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Moving Characteristics of Weld Edges during Solidification in Relation to Solidification Cracking in GTA Weld of Aluminum Alloy Thin Sheet†

Fukuhisa MATSUDA*, Kazuhiro NAKATA** and Shoji HARADA***

Abstract

Deformations around the end of puddle during welding on 2 mm thick aluminum alloy sheets were measured by a new contactless method, by means of film recording. Moreover, the accuracy of this measuring method was investigated. The effects of welding conditions, the rigidity of test pieces and the measuring location on test piece on the deformation characteristics which occurs in the transverse direction of welding seam near the end of puddle during welding were investigated. Their results were adopted to investigate initiating and propagating mechanism of solidification crack. Moreover using the measured deformation speed the reasonable specimen size and the shape were investigated for the solidification crack susceptibility test of thin sheet.

KEY WORDS: (GTA Welding) (Aluminum Alloy) (Hot Cracking) (Deformation) (Weldability Tests)

1. Introduction

In fusion welding the processes of deformation and solidification of weld metal take place simultaneously. It is very important to know the characteristics of the deformation at high temperature since the hot crack is formed in the brittleness temperature range during solidification.

Moreover, in order to deepen the right comprehension for the occurring mechanism of hot cracking, it is also necessary to know the effects of the welding conditions, the rigidity of workpieces and thermal and physical properties of alloys on the quantity and the rate of deformations in solidification temperature range of weld puddle during welding.

The measurements of the deformation in solidification temperature range during welding have been tried, so far, by means of two types of methods, that is, contact and contactless-to-workpiece methods as mechanical dial gauge¹⁾ and strain gauge²⁾, and filming³⁾ and Moire fringe techniques⁴⁾, respectively. However, it is problem in contact method that the measuring area is so limited and the strength of the heated metal is extremely low and is commensurate with pressure exerted by gauge tips. Moire fringe techniques is better in accuracy but becomes complicated in device while the filming technique is opposite to Moire techniques.

The aim of this investigation is to comprehend the macroscopic moving characteristics of weld edges with and without cracking, then the authors have used the filming technique in this investigation. This process is also convenient for this purpose, as the mutual positions of the measuring points which are marked in the non-melt region close to weld edges and the trailing edge of the molten puddle are simultaneously recorded on the same film.

Using this filming technique which is called "Camera process" by the authors, the authors have tried to investigate the moving characteristics near trailing end of molten puddle during GTA bead-on-plate welding of aluminum alloy sheets, changing welding conditions, size and thickness of sheet and type of alloy sheet.

Furthermore the authors have discussed about the size and shape of Houldcroft type cracking test specimen of aluminum sheet.

2. Background and Object

Solidification cracking of weld metal during welding is caused by a succession of low ductility of weld metal and high tensile deformation during solidification. Schematic illustration of the moving characteristics of weld edges near the trailing end of the puddle is shown in Fig.1 which was preliminarily investigated by one of the authors¹⁾.

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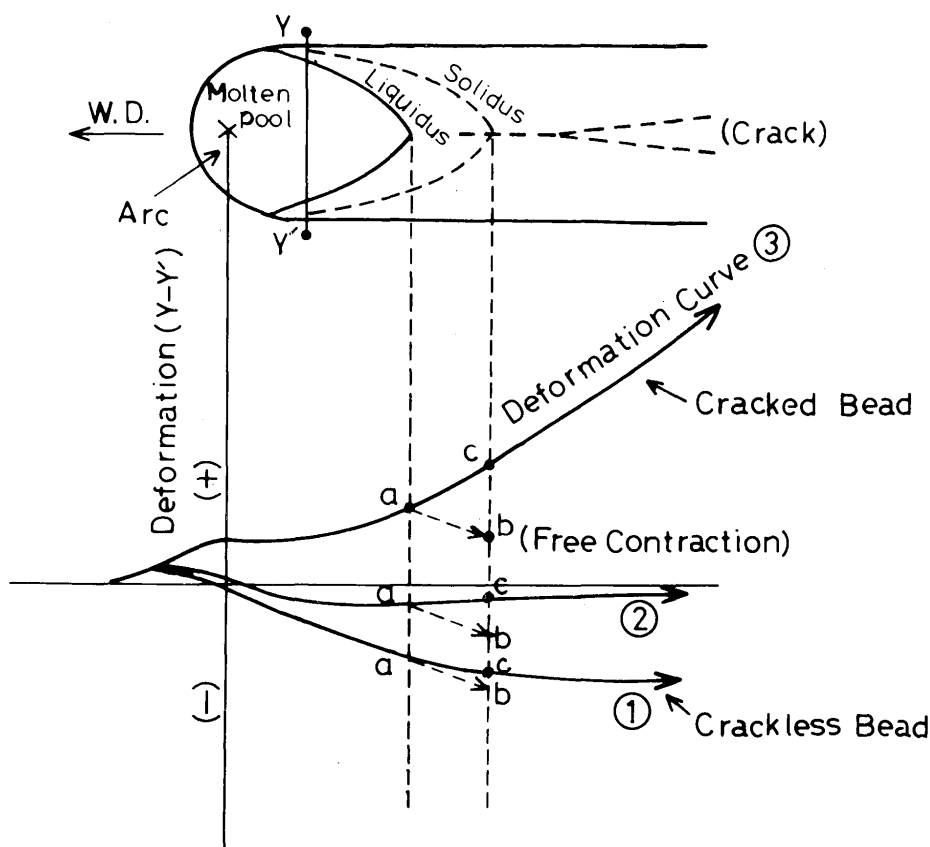


