

Susceptibility of Aluminium Alloys to Solidification Cracking: Testing and Prediction

By

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Dedicated to my wife and my daughter,
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Abstract

Solidification cracking is a serious weld defect in welding aluminum (Al) alloys. It occurs in the mushy zone (a small weak semisolid immediately behind the weld pool) when the critical strain rate of the mushy zone is exceeded. Most tests for evaluating the solidification cracking susceptibility cannot determine the critical strain rate of the mushy zone. In the present thesis, welding of Al alloys was studied using a new test for evaluating the crack susceptibility and a new index for predicting the crack susceptibility. The test, called the transverse motion weldability (TMW) test, was developed. This test is unique in that a stationary upper sheet is lap-welded to a lower sheet moving slowly at the speed V in the transverse direction of welding to induce transverse tensile strain and hence cracking in the mushy zone. Cracking occurs when a critical V , i.e., V_c , is exceeded. The TMW test showed that the susceptibility to solidification cracking increased in the order of 2219 Al, 2014 Al, 2024 Al, 7075 Al and 6061 Al. This ranking is consistent with that based on other tests. It is also consistent with that predicted based on the crack susceptibility index, which is the maximum $\left| dT/d(f_s)^{1/2} \right|$ (where T is temperature and f_s fraction of solid). The test was also used to see how effective Al filler metals reduce the crack susceptibility of Al alloys. The effectiveness observed agreed with that reported previously, shown in filler-metal guides, and predicted based on the index. To determine the local strain rate in the mushy zone near the crack, a new approach based on the TMW test and the weld microstructure was developed. Crack susceptibility of commercial wrought aluminum alloys were explained to provide a better understanding for solidification cracking.

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1. INTRODUCTION AND BACKGROUD

Solidification cracking, known as hot cracking phenomena in welds (Ref. 1), is a serious weld defect. This cracking also occurs in casting, called hot-tearing. Alloys are more prone to solidification cracking than the pure metals. When an alloy is welded, it tends to contract during solidification due to solidification shrinkage and thermal contraction. However, it cannot freely contract when the semi-solid metal, mushy zone, is constrained (self-constraints or clamps). A tension is induced in the mushy zone by the restricted contraction of the alloy and this causes solidification cracking. Solidification cracks involve an interaction between metallurgical (solidification temperature range, amount and distribution of liquid during terminal solidification, ductility of solidified weld etc.) and mechanical (contraction stresses and degree of restraint) factors which are driven by the temperature gradients (Refs. 2, 3).

Cracking models and tests have been used to study solidification cracking (Ref. 4). Most recently, Kou proposed a simple criterion to explain three factors playing an important role during solidification cracking: separation of grains due to tensile stresses to cause cracking; grain growth toward each other to bond and resist cracking; and liquid feeding along the grain boundaries to resist cracking (Ref. 5). Kou also proposed to use a simple index, that is maximum $\left| dT/df_s \right|^{1/2}$ where T temperature and f_s fraction solid, to predict susceptibility of Al alloys to solidification cracking (Ref. 6).

The solidification cracking tests have been used to investigate susceptibility of the alloys. In such cracking tests, the contraction of the workpiece is restricted with either certain welding design and/or applied external force to induce tension in the mushy zone and cause cracking. Some of these cracking tests are criticized for applying global strains rather than localized strains in the

mushy zone, employing higher deformation or strain rates than the ones observed in actual welding conditions, and having a complicated test apparatus.

A simple cracking test, named transverse motion weldability (TMW) test, has been developed to assess susceptibility to solidification cracking and as an alternative to the other cracking tests with a simple test apparatus. The developed test only applies deformation or displacement to the mushy zone in which solidification cracking occurs. Thus, liquation cracking, another type of hot crack occurring in heat affected zone, is not likely to occur and it has never been observed in the conducted tests. The applied displacement rates are not too high. The test can also be useful to computer modeling of solidification cracking by providing quantitative test results such as displacement and strain rates. It is worth to mention that the word of “deformation” has been recently found inappropriate for the mushy zone, thus the word of “displacement” is used instead.

The cracking test has also been used to check the validity of Kou’s cracking index (Ref. 6) for predicting solidification cracking susceptibility of Al alloys. The capability of employing both gas tungsten arc welding (without using filler metal) and gas metal arc welding in the test allowed to study the susceptibility of workpiece to solidification cracking and filler metal effect on solidification cracking. Thus, the test allowed checking the predictions made with the cracking index for Wrought Al alloys and the filler metal effect.

Characteristics of solidification cracking, and models and tests developed for cracking during solidification will be reviewed in this chapter to provide a better understanding.

1.1. Characteristics of Solidification Cracking

Cracking can occur during solidification and it is called hot tearing in casting (Refs. 7, 9) and solidification cracking in welding (Ref. 2). Some of the well-known susceptible alloys to cracking

during solidification are Al alloys, stainless steels and Ni-based alloys. Fig. 1.1 shows an example of solidification cracking in 6061 Al alloy welded by gas-metal arc welding (Ref. 2).

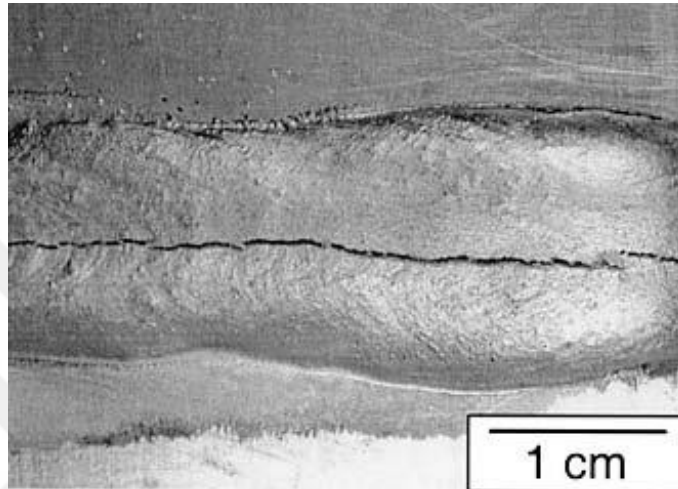


Fig. 1.1 Solidification cracking in 6061 Al weld made by gas-metal arc welding (Ref. 2)

As can be seen in Fig. 1.2, solidification cracking occurs along grain boundaries, that is, intergranular cracking (Ref. 9). The cracks caused by both hot tearing and solidification cracking have clear dendritic fracture surfaces. Fig. 1.3 (Ref. 10) illustrates fracture surface of hot tearing in 5182 Al alloy.

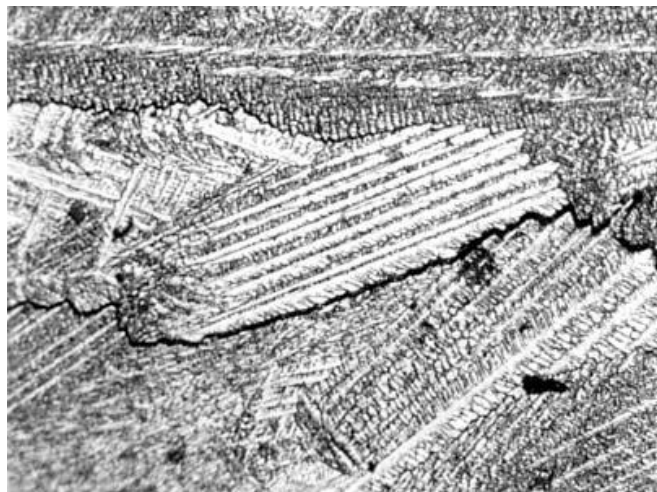


Fig. 1.2 Solidification cracking in a bead-on-plate weld of 7075 Al made by gas-tungsten arc welding (Ref. 9)

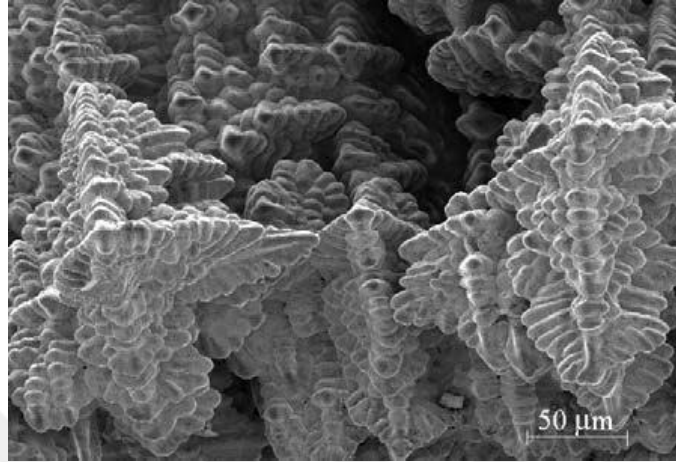


Fig. 1.3 SEM image showing a dendritic fracture surface of hot tearing in 5182 Al (Ref. 10)

1.2. Theories for Solidification Cracking

The recent theory proposed by Kou (Ref. 5) was applied to Al alloys (Refs. 6, 11-15) will be reviewed first. Kou considered three key factors in cracking during solidification and these factors may provide the common basis to understand the previous theories to be reviewed subsequently. Kou explained his theory (Ref. 5) using ring casting test (Ref. 15), which has been used to assess the susceptibility of alloys to cracking during solidification in both casting and welding. As shown in Fig. 1.4a, the mold for ring casting test consists of three parts: a core, a ring and a bottom piece (Ref. 15). The melt (liquid alloy) is poured into the open annulus between the core and the ring of the mold. Solidification shrinkage and thermal contraction cause the alloy to contract as it cools and solidifies because the higher density of the solid metal than that of the liquid metal causes metals to contract during solidification. For example, solidification shrinkage can be as high as 6.6% for Al alloys (Ref. 7). The core of the mold obstructs free contraction of the solidifying metal in the radial direction r . This induces a severe contraction in the circumferential direction θ which is the normal stress $\sigma_{\theta\theta}$. This tension causes to crack initiation at the core surface and the cracks can propagate in the radial direction as shown in Fig 1.4b.

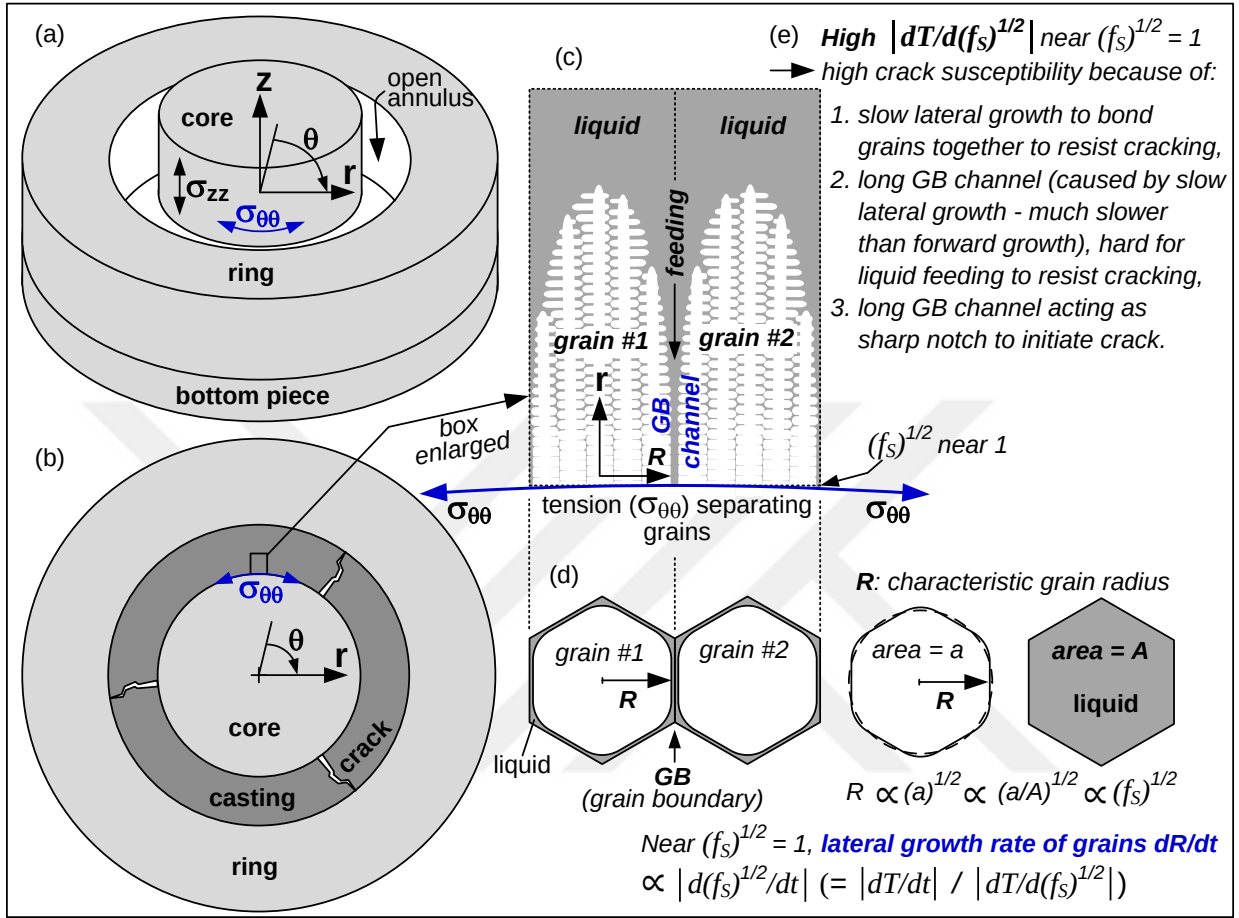


Fig. 1.4 Crack-susceptibility index and ring casting test mold with three pieces: core, ring and bottom piece (Ref. 15): (a) the tensile stresses $\sigma_{\theta\theta}$ and σ_{zz} shown at core surface of ring casting test (solidifying metal is not shown for a clear view); (b) top view of mold with solidifying metal illustrating radial tears caused by $\sigma_{\theta\theta}$; (c) longitudinal cross-sections of two columnar grains, the boxed area in (b), growing in the radial direction from the core surface; (d) transverse cross-sections of the grains in (c) near $(f_s)^{1/2} = 1$ (near end of solidification) where f_s is fraction solid; (e) the crack susceptibility index $|dT/d(f_s)^{1/2}|$ near $(f_s)^{1/2} = 1$ and causes of high crack susceptibility

It is worth to mention that another tension can also develop in the axial direction z , that is, the normal stress σ_{zz} , as shown in Fig 1.4a, especially when the annulus of the mold between the ring and core is very deep. This tension can contribute to the crack initiation at the core surface as well.

Fig 1.4c shows that two columnar grains growing in the radial direction r from the core wall and

the tension along the circumferential direction separates the grains from each other to cause cracking. The rest of the figure will be discussed subsequently.

Kou's criterion (Ref. 5) proposed for cracking during solidification will be explained next using Fig. 1.5 (Ref. 6). The longitudinal cross-section of two columnar dendritic grains growing side by side in the axial direction z is shown in Fig. 1.5a. ϕ is the grain spacing. R , the characteristic radius of the growing grains, is a function of z , that is, $R(z)$. These grains can be considered as the grains at the centerline of the mushy zone, where cracking most often occurs during welding. By assuming grain #1 stationary and grain #2 moving to right at the velocity of V_{local} , they are being separated by local tensile deformation at V_{local} in the transverse direction. This tensile deformation can be either self-induced due to solidification shrinkage and thermal contraction, as depicted in Fig. 1.4, or applied with an external force. The transverse cross-section of the grains is shown in Fig. 1.5b. To analyze the susceptibility to solidification cracking a control volume Ω between the two grains is considered. Fig. 1.5c shows the volume element Ω with three significant factors that affect cracking during solidification: 1. separation of the grains in lateral direction by the local deformation V_{local} causes cracking by increasing the space in Ω , 2. the growth of the grains toward each other with the rate of dR/dt to bound together resists cracking by decreasing the space in Ω , 3. liquid feeding with the velocity v_z along the grain boundary resists cracking with the net volume liquid flow rate (flow rate into Ω minus flow rate out of Ω). If the rate of space increase in Ω due to the separation of grains is greater than the rate of space decrease in Ω due to the growth of grains and net volume of liquid feeding flow rate, formation of a void occurs to cause cracking. Kou also derived a mathematical expression for his criterion for cracking during solidification (Ref. 5).

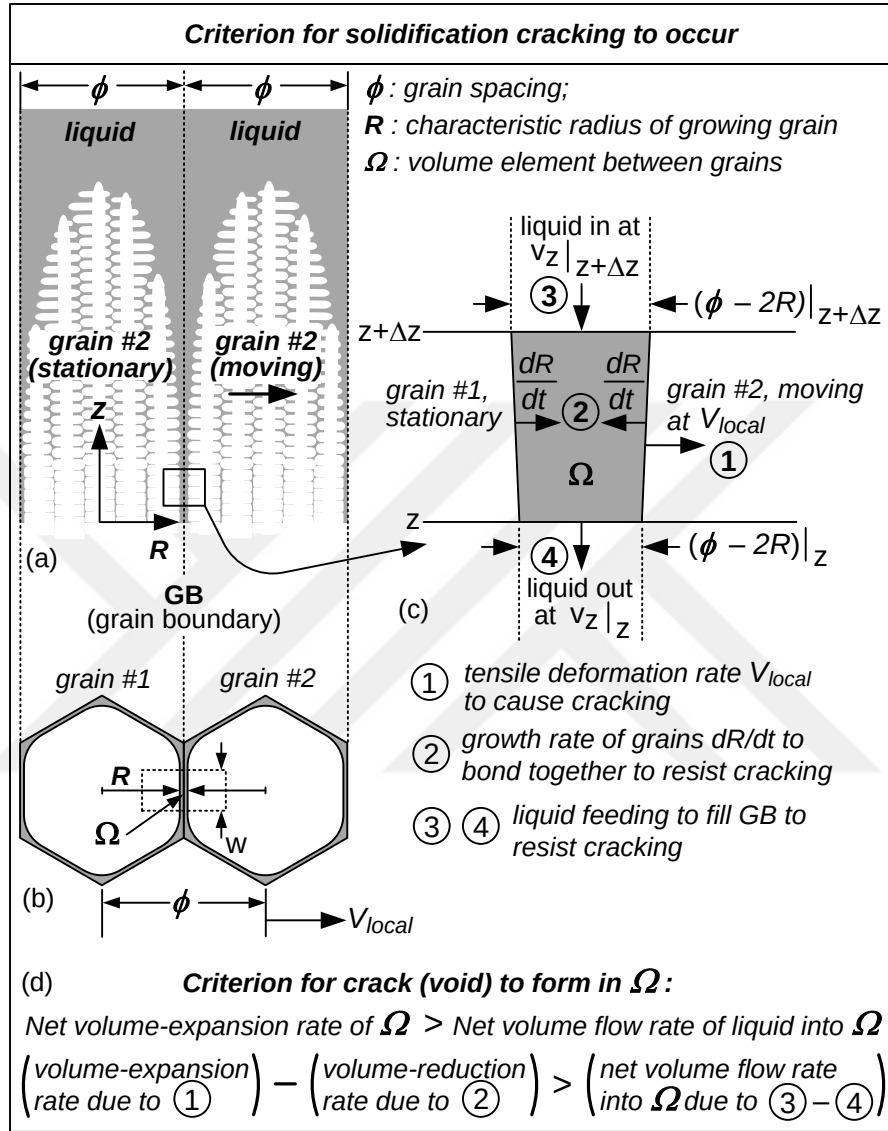


Fig. 1.5 Kou's criterion for solidification cracking explained (Ref. 6): (a) longitudinal cross-section of columnar dendritic grains in the mushy zone; (b) transverse cross-section of the grains in (a); (c) volume element Ω (shaded) for space between the grains in (a) explaining three factors in the cracking mechanism; (d) criterion for cracking to occur

In welding, solidification cracking is caused by obstructed contraction of the mushy zone which is located between the advancing weld pool and the solidified weld metal. In ring casting test, the presence of the core causes the obstructed contraction. The obstructed contraction in welding is caused by the fact that the mushy zone is hindered by the workpiece, which is much

larger and more rigid than the mushy zone. If the workpiece is constrained by clamps, the obstructed contraction of the mushy zone can be worse.

It is also worth to mention that solidification cracking occurs during the terminal stage of solidification. A small amount of little liquid is left at the terminal stage of solidification to feed the grain boundaries if the grain boundaries keep opening under the induced tension by obstructed contraction. At earlier stages of solidification, however, there is more liquid to feed the grain boundaries and there are wider grain boundary channels thus solidification cracking is unlikely.

Lippold (Ref. 16) reviewed five previous solidification cracking theories or models including the shrinkage-brittleness theory of Pumphrey and Jennings (Ref. 17), the strain theory of Apblett and Pellini (Ref. 18), the generalized theory of Borland (Ref. 19), the modified generalized theory of Matsuda et al. (Ref. 20), and the technological strength theory of Prokhorov (Ref. 21). The shrinkage-brittleness theory suggests that grains bridge by interacting with each other and form a coherent rigid network at the so-called “coherency temperature”; and cracking can only occur after formation of the solid-solid bridging in which strain can accumulate in the structure. Lippold (Ref. 16) indicated that there is usually no such evidence showing solid fracture on the fracture surface of a solidification crack to support the theories such as the shrinkage-brittleness theory (Ref. 17) and the theory of Borland (Ref. 19). Alternatively, Apblett and Pellini (Ref. 18), in the strain theory, considered that thin intergranular liquid films separate the grains from each other when cracking occurs at the terminal stage of solidification. Lippold (Ref. 16) pointed out that the strain theory is consistent with the typical smooth dendritic fracture surfaces of solidification cracking, however, the theory does not consider the concept of crack healing during solidification. He found Prokhorov’s theory (Ref. 21) useful for explaining the ductility/strain contribution, however, the

theory does not address the metallurgical factors or the fracture aspect of cracking during solidification.

In addition to the theories mentioned above, Rappaz, Drezet and Gremaud developed a model, known as RDG model, for hot tearing in casting (Ref. 22), and this model has been applied to welding as well. The RDG model has been considered the first model for hot tearing with a physically sound basis. As can be seen in Fig. 1.6a, both tensile deformation and liquid feeding were considered to compensate the mass balance. However, it misses the consideration of the growth of grains toward each other to bond together and resist cracking.

The pressure change of the interdendritic liquid is schematically shown in Fig. 1.6b. Near the dendrite tips the pressure is at the level of metallostatic pressure (p_m) and this drops down to cavitation pressure (p_c) near the dendrite roots. It was assumed that a void may form to cause cracking if the pressure falls below the cavitation pressure of 2 kPa (0.02 atm). Drezet et al. (Ref. 23) studied the applicability of the RDG model on solidification cracking in Al alloys by presenting a 2D granular model as a solution for the problem with the definition of the coherency point in low concentration alloys. Coniglio et al. (Refs. 24, 25) also reviewed the RDG model for solidification cracking in Al welds but they stated that a very high pressure, 10^3 to 10^4 atm (Refs. 8), is required for the cavitation to occur. Therefore, they proposed a porosity-based model for the crack initiation suggesting that pores form from preexisting pore nuclei instead of forming by cavitation due to the pressure drops (Refs. 24, 25). A crack growth model was also proposed for Al alloys to relate the crack growth rate to the local strain rate, but the model could not extend to the different compositions of the alloys (Ref. 25).

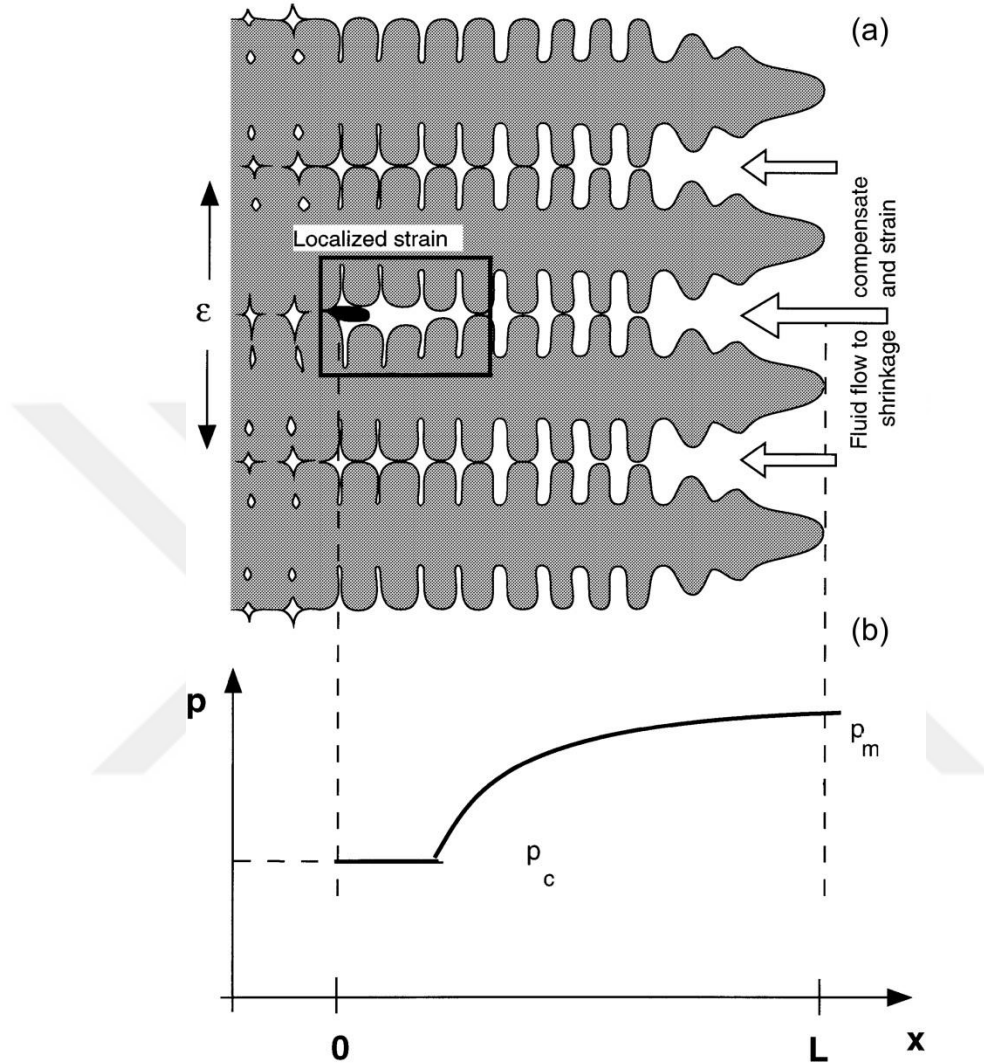


Fig. 1.6 RDG (Rappaz, Drezet and Gremaud) cracking model (Ref.22): (a) the sketch for hot tearing formation between the columnar grains caused by local strains; (b) change in the pressure of interdendritic liquid with respect to (a)

1.3. Index for Solidification Cracking Susceptibility

Kou proposed a simple index to predict susceptibility to cracking during solidification (Ref. 6). This index will be explained using Fig 1.4. He related the characteristic radius of columnar dendritic grains to fraction solid f_s , as shown in Fig 1.4d (Ref. 6). Columnar dendritic grains were considered because these grains are typical in welding unless an effective grain refinement is conducted (Ref. 2). Fig. 1.4d shows the transverse cross-sections of the grains in Fig. 1.4c by

considering that the grains grow side by side as hexagonal columns for convenience of analysis. Area of the transverse cross-section of the hexagonal column is taken as A . The cross-sections of the columnar grains are initially round, and they become more hexagonal toward the end of solidification. Since the hexagonal area is close to area of a circle, the transverse cross-sections of the grains at the terminal stage of solidification can be calculated using the circular area. If the characteristic radius of the grain is R , the area of the cross-section of the grain is πR^2 . The fraction of solid f_s , that is, the ratio of the solid to the liquid, is approximated as $\pi R^2/A$. The remaining liquid between the two grains is neglected since the amount of the liquid is very small at the terminal stage of solidification. Thus, R is proportional to the square root of the circular area, and hence $(f_s)^{1/2}$, as an approximation.

Kou (Ref. 6) indicated if the growth rate of grains dR/dt near $(f_s)^{1/2} = 1$ is small, that is, if the grains grow slowly near the end of solidification, the susceptibility to cracking becomes high. The reasons for the high crack susceptibility are explained in Fig. 1.4e (Refs. 6, 15). Firstly, delayed or slow bonding between grains causes decrease in the resistance to solidification cracking. Secondly, long grain boundary channels caused by slow grain growth results in slow liquid feeding and hence decrease in the resistance to cracking. Thirdly, the long grain boundary channels can initiate cracking by acting as sharp notches.

Since dR/dt , lateral growth rate of the grains, is proportional to $d(f_s)^{1/2}/dt$, it is also proportional to $(dT/dt)/(dT/d(f_s)^{1/2})$ considering the change in temperature. Kou (Ref. 6) proposed that a high $\left| dT/d(f_s)^{1/2} \right|$ near $(f_s)^{1/2} = 1$ suggests a small grain growth rate dR/dt near $(f_s)^{1/2} = 1$ and hence a high susceptibility to cracking. Thus, as shown in Fig. 1.4e, he used $\left| dT/d(f_s)^{1/2} \right|$ near $(f_s)^{1/2} = 1$ as an index for crack susceptibility (Ref. 6). Absolute value is preferred not to deal with negative

quantities. The index can also be interpreted as follows. High $\left| dT/d(f_s)^{1/2} \right|$ near $(f_s)^{1/2} = 1$ mathematically means, considering a given temperature drop $|dT|$, the $d(f_s)^{1/2}$ must be very small and hence the increase of grain radius dR is very small. Thus, the slow lateral growth rate of grains results in delay in bonding between grains near $(f_s)^{1/2} = 1$ and increase in the crack susceptibility.

The analytical equations such as the Gulliver-Scheil (Refs. 26, 27) and the Kurz-Fisher (Ref. 28) equations or commercial thermodynamic software can be used to calculate the relationship between T and f_s and hence $(f_s)^{1/2}$. The curve of T vs. $(f_s)^{1/2}$ of alloys can be used to determine $\left| dT/d(f_s)^{1/2} \right|$ near $(f_s)^{1/2} = 1$. Kou (Ref. 5) proposed to use the maximum steepness $\left| dT/d(f_s)^{1/2} \right|$ as the cracking index because the maximum steepness of the T vs. $(f_s)^{1/2}$ curve often occurs near $(f_s)^{1/2} = 1$ and this has been shown for commercial wrought Al alloys and binary Al alloys (Refs. 6, 11-15).

Kou (Ref. 5) pointed out that the crack susceptibility does not completely end at $f_s = 1$ but just before it, e.g., at $f_s = 0.98$. As fraction solid f_s approaches to 1, the remaining liquid at the grain boundaries cannot form a continuous film to separate the grains to cause cracking. At the very end of solidification (near $f_s = 1$), the only remaining liquid is with the form of isolated droplets and the grains can bond together to eliminate the susceptibility to cracking.

Fig. 1.7 shows the directional solidification of succinonitrile-acetone, an organic alloy, observed with a stationary “window” (Ref. 22). As can be seen in Fig 1.7a and even in Fig 1.7b, the liquid flow can easily occur toward the roots of the dendrites because the dendritic network is open. At $f_s = 0.82$ ($t = 30$ s) in Fig. 1.7c, there is a continuous liquid between columnar dendrites and the dendrite arms are not bridged yet. However, from Fig 1.7d through 1.7e, the bounding of the grains occur with longer period of time and the remaining liquid appears as isolated droplets

along the grain boundaries. Ultimately, at $f_s = 0.98$ ($t = 1500$ s) in Fig. 1.7e, an extensive bonding between the dendrites occurs and hence solidification cracking is not likely.

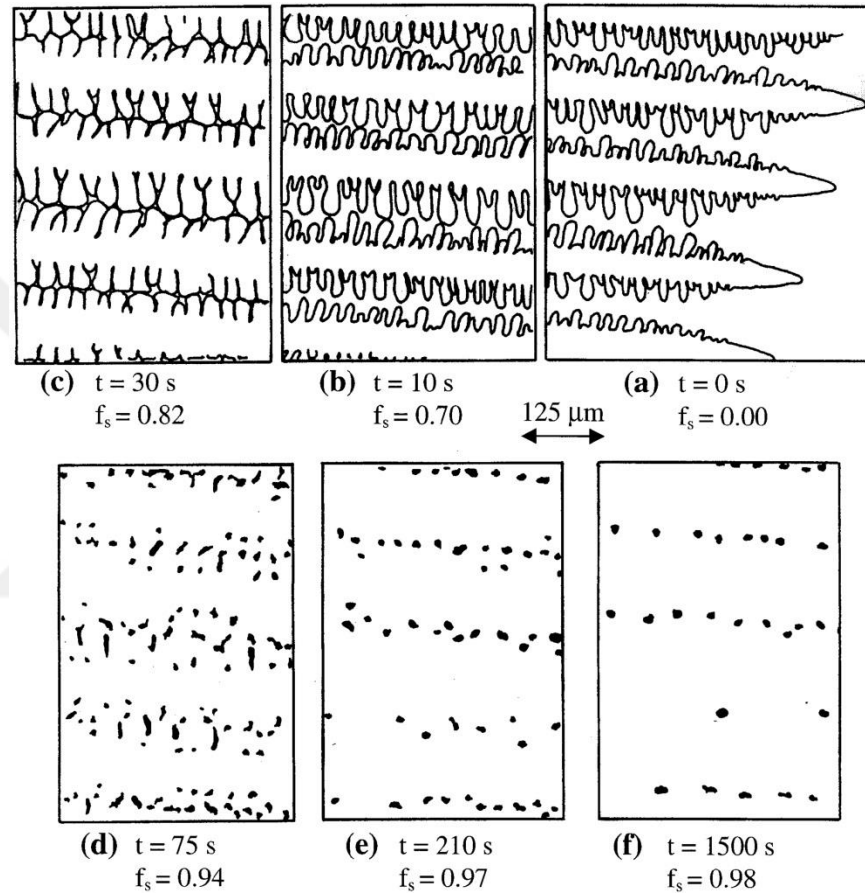


Fig. 1.7 Directional solidification of succinonitrile-acetone alloy in Bridgman-type apparatus: from (a) through (f) were traced from micrographs obtained at various times of solidification with the method of fixed “window of observation”. At $f_s = 0.98$ and hence $(f_s)^{1/2} = 0.99$, extensive bonding occurring between columnar dendritic grains with few isolated spots of liquid (L) (Ref. 22)

It was assumed that the extensive bonding between grains occurs at $f_s = 0.98$ to end the susceptibility to cracking in the RDG model (Ref. 22). However, Clyne and Davies (Ref. 29) claim that the extensive bonding occurs when $f_s = 0.99$. Kou (Refs. 5, 6), and Liu and Kou (Refs. 11-15) also considered that the extensive bounding occurs at $f_s = 0.98$, that is, $(f_s)^{1/2} = 0.99$, and they

showed that maximum steepness $\left| dT/d(f_s)^{1/2} \right|$ before or at $(f_s)^{1/2} = 0.99$ can be used to calculate crack susceptibility predictions for binary Al alloys and commercial wrought Al alloys.

Kou (Ref. 6) used commercial software Pandat (Ref. 30) and its Al databases PanAluminum (Ref. 31) to calculate $T-(f_s)^{1/2}$ curves of Al alloys. In Fig. 1.8, two $T-(f_s)^{1/2}$ curves are shown for welding Al alloy 2014 without a filler metal (solid line) and with filler metal 4145 Al (dotted line) (Ref. 6). The dilution ratio of the weld was assumed to be 20%, that is, the weld consists of 20% 2014 Al and 80% 4145 Al. Since the extensive bounding occurs when $(f_s)^{1/2}$ is at 0.99 and cracking susceptibility ends beyond this point, thus the maximum steepness was not considered beyond it. The calculated maximum steepness of the $T-(f_s)^{1/2}$ curve of 2014 Al, 2564°C, was reduced by filler metal 4145 Al to 1013°C, and this shows a significant reduction in the susceptibility to cracking. This prediction was found consistent with filler metal guides (Refs. 32, 33) recommending 4145 Al to reduce the crack susceptibility of 2014 Al. Another prediction was made for 6061 Al alloy, as can be seen in Fig. 1.9 (Ref 6). The maximum steepness of 6061 Al curve, 4848°C, is reduced by filler metal 4043 Al to 1352°C, and this is also consistent with the filler metal guides (Refs. 32, 33).

