist cracking. However, it is not intended here to imply that increasing the welding speed will always reduce the susceptibility to solidification cracking. It is likely that increasing the welding speed significantly may cause other significant changes, e.g., the pool shape, solidification structure, and so on, to change the crack susceptibility.

Repeatability of the Present Test

The repeatability of the present test can be explained as follows: First, the normalized crack length was plotted against the deformation rate \( V \) in ten different cases. In all cases, a distinct transition range was observed. Furthermore, the location of the transition range on the \( V \) axis, that is, the \( V \) level of the transition range, can be determined accurately. On the average, eight data points (eight samples) per

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<td><strong>Varestraint Test</strong></td>
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<td>solidification cracking susceptibility</td>
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<td>use of filler metal to test its crack reduction</td>
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<td>deformation imposed</td>
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<tr>
<td>deformation rate</td>
</tr>
<tr>
<td>crack susceptibility index</td>
</tr>
<tr>
<td>crack initiation and crack propagation</td>
</tr>
<tr>
<td>interference by liquation cracking</td>
</tr>
<tr>
<td>mechanical devices required</td>
</tr>
<tr>
<td>equipment cost</td>
</tr>
<tr>
<td>workpiece material required</td>
</tr>
</tbody>
</table>

**Table 2 — Composition of Weld in wt-% Made by Welding 6061 Al with 4043 Al (Fig. 12)**

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Ni</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece 6061</td>
<td>0.72</td>
<td>0.6</td>
<td>0.33</td>
<td>0.08</td>
<td>1.0</td>
<td>0.20</td>
<td>–</td>
<td>0.10</td>
<td>0.02</td>
<td>balance</td>
</tr>
<tr>
<td>Filler 4043</td>
<td>5.0</td>
<td>0.80</td>
<td>0.30</td>
<td>0.05</td>
<td>0.05</td>
<td>–</td>
<td>–</td>
<td>0.10</td>
<td>0.20</td>
<td>balance</td>
</tr>
<tr>
<td>Weld (47.8% dilution)</td>
<td>2.79</td>
<td>0.70</td>
<td>0.31</td>
<td>0.06</td>
<td>0.50</td>
<td>0.10</td>
<td>–</td>
<td>0.10</td>
<td>0.11</td>
<td>balance</td>
</tr>
</tbody>
</table>
case would be sufficient for this. With more experiments conducted to add more data points, the location of the transition range on the V axis would not change significantly. The width of the transition range can be affected, but this is not important because the crack susceptibility is affected by the V level of the transition range, not by its width. As mentioned previously, the higher the V level of the transition range is, the lower the crack susceptibility becomes.

**Comparison with Varestraint Testing**

Figure 19 summarizes the differences between the test developed in the present study and the Varestraint test (Ref. 41). Both tests can evaluate the susceptibility to solidification cracking. However, the present test can provide valuable additional information, such as the effect of the filler metal on the crack susceptibility and the local deformation rate in the mushy zone. The latter is responsible for solidification cracking, and it can be useful information, for instance, in verifying the computer simulation of solidification cracking. The global deformation rate of the workpiece in the Varestraint test differs significantly from and does not reveal the local deformation rate in the mushy zone.

Unlike the Varestraint test, the present test can apply slow deformation or strain rates realistic for welding, ensure crack initiation before testing crack propagation, and keep liquidation cracking from interfering with solidification cracking. The present test is simple and inexpensive, and it requires only a relatively small workpiece.

The authors have demonstrated the use of autogenous GTAW in the new test. The repeatability is better than that with GMAW. Since plenty of results have already been presented here, the results of the autogenous GTAW was submitted for publication elsewhere (Ref. 47).

**Summary and Conclusions**

1) A new methodology for testing solidification cracking has been developed, that is, welding two pieces of materials while one piece moves in a straight line normal to the welding direction at the speed V. This methodology is useful because V is the lateral tensile deformation rate of the mushy zone that causes solidification cracking.

2) The range of V over which the transition from no crack propagation to full crack propagation occurs can be determined by plotting the normalized crack length against V.

3) In all the ten different cases considered in the present study, a distinct transition range was observed. In each case, about eight data points were sufficient to show clearly the location of the transition range on the V axis, i.e., the V level of the transition range. The width of the range was not as clear, but this is not important.

4) A transition range located at a higher level of V indicates a lower crack susceptibility because a faster deformation rate V is required to cause crack propagation, that is, crack propagation is more difficult.

5) The V level of the transition range increases, that is, the crack susceptibility decreases, in the order of 6061 Al, 7075 Al, 2024 Al, 2014 Al, and 2219 Al, consistent with reported data.

6) The V level of the transition range increases, that is, the crack susceptibility decreases, when 6061 Al and 7075 Al are welded with filler metal 4043 Al, and 2014 Al and 2024 Al with filler metal 4145 Al, consistent with published data and filler-metal guides.

7) The present test has the following significant advantages over the Varestraint test: It can allow the use of filler metals to evaluate their significant effect on solidification cracking, impose slow deformation rates as those in welding practice, reveal the local deformation rate in the mushy zone that causes cracking, determine the transition range for crack propagation, keep liquidation cracking from interfering with tests of solidification cracking, and significantly reduce the costs of both the apparatus and the workpiece material.

8) Because the Varestraint test has long been the most widely used test for studying the important subject of solidification cracking, the present test is particularly significant.

**Acknowledgments**

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**References**