Fig. 1 Schematic illustration of typical curves for moving characteristics of weld edges near trailing end of weld puddle.

In the upper figure weld bead surface is exaggeratedly illustrated with molten puddle contours by liquidus (T_L) and true solidus (T_S) isothermal lines. In the lower figure the moving characteristics of the distance between Y and Y', that is, near weld edges which was marked before welding, are illustrated against time or location along the weld line, when a welding bead is placed. Three typical examples of the characteristics are shown as curves (1), (2) and (3). All these curves are firstly moved to (+) side by expansion due to access of the arc, though amount is differentiated with the variation of weld heat input, and successively to (-) side by contraction due to cooling of the weld zone.

In curve (1) a considerable contraction is seen in the solidification range between T_L and T_S . This is actually observed in the full-penetrated weld bead without cracking on thin sheet.

In curve (2) very little contraction occurs in the range, which is seen in the weld of rigid-held plate. This is actually observed in the surface-molten weld bead on thick plate.

In curve (3) a considerable expansion occurs again in the range after little contraction, which is seen in the full-

penetrated weld bead with a centerline cracking in rear of the weld puddle on thin sheet. This is caused by a large tearing strain transversely at the center of weld bead which is induced by the opening action of the separated weld bead due to a longitudinal heat expansion. This is actually observed in the crackless weld bead in Houldcroft-type cracking test for example.

Now consider the movement between Y-Y' in curve (3), the deformation curve whose displacement at T_L was point a is moved to point c at T_S . It is considered, however, that, if the restraint is completely free in the weld metal, the displacement between Y-Y' would be moved to point b at T_S according to free contraction of the weld bead. Therefore in curve (3) the weld metal was extended by the external force from point b to c during solidification. This displacement is probably concentrated in the weld centerline and is a considerable value in curve (3). Then, as the displacement \overline{bc} is lowered with an advance of welding and reached the value less than D_{min} , the centerline cracking will be vanished.

In the weld metal in curve (1) there is usually no cracking. Moreover for some cases in curve (1) \overline{bc} shows negative value, which means compression, due to turning

upside down the location of b and c. Usually in curve (2) there is no cracking in the weld bead, but exceptionally cracking occurs in case of the weld of low D_{\min} during solidification, because tensile strain due to weld metal contraction is transversely loaded.

As mentioned in the above, it is very important to understand the moving characteristics of the weld edges during solidification in welding as well as the value of solidification ductility of the weld metal, in order to investigate the solidification cracking phenomena.

3. Experimental Procedure

3.1 Materials used and welding condition

Main aluminum alloys used are commercially available materials which are designated as 5052 and 5083 of Al-Mg alloy and 2017 of Al-Cu alloy whose thickness are mostly 2 and partly 4, 6 and 10 mm. The size in the specimen is about 150 mm in length and 100 to 350 mm in width with or without parallel slits as shown in Fig. 2(a) and (b).