Fig. 1.10 shows the $T-(f_s)^{1/2}$ curves of commercial wrought Al alloys 2219, 2014, 2024, 7075 and 6061 Al alloys (Ref. 6). Again, the maximum steepness of the curves was calculated for these alloys regarding that the extensive bounding occurs at $(f_s)^{1/2} = 0.99$. As shown in Fig. 1.11a, the maximum steepness of the $T-(f_s)^{1/2}$ curve increases in the order of 2219, 2014, 2024, 7075 and 6061 indicating that the crack susceptibility increases in the same order. This crack susceptibility order was consistent with the experimental results of solidification cracking tests performed by Dowd (Ref. 34), and Dudas and Collins (Ref. 35), as shown in Fig. 1.11b. The freezing range of

the alloys (shown in Fig. 1.11c) were also calculated using the software Pandat (Ref. 30) and its databases PanAluminum (Ref. 31) but no close correlation was found with the susceptibility ranking of the alloys. This susceptibility index has potential to be used to develop new alloys and find proper filler metals to avoid solidification cracking.

Liu and Kou (Ref. 11) derived analytical expressions to calculate crack susceptibility of binary Al-Cu, Al-Si and Al-Mg alloys considering no-diffusion and diffusion in solid. They used Eq. [1.1], known as Scheil equation (Ref. 26), to relate the maximum $|dT/d(f_s)^{1/2}|$ to the phase diagrams (Ref. 11).

$$f_s = 1 - \left(\frac{T_m - T}{T_m - T_L} \right)^{\frac{1}{k-1}} = 1 - \left(\frac{T_m - T}{-m_L C_o} \right)^{\frac{1}{k-1}} \quad [1.1]$$

where f_s is fraction solid, T_m melting point of pure solvent, T temperature, T_L liquidus temperature, k equilibrium segregation coefficient, m_L slope of the liquidus line of the phase diagram, and C_o solute content of the alloy before solidification.

Scheil equation uses the following assumptions: equilibrium at the solid and liquid interface, no diffusion in solid, complete diffusion in liquid and straight liquidus and solidus lines of the phase diagrams (Ref. 2). Scheil equation can be written as follows for eutectic transformation by using fraction of eutectic f_E and fraction of eutectic liquid f_{LE} and considering the relation of $f_E = f_{LE} = 1 - f_{SE}$:

$$f_E = 1 - f_{SE} = \left(\frac{T_m - T_E}{-m_L C_o} \right)^{\frac{1}{k-1}} \quad [1.2]$$

where f_{SE} is fraction solid at eutectic temperature T_E .

If Eq. [1.2] is differentiated with respect to temperature T , it becomes

$$\frac{df_s}{dT} = -\left(\frac{1}{k-1}\right)\left(\frac{T_m-T}{T_m-T_L}\right)^{\frac{1}{k-1}-1} \left(\frac{-1}{T_m-T_L}\right) = \frac{1-f_s}{(k-1)(T_m-T)} \quad [1.3]$$

When the chain rule is used,

$$\frac{d(\sqrt{f_s})}{dT} = \frac{1}{2\sqrt{f_s}} \frac{df_s}{dT} = \frac{1}{2\sqrt{f_s}} \frac{(1-f_s)}{(k-1)(T_m-T)} \quad [1.4]$$

Since the defined steepness of the curve is the absolute value of the slope of the curve of T vs. f_s , the steepness of the curve can be written as follows using m_L and C_o :

$$\left| \frac{dT}{d(\sqrt{f_s})} \right| = \frac{2(1-k)(T_m-T)\sqrt{f_s}}{1-f_s} = \frac{2(1-k)(-m_L)C_o\sqrt{f_s}}{(1-f_s)^{2-k}} \quad [1.5]$$

It can be seen from Eq. [1.5], the steepness of the curve of T vs. f_s , $\left| dT/d(f_s)^{1/2} \right|$, reaches its maximum at T_E , thus Eq. [1.5] can be written as follows:

$$\left| \frac{dT}{d(\sqrt{f_s})} \right|_{at (f_{SE})^-} = \frac{2(1-k)(T_m-T_E)\sqrt{f_{SE}}}{1-f_{SE}} = \frac{2(1-k)(T_m-T_E)\sqrt{1-f_E}}{f_E} \quad [1.6]$$

It was pointed that the curve of T vs. f_s has an abrupt change in steepness at f_{SE} , according to Scheil equation (Ref. 11). The steepness is maximum at $(f_{SE})^-$ as given by Eq. [1.6] and minimum and zero at $(f_{SE})^+$.

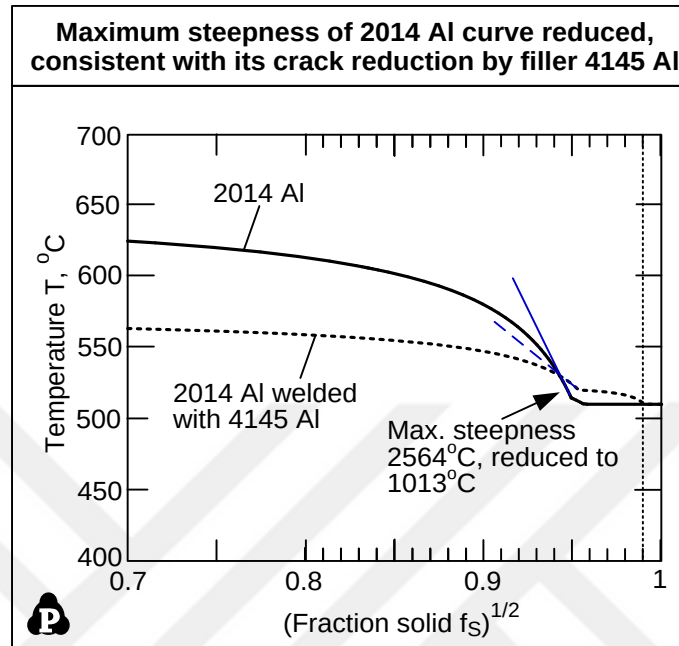


Fig. 1.8 $T-(f_s)^{1/2}$ curves of Al alloy 2014 without and with filler metal 4145 Al plotted using commercial software Pandat (Ref. 23). Maximum steepness $|dT/d(f_s)^{1/2}|$ of 2014 Al curve (2564 $^{\circ}\text{C}$) reduced by filler metal 4145 Al to 1013 $^{\circ}\text{C}$, consistent with filler metal guides to avoid cracking (Refs. 28, 29). From Kou (Ref. 6)

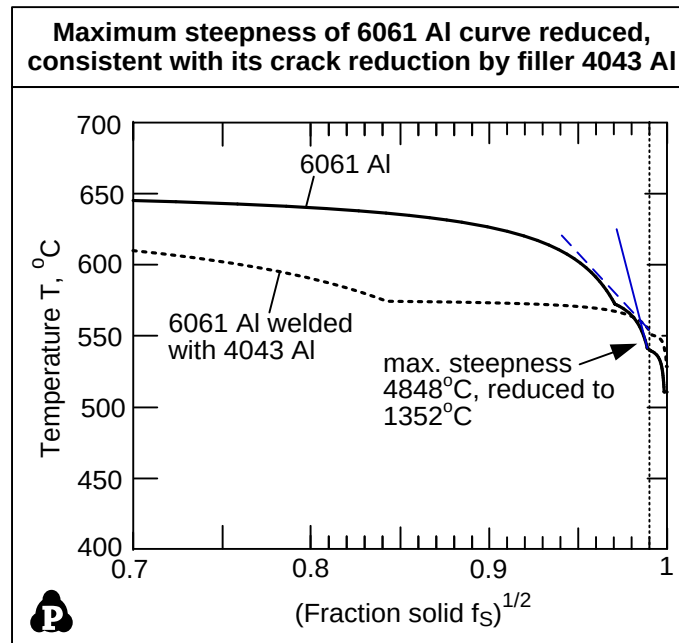


Fig. 1.9 $T-(f_s)^{1/2}$ curves of Al alloy 6061 without and with filler metal 4043 Al plotted using commercial software Pandat (Ref. 23). Maximum steepness $|dT/d(f_s)^{1/2}|$ of 6061 Al curve (4848 $^{\circ}\text{C}$) reduced by filler metal 4043 Al to 1352 $^{\circ}\text{C}$, consistent with filler metal guides to avoid cracking (Refs. 28, 29). From Kou (Ref. 6)

Eq. [1.6] illustrates that equilibrium segregation coefficient k , the temperature range ($T_m - T_E$) and fraction of eutectic f_E are key properties of the alloys that affect susceptibility to solidification cracking. As can be seen, with a greater k , smaller ($T_m - T_E$) and greater f_E , the crack susceptibility index $|dT/d(f_s)^{1/2}|$ gets smaller. Increasing fraction eutectic f_E with decreasing crack susceptibility index $|dT/d(f_s)^{1/2}|$ is consistent with the fact that liquid feeding becomes easier when there is plenty of eutectic liquid available at the roots of the columnar grains (Ref. 8).

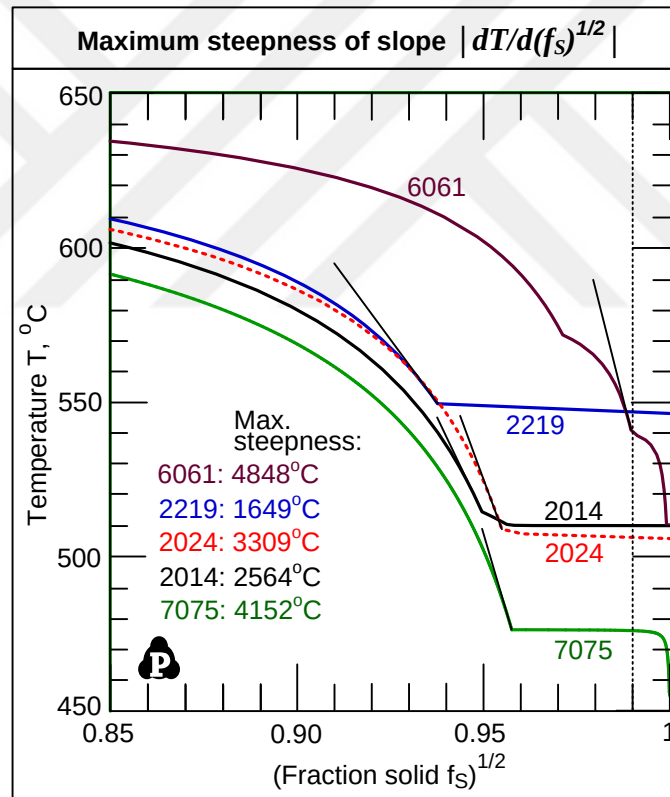


Fig. 1.10 $T-(f_s)^{1/2}$ curves of commercial wrought Al alloys plotted using commercial software Pandat (Ref. 26). Maximum steepness $|dT/d(f_s)^{1/2}|$ of commercial wrought Al alloys 2014, 2024, 2219, 6061 and 7075 calculated (Ref. 6). From Kou (Ref. 6)

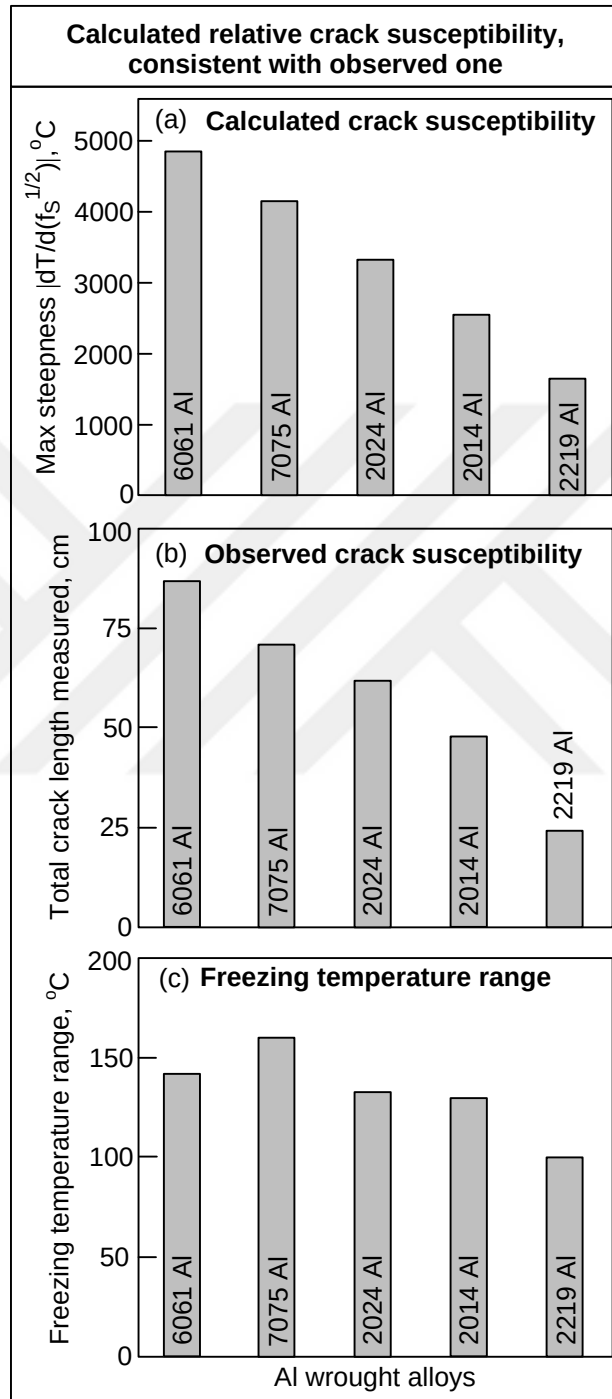


Fig. 1.11 Comparisons for the susceptibility of Al alloys to solidification cracking (Ref. 6): (a) calculated results in Fig. 1.10 using the maximum steepness of the $T-(f_s)^{1/2}$ curves; (b) experimental results from solidification cracking tests (Refs. 34, 35); (c) freezing temperature ranges of the alloys

1.4. Solidification Cracking Tests

To study susceptibility of alloys to cracking during solidification, cracking tests have been developed. As discussed earlier, solidification cracking occurs when there is tension in the mushy zone during solidification. In the cracking tests, this tension is either self-induced or imposed on the workpiece before welding or during welding.

Matsuda et al. (Ref. 36) studied the moving characteristics of weld edges to show the deformation of the mushy zone during solidification for cracked and crack-free weld beads. As shown in Fig. 1.12, two indents on a thin sheet were made with 10 mm distance between them to observe the change of this distance with a camera during solidification of the weld. As can be seen from the figure, when the weld bead was cracked, the distance between the indents increased and this was shown as positive deformation. When the weld bead was made without cracking, the distance between the indents decreased and this was shown as negative deformation. It shows that the negative and positive deformation respectively represent the contraction and expansion of the mushy zone. This indicates that the workpiece contracts during solidification and if it cannot contract freely, solidification cracking can occur. Cracking tests with external force basically cause cracking by preventing the contraction of workpiece and separating the grains (forming up during solidification) from each other.

Numerous tests developed for hot tearing and solidification cracking were reviewed by Kannengiesser and Boellinghaus (Ref. 4). Some of these tests will be discussed as follows.

1.4.1. Vareststraint Test

Vareststraint Test is shown in Fig. 1.13 (Ref. 2). Savage and Lundin (Ref. 37) originally developed the Vareststraint test in 1965 and it has been most widely used test for evaluating solidification cracking susceptibility since then. Gas-tungsten arc welding (GTAW) is used in the

test without a filler metal. As shown in Fig. 1.13a, the dimensions of the standard specimen are 27 mm thick, 203 mm long and 102 mm wide. An augmented strain is applied by a pneumatic system in the welding direction and the workpiece is suddenly bent against a curved mandrel (or bending block) during welding. Senda et al. (Refs. 38, 39) developed the transverse Varestraint test, as shown in Fig. 1.13b, in which bending of the workpiece is suddenly done in the transverse direction of welding. In both tests, the applied strain can be calculated with as follows: $\varepsilon = H/(2R+H) \times 100\%$, where H is thickness of the specimen and R is the radius of the curvature of the bending block. Filler metal cannot be directly used in the test because the crown of the weld would make thickness of the specimen H vary across the weld width. The reason for having a sudden bending action is to prevent the applied strain from varying along the weld. The total or maximum crack length is used as the crack susceptibility index. Fig. 1.13c illustrates the cracks caused by the sudden bending during welding a ferritic stainless steel in Varestraint test (Ref. 40).

To evaluate the filler metal effect on the cracking susceptibility a multi-step procedure could be used. For example, to study the filler metal effect in Varestraint test, Lippold and Savage (Ref. 41) firstly made a 2 mm deep and 16 mm wide groove in a stainless steel plate, then used gas-metal arc welding (GMAW) to deposit the filler metal in the groove, and then machined the crown of the weld to make the surface of the weld bead and plate even. Eventually, gas-tungsten arc welding (GTAW) was used for Varestraint testing after the three step procedure by restricting GTAW within the weld bead previously made by GMAW.

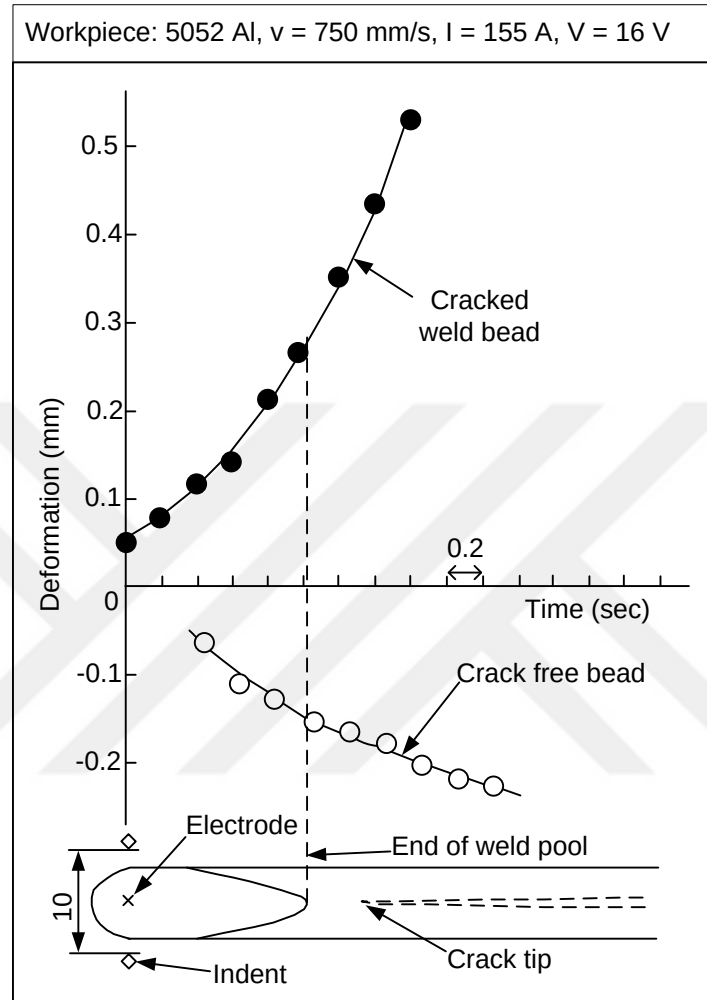


Fig. 1.12 Deformation of the weld edges during welding for cracked and crack-free weld beads (Ref. 36)

Due to the sudden bending in Varestraint test, Coniglio (Ref. 42) pointed out that the strain rate in the test is unrealistically high and the strain is globally applied to the workpiece instead of locally within the mushy zone. When the applied strain is global, it may result in cracks outside of the fusion zone (known as liquation cracking) and this could relieve the strain of the mushy zone. Coniglio (Ref. 42) also indicated that actual strain rate measurements (up to 130 %/s) in Varestraint test exceed both the strain rates observed in real-world welding (typically less than 8 %/s) and the critical strain rate required for formation of a crack (less than 5 %/s in aluminum arc welding).

Nakata et al. (Ref. 43) developed slow-bending Varestraint test to lower the strain rate. However, Coniglio (Ref. 42) argued that the applied global strain to the workpiece still does not represent the local strain in the weld (or mushy zone) that causes cracking during solidification.

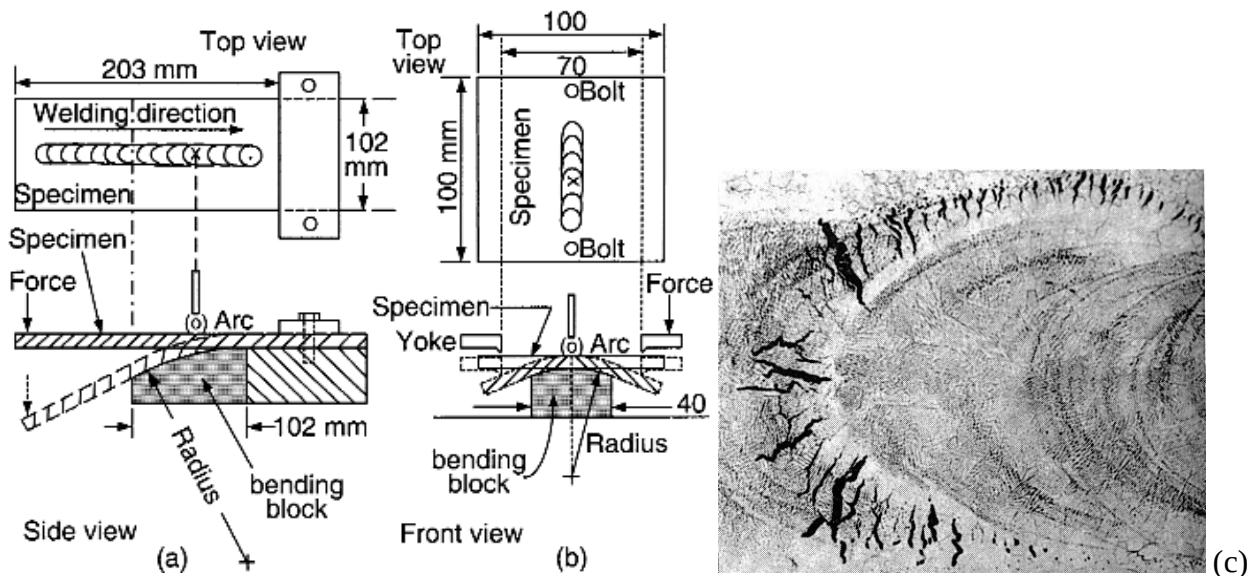


Fig. 1.13 Varestraint solidification cracking test (most widely used susceptibility test since 1965): (a) longitudinal Varestraint test (Ref. 37); (b) transverse Varestraint test (Ref. 38); (c) ferritic stainless-steel weld after testing by Varestraint test (Ref. 40). From Kou (Ref. 2)

1.4.2. Controlled Tensile Weldability (CTW) Test

Controlled Tensile Weldability (CTW) Test, shown in Fig. 1.14, was developed by Coniglio and Cross (Refs. 24, 25). Gas-tungsten arc welding is used to conduct the test. The test specimen, 4 mm thick, 120 mm long and 40 mm wide is used with two larger plates, called test coupons, each 8 mm thick, 150 mm long and 300 mm wide. These test coupons are used to connect the test specimen to a horizontal tensile testing machine for pulling it normal to the welding direction during welding. The strain rate across the weld is measured with an extensometer with the gauge length of 10.5 mm that is attached underneath of the specimen corresponding to the weld bead. Various crosshead speeds of the horizontal testing machine are used to repeat the test and

determine the critical crosshead speed of the alloy which is the minimum speed needed to cause solidification cracking. The critical crosshead speed is then divided by the gauge length (10.5 mm) of the extensometer to obtain the critical strain rate. To study solidification cracking with CTW test Coniglio and Cross (Ref. 24) welded 6061 Al with and without filler metal 4043 Al using different dilution levels. The test results showed that the critical strain rate increased with increasing the amount of 4043 Al in the weld metal, and this is consistent with the practice of using 4043 Al as the proper filler metal to reduce the crack susceptibility of 6061 Al. CTW test, unlike Varestraint test, provided quantitative test results with critical displacement or strain rates and the critical strain rate results were used to develop a crack growth model for solidification cracking (Ref. 25).

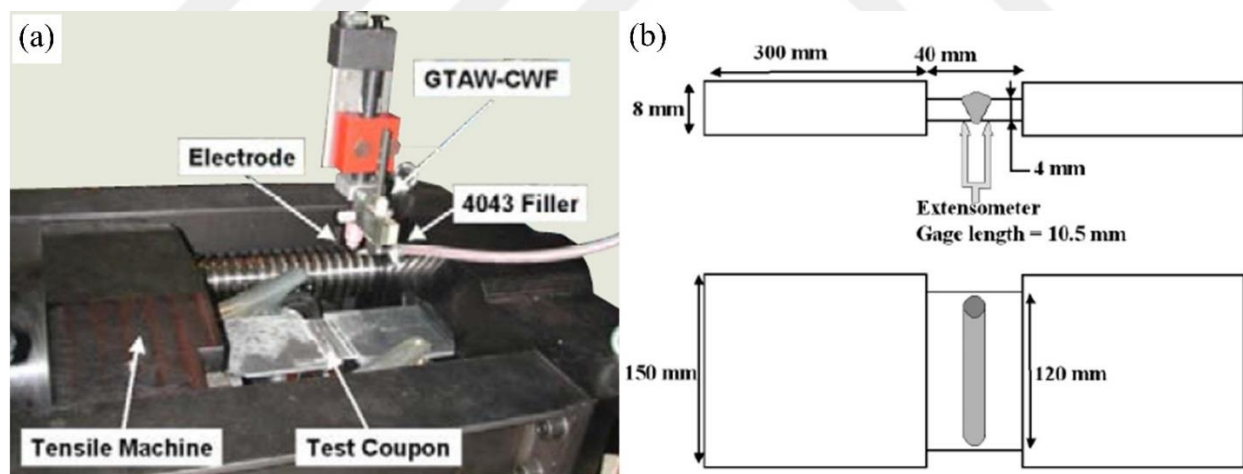


Fig. 1.14 Controlled tensile weldability (CTW) test (Ref. 24): (a) photograph for the test apparatus; (b) sketched side and top views. An extensometer used to measure the average strain across the weld

1.4.3. Houldcroft Test

Houldcroft Test, also called fishbone test, was developed by Houldcroft (Ref. 44). A thin sheet is used as the test specimen (Refs. 44-50). The specimen is not clamped and free from any constraints. As illustrated in Fig. 1.15, on both sides of the specimen slots were cut with increasing

depth to allow stresses along the length of the weld to gradually decrease and hence stop the crack. Solidification cracking is initiated by starting welding at the left edge of the specimen and it propagates along the centerline of the specimen, as shown in Fig. 1.15b. The tension in the mushy zone and its surroundings is reduced with the slots as the weld pool proceeds. This reduction in the tension brings the crack to stop before reaching the other end of the specimen. Crack length in the weld is used as crack susceptibility index, i.e., longer the crack length, higher the crack susceptibility is.

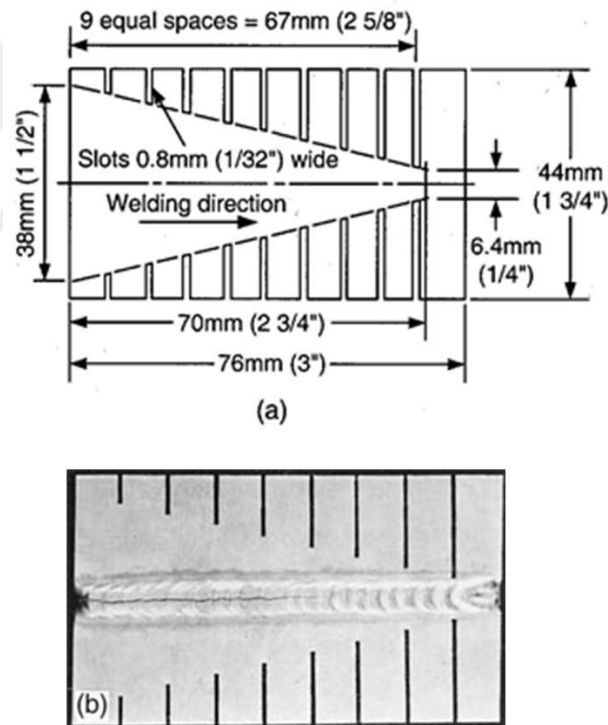


Fig. 1.15 Houldcroft test (Ref. 44): (a) sketched test design; (b) tested specimen made of Al alloy (Ref. 45). From Kou (Ref. 2)

1.4.4. Cast-Pin Test

Cast-Pin Test, also called cast pin tear test, was originally developed by Hull (Ref. 51) and modified by Lippold and coworkers (Ref. 52). The test is shown in Fig. 1.16 (Ref. 53). Small charges of a metal is melted by a cup-shaped induction coil designed for levitation melting and

casting into the pin shaped cavity of a water-cooled copper mold (Ref. 51). The tension in the test is self-induced by two sources: shrinkage of the alloy during cooling and thermal expansion of the mold (Ref. 54). As shown in Fig. 1.17, cracking is typically observed near the cast pin head where the strain concentration is accumulated (Ref. 54).

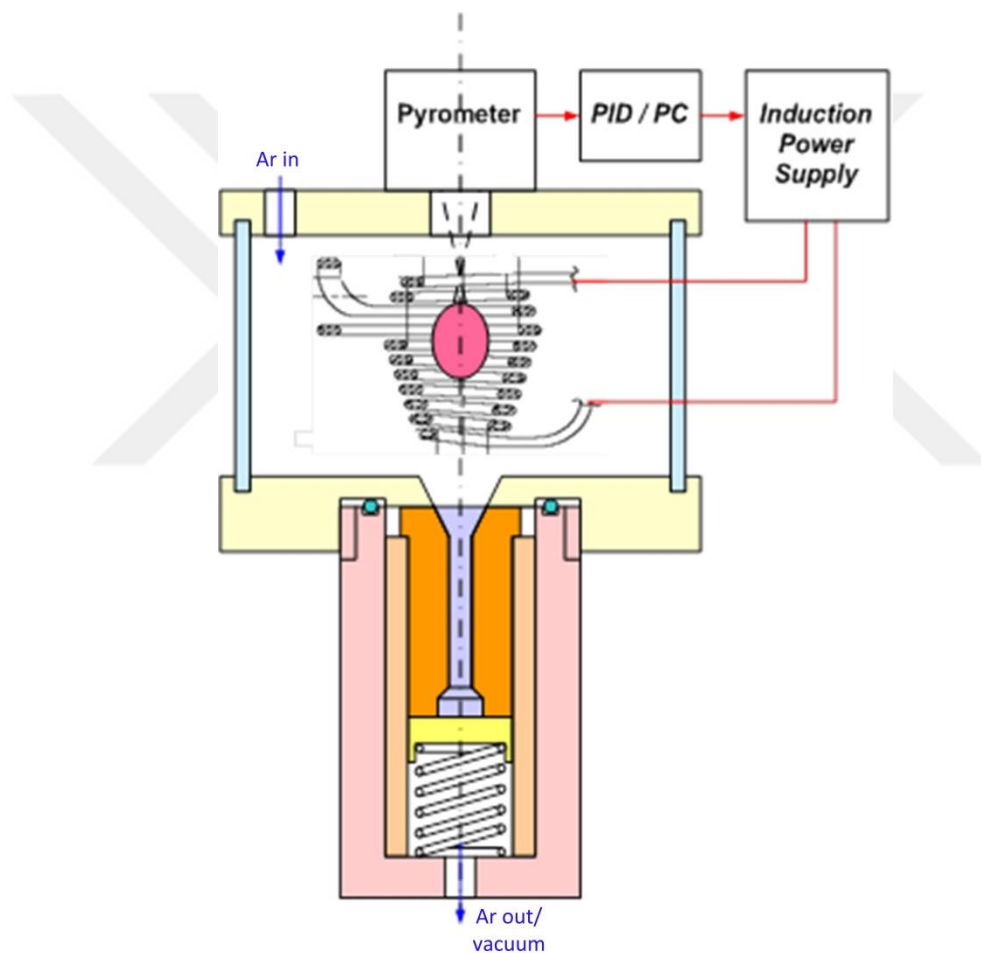


Fig. 1.16 Cast-pin test sketched (Ref. 53) originally developed by Hull (Ref. 51) and modified by Lippold and coworkers (Ref. 52)

Several molds with variable geometry are used to do testing. The longer length of the pin is, the more tendency for contraction and tension to cause cracking. The susceptibility of the alloy to solidification cracking is determined by comparing the length of the cast pins cracked during

testing. Shorter the length of the cast pin which cracks first, higher susceptibility to cracking is. Only a small amount of material is sufficient for testing but there is usually a need to prepare the charge by arc melting in vacuum.

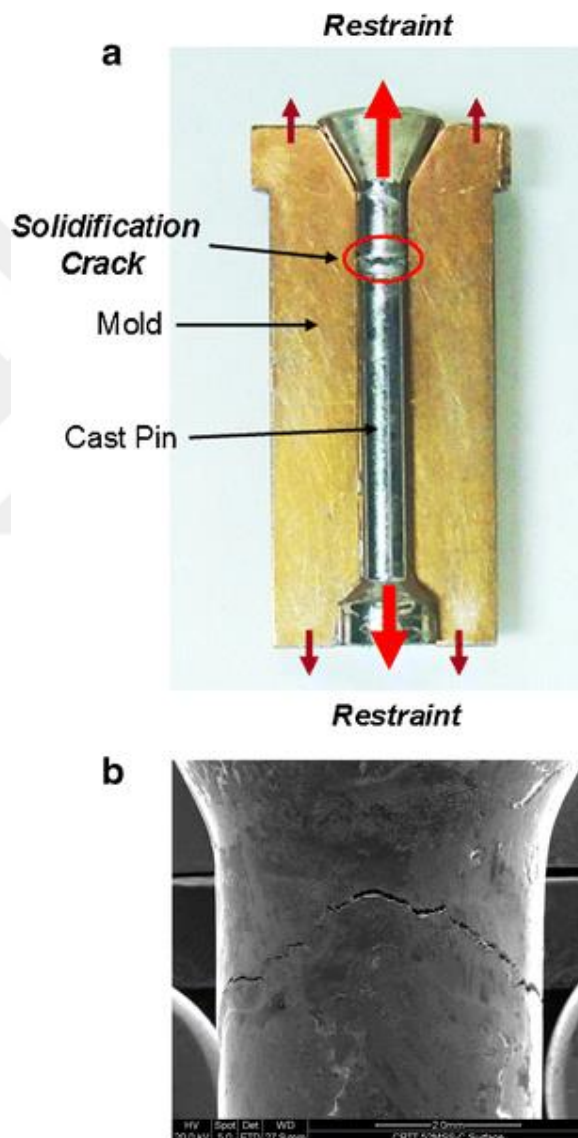


Fig. 1.17 Tested specimen by cast-pin test (Ref. 54): (a) Cu-Be mold and cast pin; (b) cracking observed near the upper end of the cast pin

1.4.5. Ring-Casting Test

Ring-Casting Test, described previously in Fig. 1.4, was used to study solidification cracking for Al ternary systems (Ref. 55, 56). The core of the ring casting mold prevents the solidifying alloy from contracting during solidification and hence inducing tension in the mushy zone to cause cracking. The total length of the crack is used as the index for susceptibility to cracking.

Other Tests are also available to study solidification cracking such as variable deformation rate (VDR) and Sigmajig tests. In VDR test, T-joint of the two pieces was done by gas-metal arc welding by rotating the lower piece during welding to cause cracking (Ref. 57). In Simgajig test, the tensile strain is applied to the workpiece before welding and welding direction is normal to the applied strain (Refs. 58-60).

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2. A NEW TEST FOR SOLIDIFICATION CRACKING SUSCEPTIBILITY

2.1. 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 solidification 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. On the other hand, 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 occurs 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 to make it susceptible to solidification cracking.

2.1.1. Models for cracking during solidification

Numerous models or criteria have been proposed for cracking during solidification in castings, including stress-based models, strain-based models 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 separate the grain-boundary liquid films. It became clear more recently that the strain rate, instead of the strain itself, 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, $d\varepsilon/dT$, 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 $d\varepsilon/dT$ 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 2×10^3 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 $(f_s)^{1/2} = 1$, Kou (Refs. 17) derived a criterion for cracking to occur during solidification. According to the criterion, if the rate of space increase due to grain separation under tension minus the rate of space decrease due to lateral grain growth exceeds 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 are available, such as micro porosity, folded oxide films, or external surfaces (Ref. 8).

Kou found a simple index to predict the susceptibility to cracking, that is, the steepness $\left| dT/d(f_s)^{1/2} \right|$ of the curve of T vs. $(f_s)^{1/2}$ near $(f_s)^{1/2} = 1$, where T is temperature and f_s the fraction solid (Ref. 18). He showed that a high $\left| dT/d(f_s)^{1/2} \right|$ near $(f_s)^{1/2} = 1$ causes: 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. Since the maximum steepness occurs near $(f_s)^{1/2} = 1$, an option is to use the maximum $\left| dT/d(f_s)^{1/2} \right|$ as the index for the susceptibility to solidification cracking (Ref. 19). For binary alloys, simple analytical equations describing f_s as a function of T can be used to plot the T - $(f_s)^{1/2}$ curve (Refs. 20-23). For multicomponent alloys, several commercial thermodynamics software package and databases are available to do it. The steepness $\left| dT/d(f_s)^{1/2} \right|$ is the absolute value of the slope $dT/d(f_s)^{1/2}$. 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).

2.1.2. Tests for solidification cracking susceptibility

Numerous tests have been developed to evaluate solidification cracking (Ref. 25). Essentially, three different types of tests have been developed to evaluate the susceptibility of welds to solidification cracking. In the first type of tests, 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 displacement (or strain) or displacement rate (or strain rate) needed to cause cracking. In the second type of tests, 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 tests, deformation (or strain) is applied to the workpiece during welding. For instance, in the Varestraint test (Refs. 41-43) the workpiece is bent suddenly during welding. In the programmable deformation cracking (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. 2.1. 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 27 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. (Refs. 42, 43), in which the workpiece is bent suddenly in the transverse direction of welding. In either case, the strain $\varepsilon = H/(2R+H) \times 100\%$, where R is the radius of curvature of the mandrel (bending block) and H the specimen thickness. No filler metal can be used because the crown will make H vary across the width of the weld. By bending the workpiece suddenly, the applied strain would not vary along the weld. The maximum or total crack length is used as the index for the susceptibility to solidification cracking. Spot welding has also been conducted using the transverse version.

The Varestraint test can be used to evaluate the effect of filler metals on the susceptibility of an alloy to solidification cracking, but a multi-step procedure is often required. For instance,

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 GMAW, and then removed the weld reinforcement by machining. The specimen prepared by this 3-step procedure was then used for Varestraint testing, with GTAW restricted to within the weld made previously by GMAW.

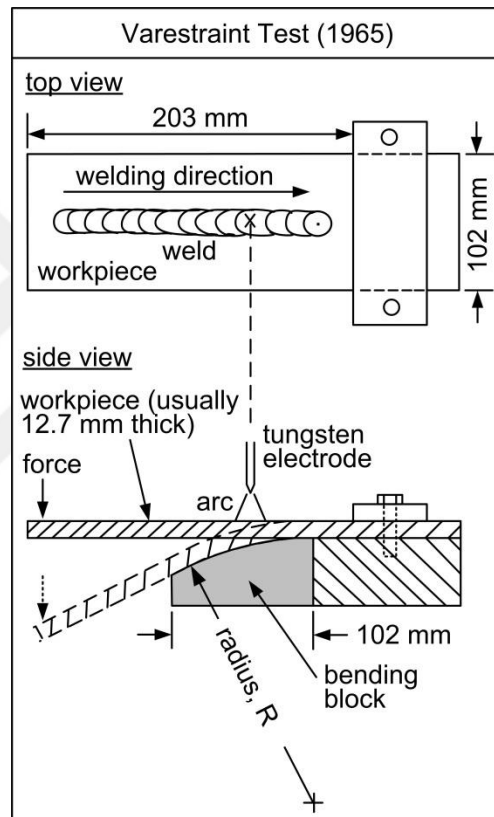


Fig. 2.1 The Varestraint test developed by Savage and Lundin in 1965 (Ref. 41) has become the most widely used test for solidification cracking. The workpiece, usually 12.7 mm thick, is bent suddenly during welding to cause cracking.

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 that 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) (Ref. 46). He further pointed out that in

Varestraint testing the weld metal shows significantly higher strains (over 2 %) and strain rates (over 100 %/s) than the applied strain (0.5 %) and strain rate (40 %/s) calculated based on $\varepsilon = H/(2R+H) \times 100\%$ (Ref. 46). 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 workpiece 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) is rotated at a constant angular speed ω 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 is deformation, t time and L the distance from the torch to the axis of rotation. dD/dt decreases continually as the welding torch advances and eventually brings the crack to a stop. The critical deformation rate is $(dD/dt)_c = L_c\omega$, where L_c is the distance at which the crack stops. Alloys that are more crack resistant showed higher $(dD/dt)_c$ values. This suggests that the local deformation (strain) rate plays a critical role in solidification cracking. Liquation cracking is not expected since 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) that are needed to connect the smaller sheet to a horizontal tensile testing machine to pull it normal to the welding direction during GTAW. To measure the deformation (or displacement) and hence transverse

strain across the weld, an extensometer is attached underneath the weld at a gauge length of 10.5 mm. The test is repeated at various crosshead speeds to determine the minimum speed needed to cause solidification cracking, that is, the critical crosshead speed, 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.

Since an alloy melts over a temperature range, the material in the weld pool is completely melted and the material in the region immediately next to the weld pool is partially melted, with liquid formation (called liquation) along grain boundaries. This region is called the partially melted zone, which can crack under tension (called liquation cracking). Except for the ring-casting test, the cast-pin test and the VDR test, liquation cracking can occur, and it can 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 displacement 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 displacement 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 displacement 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.

2.2. Experimental Procedure

An innovative methodology 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 together two pieces of materials while one piece moves normal to the welding direction. One such example is welding a lap joint and another is welding a T-joint. In either case, either one of the two members being joined can move normal to the welding direction.

Fig. 2.2a 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. In the mushy zone, this can induce a transverse tensile displacement rate $V = dD/dt$, where D is displacement. Fig. 2.2b shows how the lap welding in Fig. 2.2a can be implemented. The photo shows the arrangement of the workpiece and the torch for GMAW. In order not to block the view of the lap joint, the torch 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. 2.2c.

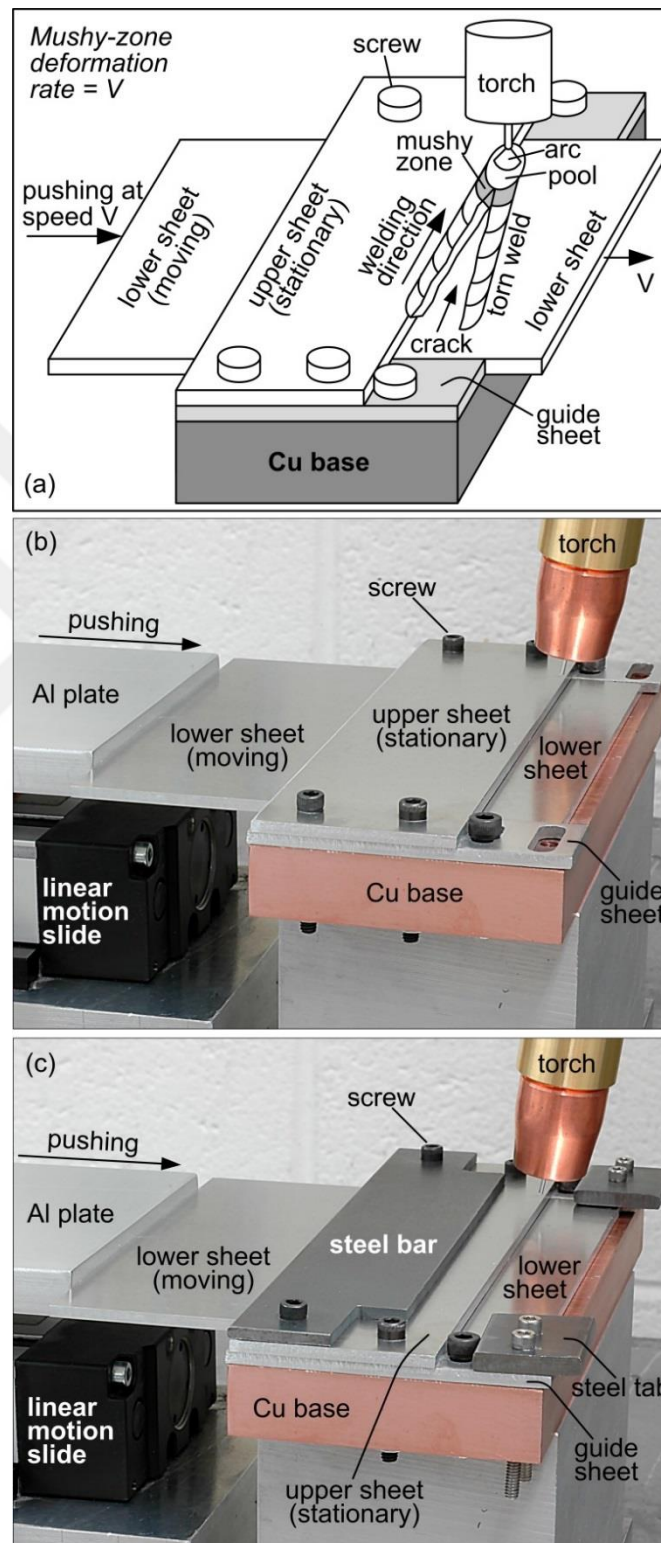


Fig. 2.2 The present test: (a) Schematic; (b) photo before welding (upper, lower and guide sheets all 3.2 mm thick, but can be 1.6 mm); (c) 3.2 mm thick steel bar and tabs for preventing workpiece distortion

Initially, the lower sheet stuck out of the upper sheet by 19 mm. 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. 2.3, the moving plate was mounted on a lead-screw assembly driven by a motor. Since the mushy zone is semisolid, it has little strength. Thus, a small ordinary motor sufficed. For programming purposes, however, a servomotor was used. The control unit was hooked up 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 2.1. Gas-metal arc welding (GMAW) 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 are as follows: Ar shielding at 3.54×10^{-4} m³/s (45 cfh), DCEP (direct current electrode positive) polarity, 23 V welding voltage, 5.1 mm/s (12 ipm) torch travel speed, 1.2 mm filler metal diameter, 93 mm/s (220 ipm) wire feed speed (except for 7075 wire at 116 mm/s or 275 ipm) and the corresponding welding current was 124 - 133 A). The torch was tilted 10° toward the joint and 10° backward (dragging).

To avoid filler metal piling up at the start of the weld, the torch 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.

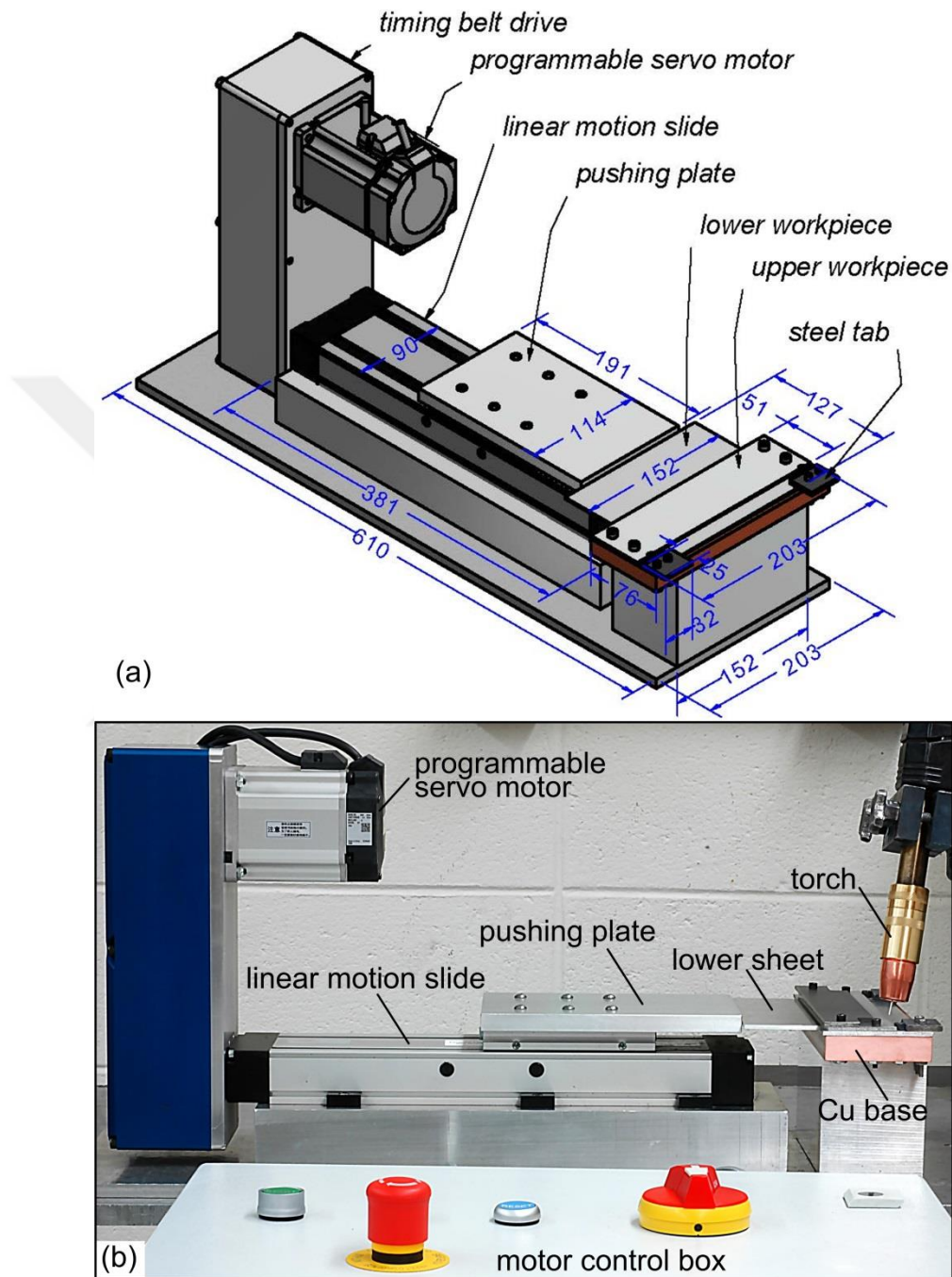


Fig. 2.3 Apparatus for the present crack susceptibility test: (a) Schematic; (b) photo. The control unit is connected to a computer used for programming the moving speed and for data acquisition

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 to, for instance, 0.6, 0.4 and 0.2 mm/s during

one welding experiment. It was hoped that this would determine the critical displacement rate in one single experiment. However, the critical displacement rate determined by this multi-speed 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.

Table 2.1 Compositions of materials in weight percent

	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al
Plates										
2014	0.80	0.19	4.84	0.73	0.57	0.008	0.010	0.023	0.04	Bal.
2219	0.16	0.12	5.82	0.33	0.004	0.002	0.03	0.02	0.04	Bal.
2024	0.09	0.19	4.4	0.57	1.4	0.01	-	0.14	0.02	Bal.
6061	0.72	0.6	0.33	0.08	1.0	0.20	-	0.10	0.02	Bal.
7075	0.07	0.17	1.5	0.03	2.4	0.19	-	5.7	0.03	Bal.
Wires										
2014	0.92	0.31	4.56	1.04	0.31	0.047	0.02	0.183	0.027	Bal.
2024	0.58	0.26	4.36	0.60	1.27	-	-	0.112	0.03	Bal.
2319	0.1	0.15	6.3	0.3	-	-	-	-	0.15	Bal.
6061	0.52	0.32	0.27	-	0.78	0.100	0.007	0.036	0.015	Bal.
7075	0.41	0.25	1.4	0.022	2.3	0.174	-	5.80	0.014	Bal.

After welding, the fracture surface of the fusion zone was examined to confirm its dendritic feature characteristic of solidification cracking. Welds made with non-matching filler metals were cut in the transverse cross-section, polished and etched with the Keller's etching solution (5 mL HNO₃, 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:

$$D = (A_U + A_L) / (A_U + A_L + A_F) \quad [2.1]$$

Assuming complete mixing in the weld pool as an approximation, the composition of the weld was calculated using the following equation (Ref. 1):

$$(\text{wt\% } E)_{\text{weld}} = D \times (\text{wt\% } E)_{\text{work}} + (1 - D) \times (\text{wt\% } E)_{\text{filler}} \quad [2.2]$$

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.

2.3. Results and Discussion

Fig. 2.4 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 with 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.

Fig. 2.5 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. 2.5a. As shown by the SEM images in Figs. 2.5b and 2.5c, dendrites are visible on the fracture surface. This confirms cracking occurred during solidification, that is, solidification cracking.

2.3.1. Matching filler metals

Fig. 2.6 shows the test results of 6061 Al welded with 6061 Al as the filler metal. The normalized crack length is plotted against moving speed of the lower sheet. 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. 2.4b, the normalized crack length is $L_{\text{crack}}/L_{\text{weld}}$, where L_{crack} and L_{weld} are, respectively, the crack length and the weld length corresponding to the moving speed at which crack propagation was tested.

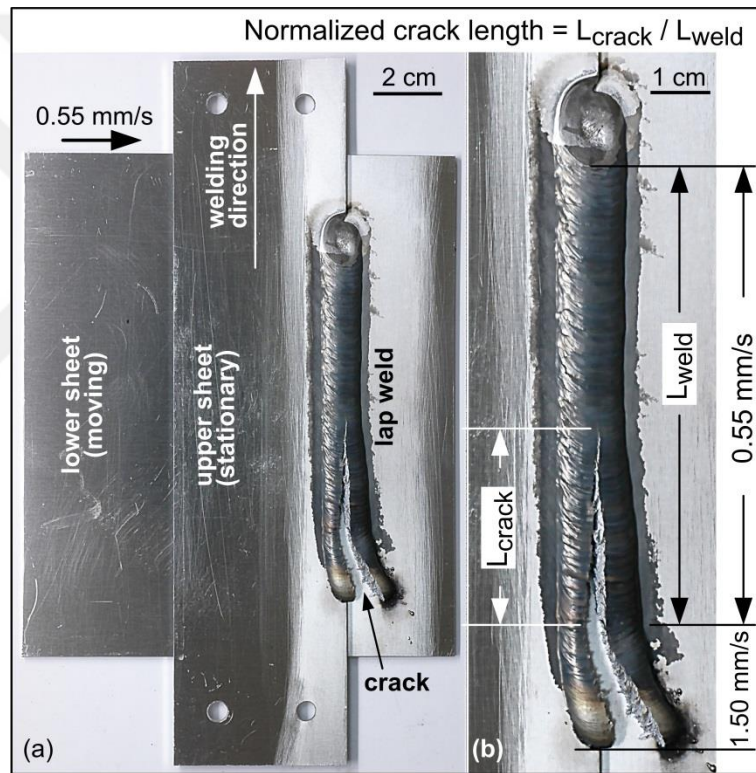


Fig. 2.4 The 6061 Al welded with filler 4043 Al: (a) Overview; (b) enlarged. The speed of the lower sheet was $V = 1.5$ mm/s in the initial part (about 25 mm) of the weld to ensure crack initiation. Crack propagation occurred at $V = 0.55$ mm/s. L_{crack} and L_{weld} are, respectively, the crack length and weld length, excluding the initial part of the weld

A blue curve is drawn to best fit the data points in Fig.2.6. As shown, the normalized crack length increases from 0 at about $V = 0.04$ mm/s to 1.0 at $V = 0.23$ mm/s. Hereinafter, the range of V over which the normalized crack length increases from 0 to 1.0 will be called the critical lower-

sheet speed V_c . Thus, for 6061 Al welded with 6061 Al as filler, the V_c is 0.135 ± 0.095 mm/s under the welding conditions involved here.

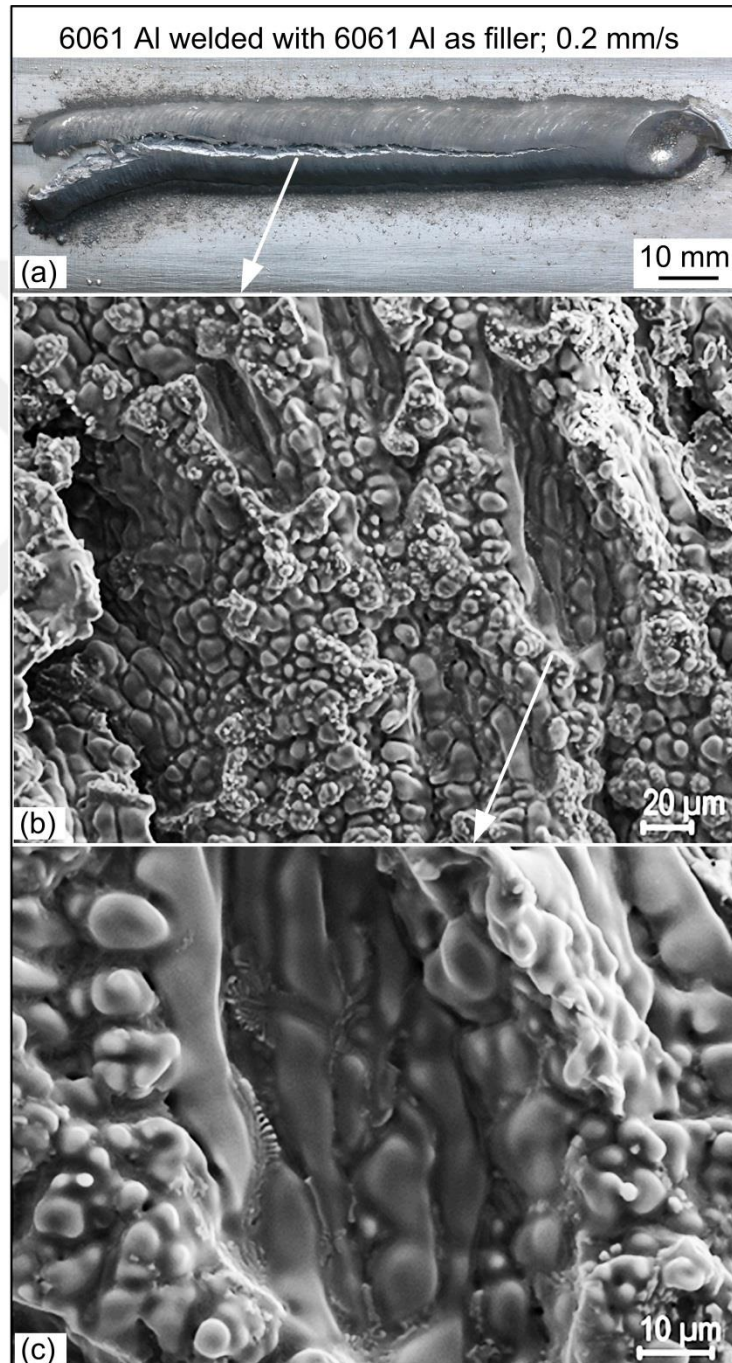


Fig. 2.5 Fracture surface of 6061 Al welded with 6061 Al: (a) Location of fracture surface; (b) SEM image showing dendrites and thus confirming solidification cracking; (c) higher magnification

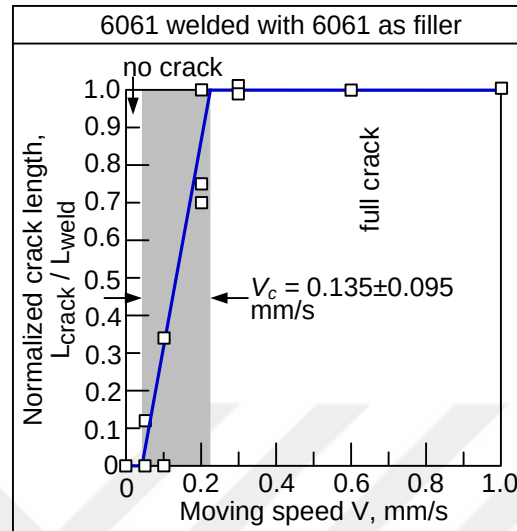


Fig. 2.6 Test results of 6061 Al welded with 6061 Al as filler metal. The critical moving speed of the lower-sheet V_c is 0.135 ± 0.095 mm/s

Similar test results are shown in Figs. 2.7 through 2.10 for alloys 7075 Al, 2024 Al, 2014 Al and 2219 Al welded with matching filler metals. 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% added for grain refining (which can reduce the susceptibility to solidification cracking).

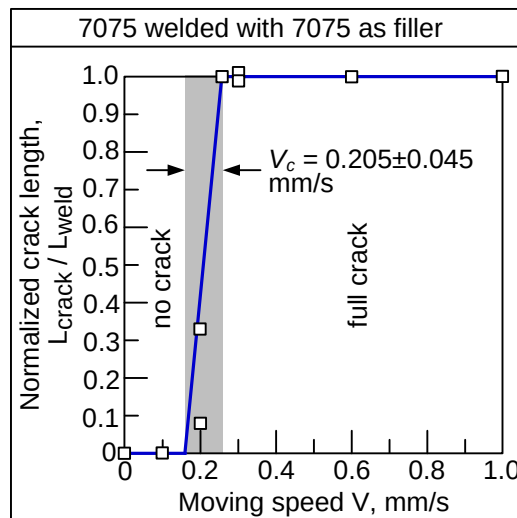


Fig. 2.7 Test results of 7075 Al welded with 7075 Al as filler metal. $V_c = 0.205 \pm 0.045$ mm/s

Fig. 2.11a summarizes the critical moving speeds V_c of the five Al alloys shown in Figs. 2.6 through 2.10. As shown, the critical lower-sheet moving speed V_c increases in the order of 061 Al, 7075 Al, 2024 Al, 2014 Al and 2219 Al. This means crack resistance to solidification cracking increases in the same order. Thus, the crack susceptibility should decrease in the same order. This order is consistent with the data reported by previous investigators shown in Fig. 2.11b (Refs. 47, 48).

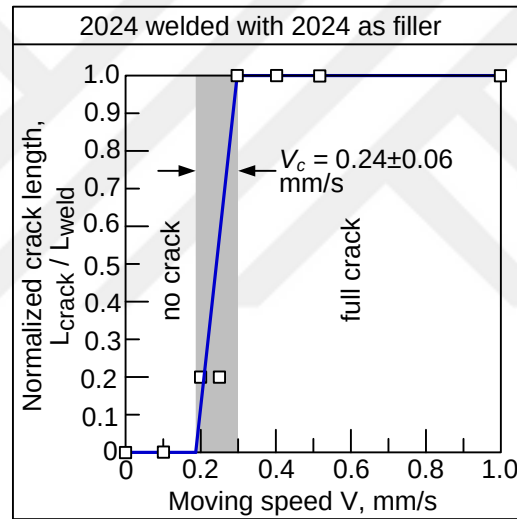


Fig. 2.8 Test results of 2024 Al welded with 2024 Al as filler metal. $V_c = 0.24 \pm 0.06$ mm/s

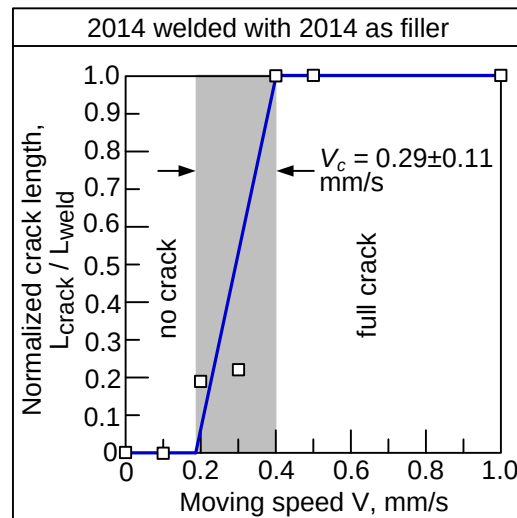


Fig. 2.9 Test results for 2014 Al welded with 2014 Al as filler metal. $V_c = 0.29 \pm 0.11$ mm/s

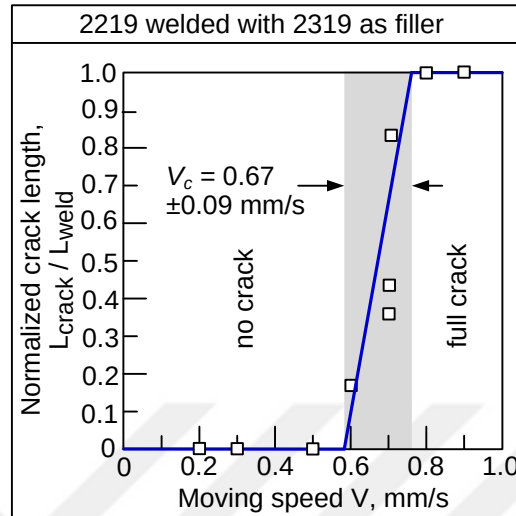


Fig. 2.10 Test results for 2219 Al welded with 2319 Al as filler metal. $V_c = 0.67 \pm 0.09$ mm/s

Alloy 2219 Al appears to have a significantly lower crack susceptibility than the other alloys including 2014 Al. This difference can be seen in both Figs. 2.11a and 2.11b but is clearer in the former. One possible explanation for this 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 gas-tungsten arc welding (Ref. 49), and the results are similar to those in Figure 2.11a, but the difference between 2219 and 2014 is significantly less than that in Figure 2.11a.

Before leaving 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 displacement rate or moving speed in Fig. 2.11a ranges from 0.05 to 0.9 mm/s. This range of the moving speed 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 0.005 to 0.09 per second or 0.5 - 9% 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.

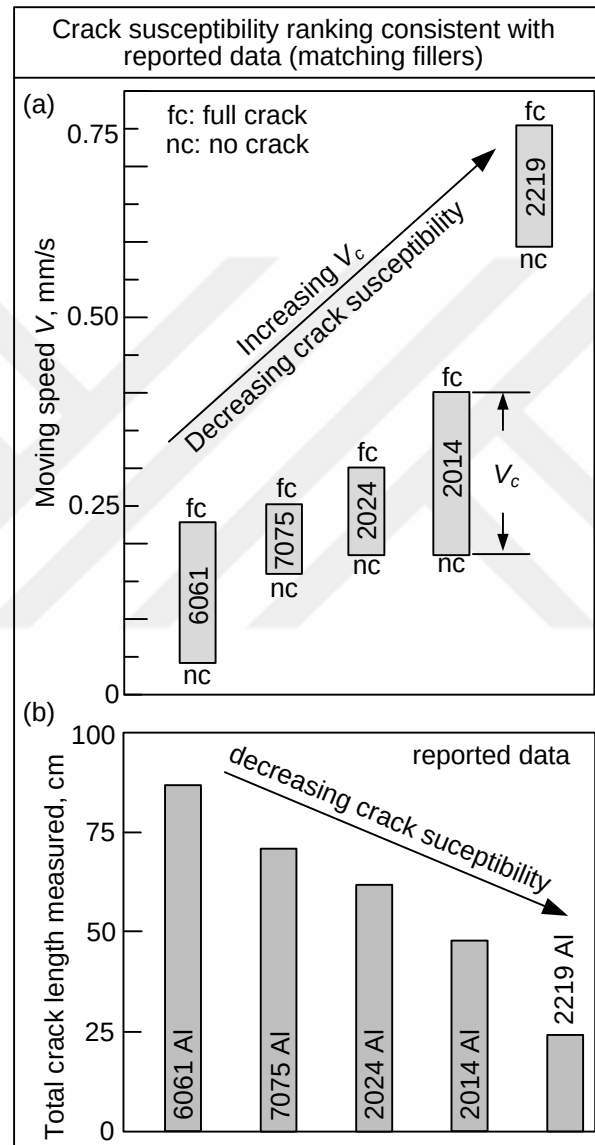


Fig. 2.11 Ranking crack susceptibility of Al alloys: (a) Based on the critical moving speed of the lower-sheet V_c (a higher V_c means faster moving speed of the lower-sheet is required for cracking to occur, i.e., crack propagation is more difficult to occur); (b) reported data (Refs. 48, 49)

It is also worth pointing out that the results in Figs. 2.6 through 2.10 demonstrate clearly the important role played by the displacement 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.

2.3.2. Non-matching filler metals

Fig. 2.12 shows the transverse cross-section of the weld shown previously in Fig. 2.4. The transverse macrograph was taken near the end of the crack. The areas denoted by A_U , A_L and A_F represent, respectively, contributions to the weld metal from the upper sheet, lower sheet and filler metal that were melted and mixed with the melted workpiece material 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. [2.1], areas A_U , A_L and A_F can be used to determine 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 metals using Eq. [2.2]. Using the weld in Fig. 2.12 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. [2.2] and is shown in Table 2.2.

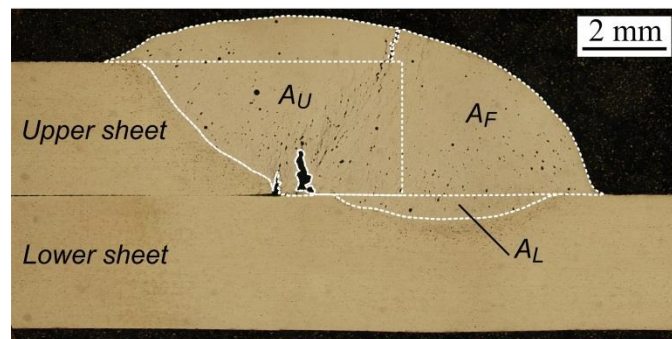
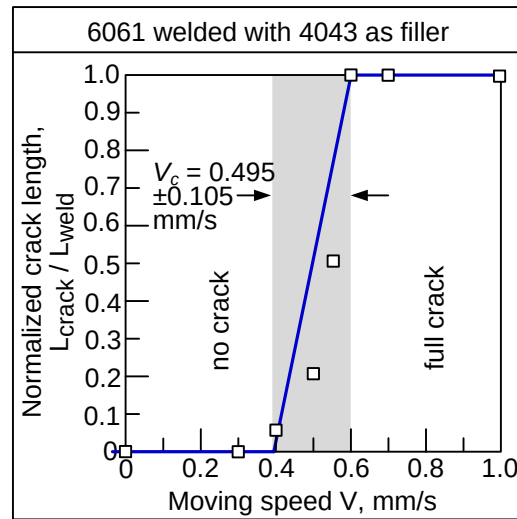


Fig. 2.12 Transverse cross-section of the weld in Fig. 2.4 near the end of the crack. Areas A_U , A_L , and A_F (excluding cracks) represent contributions to the weld metal from the melted upper sheet, lower sheet, and filler metal, respectively, which are used in Eq. 1 to calculate the weld metal composition

Table 2.2 Composition of weld in wt% made by welding 6061 Al with 4043 Al (Fig. 2.12)

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Workpiece 6061	0.72	0.6	0.33	0.08	1.0	0.20	0.10	0.02	balance
Filler 4043	5.0	0.80	0.30	0.05	0.05	-	0.10	0.20	balance
Weld (47.8% dilution)	2.79	0.70	0.31	0.06	0.50	0.10	0.10	0.11	balance

Fig. 2.13 shows the test results of welding 6061 Al with 4043 Al as a non-matching filler metal, which is a commonly used commercial filler metal. The normalized crack length is plotted against the moving speed V of the lower-sheet and the data points are best fitted with the blue curve. The highlighted range of the moving speed V is the critical lower-sheet speed V_c . The critical lower-sheet speed V_c was found as 0.495 ± 0.105 mm/s. Similar results are shown in Fig. 2.14 for welding 7075 Al with filler metal 4043 Al, Fig. 2.15 for welding 2024 Al with filler metal 4145 Al, and Fig. 2.16 for welding 2014 Al with filler metal 4145 Al.