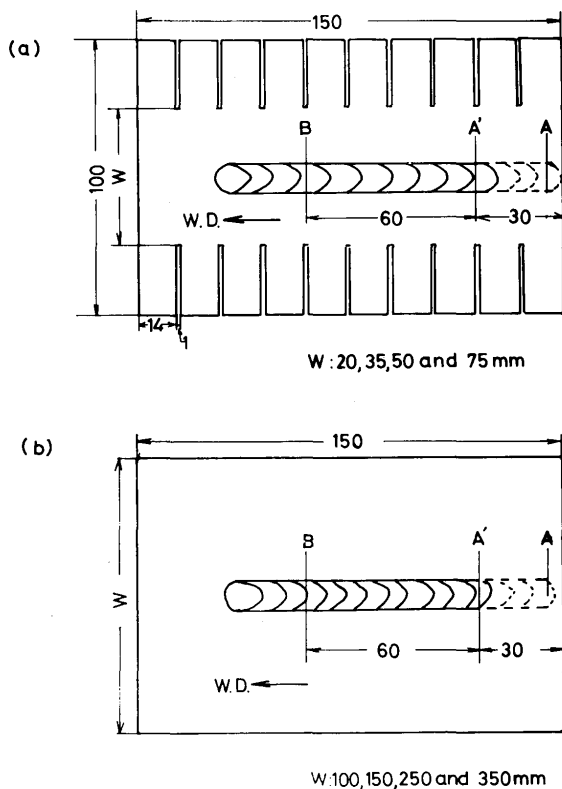


Fig. 2 Shape and size of test specimen used.

The actual specimen width, W, is varied from 20 to 350 mm with a change in the depth of the slits and more than 100 mm is widened the width in order to understand

the effect of the rigidity of workpiece on the moving characteristics of weld edges.

The specimen was welded by a bead-on-plate GTA welding (dcrp) using argon gas without filler wire, at the welding speed of 200 to 1000 mm/min. The welding GTA torch is moved with the predetermined welding speed.

For 2 mm thick specimens arc power was changed to the value such as would provide full penetration and the constant weld width of about 7.5 mm at the top with any of the selected welding speeds. Normally welding current was selected 75 amp for 200 mm/min of welding speed, 85 - 90 amp for 300 mm/min, 110 - 120 amp for 500 mm/min, 140 - 150 amp for 750 mm/min, 160 amp for 1000 mm/min under arc voltage of 16 volt. Moreover, in order to compare the change in moving characteristics between crackless and cracked weld beads, the location of welding start is selected at A for the former and A' for the latter. When the end of the specimen was melted on the welding start, the crack usually occurs and continued along the center on weld bead as welding is advanced.

3.2 Measuring technique of moving weld edges

The location measured for moving characteristics was set at B in Fig. 1 where a steady-state bead is performed. Measuring points are marked on the specimen surface with the indentation of Vickers hardness tester (10 to 50 kg load) before welding as shown in Fig. 3. The distance

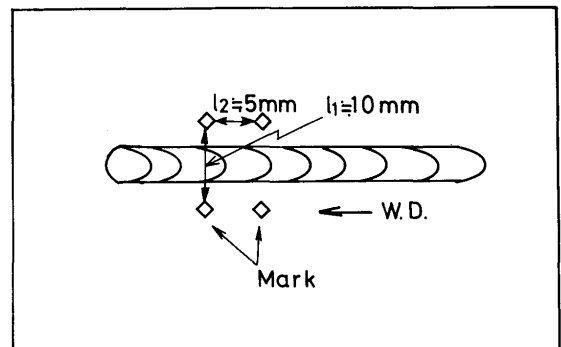


Fig. 3 Location of marks on test specimen for measuring deformation.

between two points is placed about 10 mm transversely and about 5 mm longitudinally for the axis of the welding bead.

The schematic arrangement and overall view of "the camera method" are shown in Fig. 4 and Fig. 5. By a 35 mm camera the filming is carried out aiming at the marks during welding at a magnification of X2 on film

screen in film speeds of 5 frames a second by the motor driven system. When the films exposed have been developed with a regular condition, the distances between two points are measured by 1/100 mm with a micrometer at X20 magnification. It is thus possible to determine the

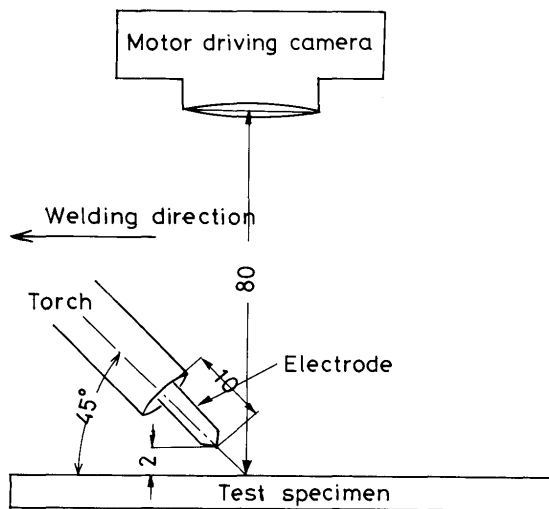


Fig. 4 Schematic illustration of arrangement for new measuring method.