Fig. 2.13 Test results of 6061 Al welded with 4043 Al as filler metal. $V_c = 0.495 \pm 0.105$ mm/s

The test results in Figs. 2.13 through 2.16 for welds made with non-matching filler metals are summarized in Fig. 2.17. For comparison, the test results of welds made with matching filler metals are also included. As shown, the critical lower-sheet speed V_c 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 moving speed of the lower-sheet V must 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).

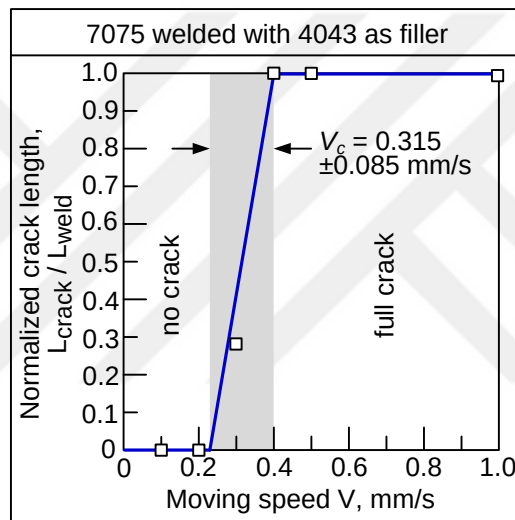


Fig. 2.14 Test results of 7075 Al welded with 4043 Al as filler metal. $V_c = 0.315 \pm 0.085$ mm/s

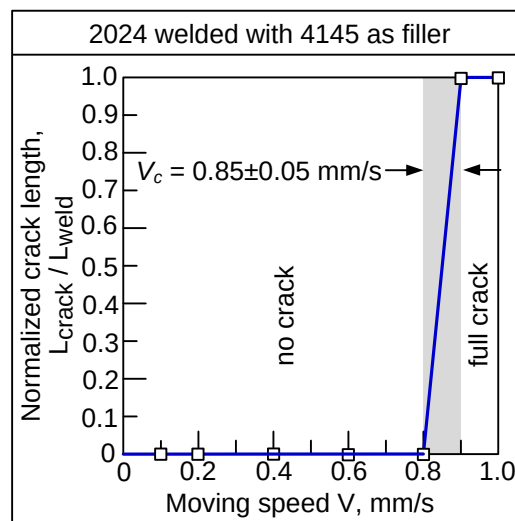


Fig. 2.15 Test results of 2024 Al welded with 4145 Al as filler metal. $V_c = 0.85 \pm 0.05$ mm/s

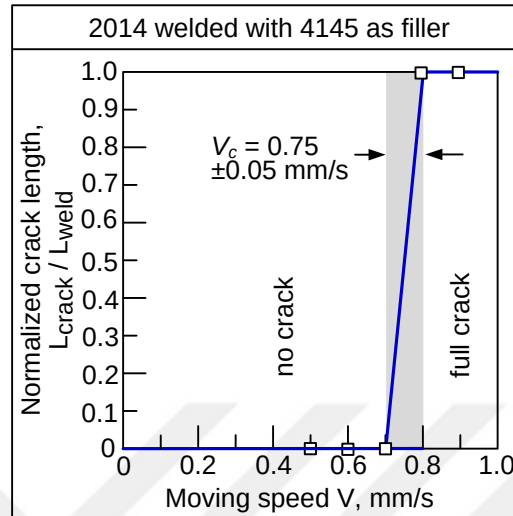


Fig. 2.16 Test results of 2014 Al welded with 4145 Al as filler metal. $V_c = 0.75 \pm 0.05 \text{ mm/s}$

The critical lower-sheet speed V_c is also at a significantly higher V level in welding 2014 Al with 4145 Al as the filler metal than 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).

As also shown in Fig. 2.17, in welding 7075 Al, the critical lower-sheet speed V_c 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). As for the case of welding 2024 Al with 4145 Al as the filler metal, the V_c is also at a higher V level with 4145 Al as the filler metal than with 2024 Al. Since the filler metal guides (Refs. 50, 51) do not specify any filler metals for Al alloys 2024 and 7075, these test results can contribute to the literature.

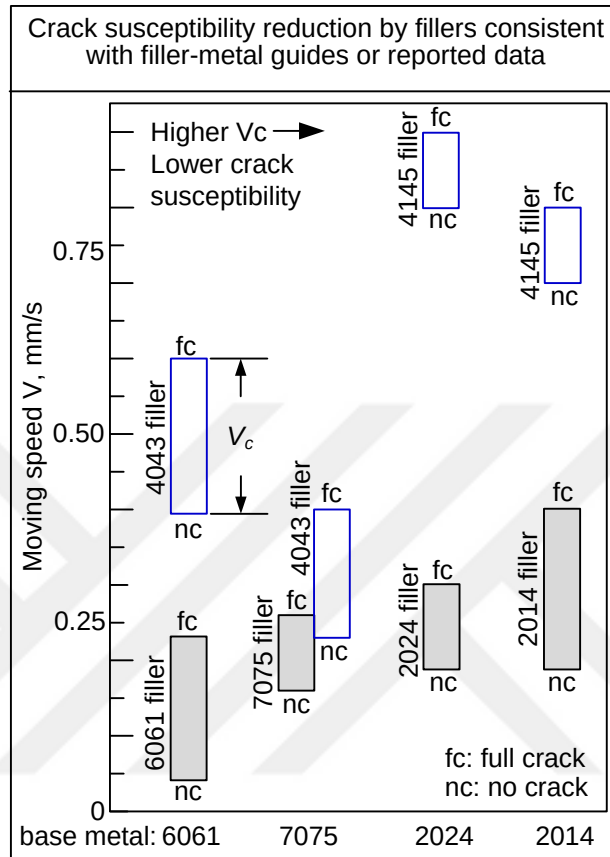


Fig. 2.17 Effect of filler metals on crack susceptibility. Filler 4043 Al raises the critical moving speed of the lower-sheet V_c of 6061 and 7075, and thus reduces their crack susceptibility, so does filler 4145 Al for 2014 Al and 2024 Al.

2.3.3. Effect of travel speed

Fig. 2.18 shows the results of welding 6061 Al with a matching filler metal at the torch travel speed of 10 mm/s. The critical lower-sheet speed V_c of 0.25 ± 0.05 mm/s here is higher than $V_c = 0.135 \pm 0.095$ mm/s at the torch travel speed of 5 mm/s. This indicates that the crack susceptibility is lower at 10 mm/s than at 5 mm/s. Since 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 torch travel speed alone, which could also change the displacement rate of the mushy zone. Instead, the displacement rate or moving speed 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 displacement 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 displacement rate separating the grains to cause cracking, 2. lateral growth rate of grains toward each other to bond together and resist cracking, 3. liquid feeding rate of the grain boundary. Under the same tensile displacement 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 mode, etc., to change the crack susceptibility.

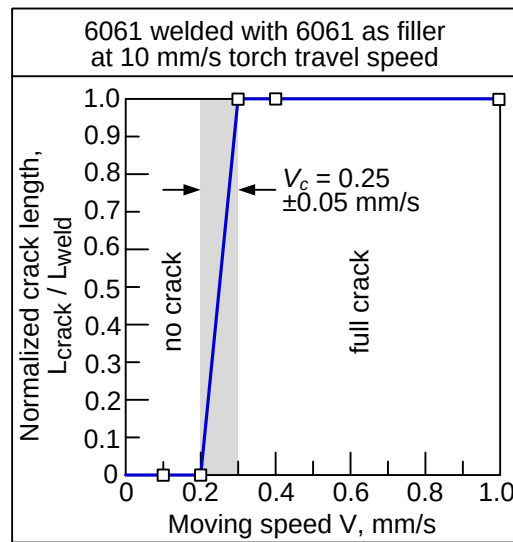


Fig. 2.18 Test results of 6061 Al welded with 6061 Al as filler metal at 10 mm/s torch travel speed. $V_c = 0.25 \pm 0.05 \text{ mm/s}$

2.3.4. 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 moving speed V in ten different cases. In all cases a distinct critical

moving speed V_c range was observed. Furthermore, the location of the critical moving speed of the lower-sheet V_c on the V -axis can be determined accurately. On the average, eight data points (eight samples) per case would be sufficient for this. With more experiments conducted to add more data points, the location of the V_c on the V -axis would not change significantly. The range of the V_c can be affected, but this is not important because the crack susceptibility is affected by the V level of the V_c , not by its range. As mentioned previously, the higher the V level of the V_c is, the lower the crack susceptibility becomes.

The authors have demonstrated the use of autogenous gas-tungsten arc welding (GTAW) in the new test (Ref. 49). The repeatability is better than that with GMAW.

2.3.5. Comparison with Varestraint test

Fig. 2.19 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 displacement rate in the mushy zone. The latter is responsible for solidification cracking and it can be useful information, for instance, for 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 displacement rate in the mushy zone. Unlike the Varestraint test, the present test can apply slow displacement or strain rates realistic for welding, ensures crack initiation before testing crack propagation, and keeps liquation cracking from interfering with solidification cracking. The present test is simple and inexpensive, and it requires only a relatively small workpiece.

<i>Comparing the Varestraint test and the present test</i>		
	Varestraint Test	Present Test
<i>solidification cracking susceptibility</i>	<i>can be tested</i>	<i>can be tested</i>
<i>use of filler metal to test its crack reduction</i>	<i>no</i>	<i>yes</i>
<i>deformation imposed</i>	<i>global deformation of workpiece</i>	<i>local deformation of mushy zone, which causes cracking</i>
<i>deformation rate</i>	<i>fast (workpiece bent suddenly)</i>	<i>can be much slower as in actual welding</i>
<i>crack susceptibility index</i>	<i>crack length (qualitative information)</i>	<i>crack transition range (quantitative information)</i>
<i>crack initiation and crack propagation</i>	<i>cannot be separated</i>	<i>can be separated</i>
<i>interference by liquation cracking</i>	<i>yes</i>	<i>no</i>
<i>mechanical devices required</i>	<i>pneumatic system and bending blocks</i>	<i>motor</i>
<i>equipment cost</i>	<i>higher</i>	<i>much lower</i>
<i>workpiece material required</i>	<i>more</i>	<i>much less</i>

Fig. 2.19 Differences between the present test and the most widely used Varestraint test (Ref. 41). Liquation cracking refers to cracking along the weld edge, which is not solidification cracking but can interfere with it during testing

2.4. Summary and Conclusions

1) An innovative methodology for testing solidification cracking has been developed, that is, welding together two pieces of materials while one piece moves normal to the welding direction at the speed V . This methodology is useful because V is the lateral tensile displacement rate of the mushy zone that causes solidification cracking.

2) The range of the critical moving speed of the lower-sheet V_c over which the transition from no crack propagation to full crack propagation occurs can be determined by plotting the normalized crack length against moving speed V .

3) In all the ten different cases considered in the present study, a distinct V_c was observed. In each case, about eight data points were enough to show clearly the location of the V_c on the V -axis, i.e., the critical moving speed of the lower-sheet to cause cracking. The range of the V_c was not as clear, but this is not important.

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

5) The V_c 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_c 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 displacement rates as those in welding practice, reveal the local displacement rate in the mushy zone that causes cracking, determine the critical moving speed V_c for crack propagation, keep liquation cracking from interfering with tests of solidification cracking, and significantly reduce the costs of both the apparatus and the workpiece material.

8) Since 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.

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3. TESTING WELDS WITHOUT FILLER METALS

3.1. Introduction

3.1.1. Crack susceptibility index

Cracking can occur during solidification of an alloy such as aluminum alloys, stainless steels and Ni-base alloys, known in welding as solidification cracking (Ref. 1) and in casting as hot tearing (Refs. 2, 3). Fig. 3.1 is a schematic sketch of the weld pool and its surroundings. An index for predicting the solidification cracking susceptibility is also shown, which will be explained subsequently. As shown in Fig. 3.1a the mushy zone is the semisolid region located between the advancing weld pool and the completely solidified weld metal behind it in the fusion zone. During cooling and solidification, the mushy zone tends to shrink due to solidification shrinkage and thermal contraction but cannot shrink freely because it is connected to the bulk workpiece, which is much cooler and larger in size than the mushy zone and is rigid. This obstructed shrinkage can induce significant tension in the mushy zone to cause cracking (Ref. 4). Liquid metal shrinks upon solidification because of the higher density of solid metal than liquid metal, called solidification shrinkage, which is 6.6% for Al (Ref. 2). Solid metal shrinks upon cooling because of its thermal expansion coefficient.

In welding, dendritic grains in the mushy zone are usually columnar unless effective grain refining is conducted. Fig. 3.1b shows schematically two columnar dendritic grains growing in the welding direction along the centerline of the mushy zone. They are being separated from each other by the tension induced in the transverse direction by obstructed shrinkage of the mushy zone. This can cause intergranular cracking to occur near $(f_s)^{1/2} = 1$, where f_s is fraction solid, because not much liquid is left to fill a void if it forms. However, the grains are also growing toward each other to bond together and resist cracking. Fig. 3.1c shows how their transverse growth rate dR/dt can be related to $d(f_s)^{1/2}/dt$, where R is the characteristic grain radius and t time (Refs. 5, 6). Since

$d(f_s)^{1/2}/dt = (dT/dt) / (dT/d(f_s)^{1/2})$, dR/dt is inversely proportional to $|dT/d(f_s)^{1/2}|$, where T is temperature.

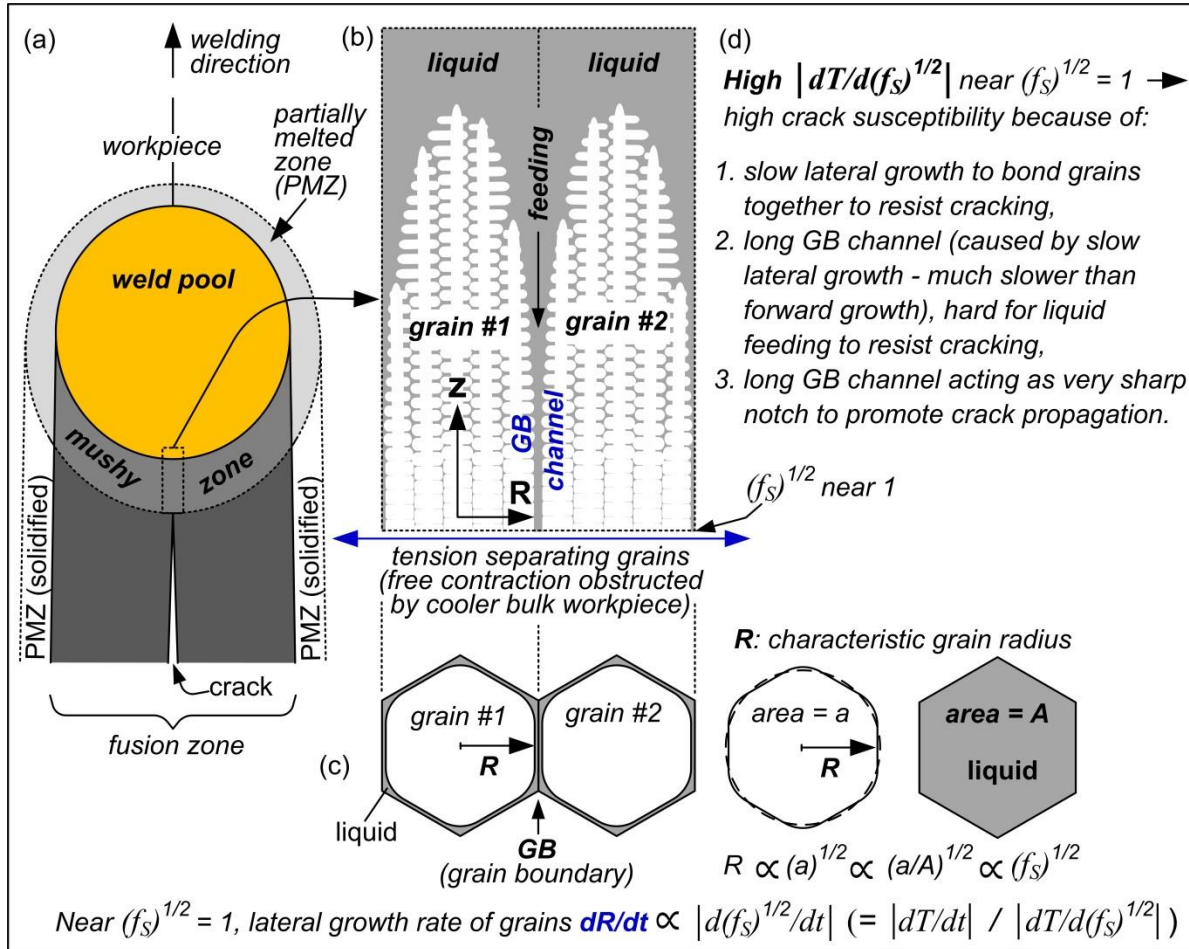


Fig. 3.1 Index for susceptibility to solidification cracking: (a) top view of welding zone; (b) columnar grains in boxed area in (a) growing along centerline of mushy zone; (c) transverse cross-sections of columnar grains near $(f_s)^{1/2} = 1$ showing lateral growth rate of the grains; (d) crack susceptibility index $|dT/d(f_s)^{1/2}|$ near $(f_s)^{1/2} = 1$

A high $|dT/d(f_s)^{1/2}|$ near $(f_s)^{1/2} = 1$ thus suggests a slow transverse growth rate for the grains to bond together and resist cracking as explained in Fig. 3.1d (Refs. 5, 6). It also suggests a long grain boundary channel to slow down (due to the viscosity of liquid) the liquid feeding needed to resist cracking (Ref. 7). The channel is long because grain growth is much slower in the transverse

direction than in the longitudinal direction. Furthermore, a long grain-boundary channel can provide a very sharp notch to help crack propagation. Thus, an alloy with a higher $\left| dT/d(f_s)^{1/2} \right|$ near $(f_s)^{1/2} = 1$ can be expected to be more susceptible to cracking during solidification (Refs. 5, 6).

Thus, Kou (Ref. 5) proposed to use the steepness $\left| dT/d(f_s)^{1/2} \right|$ of the curve of T vs. $(f_s)^{1/2}$ near $(f_s)^{1/2} = 1$ as the index for the crack susceptibility of Al alloys. The higher the index is, the greater the extent of crack propagation (Section 2.3.3, Kou (Ref. 5)). A high index also favors crack initiation but crack nucleation sites are required (Section 2.3.2, Kou (Ref. 5)), such as folded oxide films, gas trapped at the apex of oxides or the weld surface (Refs. 5, 8). Since the maximum steepness occurs near $(f_s)^{1/2} = 1$, he also proposed to use the maximum steepness $\left| dT/d(f_s)^{1/2} \right|$ as the index (Ref. 6). Extensive bonding between grains has to occur to end the crack susceptibility when too little liquid is left to form continuous liquid films along grain boundaries. He assumed this occurs at $(f_s)^{1/2} = 0.99$ or $f_s = 0.98$ (Ref. 6). Kou (Ref. 6) and Liu and Kou (Refs. 9-13) showed that the maximum steepness $\left| dT/d(f_s)^{1/2} \right|$ up to $(f_s)^{1/2} = 0.99$ works well as the crack susceptibility index for binary Al alloys and commercial wrought Al alloys. In the prominent RDG model proposed by Rappaz, Drezet and Gremaud in 1999 (Ref. 14), extensive bonding was also assumed to occur at $f_s = 0.98$. The RDG model, which considered both tensile deformation and shrinkage feeding, was the first hot-tearing model that has a physically sound basis. As already mentioned, Kou's criterion (Ref. 5) further considered the transverse growth of columnar grains to bond together and resist cracking.

Liu and Kou (Refs. 9-12) showed that $\left| dT/df_s \right|$ and hence $\left| dT/d(f_s)^{1/2} \right|$ can be significantly reduced if solute back diffusion from the interdendritic liquid into solid dendrites is significant.

The phase diagram of the binary Al-Mg system shows an unusually high solubility of Mg in the Al-rich solid phase, which promotes back diffusion of Mg significantly (Ref. 12). Thus, depending on the welding conditions involved, significant Mg back diffusion may occur. If so, the crack susceptibility can be reduced significantly (Refs. 9, 11, 12).

3.1.2. Crack susceptibility tests

Various tests for the susceptibility to solidification cracking have been reviewed recently by Kannengiesser and Boellinghaus (Ref. 15). The Murex, VDR and CTW tests are described briefly here as some readers might wish to compare them with the test developed in the present study. The Vareststraint test will be described in greater detail in a separate section subsequently. In the Murex hot-cracking test (Ref. 16), two parallel plates held edge-on (lap joint with zero overlap) are welded together along the joint line (where the two edges meet) while rotating one plate away from the other so as to open out the weld to cause cracking. The axis of rotation is the joint line. In the variable deformation rate (VDR) test (Ref. 17), on the other hand, a vertical plate at the top and a horizontal plate at the bottom forming an inverse-T joint are welded together while rotating the latter away from the weld to cause it to crack. In both tests the rotation speed is constant. The difference, however, is in the axis of rotation. It is parallel to the welding direction in the Murex test but normal to the welding direction in the VDR test as pointed out by Coniglio (Ref. 18).

The third test to be described here is the controlled tensile weldability test (CTW) of Coniglio et al. (Refs. 8, 18, 19). In this test, the workpiece is a single sheet that is bead-on-plate welded while being stretched normal to the welding direction to cause cracking by a horizontal tensile testing machine. A tensile testing machine is required because the solid workpiece needs a

significantly high tensile force to stretch. An extensometer is mounted from below the sheet across the bottom of the weld to measure the local tensile displacement rate across the mushy zone.

The main objective of the present study was to develop a simple test to address the several significant issues associated with the most widely used Varestraint test. Besides the Varestraint test, the present test is significantly different from other previously developed tests, including, the Murex, VDR and CTW tests. The present test, named transverse motion weldability (TMW) test, was used to check the validity of predicting the crack susceptibility of Al alloys based on the maximum $|dT/d(f_s)^{1/2}|$ as the crack susceptibility index (Ref. 6). It was intended to compare the crack susceptibility using the same crack susceptibility test under the same welding conditions, instead of using existing test data in the literature generated from different tests by different investigators under different welding conditions.

3.1.3. Commercial wrought Al alloys

Fig. 3.2a shows the curves of T vs. $(f_s)^{1/2}$ for commercial wrought Al alloys 2024 Al, 2219 Al, 6061 Al and 7075 Al. Commercial thermodynamic software packages Pandat (Ref. 20) and Al database PanAluminum (Ref. 21) were used to calculate these curves (Ref. 6). Pandat (Ref. 20) is not yet set up to calculate diffusion in multicomponent Al alloys. Thus, the Scheil solidification model (Ref. 2) was adopted, which is considered more realistic than the equilibrium solidification model. However, the equilibrium segregation coefficient k and the liquidus slope m_L were both temperature dependent.

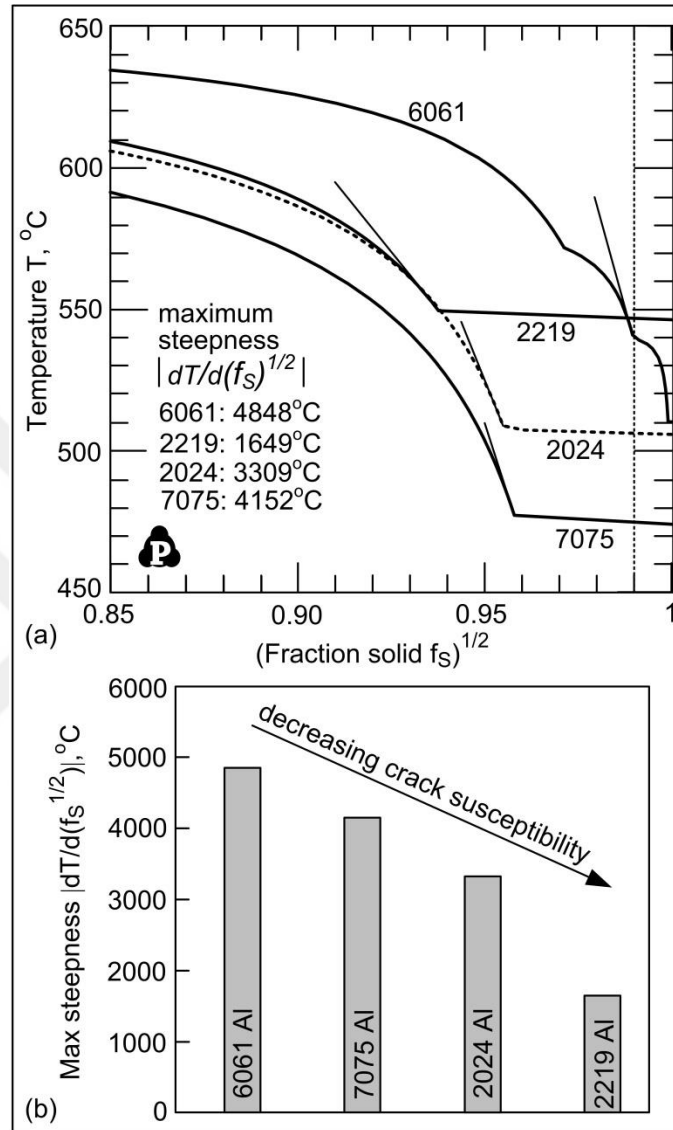


Fig. 3.2 Crack susceptibility of wrought Al alloys 6061 Al, 7075 al, 2024 Al and 2219 Al: (a) $T-(f_s)^{1/2}$ curves showing maximum steepness $|dT/d(f_s)^{1/2}|$ up to $(f_s)^{1/2} = 0.99$, beyond which extensive bonding is assumed to occur and end crack susceptibility; (b) predicted crack susceptibility based on the maximum steepness decreases in the order of 6061 Al, 7075 al, 2024 Al and 2219 Al (Ref. 6)

The maximum steepness $|dT/d(f_s)^{1/2}|$ up to $(f_s)^{1/2} = 0.99$ is shown in Fig. 3.2a. As mentioned previously, extensive bonding is assumed to end the crack susceptibility at $(f_s)^{1/2} = 0.99$ because the liquid remaining may be too little to form continuous liquid films along grain boundaries to

cause solidification cracking. The maximum steepness $\left| dT/d(f_s)^{1/2} \right|$ up to $(f_s)^{1/2} = 0.99$ is highest for 6061 Al. Thus, near the end of solidification, its columnar grains grow most slowly toward each other to bond together and resist cracking and its liquid feeding to resist cracking is most difficult. Fig. 3.2b shows the ranking of the alloys based on the maximum steepness $\left| dT/d(f_s)^{1/2} \right|$ up to $(f_s)^{1/2} = 0.99$ as the index for the solidification cracking susceptibility. As shown, 6061 Al ranks the highest in the cracking susceptibility index. The index decreases in the order of 6061 Al, 7075 Al, 2024 Al and 2219 Al, suggesting the crack susceptibility decreases in the same order.

3.2. Experimental Procedure

A simple test for the solidification cracking susceptibility, called transverse motion weldability (TMW) test, was developed in the present study. 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 Vareststraint testing, it was decided to weld together two pieces while one piece moves in a straight line normal to the welding direction at speed V . This approach is very simple to use and analyze the test results because V is the transverse displacement rate of the mushy zone during welding. This is the local displacement rate in the mushy zone that causes solidification cracking - not the global deformation rate in the workpiece.

Fig. 3.3a is a schematic sketch of lap welding two sheets in accordance with the new methodology. During welding, the upper sheet is stationary while the lower sheet moves at speed V normal to the welding direction to cause tension in the mushy zone. The mushy zone is subjected to a tensile displacement rate $V = dD/dt$, where D is displacement. Fig. 3.3b is a photo showing part of the apparatus. The torch for gas-tungsten arc welding (GTAW, also called TIG welding) is positioned near its ending position instead of starting in order not to block the view of the lap joint.

The lower sheet is 3.2 mm thick, 102 mm wide and 127 mm long, and the upper sheet 3.2 mm thick, 152 mm wide and 51 mm long. The surface of each sheet near the joint was cleaned with a steel brush to remove the oxides and then cleaned with acetone before welding. A different thickness can also be used, e.g., 1.6 mm. Table 3.1 shows the compositions of the workpiece used in the present study.

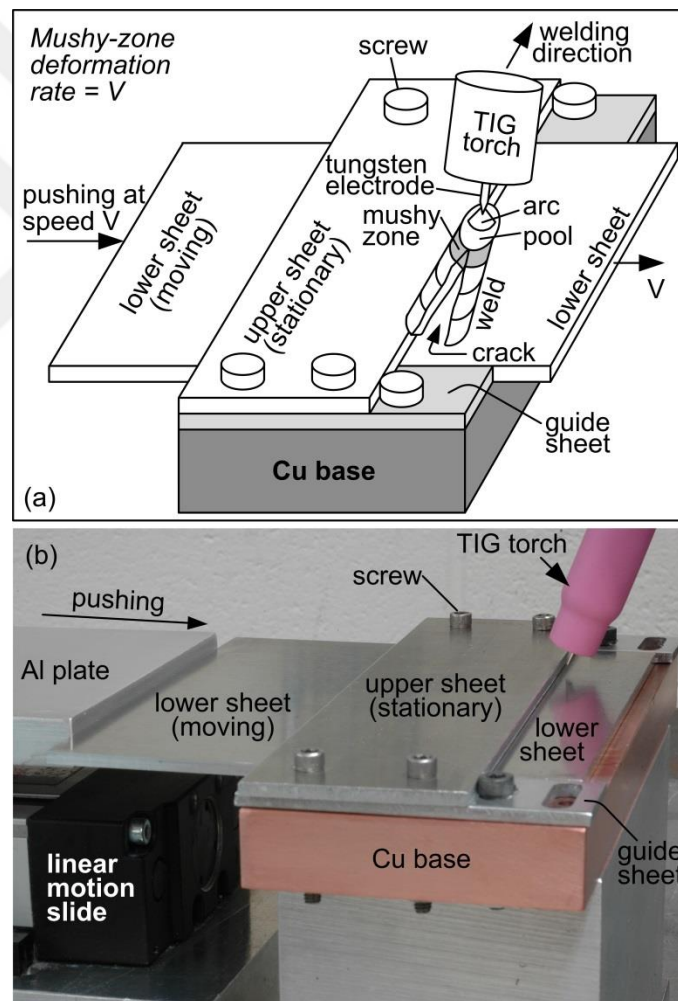


Fig. 3.3 Simple novel solidification cracking test, called transverse motion weldability (TMW) test, developed in the present study (a) schematic sketch; (b) apparatus. A stationary upper sheet is lap welded to a lower sheet moving at a constant speed V normal to the welding direction to cause cracking

Table 3.1 Compositions of workpiece materials in wt%

	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al
2024	0.09	0.19	4.4	0.57	1.4	0.01	-	0.14	0.02	Bal.
2219	0.16	0.12	5.82	0.33	0.004	0.002	0.03	0.02	0.04	Bal.
6061	0.72	0.6	0.33	0.08	1.0	0.20	-	0.10	0.02	Bal.
7075	0.07	0.17	1.5	0.03	2.4	0.19	-	5.7	0.03	Bal.

Initially, the leading edge of the lower sheet stuck out beyond the upper sheet by 19 mm. The lower sheet was moved normal to the welding direction by a 12.7 mm thick Al plate mounted on a lead-screw assembly driven by a motor. A small ordinary motor can be used because the mushy zone is semisolid and thus very weak. For programming purposes, however, a servomotor was used, with its control unit hooked up to a computer for both speed control and data acquisition.

Lap welding was conducted by gas-tungsten arc welding without a filler metal. The welding conditions were as follows: Ar shielding at $3.54 \times 10^{-4} \text{ m}^3/\text{s}$ (45 cfh), AC polarity with 70% balance (70% electrode negative polarity and 30% electrode positive polarity), 160 A welding current, 2.1 mm/s torch travel speed, 3.2 mm diameter tungsten electrode with about 15° electrode tip angle. The torch was tilted 20° toward the joint. These same welding parameters were used for testing the crack susceptibility of the four different alloys 2219, 2024, 6061, 7075 Al. Constant welding parameters may not be the best way to compare the crack susceptibility of different Al alloys. But it would be very difficult to find different welding parameters for different alloys such that they all have the same weld pool size, cooling rate, temperature gradient, etc. to be tested for the crack susceptibility and compared.

The present test was conducted in the following order: (1) the lower sheet was put in motion, (2) the arc was initiated, and (3) the torch was moved in the welding direction at about 2 seconds after arc initiation to allow a weld pool to form between the lower and upper sheets. The servomotor was programmed to push the lower sheet at 0.7 mm/s for a distance up to about 30 mm before making a step change to a lower predetermined constant speed, e.g., 0.1 mm/s. The higher initial moving speed of 0.7 mm/s was to ensure successful crack initiation. The servomotor was set at a maximum torque of 1 Nm (Newton meter). The servomotor automatically stopped when crack stopped propagating.

After welding, the fracture surface of the fusion zone was examined. For microstructural analysis, the welds 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).

3.3. Results and Discussion

3.3.1. The present test

Fig. 3.4 shows a weld made by welding 7075 Al at the torch travel speed of 2.1 mm/s without a filler metal. The speed of the lower sheet was 0.70 mm/s up to about 30 mm of the starting end of the weld, before being stepped down to 0.1 mm/s for the rest of the weld. This is why the crack is wider in the initial 30 mm of the weld. As mentioned previously, the higher initial moving speed, 0.7 mm/s, was to ensure successful crack initiation.

Fig. 3.5 shows the SEM images of the fracture surface of the 7075 Al weld shown in Fig. 2.4. Dendrite arms are visible, which confirms cracking occurred during solidification, that is, solidification cracking. Fig. 3.6a shows the transverse cross-section of the same weld near the end of the crack. Cracking is intergranular as can be seen in Fig. 3.6b.

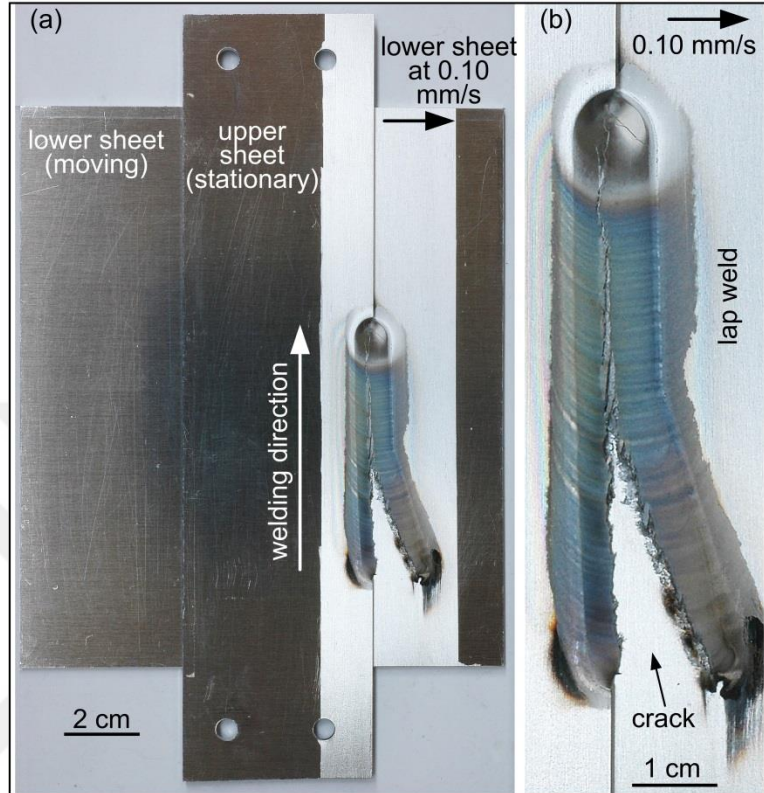


Fig. 3.4 Workpiece after testing: (a) overview (no distortion); (b) weld enlarged. Workpiece: 7075 Al; travel speed: 2.1 mm/s; lower sheet moving speed: 0.10 mm/s (initially 0.70 mm/s up to about 30 mm weld length to ensure crack initiation)

Fig. 3.7 shows the normalized crack length $L_{\text{crack}}/L_{\text{weld}}$, where L_{crack} and L_{weld} are, respectively, the crack length and the weld length corresponding to the moving speed at which crack propagation was tested. These lengths exclude the initial portions produced under the high moving speed (0.70 mm/s) of the lower sheet to ensure crack initiation. Since the welds were not identical in length though close, it was decided to use the normalized crack length instead of the crack length itself.

Fig. 3.8 shows the test results of 2024 Al. The normalized crack length $L_{\text{crack}}/L_{\text{weld}}$ is plotted against the moving speed of the mushy zone V , which is also the moving speed of the lower sheet to cause crack propagation. A blue curve is drawn to best fit the data points. As shown, the normalized crack length increases from 0 at about $V = 0.095$ mm/s to 1.0 at $V = 0.15$ mm/s. Thus,

a transition range of V exists over which the normalized crack length increases from 0 to 1.0. Thus, this transition range will be called as the critical moving speed of the lower-sheet V_c and $V_c = 0.125 \pm 0.0275$ mm/s for welding 2024 Al under the welding conditions used here.

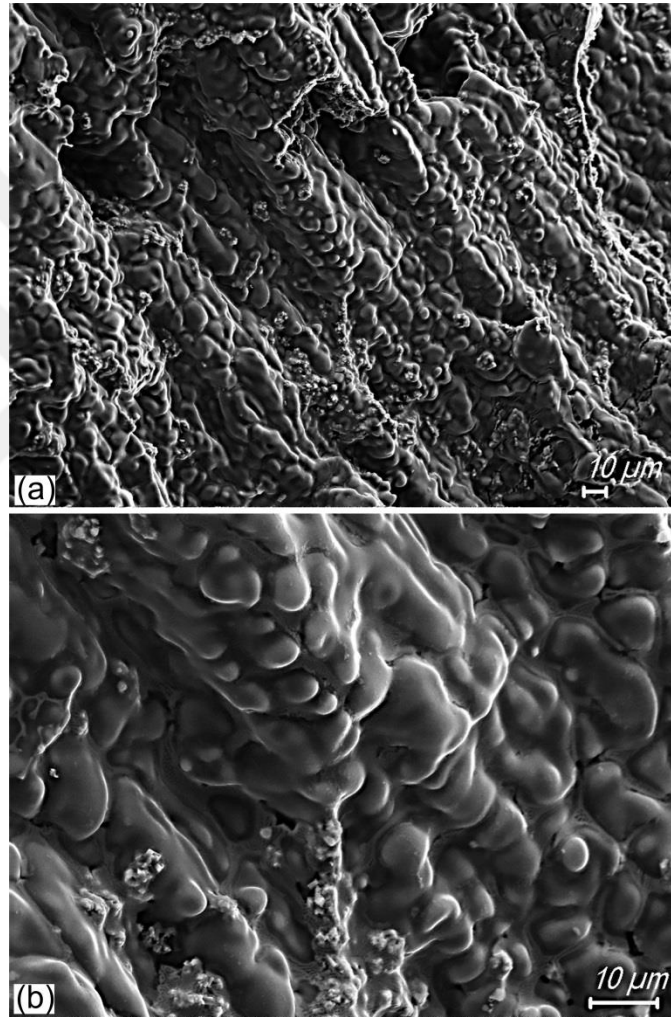


Fig. 3.5 SEM images of the fracture surface of the 7075 Al weld in Fig. 3.4: (a) Lower magnification; (b) higher. The dendritic feature of the fracture surface confirms solidification cracking

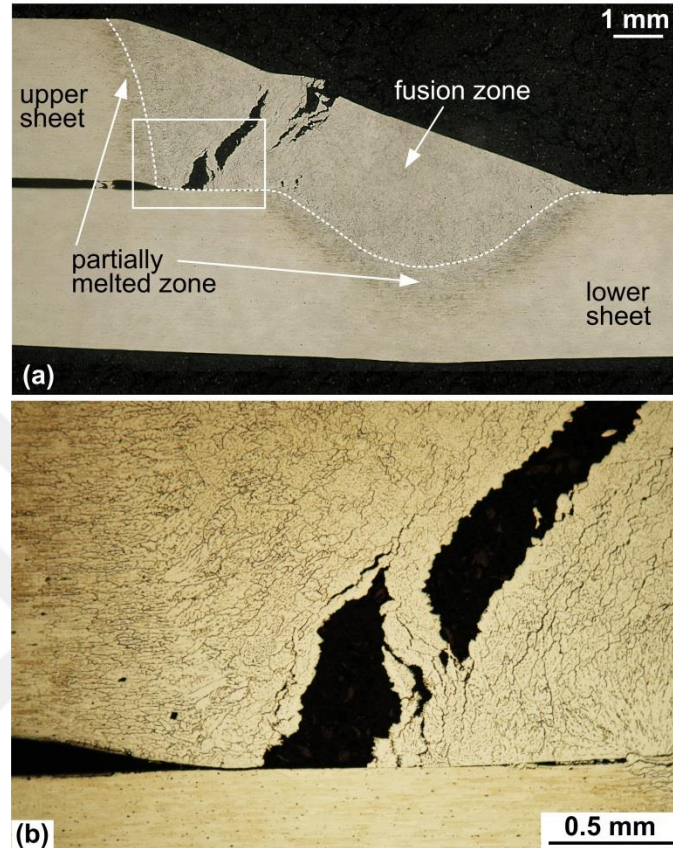


Fig. 3.6 Transverse cross-section showing solidification cracking in the 7075 Al weld in Fig. 3.4: (a) macrograph; (b) micrograph in boxed area in (a) showing solidification cracking is intergranular

Referring to Fig 3.8 again, the blue curve represents eight data points, and the shaded area represents the critical moving speed of the lower-sheet V_c from no to full crack propagation. All data points beyond the V_c show 100% normalized crack length, and all those before the V_c showed 0% crack propagation. This indicates good reproducibility outside the V_c . The data points near the V_c were repeated. The two data points at 0.15 mm/s are nearly identical to each other and nearly 100%. Thus, 0.15 mm/s was taken as the upper bound of the V_c . At 0.10 mm/s the two data points are $6 \pm 6\%$. So, the lower bound was taken slightly below 0.10 mm/s, i.e., 0.095 mm/s. Thus, the reproducibility of the present test for 2024 Al is acceptable. Data scatter occurs only within the

V_c , which is not unusual for something in transition. Similar test results are shown in Fig. 3.9 for alloy 2219 Al and Fig. 3.10 for 7075 Al. The reproducibility of the present test is again acceptable.

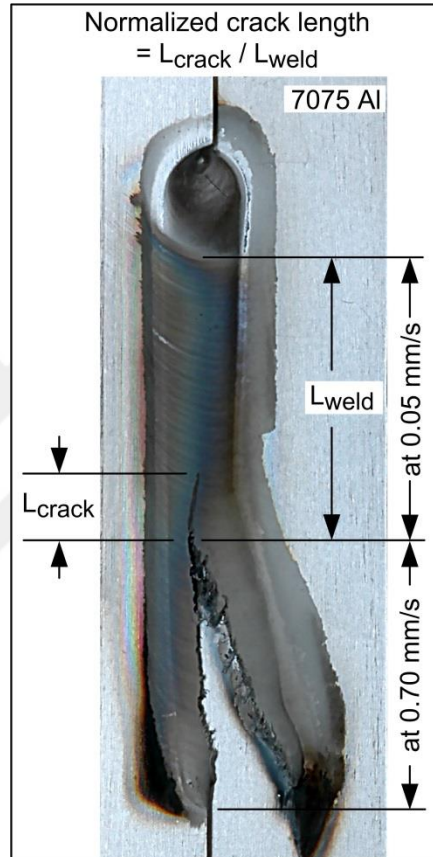


Fig. 3.7 Normalized crack length L_{crack}/L_{weld} , where L_{crack} and L_{weld} are respectively crack length and weld length produced under the moving speed intended for crack propagation (0.05 mm/s in this case). The initial ones under 0.70 mm/s to ensure crack initiation are excluded

The results for 6061 Al are shown in Fig. 3.11. Again, all data points beyond the V_c show 100% normalized crack length, and the two data points at 0.05 mm/s are nearly identical at 100%. These data points show good reproducibility of the upper bound of V_c . It is interesting to see that solidification cracking can occur at $V = 0$ mm/s, that is, without any externally applied tensile deformation. The data points scatter a lot but, as mentioned previously, significant data scatter is not unusual for something in transition. Kou (Ref. 6) showed solidification cracking in a 1.6 mm

thick sheet of 6061 Al bead-on-plate welded by gas-tungsten arc welding without a filler metal. No tension was applied externally during welding. With the servo motor programmed to suddenly reverse the moving direction of the lower sheet, a compressive displacement rate of 0.05 mm/s, that is, $V = -0.05$ mm/s, was applied and cracking was reduced. This was also observed by Coniglio and Cross in 6061 Al (Refs. 8, 19). It suggests that in a highly crack-susceptible alloy like 6061 Al, the tension induced by shrinkage is high and the amount of liquid available near the end of solidification to feed the shrinkage is small. Consequently, cracking can occur without externally applied tension and compression is needed to reduce cracking. This is consistent with the criterion proposed by Kou (Ref. 5) for solidification cracking. No tests were conducted at moving speed more negative than $V = -0.05$ mm/s. This is because crack initiation needs to occur first before crack propagation can be examined. Reversing from $V = 0.7$ mm/s to $V = -0.10$ or -0.20 mm/s instantaneously was difficult to do with the servo motor used in the present study.

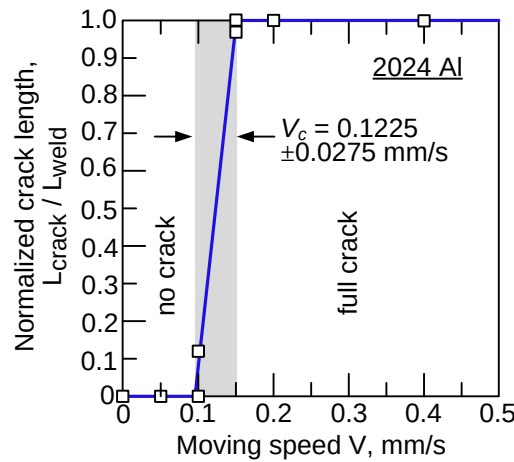


Fig. 3.8 Test results of 2024 Al. The highlighted area shows the critical lower-sheet speed V_c from no crack propagation at $V = 0.095$ mm/s to full crack propagation at $V = 0.150$ mm/s. $V_c = 0.1225 \pm 0.0275$ mm/s

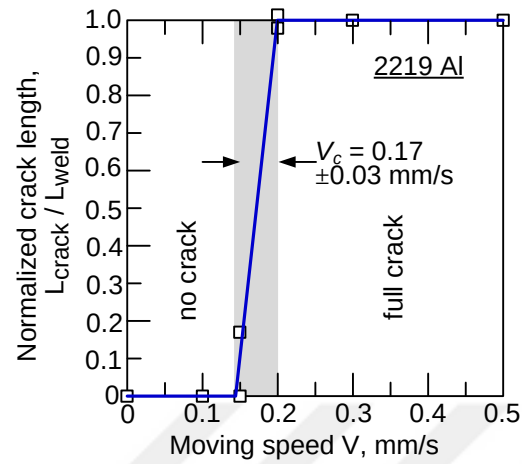


Fig. 3.9 Test results of 2219 Al. $V_c = 0.17 \pm 0.03$ mm/s

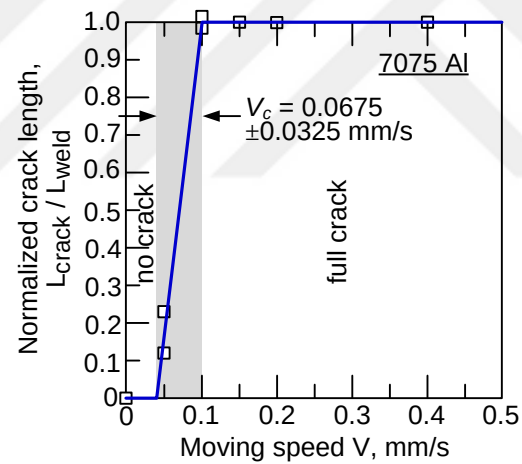


Fig.3.10 Test results of 7075 Al. $V_c = 0.0675 \pm 0.0325$ mm/s

Fig. 3.12 summarizes the V_c of the four Al alloys shown in Figs. 3.8 through 3.11. As shown, the V_c increases in the order of 6061 Al, 7075 Al, 2024 Al and 2219 Al. This indicates that the crack susceptibility decreases in the same order. The crack susceptibility is lower if V_c at a higher V level because the fact that a faster moving speed V is required to cause crack propagation means the more difficult it is for crack propagation to occur and hence a lower crack susceptibility.

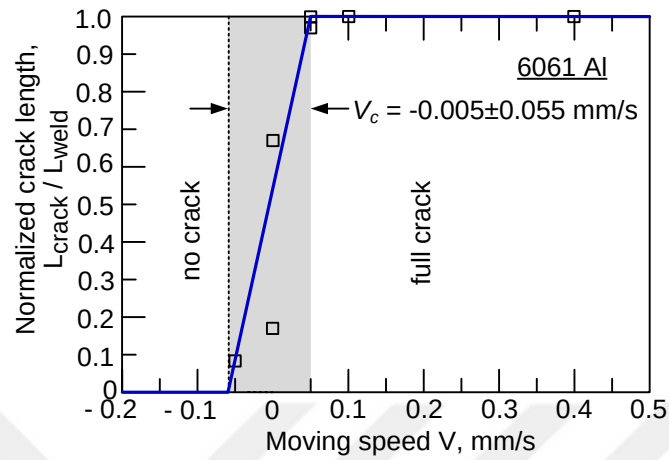


Fig. 3.11 Test results of 6061 Al. $V_c = -0.005 \pm 0.055$ mm/s

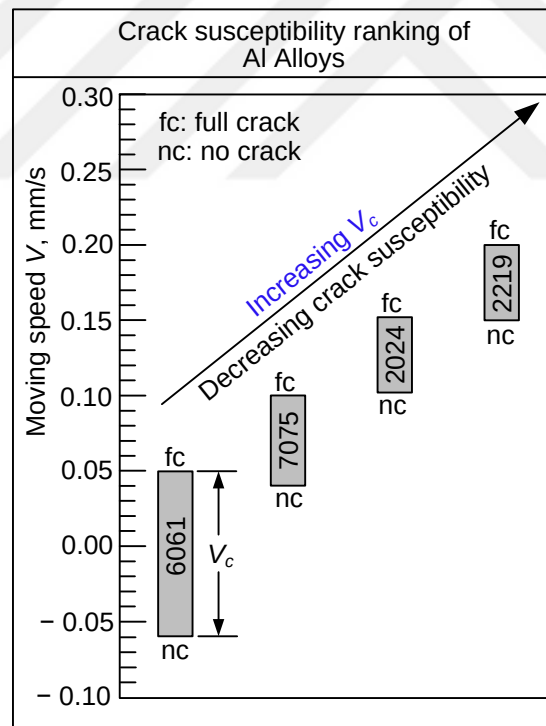


Fig. 3.12 The critical lower-sheet moving speed V_c increasing, i.e., the crack susceptibility decreasing, in the order of 6061 Al, 7075 Al, 2024 Al and 2219 Al, consistent with the predicted crack susceptibility in Fig. 3.2b based on the maximum steepness $|dT/d(f_s)^{1/2}|$ as the crack susceptibility index

The order of the crack susceptibility of wrought Al alloys shown in Fig. 3.12 is consistent with the predicted one shown in Fig 3.2b. Thus, the present test can be used to check the validity of

predicting the crack susceptibility based on the maximum steepness $\left| dT/d(f_s)^{1/2} \right|$ up to $(f_s)^{1/2} = 0.99$ as the crack susceptibility index. It is worth mentioning that the crack susceptibility ranking shown in Fig. 3.12 is also consistent with reported test data in the literature (Refs. 6, 22, 23).

The results in Figs. 3.8 through 3.11 demonstrate clearly the key role played by the deformation (or strain) rate in solidification cracking. Below the V_c , cracking cannot propagate. This is consistent with the criterion for solidification cracking proposed by Kou (Ref. 5). As illustrated in Fig. 3.1d, 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. Coniglio and Cross (Ref. 8) have also reported the significant role of the strain rate.

3.3.2. Differences from Murex, VDR and CTW tests

To test the susceptibility of an alloy to cracking during solidification in welding, significant tension needs to exist during solidification, either self-induced tension or tension imposed on the workpiece before welding or tension imposed on the workpiece during welding. In principle, all tests are similar because they all use tension to cause cracking during solidification. In reality, however, tension is induced or imposed in a distinctly different way in each test. For instance, tension can be self-induced by making a circular weld or a ring casting. The workpiece can be stretched before welding either normal or parallel to the welding direction. Tension can be imposed during welding by stretching the workpiece either normal or parallel to the welding direction, or by rotating one member of the workpiece relative to the other, with the axis of rotation either parallel or normal to the welding direction. Each test has been considered as a different test and given a different name (Refs. 1, 15). To the best knowledge of the authors, tension has not been imposed during welding by taking the simple action of merely moving one member of the workpiece in a straight line normal to the welding direction.

In the VDR test (Ref. 17) the weld is split in half along the weld centerline, with a curved half weld on the lower plate. This may make the present test look similar to the VDR test even though in the present test the half weld on the lower sheet is straight instead of curved. More importantly, the present test differs from the VDR test in several significant ways. First, the lower piece is rotated in the VDR test but it moves in a straight line in the present test. The mechanism required for rotating the lower plate while welding it to a stationary plate makes the VDR test apparatus very complicated and big as shown by its schematic sketch and photo (Ref. 17). The present test, however, does not require any rotation at all. Only a motor mounted on a sliding stage is needed to move the lower sheet in a straight line. The test apparatus is very simple, compact and easy to use as already shown in Fig. 3.3. The VDR test is rarely used if it has been used at all.

Second, even though the angular rotation speed ω is constant in the VDR test, the radius of rotation R and hence the deformation rate $R\omega$ continue to decrease during welding. This is why “variable deformation rate” is the name of this test. As the torch moves toward the axis of rotation during welding, the radius of rotation R decreases. In the present test, however, the deformation or displacement rate can be constant or programmed to decrease, increase or even reverse from tension to compression during welding with the help of the servo motor.

Third, since the deformation rate decreases during the VDR test, the deformation rate at which the crack stops is taken as the critical deformation rate $R_c\omega$, where R_c is the radius at which the crack stops. The VDR test results showed wide scatter in R_c . During the early stage of the present study, it was thought that the critical deformation or displacement rate could be determined in one single experiment if the motor speed and hence the displacement rate were programmed to decrease during welding. Unfortunately, wide scatter in the critical displacement rate was

encountered. Since then, it was decided to keep the displacement rate constant during crack initiation, decrease it suddenly to a lower level, and then keep it constant at the lower level for crack propagation. It is not possible to keep the deformation or displacement rate constant in the VDR test to reduce data scatter or other problems because the radius of rotation R and hence the deformation or displacement rate $R\omega$ decrease monotonically during welding.

As for the Murex test (Ref. 16) and the CTW test (Refs. 8, 18, 19), the welds crack along the weld centerline but they do not split and open wide like the welds in the present study (Fig. 3.4a). (The open crack makes the fracture-surface sample easy to prepare.) This is because these tests are very different from the present test in the first place. As already mentioned, in the Murex hot-cracking test (Ref. 16) two parallel plates held edge-on are welded together along the joint line (where the edges meet) while rotating one plate away from the other to cause cracking. There is nothing close to this procedure in the present test. The requirement for a mechanism to rotate one plate while welding it to the other makes the apparatus much more complicated and bigger than that in the present test. In the CTW test (Refs. 8, 18, 19) the workpiece to be welded is a single sheet and it is stretched in the transverse direction by a tensile testing machine during welding. An extensometer is mounted across the bottom of the weld to determine the tensile strain. There is nothing close to this procedure in the present test, either. Since a tensile test machine is not required in the present test, the cost of the apparatus is very low. It is believed that the present test is different from all previous tests including, the Murex, VDR and CTW tests.

3.3.3. Comparing the present test with Varestraint test

As mentioned previously, the main objective of the present study was to develop a test that overcomes several significant issues in the most widely used Varestraint test. For convenience of

discussion, the Varestraint test is shown schematically in Fig. 3.13. It was originally developed by Savage and Lundin (Ref. 24) in 1965 and it has become the most widely used test for solidification cracking since then. In this test, the workpiece is bent suddenly against a mandrel (the bending block) during welding to induce cracking. The applied strain $\varepsilon = H/(2R+H) \times 100\%$, where R is the radius of curvature of the mandrel and H the specimen thickness. Since the targeted strain is not reached until the workpiece is bent fully against the mandrel, bending needs to be very fast (i.e., sudden bending) to ensure that all cracks form under the same level of strain. Consequently, the deformation rate is unrealistically high and the global deformation rate of the workpiece does not reveal the local deformation rate of the mushy zone that causes cracking.

Coniglio (Ref. 18) indicated that in Varestraint testing, the applied strain is global in the workpiece rather than local within the mushy zone and that the strain rate is very high. He pointed out that 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 that in Varestraint testing the weld metal shows significantly higher strains (over 2 %) and strain rates (over 100 %/s) than the applied strain (0.5 %) and strain rate (40 %/s) calculated based on $\varepsilon = H/(2R+H) \times 100\%$. Nakata et al. (Ref. 25) subsequently lowered the strain rate, called the slow-bending Varestraint test. However, according to Coniglio (Ref. 18), the global strain in the workpiece still does not represent the local strain in the mushy zone that causes solidification cracking.

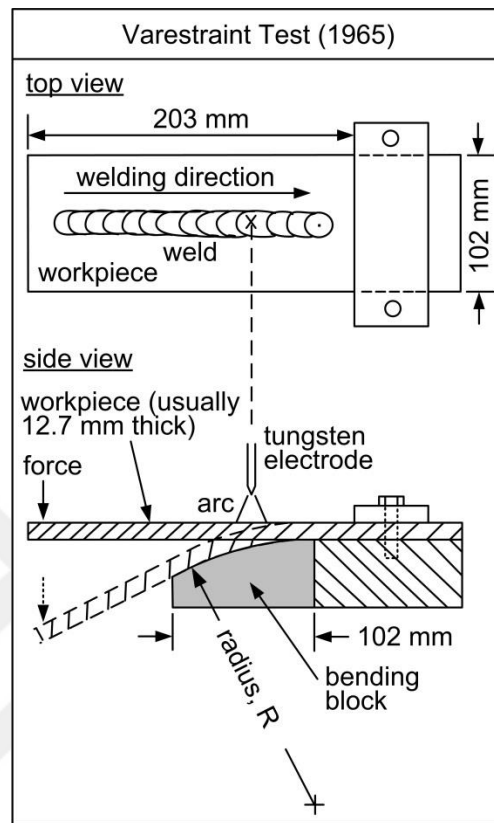


Fig. 3.13 The Varestraint test (Ref. 24), which has become the most widely used test for solidification cracking since 1965. The workpiece is bent suddenly during welding to cause cracking, but the deformation rate is unrealistically high and workpiece deformation cannot reveal the mushy zone deformation that actually causes cracking

Unlike Varestraint testing, the present test can cover the realistic range of deformation or displacement (or strain) rate in welding practice. Nakata et al. (Ref. 25) and Matsuda et al. (Ref. 26) observed a strain rate of 0.6 - 5.3% per second across the weld width in gas-tungsten arc welding of Al sheets without a filler metal. When the mushy zone is under tension in the transverse direction, the tensile strain is distributed across the width of the mushy zone. Thus, the displacement rate range can be divided by the width of the weld (about 8 mm on the average) and converted to a range of strain rate from 0 to 0.0623 per second. That is, from 0 to 6.23% per second. Thus, in the present test the strain rate covers that observed by Nakata et al. (Ref. 25) and Matsuda

et al. (Ref. 26). In fact, the servo motor can be set up to move the lower sheet over a very wide range of displacement rate. This displacement rate cannot be compared with that in the Vareststraint test, which is a global strain distributed in the entire workpiece.

One major advantage of the present test is that filler metals can be used to evaluate their significant effect on solidification cracking. This advantage has been demonstrated (using gas-metal arc welding) and the results agreed well with both published filler-metal guides and available experimental data. These results are published elsewhere (Ref. 27). In the Vareststraint test, as shown in Fig. 3.13, welding is conducted by the gas-tungsten arc welding process without a filler metal. No filler metal can be used because its deposit forms a crown on the top of the weld, which makes the specimen thickness H vary across the width of the weld. As mentioned previously, the applied strain $\varepsilon = H/(2R+H) \times 100\%$, where H is the thickness of the plate (specimen) and R the radius of the bending block. If a filler metal is used, for instance, through gas-metal arc welding (GMAW), in the Vareststraint test to study its effect on solidification cracking, it is deposited on the flat plate as a weld with a crown above the top surface of the plate. In other words, H increases from the original plate thickness at the weld edge to that plus the crown height at the weld central plane. The test result is no good because H and hence ε vary across the weld instead of being constant at the targeted values. In order to use the Vareststraint test to evaluate the effect of a filler metal on the crack susceptibility, the crown on the weld must be milled off first so that H is constant. The flat plate without the crown can then be used for Vareststraint testing by gas-tungsten arc welding (GTAW) without a filler metal. But the test result is still no good unless the gas-tungsten arc weld is made entirely within the first weld containing the filler metal. For instance, Lippold et al. (Ref. 28) 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 GMAW, and then removed the weld crown by milling to make H constant. The specimen prepared by this 3-step procedure was then used for Varestraint testing, with GTAW restricted to within the weld made previously by GMAW.

In the present test, the critical moving speed of the lower-sheet V_c is a piece of quantitative information showing the transition from no crack propagation to full crack propagation, and it can be useful for quantitative studies on solidification cracking such as computer simulation. In the Varestraint test, however, the maximum or total crack length used as the index for the crack susceptibility is only a qualitative piece of information.

The critical moving speed of the lower sheet V_c can be explained as follows. As mentioned previously, Kou's criterion (Ref. 5) for solidification cracking considered three factors at the grain boundary between two columnar dendritic grains growing side by side in their axial direction in the mushy zone. The first factor is the separation of the grains from each other under transverse tensile strain (induced by obstructed shrinkage) to cause cracking. The second factor is the transverse growth of the grains toward each other to bond together to resist cracking. The third factor is the liquid feeding along the grain boundary to feed shrinkage and thus resist cracking. In the proposed test, the moving lower sheet induces tensile strain in the mushy zone to separate the columnar grains and cause solidification cracking. When the moving speed is low, there is plenty of time for the columnar grains to grow toward each other and bond together to resist cracking. Liquid may also have plenty of time to flow along the grain boundary between the two grains to feed shrinkage and resist cracking. Consequently, there is no crack propagation. When the moving speed is increased to separate the grains more quickly, less time is available for transverse growth of grains and intergranular liquid feeding to resist cracking. Consequently, propagation can start to occur. With an even faster moving speed, crack propagation can continue throughout the weld.

In the present test, liquation cracking cannot interfere with solidification cracking because it either does not occur at all or is extremely slight. In the Varestraint test, however, significant liquation cracking is common. As shown in Fig. 3.1a, a partially melted zone (PMZ) exists next to the weld pool. In the PMZ liquid formation (called liquation) occurs along grain boundaries (and within grains) and intergranular cracking can occur if the PMZ is under tension (called liquation cracking (Ref. 1)). In the Varestraint test, the PMZ as well as the mushy zone is suddenly bent. Thus, liquation cracking can occur along with solidification cracking. Multiple open cracks are often visible in the PMZ after Varestraint testing. When liquation cracking occurs, the strain in the nearby mushy zone is relaxed and solidification cracking can be reduced or stopped (Refs. 29, 30). In the transverse version of Varestraint testing developed by Senda et al. (Refs. 31, 32) in 1971, liquation cracking is reduced but can still occur.

The present test is simple, requiring only a motor instead of both a pneumatic system and a series of bending blocks as in Varestraint testing. Thus, the equipment cost is significantly less than that for Varestraint testing. The amount of the workpiece material required is small in the present test. As mentioned previously, the lower sheet was 127 mm x 102 mm x 3.2 mm, and the upper sheet 152 mm x 51 mm x 3.2 mm. In the Varestraint test, the standard workpiece is much bigger, i.e., 203 mm x 102 mm x 27 mm.

3.4. Conclusions

1) A simple test, called transverse motion weldability test (TMW), for solidification cracking has been developed and used to check the validity of the recently proposed prediction of the crack susceptibility of one Al alloy relative to that of another based on the maximum steepness $\left| dT/d(f_s)^{1/2} \right|$ of the $T-(f_s)^{1/2}$ curve.

2) In the present test a stationary sheet is lap-welded to a sheet moving at the speed V in a straight line normal to the welding direction. The test is useful because V is the transverse tensile displacement rate of the mushy zone that causes solidification cracking.

3) By plotting the normalized crack length against V , the range of V over which the transition from no crack propagation to full crack propagation occurs can be determined, i.e., the critical moving speed of the lower-sheet V_c .

4) The higher the V_c is, a faster displacement rate or moving speed V is required to cause crack propagation, that is, the lower the crack susceptibility becomes.

5) The V_c increases, that is, the crack susceptibility decreases, in the order of 6061 Al, 7075 Al, 2024 Al, and 2219 Al, consistent with the predicted order of crack susceptibility. This shows that the crack susceptibility can be predicted based on the maximum steepness $\left|dT/d(f_s)^{1/2}\right|$ as the crack susceptibility index.

6) The test results demonstrate the key role of the displacement or strain rate. Below the V_c , cracks cannot propagate. This is consistent with criterion proposed by Kou for solidification cracking, i.e., two columnar 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.

7) Unlike the most widely used Varestraint test, the present test can impose slow displacement rates as those in welding practice, reveal the local displacement rate in the mushy zone that causes cracking, determine the V_c over which transition from no to full crack propagation occurs, keep liquation cracking from interfering with solidification cracking, allow the use of filler metals to evaluate their significant effect on solidification cracking, and significantly reduce the cost of the apparatus and the amount of workpiece material required.

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4. TESTING FILLER-METAL EFFECT IN WELDING AL ALLOYS 2024 AND 6061

4.1. Introduction

Welds of aluminum (Al) alloys are known to be susceptible to cracking during solidification. Because of solidification shrinkage (solid density > liquid density) and thermal contraction, the mushy zone (a weak semisolid between the weld pool and the solidified weld metal) must shrink. However, the mushy zone cannot shrink freely because it is connected to the much bigger and more rigid workpiece. Shrinkage can be more difficult if the workpiece is clamped down tightly. This obstructed shrinkage induces tensile deformation in the transverse direction of the mushy zone to cause cracking. To reduce the crack susceptibility, filler metals with nonmatching compositions are often required to adjust the composition of the weld metal in the fusion zone. Friction-stir welding can produce good-quality Al welds. However, arc welding can still be more versatile and cost effective in many applications if effective measures can be taken against the formation of defects in welds, especially cracking during solidification.

Dudas and Collins (Ref. 1) studied the susceptibility of high strength wrought Al alloys to solidification cracking in welding with matching and non-matching filler metals. 2024 Al was reported as the most crack-susceptible alloy in the 2000-series (Al-Cu) alloys, and 6061 Al the most crack-susceptible of all the Al alloys tested (Ref. 1). The filler metal 4043 Al significantly reduced crack susceptibility of 6061 Al, but no filler metal was reported to reduce the crack susceptibility of 2024 Al (Ref. 1).

Many solidification cracking tests have been developed to evaluate the crack susceptibility of alloys. So far, the solidification cracking test most widely used in the welding industry and research has been the Varestraint test developed by Savage and Lundin (Ref. 2). The standard workpiece is

203 mm long by 102 mm wide by 12.7 mm thick. During welding, the workpiece of thickness H is suddenly bent in the welding direction against a mandrel (bending block) of predetermined radius R . A tensile strain of $\varepsilon = H/(2R+H) \times 100\%$ is induced at the top surface of the workpiece. The strain induces tension in the mushy zone to cause solidification cracking. The total or maximum crack length is used as the index for the susceptibility to solidification cracking. A transverse version of the Varestraint test, called transverse Varestraint, was subsequently developed by Senda et al. (Refs. 3, 4), in which the workpiece is bent suddenly in the transverse direction of welding instead of longitudinal.

Coniglio (Ref. 5) pointed out that the tensile strain ε in the Varestraint test is the global strain in the workpiece, instead of the local tensile strain in the mushy zone responsible for solidification cracking. He also pointed out that the strain rate caused by sudden bending is too fast as compared to that in welding practice. Another issue is associated with evaluating the effect of a filler metal on solidification cracking. The filler metal increases H by forming a crown on the workpiece surface. The crown height varies across the width of the weld, so does H and hence ε . This issue may be ignored if only a qualitative comparison of weldability is needed, without specifying the strain level of the weld. To avoid this issue, however, a two-step procedure is needed, an example of which was described by Lippold and Savage (Ref. 6). The first step is to make a bead-on-plate weld with a filler metal, and then remove the crown by milling to ensure a flat workpiece surface. The second step is to conduct the normal Varestraint test (gas-tungsten arc welding without a filler metal) by making a smaller weld within the fusion boundary of the first weld.

To help address these and other issues (such as the interference of solidification by liquation cracking) associated with Varestraint testing (Refs. 2, 3, 4), Soysal and Kou (Refs. 7, 8) developed

a simple test, called Transverse-Motion Weldability (TMW) test, in which lap welding is conducted while the lower sheet moves normal to the welding direction at a predetermined speed to induce transverse tension in the mushy zone and cause solidification cracking. As the lower sheet moves at the speed V , the weld edge on it also moves away at V from the stationary weld edge on the upper sheet. In the TMW test V can be as slow as that in actual gas-tungsten arc welding, in which one weld edge also moves away from the opposite weld edge spontaneously as shown by Matsuda et. al. (Ref. 9). The test can be conducted with or without a filler metal for welding. Filler metals were used and the test results (Ref. 7) were consistent with the filler metal guides (Refs. 10, 11). The test was also conducted without filler metals (Ref. 8). The crack susceptibility ranking was 6061 Al > 7075 Al > 2024 Al > 2219 Al, which agrees with the crack susceptibility ranking of commercial wrought Al alloys.

Before the TMW test the Controlled Tensile Weldability (CTW) test was developed by Coniglio et al. (Ref. 12). In the CTW test the workpiece is welded to a larger and thicker mounting plate, one on each lateral side. The plates were then mounted on a horizontal tensile testing machine to stretch the workpiece to induce tension in the transverse direction of the weld. Since the mounting plates, workpiece, solidified weld metal and semisolid mushy zone are all being deformed during welding, an extensometer is mounted across the weld width on the bottom surface of the workpiece to measure the speed at which one weld edge moves away from the opposite weld edge, i.e., transverse displacement rate of the mushy zone. The test Soysal and Kou (Refs. 7, 8) developed has some similarity to the CTW test, but the mounting plates, extensometer and tensile testing machine are not required.