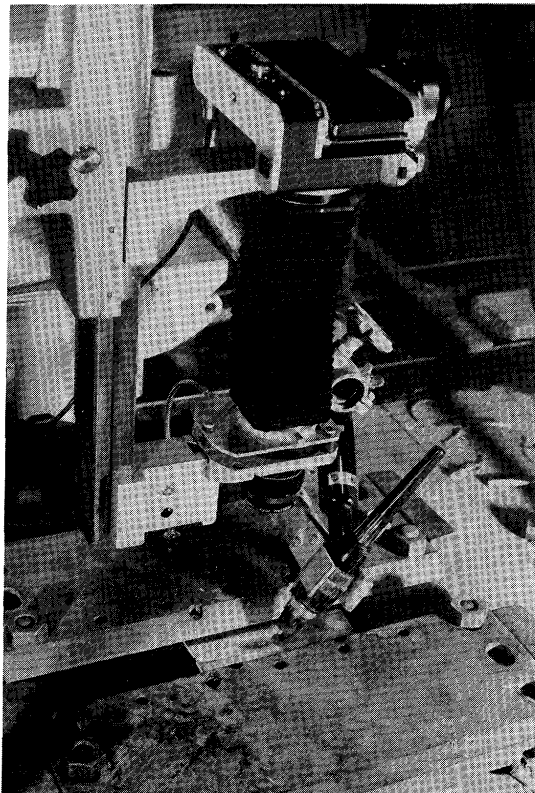


Fig. 5 Appearance of measuring method.

movement of the edges of the marking with an accuracy of 0.01 mm.

The accuracy of the measurement was discussed in Fig. 6 in correlation with the measured value on film and the true displacement of micrometer. The results show a good correlation.

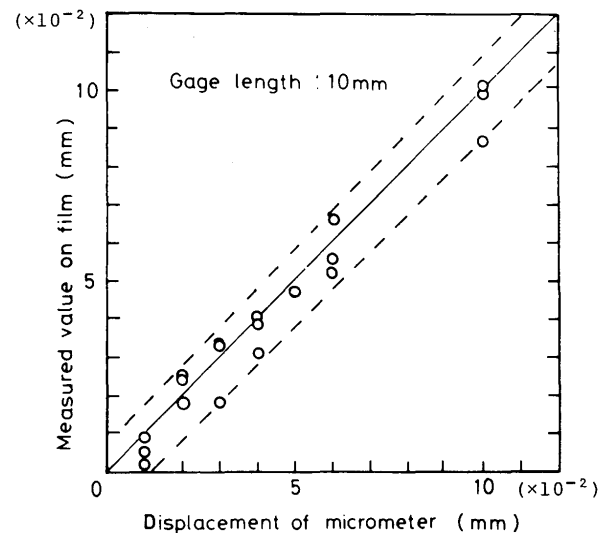


Fig. 6 Comparison of displacement in micrometer with measured value on film.

4. Experimental Results and Discussion

4.1 Moving characteristics of weld edges

Figures 7 and 8 show examples of photographs taking every 0.2 sec for low welding speed of 200 mm/min and high welding speed of 750 mm/min respectively. The torch is moving upwards and contour of it is being taken in the picture (a) of both photographs. The shape of molten puddle, the width of welding bead and the shape and location of crack tip occurred are simultaneously observed with the indentations of Vickers pyramid mark.

Figure 9 shows the moving characteristics for transverse (weld edges) and longitudinal directions to welding bead of 750 mm/min in welding speed with and without cracking. Zero on the abscissa means the instance when the tip of the welding electrode has passed on the connecting line between the first two marks and the deformation Δl in the vertical shows the difference between the instantaneous and the original distance as positive for expansion and negative for contraction.

Circle and square marks show the moving characteristics in transverse and longitudinal directions to the bead, respectively, and white and black marks mean cracked and crackless (crack free) beads, respectively. Simultaneously the location of the end of the weld puddle is represented in the lower figure which was obtained from the picture.