The present study evaluated effectiveness of filler metals in reducing solidification cracking in two highly crack susceptible Al alloys, 2024 and 6061. The purpose was to provide experimental data that can be used for selecting filler metals to suppress solidification cracking in welding 2024 Al and 6061 Al.

4.2. Experimental Procedure

The transverse-motion weldability (TMW) test used for assessing the solidification cracking susceptibility has been described in detail elsewhere (Refs. 7, 8) and will not be repeated here. As shown in Fig. 4.1, during lap welding the upper sheet is stationary and the lower sheet moves at a predetermined speed V normal to the welding direction to induce tensile deformation in the mushy zone to cause cracking.

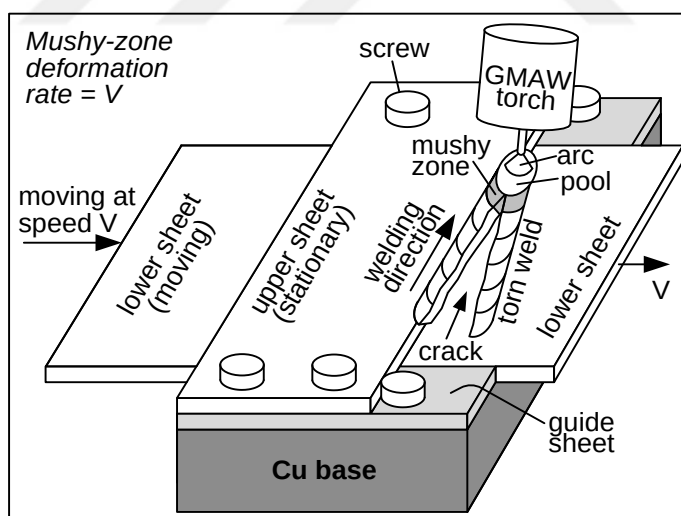


Fig. 4.1 Schematic sketch of test used for assessing susceptibility to solidification cracking (Ref. 7)

Table 4.1 shows the actual compositions of the workpiece and filler metals (1.2 mm diameter) used for welding. The upper sheet was 3.2 mm by 51 mm by 203 mm, and the lower sheet 3.2 mm by 127 mm by 152 mm. The lower sheet was positioned to stick out of the upper sheet by 19 mm

(0.75 in) before welding. A servomotor was preprogrammed by a computer to move the lower sheet. Apparently, by moving the lower sheet at a single constant speed throughout welding, the crack susceptibility can be evaluated based on crack initiation. However, in gas-metal arc welding the filler metal tends to freeze faster and melt the workpiece less at the beginning of welding than during the steady state because the workpiece is initially cold. This can cause considerable scatter in the test results. Thus, it was decided to move the lower sheet faster initially to insure crack initiation and then slower for crack propagation. Consequently, in all experiments the moving speed of the lower sheet was 1.5 mm/s initially for a distance up to about 25 mm and then lowered to the predetermined level to investigate crack propagation. After the lower sheet started to move, the carriage was turned on to move the torch at the predetermined travel speed, and the arc was initiated.

Table 4.1 Actual compositions of materials in weight percent

	Si	Fe	Cu	Mn	Mg	Cr	Ti	V	Zr	Zn	Al
Sheets											
2024	0.08	0.16	4.6	0.61	1.3	0.01	0.02	0.01	0.01	-	Bal.
6061	0.666	0.387	0.245	0.099	1.083	0.1	0.025	0.01	-	-	Bal.
Wires											
2319	0.1	0.15	6.3	0.3	-	-	0.15	-	0.18	-	Bal.
4043	5.2	0.8	0.3	0.05	0.05	0.001	0.20	-	-	0.10	Bal.
4145	9.9	0.2	3.9	0.01	0.05	0.01	-	-	-	0.04	Bal.
4943	5.42	0.12	0.005	0.005	0.4	0.001	0.017	-	-	-	Bal.

The welding conditions for gas-metal arc welding (GMAW) were: 23 V welding voltage, 5.1 mm/s torch travel speed, 85 - 89 mm/s wire feed speed (welding current of 120 - 125 A), and 3.54×10^{-4} m³/s Ar shielding. The torch was tilted 10° toward the joint and 10° backward (dragging).

After welding, the fracture surfaces were examined by scanning electron microscopy (SEM). The transverse cross-sections of the welds were cut and mechanically polished. 6061 Al welds

were etched with Keller's solution, consisting of 5 mL HNO_3 , 3 mL HCl , 2 mL HF and 190 mL distilled water. 2024 Al welds were etched with a solution consisting of 0.5 mL HF and 99.5 mL distilled water. The welds were then examined under optical and electron microscopy.

4.3. Results

Fig. 4.2 shows a 2024 Al workpiece after being welded with filler metal 2319 Al. The weld surface was cleaned with a stainless-steel wire brush before photographing. The initial moving speed of the lower sheet was 1.5 mm/s, resulting in the initial portion of the weld with a wider crack opening. After lowering the moving speed to 0.2 mm/s, the crack opening narrowed. The length of the narrower crack is labeled as L_{crack} , and the length of the weld without the wider opening is labeled as L_{weld} . The ratio of $L_{\text{crack}}/L_{\text{weld}}$ is taken as the normalized length of crack propagation.

The welds in the present study are shorter than those gas-metal arc welds in the previous study by the authors (Ref. 7). It was found that the results of shorter welds are more reproducible, i.e., with a smaller critical moving speed V_c range from no crack to full crack. A longer weld tends to get wider as it approaches the end of the workpiece. The dendritic fracture surface shown by the SEM image in Fig. 4.3 confirms that the crack was caused by solidification cracking. The fracture surfaces of cracks that occur during solidification in welding and casting typically reveal dendrites (Refs. 13, 14). This is because such cracking occurs along grain boundaries near the end of solidification, along which thin liquid films are present. When cracking occurs, the thin liquid films quickly freeze over the dendrite arms, thus resulting in dendritic fracture surfaces.

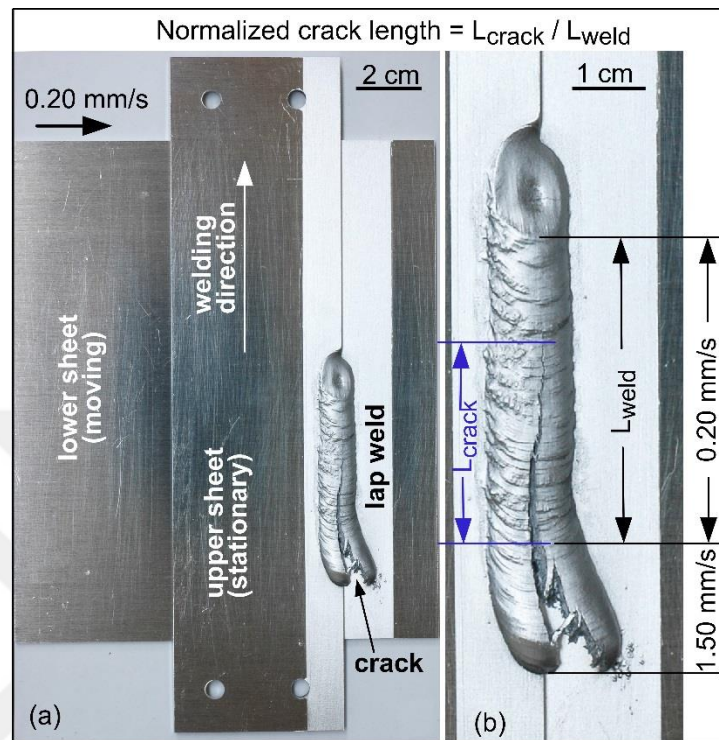


Fig. 4.2 2024 Al welded with filler metal 2319 Al: (a) overview, (b) enlarged. Lower sheet initially moved at 1.5 mm/s to ensure crack initiation and lowered to 0.2 mm/s for crack propagation. L_{crack} and L_{weld} are, respectively, length of crack propagation and length of weld from beginning of crack propagation

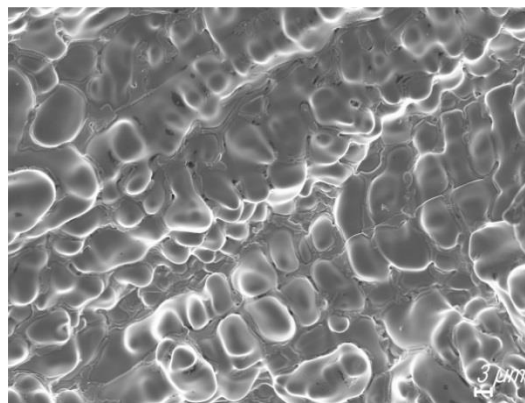


Fig. 4.3 Dendritic fracture surface of 2024 Al weld made with filler metal 2319 Al confirming solidification cracking

4.3.1. Assessing filler-metal effectiveness

Fig. 4.4 shows the welds made by welding 2024 Al with three different filler wires at the lower-sheet moving speed of 0.4 mm/s. When filler wire 2319 Al is used, solidification cracking

propagates all the way through the weld. When the filler wire is switched to 4043 Al, solidification cracking is greatly reduced, propagating only slightly after the initiation period. With 4145 Al, the reduction is even better – no crack propagation at all. The results show clearly that filler metal 4043 Al or 4145 Al can be considered if solidification cracking occurs in welding 2024 Al.

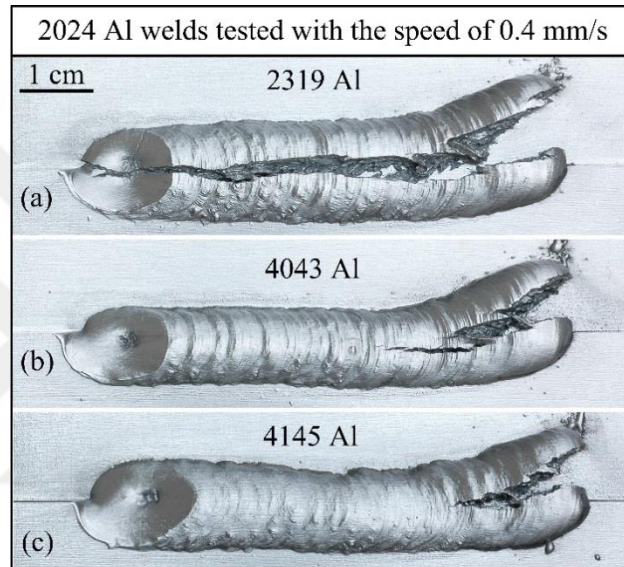


Fig. 4.4 2024 Al welded with filler metals: (a) 2319 Al, (b) 4043 Al, and (c) 4145 Al and tested with the moving speed of 0.4 mm/s

In Fig. 4.5 the normalized crack length is plotted vs. the lower-sheet moving speed V for the 2024 Al welds made with the three filler wires. As shown in Fig. 4.5a, with filler metal 2319 Al the normalized crack length increases from 0 at $V = 0.1$ mm/s to 1.0 at 0.3 mm/s. The range of V over which the normalized crack length increases from 0 to 1.0 will be called the critical moving speed of the lower-sheet V_c hereinafter. Thus, the $V_c = 0.2 \pm 0.1$ mm/s for 2024 Al welded with filler metal 2319 Al under the welding conditions used.

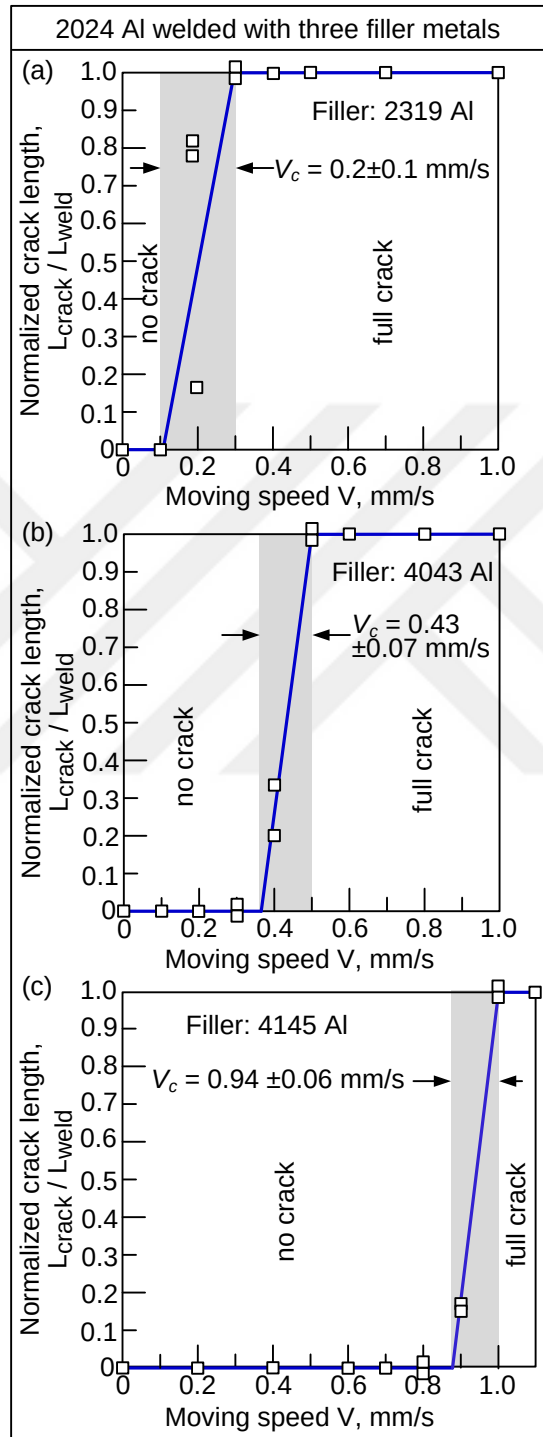


Fig. 4.5 Test results of 2024 Al welded with three filler metals: (a) 2319 Al; (b) 4043 Al; (c) 4145 Al

Similar results are shown in Fig. 4.5b for 2024 Al welded with filler metal 4043 Al and in Fig. 4.5c for 2024 Al welded with filler metal 4145 Al. As shown, the V_c increases to 0.43 ± 0.07 mm/s with filler metal 4043 Al. It increases further to 0.94 ± 0.06 mm/s with filler metal 4145 Al.

Fig. 4.6 shows the results of 6061 Al welded with two different filler metals. As shown in Fig. 4.6a, with filler metal 4943 Al the V_c is 0.45 ± 0.05 . With 4043 Al as the filler metal, the V_c is 0.44 ± 0.06 as shown in Fig. 4.6b.

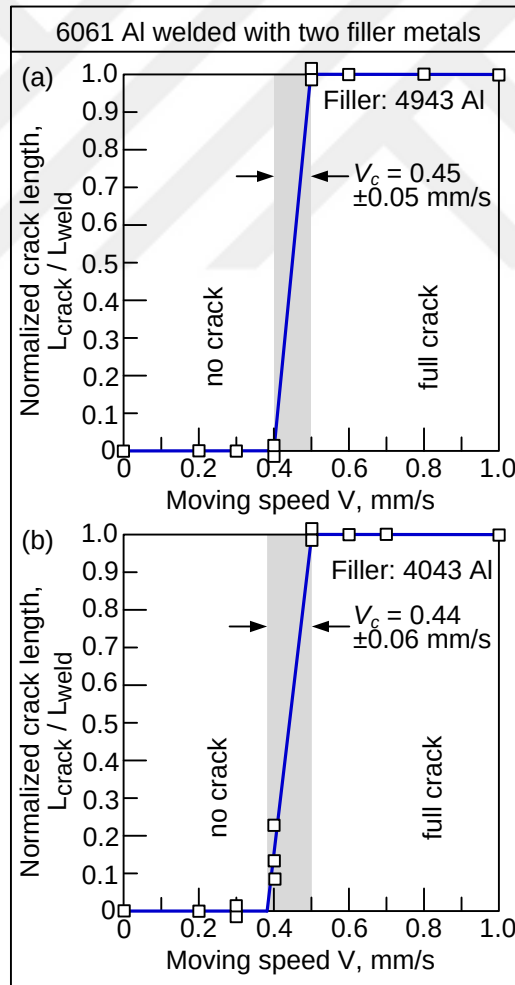


Fig. 4.6 Test results of 6061 Al welded with two filler metals: (a) 4943 Al; (b) 4043 Al

Fig. 4.7 summarizes the results of the assessment of filler-metal effectiveness. A higher V_c suggests the lower sheet needs to be moved faster to cause cracking and hence a more effective filler metal for reducing cracking. As shown, filler metal 2319 Al is least effective for 2024 Al, and filler metal 4145 Al most effective. Filler metals 4943 Al and 4043 Al have similar effectiveness. Filler metal 4043 Al appears to reduce the crack susceptibility of 2024 Al and 6061 Al to about the same level.

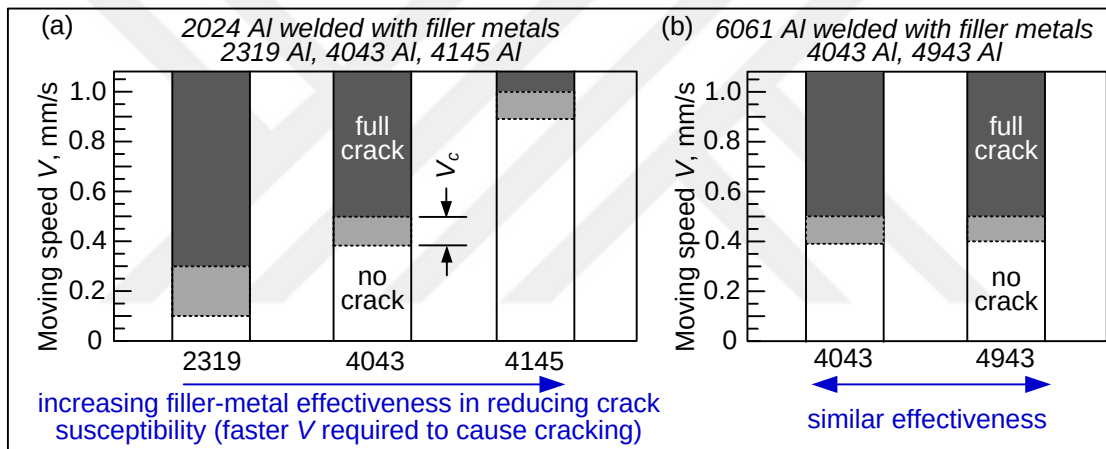


Fig. 4.7 Results of assessment of filler-metal effectiveness in welding: (a) 2024 Al (Fig. 4.5); (b) 6061 Al (Fig. 4.6). The faster the lower-sheet moving speed is required to stretch the mushy zone to cause cracking, the more effective the filler metal is in reducing the crack susceptibility

4.3.2. Macrostructure and microstructure

Fig. 4.8 shows the transverse cross-section of a 2024 Al weld made with filler metal 4145 Al. The areas of the upper and lower sheets in the weld represent the contribution of the base metal to the weld metal. The dilution level, i.e., the extent the filler metal is diluted by the base metal, is the ratio of the areas to the total area of the weld. It is about 50% for the 2024 Al welds and 47% for the 6061 Al welds. For each weld, the weld-metal composition can be calculated from the compositions of the workpiece and filler wire and the dilution level (Ref. 15). The small rectangular box indicates the location where micrographs in Figs. 4.9 and 4.10 are shown in this

and the other welds, that is, the mid height of the fusion boundary in the upper sheet. Near the fusion zone the heat-affected zone appears as a lighter-etching region due to solutionization of the precipitates present in the original workpiece. Farther away from the fusion zone, it appears as a darker-etching region of the precipitates that formed due to heating during welding (Ref. 15).

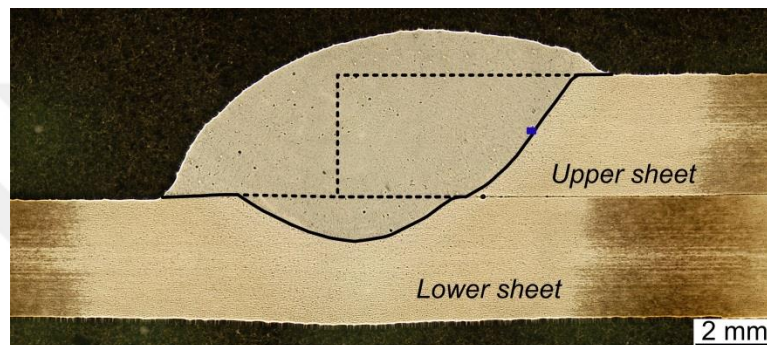


Fig. 4.8 Transverse cross-section of 2024 Al weld made with filler metal 4145 Al. Small rectangular box indicates location where micrographs were taken, i.e., fusion boundary at mid height of upper sheet. Solid lines indicate the fusion boundaries, and dotted lines the surfaces of the upper and lower sheets before welding

Fig. 4.9 shows the microstructure near the fusion boundaries of the 2024 Al welds made with filler metals 2319 Al, 4043 Al and 4145 Al. The small boxes in Fig. 4.9b and c indicate the locations where the SEM images in Fig. 11 were taken. Dendritic columnar grains can be seen in the weld metal. The eutectic exists in the interdendritic areas. With much Si provided by fillers 4043 Al and 4145 Al, the eutectic becomes darker etching than without Si. Fig. 4.10 shows the microstructure near their fusion boundaries of the 6061 Al welds made with filler metals 4043 Al and 4943 Al. The eutectic appears very thin but still continuous. Fig. 4.11 shows the SEM images of the eutectics in 2024 Al welds made with filler metals 4043 Al and 4145 Al. The results of EDX composition measurements are given in Table 4.2. As shown, these eutectics are Si rich.

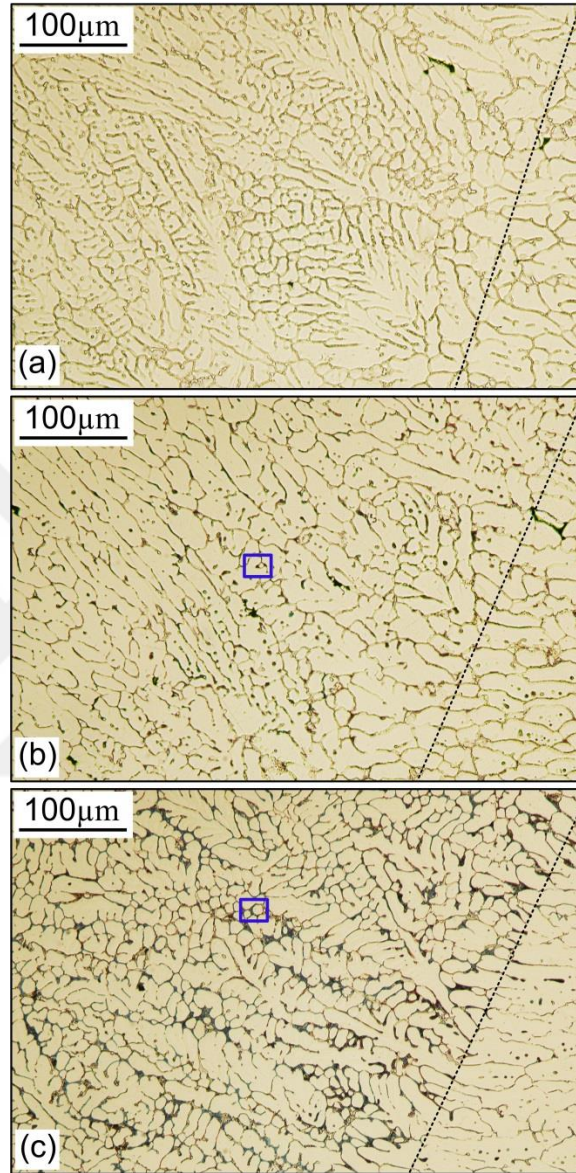


Fig. 4.9 Optical micrographs near fusion boundaries (dotted lines) of 2024 Al welded with fillers: (a) 2319 Al; (b) 4043 Al; (c) 4145 Al. Rectangular boxes in (b) and (c) indicate the locations where SEM images in Fig. 11 were taken

Table 4.2 Compositions (in weight % and atomic %) measured by EDX in 2024 Al welds made with filler metals 4043 and 4145 Al

Base-Filler #	Si	Fe	Cu	Mn	Mg	Al
	wt%; at%	wt%; at%	wt%; at%	wt%; at%	wt%; at%	wt%; at%
2024-4043 Pt 1	13.6; 13.1	-	-	-	-	86.4; 86.9
2024-4043 Pt 2	9.7; 10.9	-	23.7; 11.7	-	-	66.6; 77.4
2024-4145 Pt 1	36.5; 35.5	-	-	-	0.6; 0.7	62.9; 63.8
2024-4145 Pt 2	12.5; 15.3	6.6; 4.1	27; 14.7	4.6; 2.9	-	49.3; 63.0

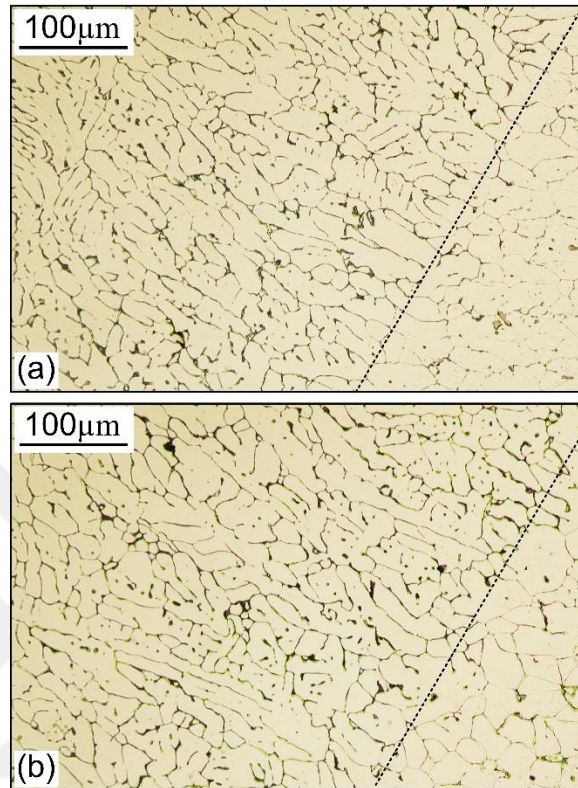


Fig. 4.10 Optical micrographs near fusion boundaries (dotted lines) of 6061 Al welded with fillers: (a) 4043 Al; (b) 4943 Al. Very thin but still continuous eutectic (dark etching) suggests thin continuous liquid films near end of solidification

4.3.3. T - f_s Curves for 2024 Al welds made with filler metals 4043 and 4145 Al

As mentioned previously, the level of filler-metal dilution by the base metal can be determined from the transverse macrograph of the weld. The dilution level can in turn be used to calculate the weld-metal composition (Ref. 15) as follows: (wt% of element E in weld metal) = (wt% of element E in base metal) $\times$ (dilution) + (wt% of element E in filler metal) $\times$ (1 – dilution). Table 4.3 shows the compositions of the 2024 Al welds made with filler metals 4043 and 4145 Al. Based on these compositions, the commercial thermodynamic software Pandat (Ref. 16), the aluminum database PanAluminum (Ref. 17) and the Scheil solidification model were used to calculate the curves of T (temperature) vs. f_s (fraction solid) of these welds. These curves, i.e., the solidification paths, of the welds are shown in Fig. 4.12. The points at which solid phases begin to form during

solidification are indicated. As can be seen on both curves, the FCC phase (the Al-rich phase) starts to form first and other phases follow. The diamond phase is essentially pure Si with the trace amount of Al in it. Fig. 4.12a shows Al_3Ti precipitates from the liquid (at 669 °C) before the FCC phase starts to form. As shown in Table 1, filler metal 4043 Al contained 0.2 wt% Ti.

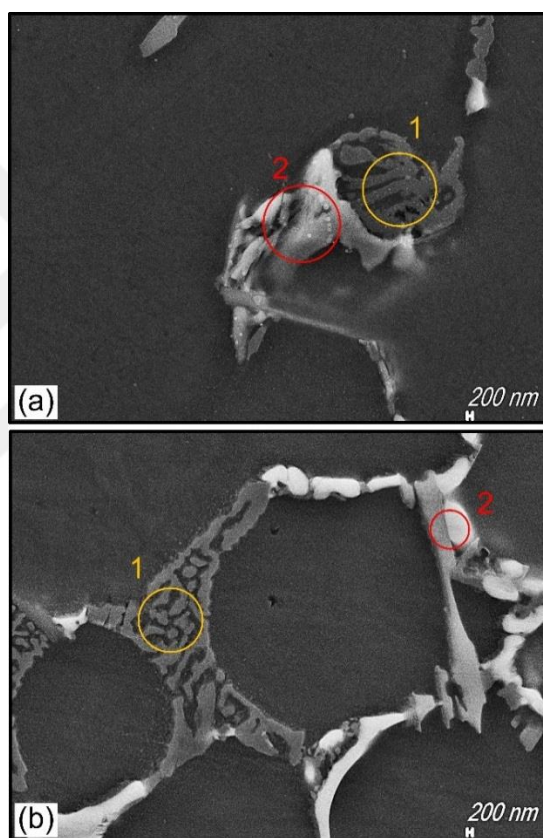


Fig. 4.11 SEM images of eutectics in 2024 Al welded with fillers: (a) 4043 Al (inside boxed area in Fig. 4.9b); (b) 4145 Al (inside boxed area in Fig. 4.9c). The compositions measured by EDX at the locations indicated by the circles are given in Table 2

The phases shown along the T-fs curves in Fig. 4.12 can be compared with the results of EDX measurements in Table 4.2 to help identify the phases shown in Fig. 4.11. For 2024 Al welded with filler metal 4043 Al (Fig. 4.11a), in view of the Si and Al contents, Point 1 in Fig. 4.11a seems to correspond to the combination of the FCC phase and the diamond phase. Likewise, in view of

the Si, Cu and Al contents, Point 2 seems to correspond to FCC + diamond + AlCu_Θ. As for 2024 Al welded with filler metal 4145 Al (Fig. 4.11b), Point 1 seems to correspond to FCC + diamond phases. Point 2 is likely to correspond to the combination of FCC + diamond + β _AlFeSi + Al₁₅_FeMn₃Si₂ + AlCu_Θ.

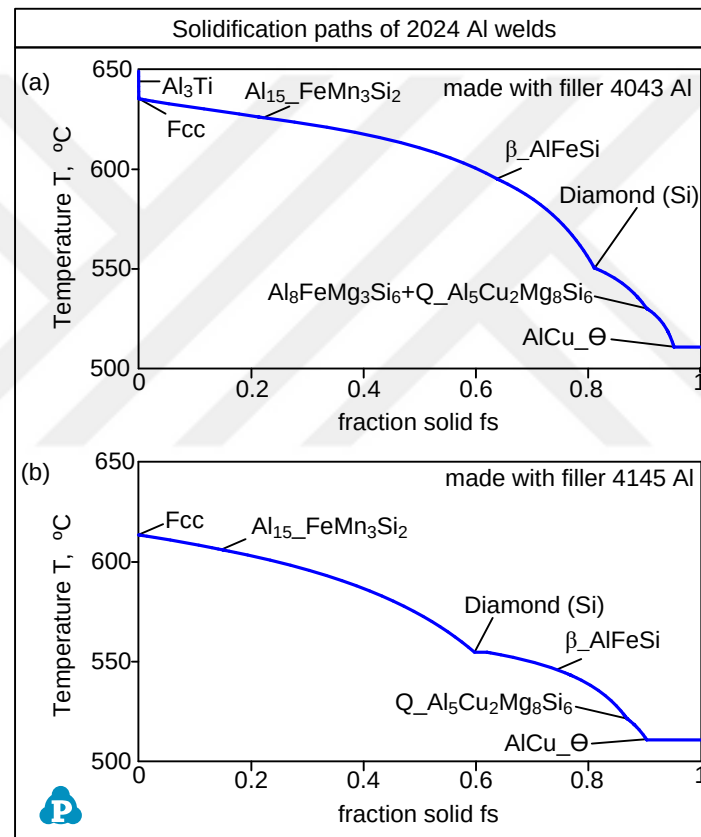


Fig. 4.12 Solidification paths calculated using Pandat (Ref. 16) and PanAluminum (Ref. 17) for 2024 Al welds made with fillers: (a) 4043 Al; (b) 4145 Al

Table 4.3 Compositions (in weight %) of 2024 Al welds made with filler metals 4043 and 4145 Al

		Si	Fe	Cu	Mn	Mg	Cr	Ti	V	Zr	Zn	Al
sheet-filler	dilution											
2024-4043	48.7 %	2.71	0.49	2.39	0.32	0.66	0.01	0.11	0.00	0.00	0.05	Bal
2024-4145	50.7 %	4.92	0.18	4.25	0.31	0.68	0.01	0.01	0.01	0.01	0.02	Bal

4.4. Discussion

4.4.1. Crack initiation and propagation

As mentioned previously, at the beginning of GMAW filler-metal droplets tend to freeze faster and hence less able to melt the base metal because the workpiece is still cold. This can cause scatter in the results of crack-susceptibility testing based on crack initiation, i.e., moving the lower sheet at a constant speed V throughout welding. To avoid this problem, crack susceptibility testing was conducted based on crack propagation, i.e., moving the lower sheet faster initially to ensure crack initiation but slower subsequently for crack propagation.

Crack susceptibility testing based on crack propagation instead of crack initiation can be justified as follows. Kou (Ref. 18) proposed a criterion for cracking during solidification by considering the space between two columnar dendritic grains near their roots. He showed that for a weld metal with a higher maximum $|dT/d(f_s)^{1/2}|$ (T : temperature; f_s : fraction of solid), the space decrease caused by its slower grain growth and liquid feeding is more likely to be slower than the space increase caused by the tensile deformation separating the grains (Ref. 18). Thus, it is more likely for a void (i.e., crack) to form inside the space either by nucleation (crack initiation) or by extension of an existing crack into it (crack propagation). Consequently, a weld metal with a higher maximum $|dT/d(f_s)^{1/2}|$ can rank higher in the crack susceptibility in the present test either based on crack initiation or crack propagation. Oxides or micro porosity can serve as the sites for nucleation of cracks (Refs, 12, 14), so can the free surface of the mushy zone (Ref. 19). In lap welding such as the present test, the free surface includes the surface of the mushy zone at the top and that on the side at the gap between the upper and lower sheets. Soysal and Kou (Refs. 7, 8) demonstrated that the crack-susceptibility ranking of commercial wrought Al alloys using the present test based on crack propagation agrees with the ranking predicted based on the maximum

$|dT/d(f_s)^{1/2}|$ as the crack susceptibility index. Furthermore, it also agrees with the ranking reported by Dowd (Ref. 20) and Dudas and Collins (Ref. 1) using other crack-susceptibility tests. The crack susceptibility of the welds in the present study was also predicted based on the maximum $|dT/d(f_s)^{1/2}|$ and the weld-metal compositions, and it agreed well with the test results (Ref. 21).

Kou's criterion for solidification cracking and index for the crack susceptibility (Ref. 18) can be related to the TMW test. In the TMW test the motion of lower sheet during lap welding can cause the columnar grains near the centerline of the mushy zone to separate from each other. For an alloy with a high $|dT/d(f_s)^{1/2}|$ near $(f_s)^{1/2}=1$, the grains grow thicker slowly near their roots as they grow longer to form a long liquid channel between them to resist liquid feeding, thus delaying the bonding between the grains and slowing down liquid feeding through the channel. Consequently, even a slow speed of the lower sheet can separate the grains to cause cracking before bonding or liquid feeding can occur to resist cracking. The slower the speed is, the higher the crack susceptibility.