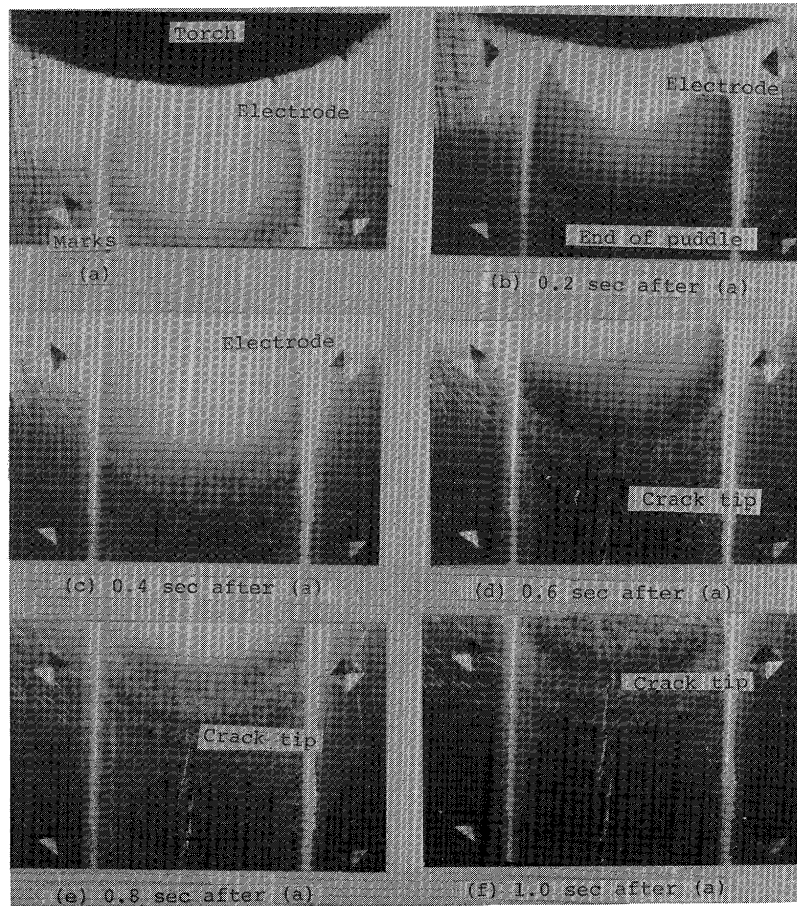


Fig. 7 Surface of weld pool in 5052 Al alloy at the moment when welding arc is passing the location being investigated ($v = 200$ mm/min, $I = 75$ A, $V = 16$ V).

As the authors described in Fig. 1, on the transverse deformation the large positive expansion rapidly occurs as a matter near the end of puddle in the cracked bead, while the negative contraction gradually occurs in the crack-free bead. However, on the longitudinal deformation positive and almost constant expansion occurs in both beads although there is a little higher in the crack-free bead. It is an interesting point that much expansion occurs in the crack-free bead in comparison with the cracked bead. However, obvious difference for moving characteristics was seen in the transverse deformation between cracked and crack-free beads. Therefore the investigation was mainly done hereafter for measuring the characteristics of transverse direction.

Figure 10 shows the effect of welding speeds, 300 and 750 mm/min, on the transverse moving characteristics on the weld beads with and without crack. The locations of the end of molten puddle and the tip of crack on film are simultaneously shown in figure.

The location of the crack tip shows a little variation

during welding, and this is obvious in case of slow welding speed.

Figure 11 (a) and (b) show the appearance of the cracked bead surface of 5052 aluminum alloy 2 mm thick thin sheet for 200 and 750 mm/min of welding speeds, respectively. The crack in (a) shows an intermittent fashion because of the elliptical puddle, while that in (b) shows a continuous fashion in the center of bead because of the teardrop-shaped puddle. From the results in Fig. 10 the weld bead of high welding speed shows much more expansion in the cracked and contraction in the crack-free bead than that of low welding speed. Then, when a crack occurs in weld bead, it is considered that the self-interruption of the crack during welding would be harder in general in case of high welding speed than in low welding speed. Moreover, the values of free contraction which was calculated from cooling curve measured during welding were filled up for reference. The amount of free contraction between the liquidus and the tip of crack is not so large in comparison with the contraction of the