4.4.2. Effectiveness of filler metals

Al filler metal guides (Refs. 10, 11) provide useful information for designing the welds for various purposes or applications of Al welds, such as better resistance to solidification cracking, higher strength, better resistance to corrosion etc. However, they do not include 2024 Al. Fig. 4.7a can be a guide for selecting filler metals to minimize the chance for solidification cracking to occur in welding 2024 Al.

By keeping the welding parameters the same in making welds with different filler metals, the effect of the filler metal on solidification cracking can be evaluated. When the filler metal is

changed, the composition, solidification path and hence crack susceptibility of the weld metal are changed significantly. The weld width may also be changed, but usually not much. Ideally, the welding parameters can be changed slightly to keep the weld width identical, but this is very difficult to do, and the effect may be small. The welding parameters can affect solidification cracking, but the effect of the weld-metal composition dominates (Ref. 15). This is why an alloy that has a high tendency to crack in casting also has a high tendency to crack in welding. If changing the welding parameters increases the dilution, the effectiveness of the filler metal in reducing cracking can be expected to decrease. In MIG welding, increasing the welding current (the wire feeding speed) causes more base metal to melt but more filler metal also melts. So, the dilution may not change a lot. Decreasing the travel speed can have a similar effect on dilution.

Fig. 4.7a shows the V_c above which the lower sheet needs to be moved to cause full cracking in welds of 2024 Al and hence the effectiveness of the filler metal in reducing their solidification cracking are affected significantly by the filler metal used. 4145 Al is most effective and 2319 Al least.

The filler metal guide (Ref. 11) indicates the new filler metal 4943 Al is effective for reducing solidification cracking in 6000 series Al alloys, without referring to the dilution level or any reports of crack susceptibility testing. As can be seen in Table 4.1, 4943 Al is close to 4043 Al in composition, but the Mg/Si ratio is raised significantly to 0.074 in 4943 Al from 0.010 in 4043 Al to increase the weld-metal strength. According to the developer of 4943 Al, the weld made with 4943 Al is higher in strength than that made with 4043 Al in the as-welded condition and is heat-treatable to gain extra strength by postweld artificial aging (Ref. 22). However, it is unclear how this much higher Mg/Si ratio may affect solidification cracking. The test results shown in Fig. 4.7b

indicate that the effectiveness of 4943 Al in reducing solidification cracking in welding 6061 Al is similar to that of 4043 Al, at least under the experimental condition used in the present study.

Fig. 4.9 shows a dark-etching phase appears in the fusion-zone microstructure of 2024 Al (~Al-4.6Cu) when the filler metal is changed from 2319 Al (~Al-6.3Cu) to 4043 Al (~Al-5Si). The calculated solidification paths of the 2024 Al welds made with filler metal 4043 Al and 4145 Al are shown in Fig. 4.12. With filler 4043 Al, the Si-rich phase (diamond A4 in structure) starts to form at about $f_s = 0.8$ (about $T = 550^\circ\text{C}$). With filler metal 4145 Al, the Si-rich phase starts to form significantly earlier at about $f_s = 0.6$ (about $T = 555^\circ\text{C}$). In both cases, the increase in the fraction solid with cooling is faster after (than before) the Si-rich phase starts to form. With 4145 Al, the fraction solid increases rapidly with decreasing temperature, causing the Al-rich dendrites to quickly bond together to resist solidification cracking (Refs. 15, 23-26). Although 4145 Al best resists solidification cracking in 2024 Al, other weld properties need to be considered as well, e.g., toughness and corrosion resistance, depending on the application of the resultant weld.

4.4.3. Strain rate in mushy zone

In gas-tungsten arc welding of Al alloys, Matsuda et. al. (Ref. 9) measured the speed at which one weld edge moved away from the opposite weld edge, and it was in the range of 0-0.9 mm/s, close to that in Figs. 4.5 and 4.6. Thus, in the TMW test the speed V of the weld edge on the lower sheet relative to that on the upper sheet is realistic from the practical welding point of view, and the strain rate experienced by the mushy zone can be expected to represent that in actual welding. Although the average strain rate of the mushy zone in the transverse direction can be taken as V divided by the weld width W , the local strain rate near the crack is likely significantly higher than V/W . Bakir et al. (Ref. 27) measured the local strain rate near the crack in laser-beam welding of

a stainless steel during the CTW test. At the crosshead speed of 1.2 to 2.3 mm/s of the tensile testing machine, the global strain rate of the entire mushy zone was 4 to 8 %/s and the local strain rate near the crack was 18 to 29 %/s.

It might be possible to estimate the local strain rate near the crack in the TMW test. The transverse micrographs of the TMW tested welds showed no evidence of separation of dendrites from each other except near the crack (Ref. 8). In the areas next to both sides of the main crack, intergranular micro fissures were found, more or less parallel to the crack and often filled with dark-etching eutectic (not shown). Closer to the crack, the micro fissures were wider. Thus, as an approximation, tensile deformation can be assumed to occur mostly in the areas next to both sides of the main crack. Preliminary examination of transverse micrographs near cracks in some welds showed the total width of these areas was on the order of 1 to 2 mm. This suggests that, just before cracking occurred, the width of the area deformed by tensile deformation, D , was about 1.5 mm. The width of the weld and hence the mushy zone W was on the order of 10 mm. Thus, the local average strain rate V/D was significantly higher than the overall average strain rate V/W . If 2024 Al welded with filler metal 4043 Al is taken as an example just for the purpose of discussion, the minimum V needed to cause cracking is about 0.4 mm/s according to Fig. 4.5b. The corresponding minimum overall average strain rate is $V/W = 0.04/s$ ($0.4 \text{ mm/s} \div 10 \text{ mm}$) or 4%/s. Likewise, the corresponding minimum local average strain rate is $V/D = 0.27/s$ ($0.4 \text{ mm/s} \div 1.5 \text{ mm}$) or 27%/s. Further analysis of the local average strain rate is needed but not here as the focus of the present study is on the effectiveness of filler metals in reducing the crack susceptibility.

4.5. Conclusions

The effect of the commercial Al filler metals on reducing the solidification-cracking susceptibility of two highly crack susceptible Al alloys 2024 and 6061 was investigated using the TMW test. The following conclusions can be drawn from the test results:

1) For welding 2024 Al, filler metal 4145 Al is highly effective against solidification cracking, 4043 Al less effective, and 2319 Al least effective. Thus, in situations where solidification cracking in 2024 Al welds is a major concern, 4043 Al or 4145 Al can be considered as the filler metal.

2) The calculated solidification paths of the 2024 Al welds show that the Si-rich phase tends to form at about 550 – 555°C during solidification but significantly earlier with filler metal 4145 Al than 4043 Al. With 4145 Al, after the formation of the Si-rich phase, the fraction solid increases rapidly during cooling to bond the Al-rich dendrites to resist cracking.

3) For welding 6061 Al, the new filler metal 4943 Al is as effective against solidification cracking as the traditional filler metal 4043 Al. Thus, if a high weld-metal strength is a high priority, filler-metal 4943 Al can be considered.

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5. PREDICTING FILLER-METAL EFFECTIVENESS IN WELDING AL ALLOYS 2024 AND 6061

5.1. Introduction

Arc welding is still the most versatile and cost-effective process for welding aluminium (Al) alloys though friction stir welding can produce high quality Al welds and is ideal for some special welding applications. The use of filler metals is the most effective method for reducing solidification cracking, including Al alloys (Ref. 1). The ability to predict how effectively filler metals reduce the susceptibility to solidification cracking can help select existing filler metals or search for new ones.

Al alloys are susceptible to cracking during solidification, called solidification cracking in welding (Ref. 1) and hot tearing in casting (Ref. 2). Due to solidification shrinkage (density of liquid < density of solid) and thermal contraction, the semisolid mushy zone tends to shrink. However, the fact that the mushy zone is connected to the more rigid and much bigger workpiece in welding makes free shrinkage impossible. Consequently, significant tension can be induced in the mushy zone, which is weak and thus can crack along grain boundaries. Tight clamping the workpiece can make it worse. A weld metal composition highly susceptible to solidification cracking can be changed to a less susceptible one by using a filler metal of a different composition.

To predict the susceptibility of Al alloys to cracking during solidification, Kou (Ref. 3) proposed a simple index for the crack susceptibility. It is the $\left| dT/d(f_s)^{1/2} \right|$ of an Al alloy near the end of its solidification, i.e., near $(f_s)^{1/2} = 1$, where T is temperature and f_s the fraction of solid. $\left| dT/d(f_s)^{1/2} \right|$ is the steepness of the curve of T vs. $(f_s)^{1/2}$ of the alloy during solidification. For convenience of discussion, consider the centreline of the mushy zone, where columnar grains are often nearly parallel to the welding direction (Ref. 1). First, solidification cracking occurs near the

end of solidification, i.e., the roots of columnar dendritic grains. So, Kou (Ref. 3) proposed that the slower columnar dendritic grains grow thicker near their roots to bond together to resist cracking, the higher the crack susceptibility is. He showed that near the roots the characteristic radius R of columnar dendritic grains is proportional to $(f_s)^{1/2}$ (Ref. 3). Thus, a higher $\left| dT/d(f_s)^{1/2} \right|$ near $(f_s)^{1/2} = 1$ means a smaller $d(f_s)^{1/2}$ or dR for a given temperature drop $\left| dT \right|$, that is, near their roots the grains grow thicker more slowly during cooling to bond together to resist cracking. Thus, a higher $\left| dT/d(f_s)^{1/2} \right|$ near $(f_s)^{1/2} = 1$ means a higher crack susceptibility.

Second, as suggested by Pellini (Ref. 4) in his strain theory of hot tearing and shown by fracture surfaces after tearing, thin liquid films exist between columnar dendritic grains near the end of solidification. Thus, if liquid can flow through the channels between the grains to feed the space forming near their roots under tension, cracking may not occur. With a high $\left| dT/d(f_s)^{1/2} \right|$ near $(f_s)^{1/2} = 1$, the grains grow longer but hardly any thicker near their roots, thus forming a long liquid channel to slow down liquid feeding to the roots (Ref. 5) and hence increase the crack susceptibility. Third, the longer the liquid channel is, the more likely it can act as a sharp notch to initiate cracking.

The proposed index for solidification cracking can be the average $\left| dT/d(f_s)^{1/2} \right|$ near $(f_s)^{1/2} = 1$. However, since the maximum $\left| dT/d(f_s)^{1/2} \right|$ often occurs near $(f_s)^{1/2} = 1$, an alternative is to use the maximum $\left| dT/d(f_s)^{1/2} \right|$ as the index, which is more convenient (Ref. 6).

The index has been found to agree well with crack susceptibility tests of commercial wrought Al alloys (Ref. 6), binary Al alloys (Refs. 7, 8), and ternary Al alloys (Refs. 9). Regarding the effectiveness of filler metals in reducing the crack susceptibility, the index has also been shown to

agree well with filler metal guides (Refs. 10, 11). However, the agreement is qualitative because the guides do not specify the level of dilution of the filler metal by the base metal in the weld, which can significantly affect the weld metal composition and hence its curve of T vs. $(f_s)^{1/2}$.

Soysal and Kou recently developed the transverse motion weldability (TMW) test (Refs. 12, 13) for evaluating the solidification cracking susceptibility. As the controlled tensile weldability (CTW) test of Coniglio and Cross (Ref. 14), a slow strain rate can be applied during welding. As shown in Fig. 5.1, the TMW test is very simple - just a commonly used lap welding process except the lower sheet is moved during welding in the transverse direction to induce transverse tension and hence cracking in the mushy zone. The mushy zone alone is deformed - not both the workpiece and the mushy zone as in most other tests - because the workpiece is solid and much larger in size than the small semisolid mushy zone. The moving speed V can be very slow, so that the mushy zone is deformed slowly as in actual welding. The slower V is required to cause solidification cracking in a weld, the higher its crack susceptibility is.

The present study was conducted to predict the effectiveness of filler metals in reducing the susceptibility of 2024 Al and 6061 Al to solidification cracking and compare it with that observed by Soysal and Kou in their TMW test (Ref. 15). 2024 Al and 6061 Al are highly susceptible to solidification cracking as shown by Dudas and Collins (Ref. 16). Filler metal 4043 Al was found effective in reducing the crack susceptibility of 6061 Al. No filler metals were used to reduce the crack susceptibility of 2024 Al.

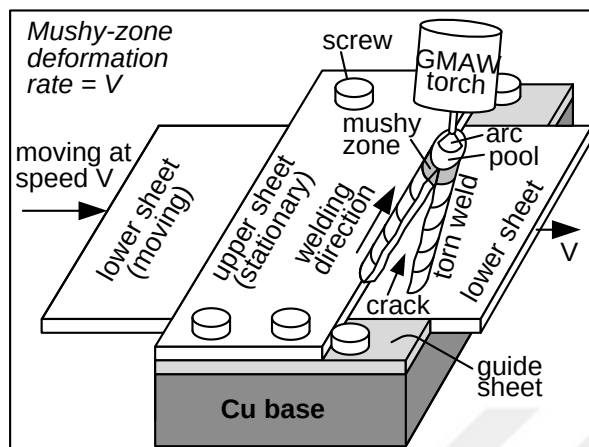


Fig. 5.1 Schematic sketch of transverse motion weldability (TMW) test developed by Soysal and Kou (Refs. 11, 12) for assessing susceptibility to solidification cracking

5.2.1. Al alloys and filler metals selected

As will be described subsequently, the present study involved two alloys, 2024 Al and 6061 Al, and four filler metals, 2319 Al, 4043 Al, 4145 Al and 4943 Al. This represents eight (2×4) different cases of combinations of alloys and filler metals. Five of the eight cases were selected in the present study, that is, 2024 Al welded with three filler metals 2319 Al, 4043 Al and 4145 Al, and 6061 Al welded with two filler metals 4043 Al and 4943 Al. This is because the five cases were studied in the TMW test of Soysal and Kou (Ref. 15), which can be used to verify the prediction of the filler-metal effect on the crack susceptibility.

6061 Al is a widely used general-purpose Al alloy, very extrudable but highly crack susceptible. 4043 Al is a general-purpose Al filler metal and, as already mentioned, was found to reduce solidification cracking in 6061 Al very effectively (Ref. 16). 4043 Al contains about 5 wt% Si, which can help reduce cracking in Al alloys because Al-Si alloys are known to have excellent resistance to hot tearing in casting. However, Al-Si alloys are not heat treatable and their strength is thus rather limited. To improve strength, a small amount of Mg can be added to make heat treating possible, as in the case of the new filler metal 4943 Al.

2024 Al is a high-strength aerospace Al alloy with about 4.5 wt% Cu, which helps provide good strength by heat treating but causes significant susceptibility to cracking during solidification. As mentioned previously, no filler metal was used to reduce the crack susceptibility of 2024 Al (Ref. 16). Filler metals for welding 2024 Al can be 2319 Al, 4043 Al and 4145 Al. 2319 Al (~Al-6.3Cu with some extra Ti for grain refining) is for welding 2219 Al (~Al-6.3Cu), another high-strength aerospace Al alloy. 4043 Al (~Al-5Si), as already mentioned, is a general-purpose Al filler metal. 4145 Al (~Al-10Si-4Cu) contains both significant Si for crack resistance and significant Cu for high strength.

5.2. Methods

5.2.1. Calculation of dilution levels

The transverse macrographs of TMW-tested welds were used to calculate their weld metal compositions as illustrated in Fig. 5.2. The cross-sectional areas representing the contributions to the weld metal by the upper sheet A_U , the lower sheet A_L , and the filler metal A_F were determined from the macrograph with the help of standard computer software. The sum ($A_U + A_L + A_F$) represents the amount of filler metal plus the amount of the base metal (from the upper and lower sheets) in the weld metal. The extent the filler metal is diluted by the base metal, called the dilution, is:

$$D = \frac{A_U + A_L}{A_U + A_L + A_F} \quad [5.1]$$

Assuming thorough mixing between the filler metal and the melted base metal in the weld pool, the content of element E in the weld metal is as follows [5.1]:

$$(wt\% E)_{weld} = D(wt\% E)_{work} + (1 - D)(wt\% E)_{filler} \quad [5.2]$$

where

$(\text{wt}\% \text{ E})_{\text{weld}}$: content of element E in wt% in the bulk weld metal,

$(\text{wt}\% \text{ E})_{\text{work}}$: content of element E in wt% in the workpiece (base metal),

$(\text{wt}\% \text{ E})_{\text{filler}}$: content of element E in wt% in the filler metal.

Table 5.1 shows the compositions of the workpiece and the filler metals used. Table 5.2 shows the levels of dilution and weld-metal compositions.

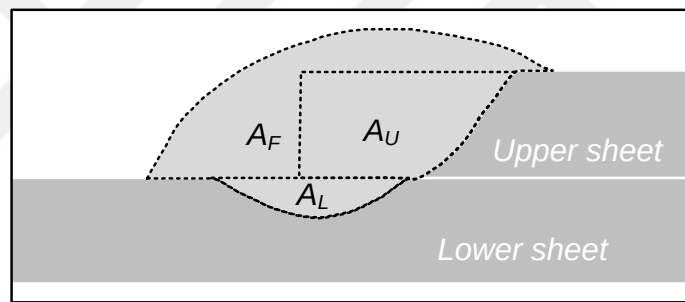


Fig. 5.2 Transverse cross-section of a lap weld made with a filler metal. Areas A_U , A_L and A_F represent contributions to the weld metal from the melted upper sheet, lower sheet and filler metal, respectively

Detailed composition measurements by electron probe microanalysis (EPMA) across welds made with non-matching filler metals have shown uniform composition in the weld metal (Refs. 17,18). This means that the local average composition in the bulk weld metal is uniform though microsegregation still exists. In gas-metal arc welding various driving forces can stir the weld pool, e.g., the Lorentz force, the surface-tension gradients along the pool surface, and the momentum of the filler metal droplets entering the weld pool (Ref. 1). Consequently, the filler metal and the base metal can be mixed thoroughly in the weld pool to produce a macroscopically uniform composition across the bulk weld metal.

Table 5.1 Compositions of materials in weight percent (Ref. 15)

	Si	Fe	Cu	Mn	Mg	Cr	Ti	V	Zr	Al
Sheets										
2024	0.08	0.16	4.6	0.61	1.3	0.01	0.02	0.01	0.01	Bal
6061	0.666	0.387	0.245	0.099	1.083	0.1	0.025	0.01	-	Bal
Wires										
2319	0.1	0.15	6.3	0.3	-	-	0.15	-	0.18	Bal
4043	5.2	0.8	0.3	0.05	0.05	0.001	0.20	-	-	Bal
4145	9.9	0.2	3.9	0.01	0.05	0.01	-	-	-	Bal
4943	5.42	0.12	0.005	0.005	0.4	0.001	0.017	-	-	Bal

Table 5.2 Compositions of the welds in weight percent

		Si	Fe	Cu	Mn	Mg	Cr	Ti	V	Zr	Al
sheet-filler	dilution										
2024-2319	51.8 %	0.09	0.16	5.42	0.46	0.67	0.01	0.08	0.01	0.09	Bal
2024-4043	48.7 %	2.71	0.49	2.39	0.32	0.66	0.01	0.11	0.00	0.00	Bal
2024-4145	50.7 %	4.92	0.18	4.25	0.31	0.68	0.01	0.01	0.01	0.01	Bal
6061-4043	44.9%	3.16	0.61	0.28	0.07	0.51	0.05	0.12	0.00	-	Bal
6061-4943	48.8%	3.10	0.25	0.12	0.05	0.73	0.05	0.02	0.00	0.00	Bal

5.2.2. Calculation of crack susceptibility

Curves of T vs. $(f_s)^{1/2}$ were calculated using commercial thermodynamic software packages Pandat (Ref. 19) and Al database PanAluminum (Ref. 20) based on the compositions given on Tables 5.1 and 5.2. The Scheil solidification model (Ref. 2) was adopted, with a temperature-dependent k (equilibrium partition coefficient) and m_L (the change in the liquid composition with temperature). The maximum steepness of the curve $\left| dT/d(f_s)^{1/2} \right|$ was used as the index for the susceptibility to solidification cracking (Ref. 6). To calculate the maximum $\left| dT/d(f_s)^{1/2} \right|$ of the T -

$(f_s)^{1/2}$ curve the slope function of Microsoft Excel was used. The slope function was applied to three sets of calculated data of T (y-axis) and $(f_s)^{1/2}$ (x-axis), namely, one set at the $(f_s)^{1/2}$ where the maximum $\left| dT/d(f_s)^{1/2} \right|$ occurs and the two sets ahead of it.

5.3. Results

Curves of T vs. $(f_s)^{1/2}$ were presented for both the workpiece and the welds to show the filler metal effect on crack susceptibility. Fig. 5.3 shows the T - $(f_s)^{1/2}$ curves calculated for the 2024 Al welds made with filler metals 2319 Al, 4043 Al and 4145 Al based on their compositions shown in Table 2. As shown, the maximum $\left| dT/d(f_s)^{1/2} \right|$ of 2024 Al is decreased by the filler metals. The extent of the decrease is most significant with filler metal 4145 Al and least with 2319 Al.

Fig. 5.4 shows the T - $(f_s)^{1/2}$ curves calculated for the 6061 Al welds made with filler metals 4943 Al and 4043 Al based on their compositions shown in Table 5.2. The vertical dotted line indicates the $(f_s)^{1/2}$ at which extensive bonding between grains is assumed to occur to end the crack susceptibility, that is, $(f_{SB})^{1/2} = 0.995$. This assumption will be discussed subsequently. For 6061 Al the maximum $\left| dT/d(f_s)^{1/2} \right|$ occurs slightly before $(f_{SB})^{1/2} = 0.995$. With filler metals 4943 Al and 4043 Al, it occurs at $(f_{SB})^{1/2} = 0.995$. As shown, the maximum $\left| dT/d(f_s)^{1/2} \right|$ of 6061 Al is decreased significantly by both filler metals. The extent of the decrease is essentially the same but somewhat greater with filler metal 4943 Al.

Fig. 5.5 summarizes the calculated crack susceptibility shown in Figs. 5.3 and 5.4. As shown, out of the five welds made with filler metals, the 2024 Al weld made with filler 4145 Al is least susceptible to solidification cracking and the 2024 Al weld made with 2319 Al is most susceptible. The dotted horizontal lines at about 1500°C indicate similar effectiveness of filler metals 4043 Al and 4943 Al in welding 2024 Al and 6061 Al. Fig. 5.6 shows the crack susceptibility test results

of these welds obtained by TMW test (Ref. 15). The region between no cracking and full cracking (cracking to the end of the weld) is called the critical moving speed of the lower-sheet V_c . The lower the V_c is, the higher the crack susceptibility becomes. These calculated results in Figure 5 are consistent with the observed results shown in Fig. 5.6.

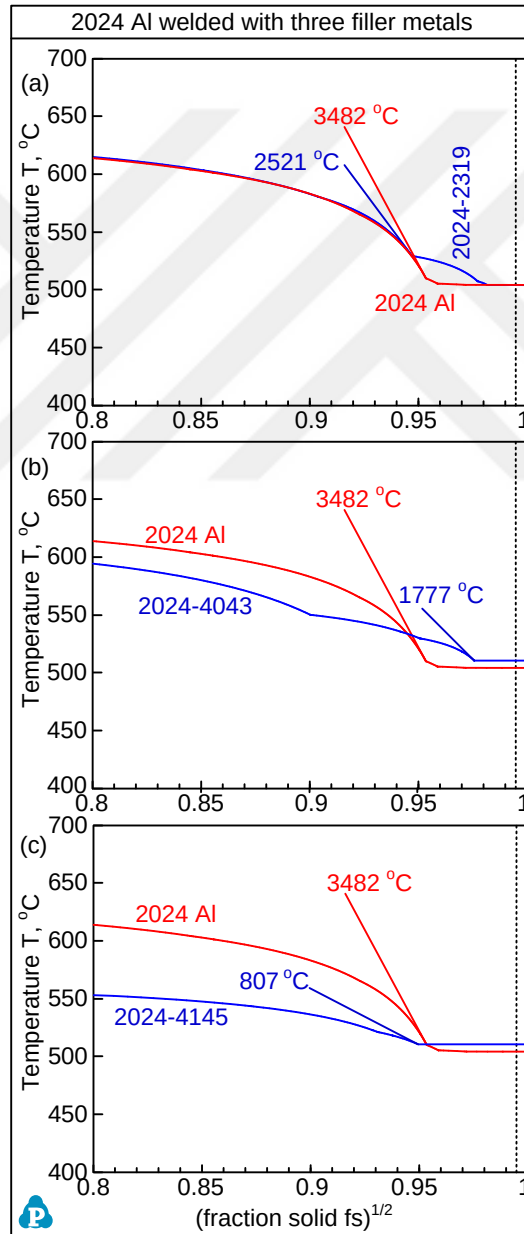


Fig. 5.3 Curves of T vs. $(f_s)^{1/2}$ for 2024 Al welded with filler metals: (a) 2319 Al; (b) 4043 Al; (c) 4943 Al. Inclined straight lines are tangents showing maximum $|dT/d(f_s)^{1/2}|$ before dotted vertical line at $(f_{SB})^{1/2} = 0.995$

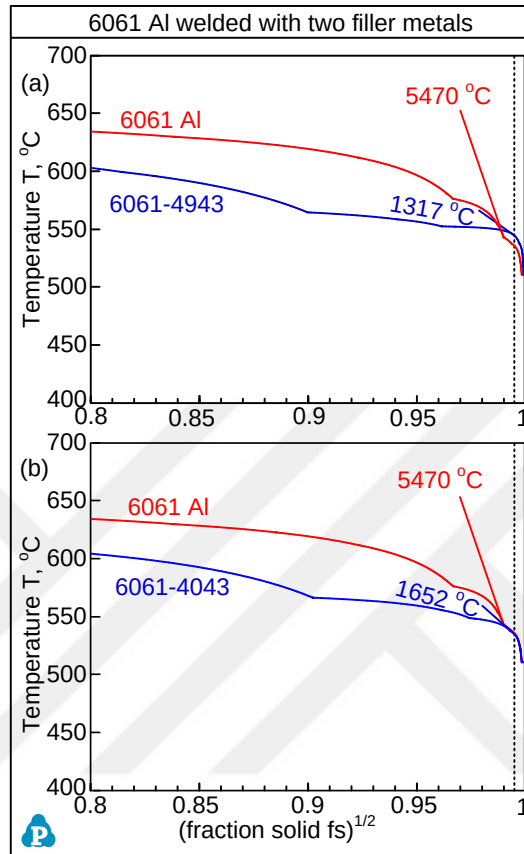


Fig. 5.4 Curves of T vs. $(f_s)^{1/2}$ for 6061 Al welded with filler metals: (a) 4943 Al; (b) 4043 Al. Inclined straight lines are tangents showing maximum $|dT/d(f_s)^{1/2}|$ before or at dotted vertical line at $(f_{SB})^{1/2} = 0.995$

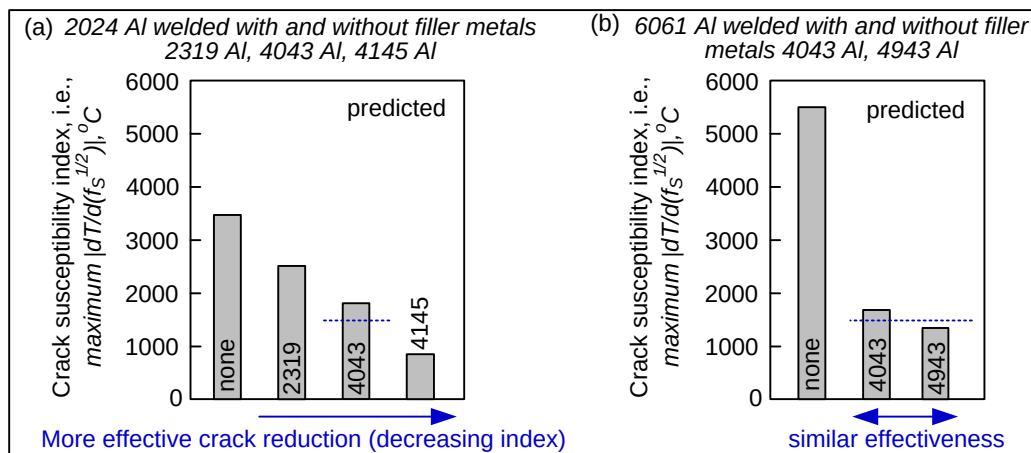


Fig. 5.5 Predicted filler-metal effectiveness based on maximum $|dT/d(f_s)^{1/2}|$ as index for crack susceptibility: (a) 2024 Al (Fig. 3); (b) 6061 Al (Fig. 4). The dotted horizontal lines at about 1500°C indicate the three welds made with filler metals 4043 Al and 4943 Al have similar crack susceptibility

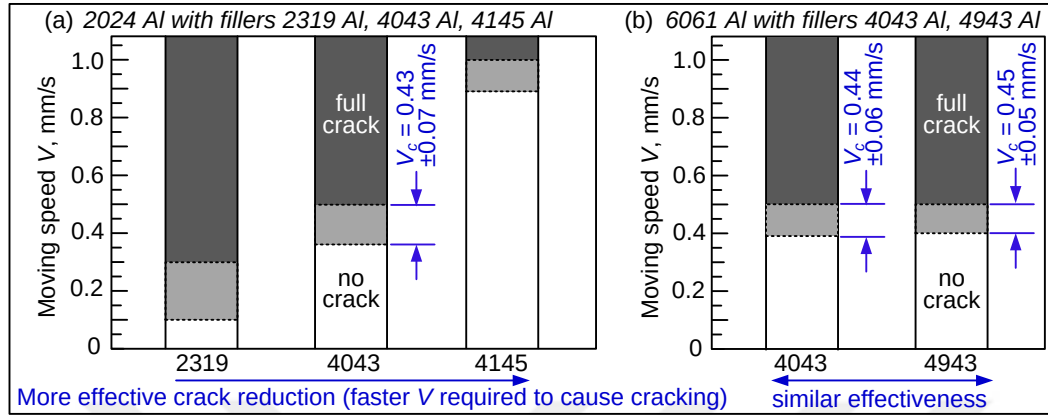


Fig. 5.6 Experimental results of assessing filler-metal effectiveness in reducing solidification cracking in welding: (a) 2024 Al; (b) 6061 Al (Ref. 13). The faster the lower-sheet moving speed is required to stretch the mushy zone to cause cracking, the more effective the filler metal is in reducing the crack susceptibility

5.4. Discussion

Regarding calculating the $T-(f_s)^{1/2}$ curves, the use of the Scheil solidification model (Ref. 21), also called the Gulliver-Scheil model (Ref. 22), is discussed as follows. The basic assumptions include no diffusion in solid, uniform composition in liquid, and equilibrium at the solid/liquid interface (Ref. 1). Kou (Refs. 3, 6), Liu and Kou (Refs. 7, 8, 23) and Liu et al. (Ref. 24) found the Scheil model works well for most commercial wrought Al alloys and binary Al alloys. A notable exception is binary Al-Mg alloys. Solid-state diffusion is known to make the $T-f_s$ curve shallower (Ref. 25) and hence the $T-(f_s)^{1/2}$ curve shallower as well (Refs. 23, 24). Analytical equations showed that the effect of solid-state diffusion increases with $k\alpha$ instead of α alone, where α is the diffusivity of the solute in solid Al and k is the equilibrium partition ratio (Ref. 25). The binary Al-Mg phase diagram shows a very high k of 0.45 (at the eutectic temperature). Thus, solid-state diffusion can be expected to reduce the $|dT/d(f_s)^{1/2}|$ of binary Al-Mg alloys significantly (Refs. 23, 24).

Fig. 5.3 shows that the extent of decrease in the maximum $\left| dT/d(f_s)^{1/2} \right|$ of 2024 Al increases in the order of 2319 Al, 4043 Al and 4145 Al. This predicted trend is consistent with that shown by the results of solidification cracking tests shown in Fig. 5.6a. It can be seen in Fig. 5.3 how fast $(f_s)^{1/2}$ increases during cooling. With filler metal 2319 Al, an amount of 79°C cooling is needed to increase $(f_s)^{1/2}$ from 0.9 to 1.0. However, it is 40°C with filler 4043 Al and only 25°C with 4145 Al. Since the characteristic radius of columnar dendritic grains is proportional to $(f_s)^{1/2}$, the lateral growth rate of columnar grains during cooling to bond together to resist cracking can be expected to increase in the order of 2319 Al, 4043 Al and 4145 Al.

Regarding the extensive bonding between grains to end the crack susceptibility, the assumption of $(f_{SB})^{1/2} = 0.995$ is discussed as follows. When too little liquid is left to form continuous liquid films, isolated liquid droplets form along grain boundaries and grains can thus bond to each other extensively to resist cracking. Let f_{SB} be the fraction solid at which extensive bonding occurs to end the crack susceptibility. If $\left| dT/d(f_s)^{1/2} \right|$ continues to increase beyond $(f_{SB})^{1/2}$, it is no longer relevant and the value of $\left| dT/d(f_s)^{1/2} \right|$ at $(f_{SB})^{1/2}$ can be taken as the maximum $\left| dT/d(f_s)^{1/2} \right|$.

Clyne and Davies (Ref. 26) assumed cracking occurs in the range of $0.90 < f_s < 0.99$. In other words, $f_{SB} = 0.99$ or $(f_{SB})^{1/2} = 0.995$. In the RDG model (Ref. 27) the susceptibility to cracking is assumed to end at $f_s = 0.98$, i.e., $f_{SB} = 0.98$ or $(f_{SB})^{1/2} = 0.99$. Kou (Ref. 6), Liu and Kou (Refs. 7, 8, 23) and Liu et al. (Ref. 24) found $(f_{SB})^{1/2} = 0.99$ works well for most commercial wrought Al alloys. The micrographs of the 6061 Al welds made with 4043 Al and 4943 Al both show very thin but still continuous eutectic films, suggesting extensive bonding can be delayed by such liquid films (Ref. 15). Thus, $(f_{SB})^{1/2} = 0.995$ instead of 0.99 may be more reasonable for these 6061 Al welds though it does not affect the 2024 Al welds.

As shown in Fig. 5.3, the $T-(f_s)^{1/2}$ curves of the 2024 Al welds are already flat well before $(f_s)^{1/2}$ reaches 0.99. Whether $(f_{SB})^{1/2} = 0.99$ or 0.995 does not matter. As for the 6061 Al welds, Fig. 5.4 shows the maximum $|dT/d(f_s)^{1/2}|$ is greatly reduced by both filler metals 4943 Al and 4043 Al. It is 1317°C with filler 4943 Al and 1652°C with filler 4043 Al, both taken at $(f_{SB})^{1/2} = 0.995$. The values change to 477°C with filler 4943 Al and 844°C with filler 4043 Al if $(f_{SB})^{1/2}$ is taken as 0.99. Regardless $(f_{SB})^{1/2}$ is taken as 0.995 or 0.99, the effectiveness of fillers 4943 Al and 4043 Al in reducing the crack susceptibility of 6061 Al does not change. However, the calculated maximum $|dT/d(f_s)^{1/2}|$ based on $(f_{SB})^{1/2} = 0.995$ (Fig. 5.5) agree better with the test results shown in Fig. 5.6 (Ref. 15) than that based on $(f_{SB})^{1/2} = 0.99$. Thus, comparing the calculated results of maximum $|dT/d(f_s)^{1/2}|$ with the experimental results of solidification cracking tests may be one way to help determine $(f_{SB})^{1/2}$. Further research is desirable to help predict f_{SB} . Phase field modeling may shed new light on solidification cracking (Refs. 28-30). It is not clear yet if it can help determine f_{SB} .