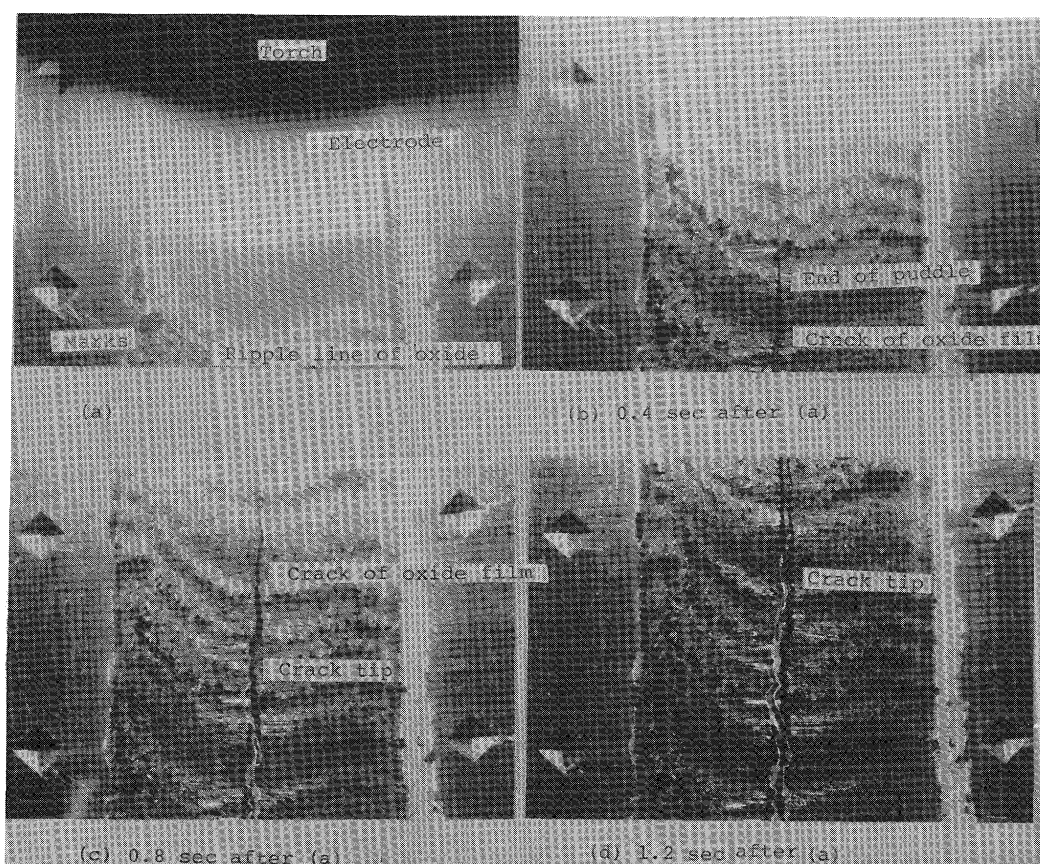


Fig. 8 Surface of weld pool in 5052 Al alloy at the moment when welding arc is passing the location being investigated ($v = 750$ mm/min, $I = 155$ A, $V = 16$ V).

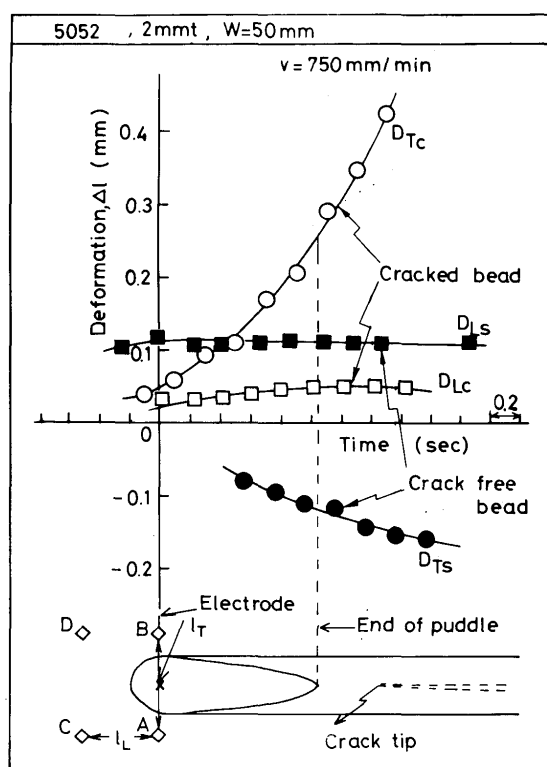


Fig. 9 Comparison of transverse deformation with longitudinal deformation during welding.