Finally, as can be expected, crack susceptibility predictions can help guide filler-metal selection to reduce the crack susceptibility. The present study has demonstrated the $T-(f_s)^{1/2}$ curve and hence the maximum $|dT/d(f_s)^{1/2}|$ can be calculated to predict the crack susceptibility. In fact, even if thermodynamic software (e.g., Pandat) and databases (e.g., PanAl) are not available for calculating the maximum $|dT/d(f_s)^{1/2}|$, it might still be possible to make simplified predictions, at least for alloys and filler metals that might be reasonably approximated as binary or ternary alloys.

As an example, the calculated crack susceptibility maps of ternary Al-Mg-Si and Al-Cu-Si systems will be applied to the welding of 6061 Al and 2024 Al with filler metals 4043 Al, 4943 Al, 2319 Al and 4145 Al. These maps were calculated by Liu and Kou (Ref. 9) based on the

maximum $\left|dT/d(f_s)^{1/2}\right|$ as the index. On the Al-Mg-Si map pure Al is the origin, the x-axis is the Si content, and the y-axis the Mg content. Contours of equal crack susceptibility index are plotted on the map. 6061 Al ($\sim\text{Al-1.0Mg-0.6Si}$) is located very close to Al-0.7Mg-0.6Si, where the crack susceptibility is the highest. This explains the very high crack susceptibility of 6061 Al. With filler 4043 Al ($\sim\text{Al-5Si}$) or 4943 Al ($\sim\text{Al-5Si-0.4Mg}$) at the dilution level of 50%, the weld metal composition on the map switches from 6061 Al far away to the midpoint of the line connecting 6061 Al and 4043 Al, where the calculated crack susceptibility is much lower. This explains why either 4043 Al or 4943 Al can reduce the crack susceptibility of 6061 Al very effectively as shown previously.

As for 2024 Al ($\sim\text{Al-4.5Cu-1.3Mg}$), on the Al-Cu-Mg map it is located close to Al-2.0Cu-1.3Mg, where the crack susceptibility is the highest. This explains the high crack susceptibility of 2024 Al. With filler 2319 Al ($\sim\text{Al-6.3Cu}$) at the dilution level of 50%, the weld metal composition on the map switches mildly from 2024 Al to the midpoint of the line connecting 2024 Al and 2319 Al, where the calculated crack susceptibility is moderately lower. With filler 4145 Al ($\sim\text{Al-10Si-4Cu}$), on the other hand, the Al-Cu-Si map seems more relevant because of its very high Si content. The map shows the highest crack susceptibility near Al-2Cu-0.2Si, which is fairly close to 2024 Al if it is taken as Al-4.5Cu as an approximation. At the dilution level of 50%, the weld metal composition switches from 2024 Al very far away to the midpoint between 2024 Al and 4145 Al, where the crack susceptibility is much lower. This explains why 4145 Al reduces the crack susceptibility of 2024 Al very effectively as shown previously.

In fact, the calculated crack susceptibility curve of the binary Al-Cu system can also be used to predict the effect of filler metal 2319 Al ($\sim\text{Al-6.3Cu}$) on the crack susceptibility of 2024 Al if it is again taken as Al-4.5Cu as an approximation. The calculated Al-Cu crack susceptibility curve

shows the crack susceptibility index (the y-axis) vs. the Cu content (the x-axis). It shows the peak crack susceptibility is located at Al-1.3Cu (Ref. 7). At the dilution level of 50%, the weld metal composition switches from Al-4.5Cu to Al-5.4Cu (midpoint between Al-4.5Cu and Al-6.3Cu). Since Al-5.4Cu is located farther away from Al-1.3Cu than Al-4.5Cu, the crack susceptibility of 2024 Al is reduced by 2319 Al.

5.5. Conclusions

The effect of filler metals on the susceptibility to solidification cracking of two highly crack susceptible Al alloys 2024 and 6061 was predicted and compared with that assessed by the TMW test for the susceptibility to solidification cracking. To allow quantitative comparison, the levels of filler-metal dilution by the base metal was not assumed but actually determined from the welds made in the TMW test. $T-(f_s)^{1/2}$ curves were calculated using the weld-metal compositions based on the actual levels of dilution. The maximum steepness $|dT/d(f_s)^{1/2}|$ of the curve of T vs. $(f_s)^{1/2}$ of the weld metal was used as the index to predict the crack susceptibility. The crack susceptibility predicted based on the index agreed well with the crack susceptibility observed in the TMW test. The present study has demonstrated that the crack susceptibility index can help find proper filler metals to avoid solidification cracking.

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6. MICROSTRUCTURAL ANALYSIS OF SOLIDIFICATION CRACKING IN ALUMINUM WELDS

6.1. Introduction

Solidification cracking is caused by tension induced by solidification shrinkage and thermal contraction during welding (Refs. 1, 2). As illustrated in Fig. 6.1, Kou (Ref. 3) considered three factors at the grain boundary during cracking. Factor 1 is the lateral separation of grains by tension to cause cracking, Factor 2 the lateral growth of grains toward each other to bond together to resist cracking, and Factor 3 liquid feeding along the grain boundary to resist cracking. Consider the volume element Ω between the roots of two grains. If the rate of Ω increases by Factor 1 exceeds that of Ω decrease by Factor 2 and that of Ω decrease by Factor 3, cracking can occur. Kou (Ref. 3) showed the radius of the dendrite roots R is proportional to $(f_s)^{1/2}$, where f_s is the fraction solid. If $|dT/dR|$ is small, i.e., the lateral growth dR is small for a given temperature drop $|dT|$ during cooling, lateral growth is slow and Factor 2 is small. Since the dendrites hardly grow thicker as they grow longer, the liquid channels between dendrites become long to resist feeding (Ref. 4) and decrease Factor 3.

Thus, a high $|dT/dR|$ and hence a high $|dT/d(f_s)^{1/2}|$ near $(f_s)^{1/2} = 1.0$ suggests a high crack susceptibility. Since the maximum $|dT/d(f_s)^{1/2}|$ often occurs near $(f_s)^{1/2} = 1.0$, Kou (Ref. 5) considered the maximum $|dT/d(f_s)^{1/2}|$ as an alternative to $|dT/d(f_s)^{1/2}|$ near $(f_s)^{1/2} = 1.0$. Fisher and Kurz (Ref. 6) and Rappaz et al. (Ref. 7) showed at $f_s = 0.98$ or $(f_s)^{1/2} = 0.99$ dendrites appear to be well bonded together, no longer susceptible to solidification cracking. Thus, Kou (Ref. 5) suggested the maximum $|dT/d(f_s)^{1/2}|$ up to $(f_s)^{1/2} = 0.99$ as the index for the susceptibility of Al alloys to solidification cracking. The index showed good agreement with results of solidification

cracking tests and filler-metal guides (Refs. 3, 5, 8-16). Kun and Kou (Ref. 17) showed that the index also worked well for Mg alloys.

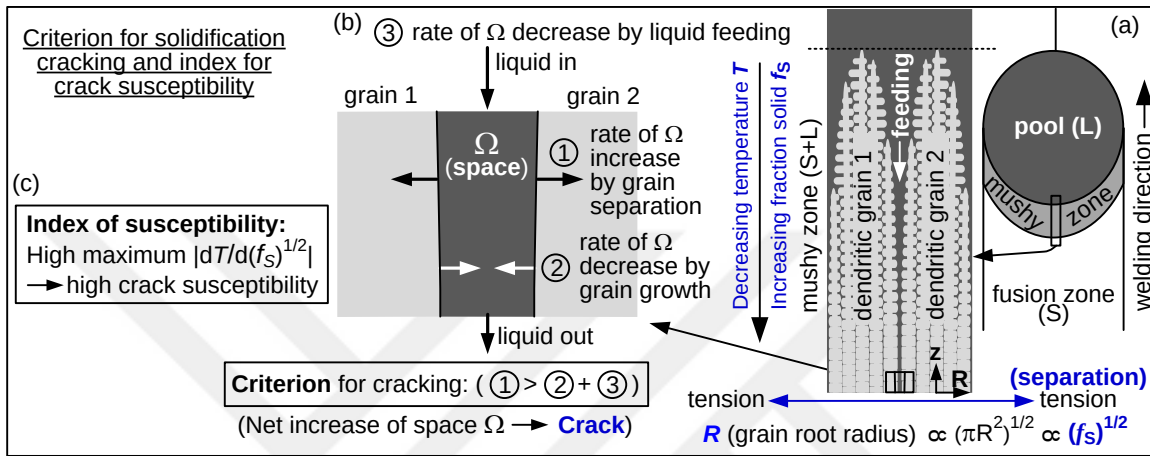


Fig. 6.1 Solidification cracking theory by Kou (Refs. 3, 5): (a) dendrites near centerline and volume element Ω near their roots; (b) criterion for cracking; (c) index for susceptibility.

Fig. 6.2 shows the Transverse Motion Weldability (TMW) test developed by Soysal and Kou for Al alloys (Refs. 18-20) and also applied to Mg alloys (Ref. 17). The lower sheet moves in the transverse direction of lap welding to induce tension and cause cracking. Unlike the Varestraint test (Ref. 21), tension can be applied slowly, and a filler wire can be used. The present study examined the microstructure of Al alloys 2024, 2219, 6061 and 7075 in the TMW test (Ref. 19) and used it to explain the relative crack susceptibility evaluated, determine the local critical strain rate near the crack and compare the rate with the evaluated susceptibility.

6.2 Experimental Procedure

In the TMW tests of Al alloys 2024, 2219, 6061 and 7075 (Ref. 19), about eight welds of each alloy were made, each weld made at a different speed of the lower sheet V . As V increased, the crack length increased from zero to the full length of the weld. The first weld to reach the full crack

length was selected, cut in the transverse direction in the middle, polished and etched for microstructural examination. For convenience of discussion, the V of this weld will be called the critical lower-sheet speed V_c . The first weld in which cracking occurred was not selected because it could have any crack length and a consistent location could not be selected for microstructural examination. 2219 Al and 2024 Al were etched with 0.5% HF in distilled water, and 6061 Al and 7075 Al with Keller's etching solution (5 mL HNO_3 , 3 mL HCl , 2 mL HF and 190 mL distilled water). The microstructure was examined by optical microscopy and scanning electron microscopy (SEM).

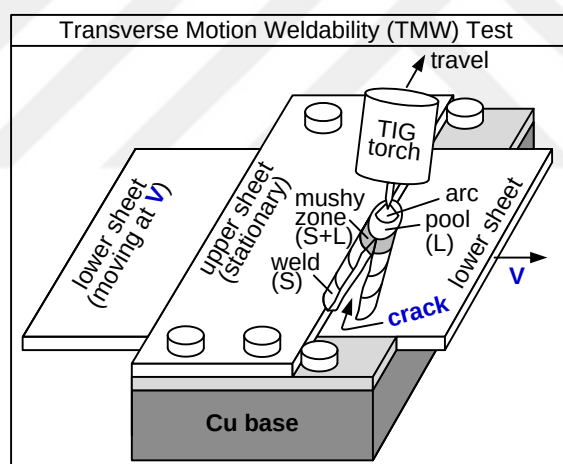


Fig. 6.2 Transverse motion weldability (TMW) test developed by Soysal and Kou (Ref. 19).

In the transverse optical micrograph of each alloy, the width of the narrow region D showing minor cracks next to the main crack was measured. V_c was divided by D to determine the critical strain rate near the crack, $\dot{\epsilon}_c$, as will be explained subsequently.

6.3 Results and Discussion

6.3.1 Backfilling of Cracks

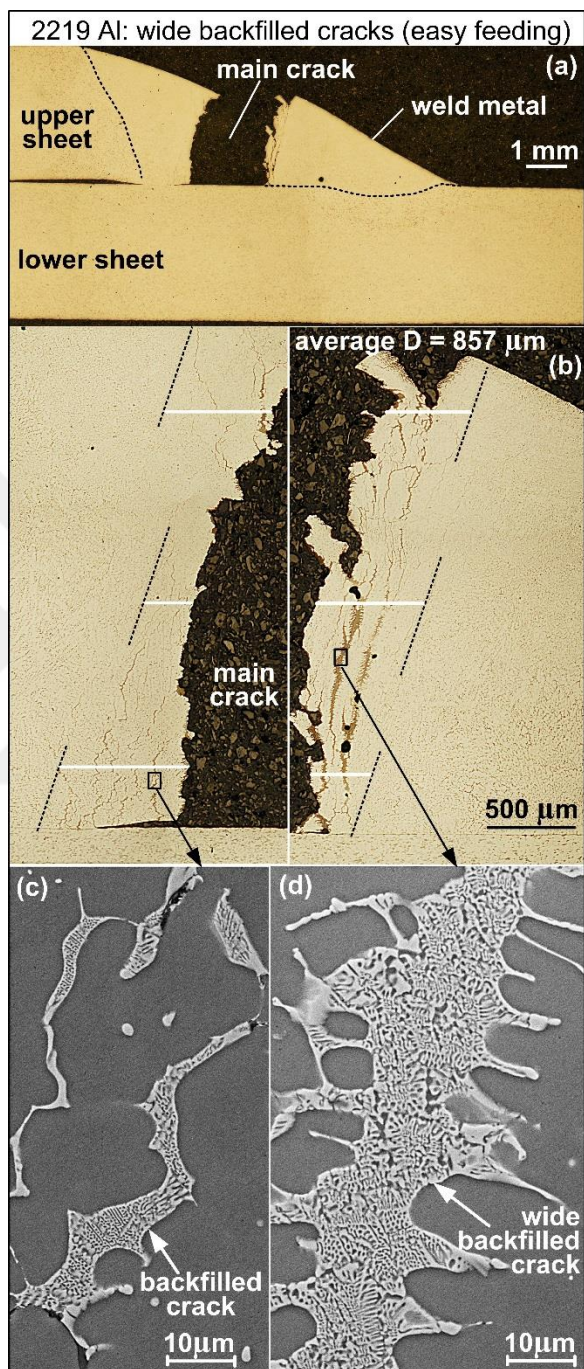


Fig. 6.3 2219 Al transverse cross-section: (a) (b) optical macrographs; (c) (d) SEM images. $V = 0.20$ mm/s. Width of region of high strain (minor cracks): 911 μm (sum of lengths of top two white lines), 760 μm (middle), and 901 μm (bottom). Average $D = 857$ μm .

Fig. 6.3 shows the transverse cross-section of the 2219 Al weld made at $V_c = 0.20$ mm/s. Minor cracks are visible on either side of the main crack. Some cracks are very wide and backfilled as shown in Fig. 6.3d. The composite-like phase in the crack is the Cu-rich eutectic. The wide backfilled cracks suggest plenty of liquid near the end of solidification and wide liquid channels between columnar grains easy for backfilling.

Like 2219 Al, almost all cracks in 2024 Al and 7075 Al were backfilled. As shown in Figs. 6.4 and 6.5, the widest backfilled cracks are significantly narrower than those in 2219 Al, suggesting liquid channels were narrower than those in 2219 Al. As shown in Fig. 6.6 for 6061 Al, the widest cracks are even narrower and are either partially backfilled or mostly open. This suggests very narrow liquid channels in 6061, difficult for feeding.

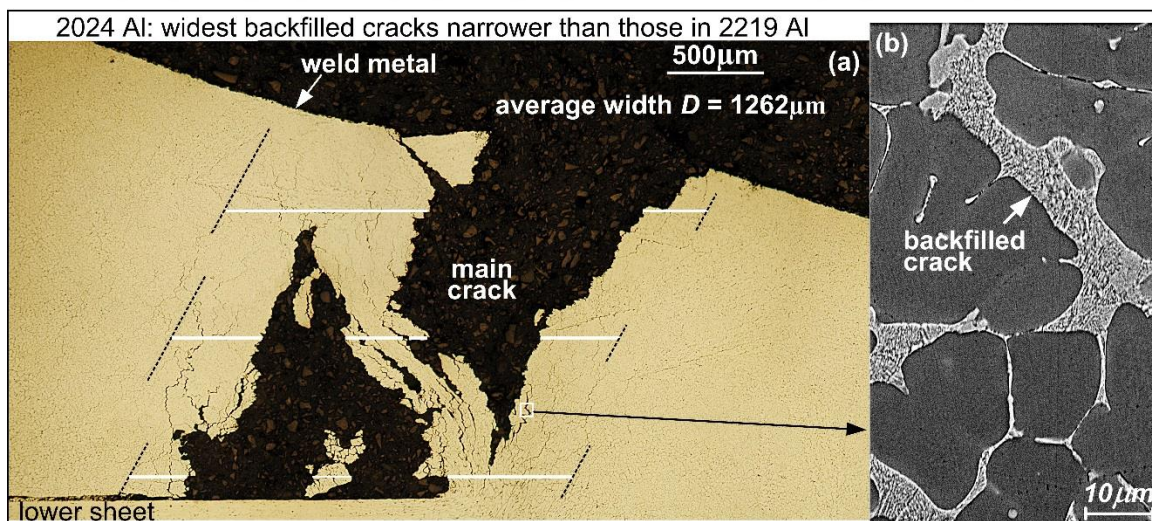


Fig. 6.4 2024 Al transverse cross-section: (a) optical micrograph; (b) SEM image. $V = 0.15$ mm/s.

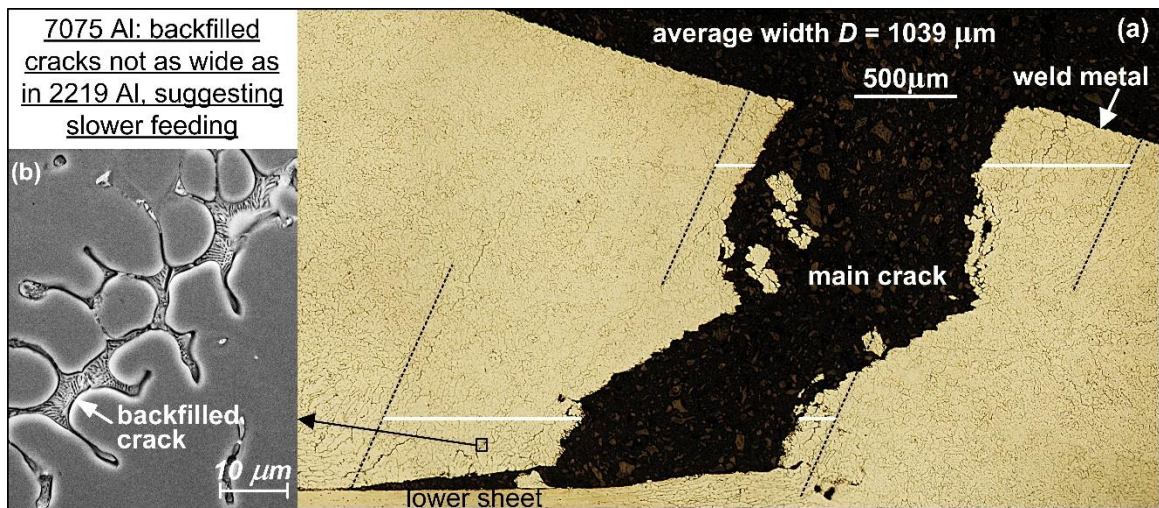


Fig. 6.5 7075 Al transverse cross-section: (a) optical micrograph; (b) SEM image. $V = 0.10$ mm/s.

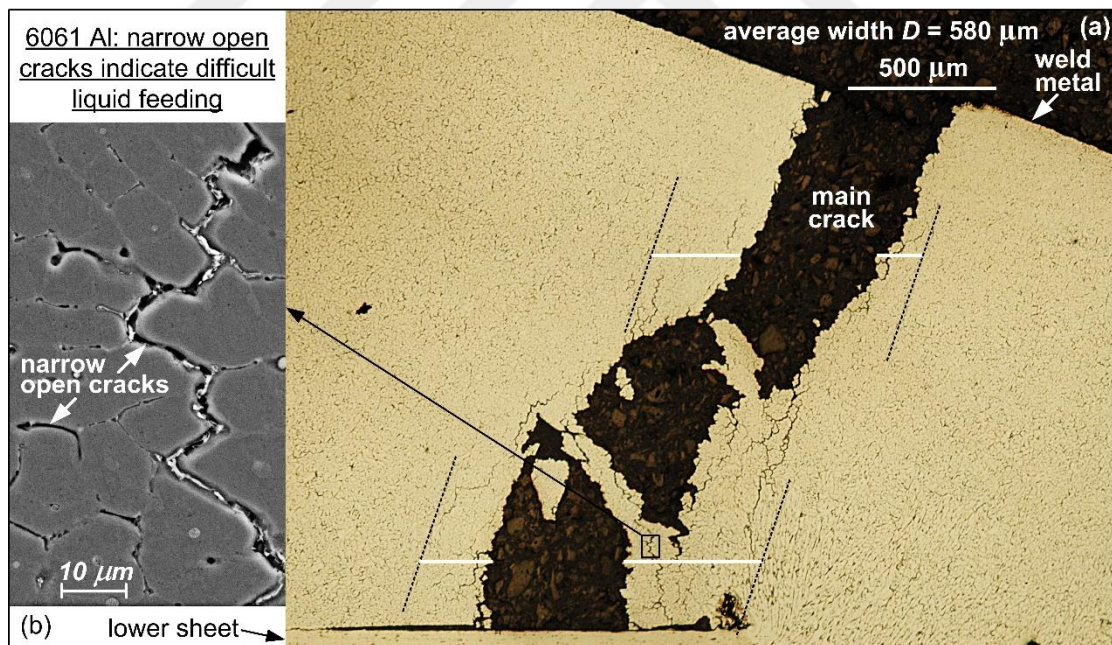


Fig. 6.6 6061 Al transverse cross-section: (a) optical micrograph; (b) SEM image. $V = 0.05$ mm/s.

6.3.2. Fracture Surfaces

The dendritic fracture surfaces in Fig. 6.7 confirm solidification cracking. When cracking occurred, most of the eutectic grain-boundary liquid immediately pulled back from the surfaces of

the bumps (secondary arms) to the surfaces of the nearly flat bases (primary arms). This minimized the surface area and hence the surface energy. Since the eutectic grain-boundary liquid was continuous, its coverage of the bases was also continuous except for 6061 Al, where regions of naked bases in Fig. 6.7d, correspond to the narrow open cracks shown in Fig. 6.6b.

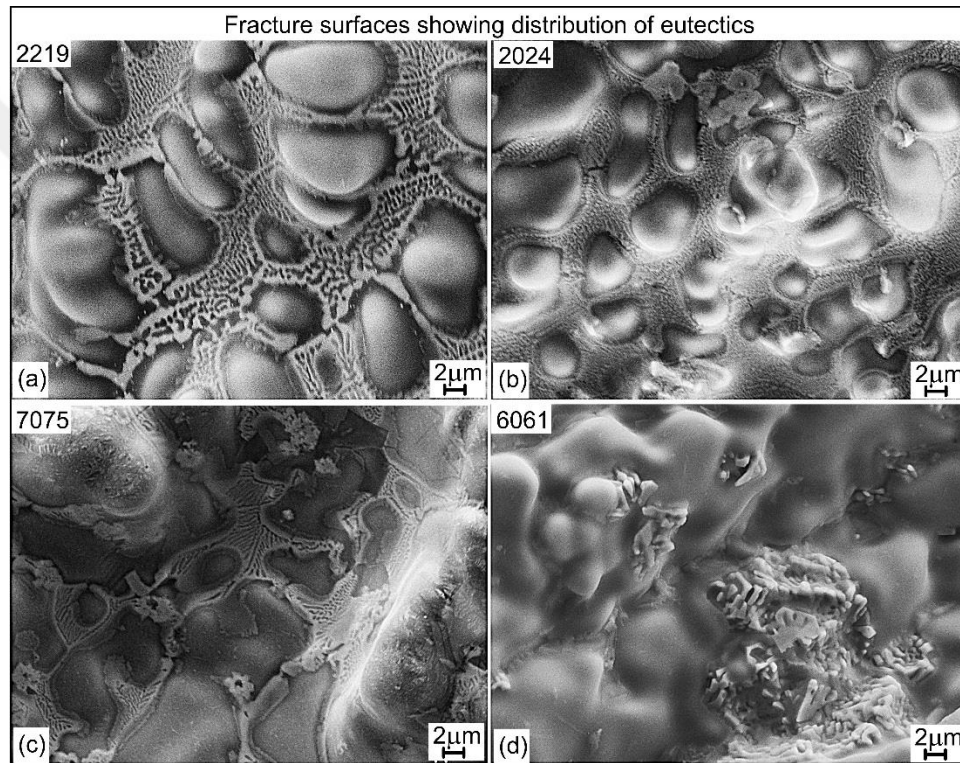
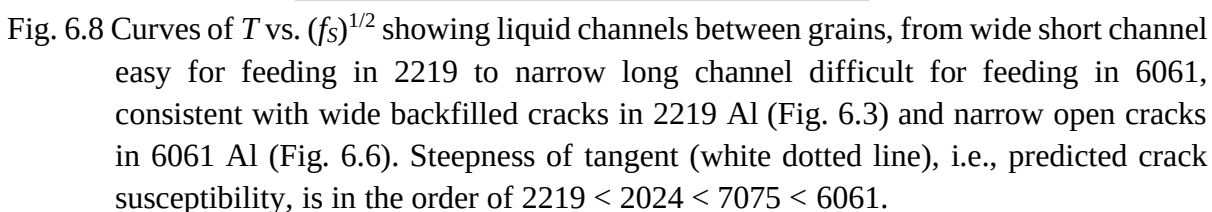


Fig. 6.7 SEM images of fracture surfaces: (a) 2219; (b) 2024; (c) 7075; (d) 6061.

6.3.3. Explanation for Crack Susceptibility and Backfilling

Since the dendrite root radius R is proportional to $(f_s)^{1/2}$ and since temperature T increases with increasing axial distance z , the outer contour of a columnar dendritic grain during terminal solidification can be represented by the curve of T vs. $(f_s)^{1/2}$ (Refs. 3, 5). The T - $(f_s)^{1/2}$ curves in Fig. 6.8, calculated using Pandat (Ref. 22) and PanAl (Ref. 23) assuming Scheil solidification (Refs. 1, 2), show widest shortest liquid channel in 2219, easiest for liquid feeding, and narrowest longest



As already shown in Figs. 6.3 through 6.6, numerous minor cracks tend to exist in a narrow region in the weld metal next to the main crack but not elsewhere in the bulk weld metal. This suggests nonuniform tensile strain in the mushy zone, highest in the narrow region just before cracking occurs. Thus, as illustrated in Fig. 6.9, the critical local average strain rate near the crack can be expressed as follows:

$$\dot{\epsilon}_{c,local} = V_c/D \quad (1)$$

where D is the width of the narrow region of minor cracks.

Taking 2219 Al in Fig. 6.3 as an example, $V = V_c = 0.20$ mm/s. At each level D is represented by the sum of the lengths of two white horizontal lines, i.e., 911, 760 and 901 μm . The average D is 857 μm and $\dot{\epsilon}_{c,local} = V_c/D = 0.233/\text{s}$ or 23.3 %/s. For 2024 Al in Fig. 6.4, $V_c = 0.15$ mm/s. The fine cracks more parallel to V than normal might be caused by the bridge across the main crack and thus are not considered. The average D is 1.262 mm and $\dot{\epsilon}_{c,local} = V_c/D = 0.119/\text{s}$. For 7075 Al in Fig. 6.5, $V_c = 0.10$ mm/s and D is 1.039 mm, thus, $\dot{\epsilon}_{c,local} = V_c/D = 0.096/\text{s}$. As for 6061 Al in Fig. 6.6, $V_c = 0.05$ mm/s and D is 0.580 mm, thus $\dot{\epsilon}_{c,local} = V_c/D = 0.086/\text{s}$.

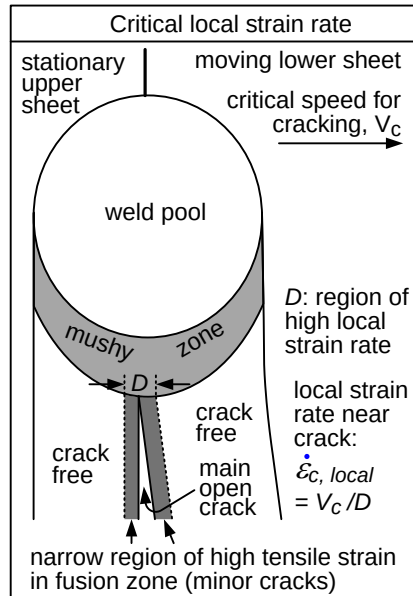


Fig. 6.9 Critical strain rate within the mushy zone near the crack.

Fig. 6.10 shows $\dot{\epsilon}_{c, local}$ in the order of 2219 Al > 2024 Al > 7075 Al > 6061 Al, just like V_c in the TMW test (Ref. 19). The lower the $\dot{\epsilon}_{c, local}$ or V_c is required to cause cracking, the higher the crack susceptibility is. Thus, the crack susceptibility is in the order of 2219 < 2024 < 7075 < 6061. In Fig. 6.8 the steepness of the tangent (white dotted line) represents the crack susceptibility index, i.e., the maximum $\left| dT/d(f_s)^{1/2} \right|$ up to $(f_s)^{1/2} = 0.99$. It is 1649°C for 2219, 3309°C for 2024, 4152°C for 7075, and 4848°C for 6061 (Ref. 5). Thus, the predicted crack susceptibility is in the order of 2219 < 2024 < 7075 < 6061. Before closing, it is worth mentioning that the critical strain rate can be measured by in-situ observation during welding (Refs. 24, 25). The method shown here seems a simple alternative.

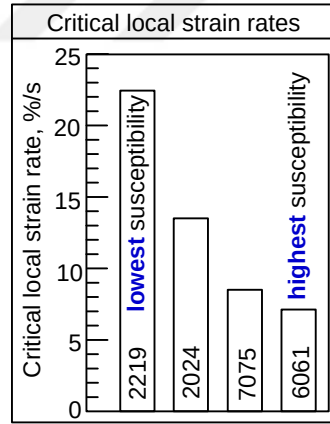


Fig. 6.10 Critical local strain rate $\dot{\epsilon}_{c, local}$ in TMW-tested Al welds determined based on transverse macrographs in Figs. 6.3 through 6.6.

6.4. Conclusions

1. Microstructural analysis of Al welds in the TMW test has shown wide backfilled cracks in 2219 consistent with its low crack susceptibility and narrow open cracks in 6061 consistent with its much higher crack susceptibility. The $T-(f_s)^{1/2}$ curves near $(f_s)^{1/2} = 1$ show in 2219 wide short

liquid channels between grains easy for liquid feeding and in 6061 narrow long channels difficult for liquid feeding.

2. The tensile strain inside the mushy zone is not uniform but much higher in the narrow region near the crack where minor cracks exist. The critical local strain rate, approximated by $\dot{\epsilon}_{c, local} = V_c/D$, has been found much higher in 2219 Al (23 %/s) than in 6061 Al (9 %/s), consistent with the much lower susceptibility of 2219 Al than 6061 Al in the TMW test.

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7. CONCLUSION

The objective of the present thesis was to better understand the solidification cracking susceptibility of wrought Al alloys. The first task was developing a new test for evaluating the susceptibility of Al alloys to solidification cracking. The transverse motion weldability (TMW) test was developed. The second task was predicting the susceptibility of Al alloys to solidification cracking. The maximum $\left| dT/d(f_s)^{1/2} \right|$ was used as the crack susceptibility index for prediction, where T is temperature and f_s the fraction of solid of an alloy during solidification.

In the transverse motion weldability (TMW) test, a stationary upper sheet was lap-welded to a lower sheet moving normal to the welding direction at the speed V to induce tension and hence cracking in the mushy zone. The mushy zone is a small, weak, semisolid region immediately behind the weld pool. The moving speed V was initially higher to ensure crack initiation but is suddenly lowered to a predetermined level to see if the crack can propagate.

Unlike other tests developed previously, the strain rate of the mushy zone is known and can be realistically slow as in real welding. Since the mushy zone is much smaller and weaker than the upper and lower sheets, tensile deformation caused by the moving lower sheet occurs only in the mushy zone, not the sheets. Thus, the overall strain rate of the mushy zone is known. Since the lower sheet can be moved as slowly as desired, the overall strain rate of the mushy zone can be very slow.

In the TMW test a critical speed of the lower sheet V_c existed, below which the crack initiated could not propagate and above which it propagated all the way to the end. The higher V_c is, the

faster the lower sheet needs to move in order for crack propagation to occur, that is, the lower the crack susceptibility becomes.

The critical moving speed of the lower-sheet V_c increased, i.e., crack susceptibility decreased, in the order of Al alloys 6061, 7075, 2024, 2014 and 2219, and this order was found consistent with reported data and susceptibility predictions based on the crack susceptibility index. The V_c also increased when Al alloys 6061 and 7075 were welded with filler metal 4043 Al, and Al alloys 2014 and 2024 with filler metal 4145 Al, consistent with published data and filler metal guides.

The TMW test and the crack susceptibility index were used to investigate the effectiveness of the commercial Al filler metals in reducing the crack susceptibility of two highly crack susceptible Al alloys 2024 and 6061. For 2024 Al, three filler metals were investigated, 2319 Al, 4043 Al and 4145 Al. Filler metal 4145 Al was found most effective and 2319 Al least effective. For 6061 Al the new commercial filler metal 4943 Al (designed to increase the weld strength of 6061 Al) was found as effective in crack reduction as the widely used 4043 Al. The effectiveness of these filler metals in reducing solidification cracking in 2014 Al and 6061 Al was also predicted based on the crack susceptibility index. The prediction agreed well with the results of the TMW test. To better understand the phases in the microstructure of the welds, the curves of temperature T vs. the fraction solid f_s were also calculated, i.e., the solidification paths.

In the TMW test the critical local strain rate near the crack can also be determined i.e., $\dot{\epsilon}_{c, local} = V_c / D$, where D is the width of the narrow highly-strained region next to the main open crack. In the micrograph of the TMW tested weld, this region and only this region shows numerous minor cracks. This suggests just before cracking occurs, the tensile strain is very high in this region and

much lower elsewhere in the mushy zone. $\dot{\epsilon}_{c, local}$ was determined in TMW-tested welds of 2024 Al, 2219 Al, 7075 Al and 6061 Al. Interestingly, the crack susceptibility ranking based $\dot{\epsilon}_{c, local}$ agreed with that based on V_c .

In summary, the TMW test is superior to previous tests for evaluating the susceptibility to solidification cracking. Unlike other tests, the overall strain rate of the mushy zone is known and is realistically slow as in real welding. As compared to other tests, the TMW test is much simpler and more cost effective. It requires only a small motor to move the lower sheet, not a pneumatic system to suddenly bend the workpiece to cause cracking (as in the Varestraint test) or a horizontal tensile testing machine to stretch the workpiece and the weld during welding. The use of the maximum $|dT/d(f_s)^{1/2}|$ of an alloy as its crack susceptibility index allows the prediction of the crack susceptibility of Al welds and the effectiveness of Al filler metals in reducing the crack susceptibility. The validity of the index has been verified by numerous data from previous tests as well as the TMW test.

List of Publications

1. Soysal, T., Kou, S., 2017. A simple test for solidification cracking susceptibility and filler metal effect. *Welding Journal*, 96(10), 389s-401s.
2. Soysal, T., Kou, S., 2018. A simple test for assessing solidification cracking susceptibility and checking validity of susceptibility prediction. *Acta Materialia*, 143, 181-197. <https://doi.org/10.1016/j.actamat.2017.09.065>
3. Soysal T., Kou S., 2019. Effect of Filler Metals on Solidification Cracking Susceptibility of Al Alloys 2024 and 6061. *Journal of Materials Processing Technology*, 266: 421-428. <https://doi.org/10.1016/j.jmatprotec.2018.11.022>.
4. Soysal, T., Kou, S., 2019. Prediction of Filler-Metal Effect on Solidification Cracking in 2024 Al and 6061 Al, *Science and Technology of Welding and Joining*, DOI: [10.1080/13621718.2019.1570683](https://doi.org/10.1080/13621718.2019.1570683).
5. Soysal, T., Kou, S., 2020. Microstructural Analysis of Solidification Cracking in Aluminum Welds, manuscript in preparation.