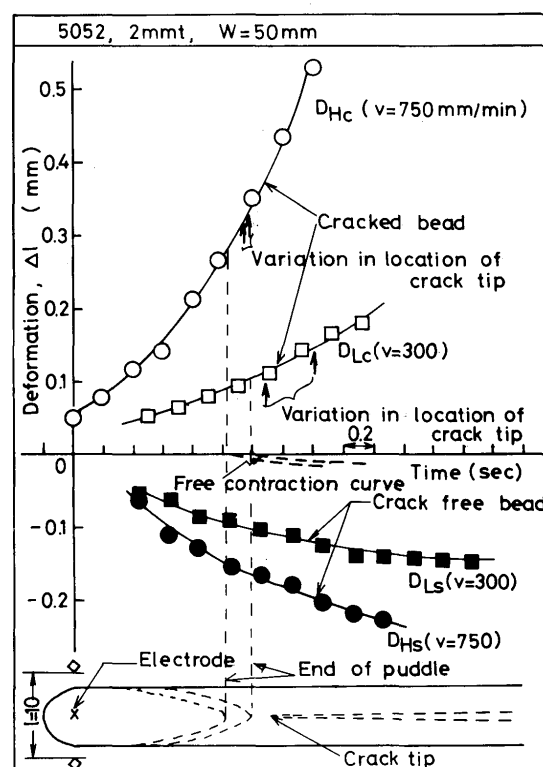
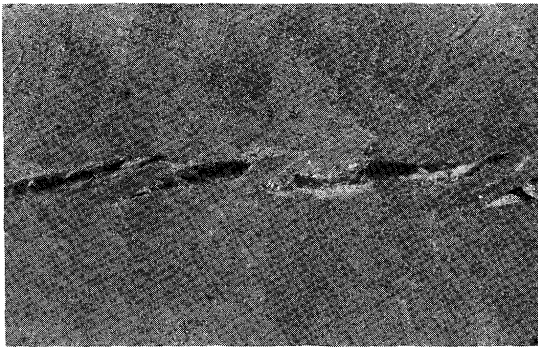
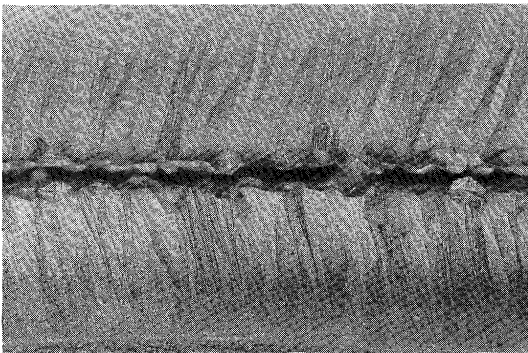


Fig. 10 Typical deformation curve at different welding speed.

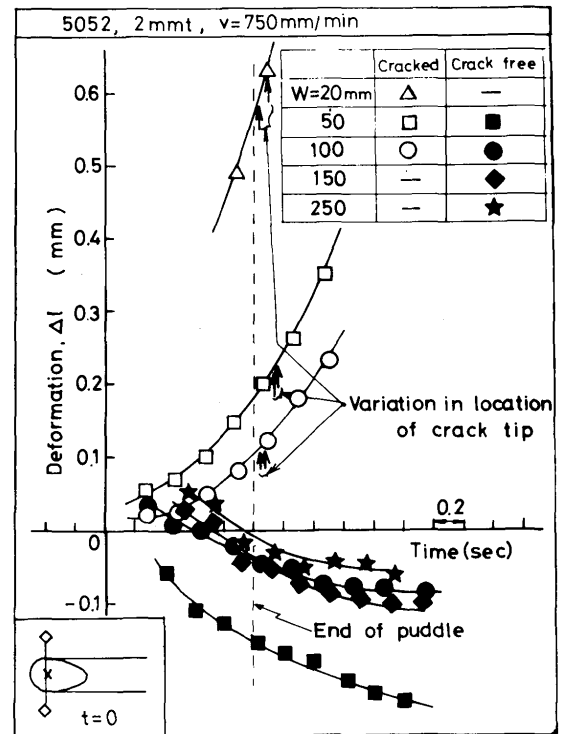
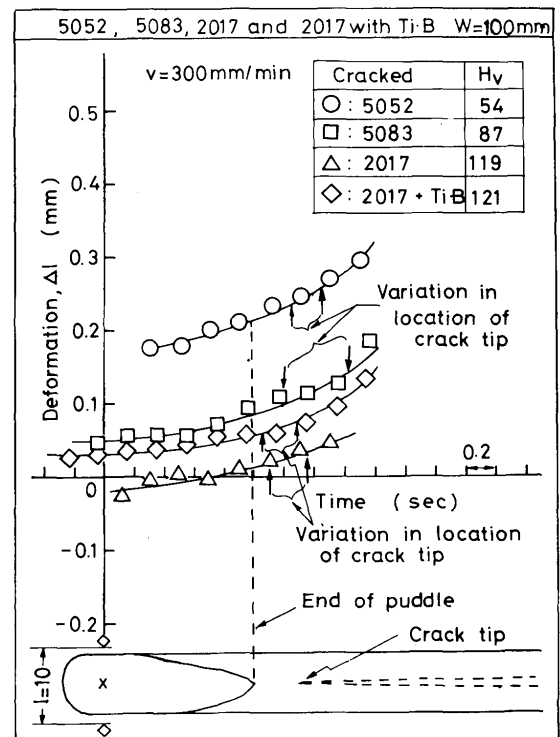
(a) low welding speed ($v=200\text{mm/min}$, $I=75\text{A}$, $V=16\text{V}$)(b) high welding speed ($v=750\text{mm/min}$, $I=150\text{A}$, $V=16\text{V}$)**Fig. 11** Typical appearance of solidification cracking along weld center.

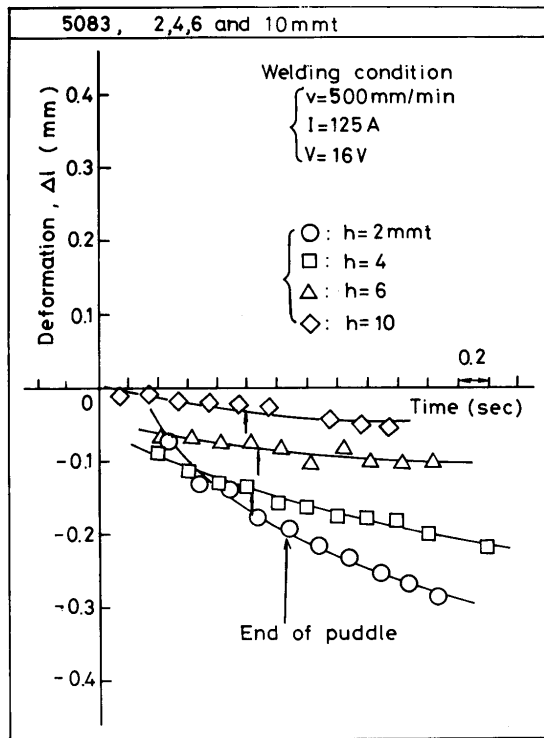
crack-free bead, though there is ignored the volume change due to solidification. Therefore it is assumed from Fig. 10 that the center of the crack-free bead would be placed in compression.

Figure 12 shows the effect of specimen width, W , that is rigidity for the deformation during welding, on moving characteristics for the weld bead in 750 mm/min of welding speed with or without cracking. The narrower the width, W , the more the moving characteristics in this high welding speed, though the difference is little for 250 to 100 mm in W in contraction of crack-free bead.

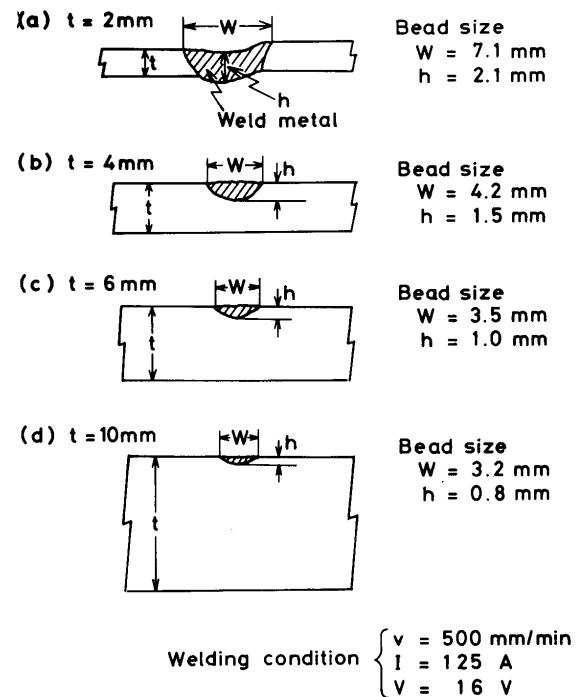
Figure 13 shows the effect of type of aluminum alloy for 2 mm thick sheet on moving characteristics of cracked bead of 300 mm/min in welding speed. The softer metal in hardness as 5052 shows much more deformation than the harder metals as 2017. This will be due to difference in the rigidity of specimen.

Figure 14 (a) shows the effect of the thickness, h , of 5083 aluminum alloy on the moving characteristics of crack-free bead under the same welding condition. Of course, the width and penetration of the weld bead were

**Fig. 12** Effect of specimen width on deformation characteristics in case of high welding speed.**Fig. 13** Effect of type of alloy on deformation characteristics.



(a) deformation characteristics



(b) dimension of weld bead in crosssection

Fig. 14 Effect of plate thickness on deformation characteristics.

varied with thickness of specimen as shown in Fig. 14 (b). The thicker the thickness of specimen, the less the deformation in contraction. There is little contraction in highly restricted weld bead as $h = 10\text{ mm}$.

The authors have, so far, measured the moving characteristics at the location B in Fig. 2 at which the weld bead is kept a steady-state condition in comparison with at A or A'. However, it is interested to know the difference in the moving characteristics of cracked bead between the start of bead at the edge of specimen, A, and the steady-state bead in the middle of specimen, B, in order to investigate the mechanism of solidification cracking in the centerline of weld. Therefore the difference was measured in Fig. 15. As the authors have expected, the moving characteristics behind the molten puddle is much prominent in the start of bead at the edge of specimen, A, than in the middle of specimen, B. The deformation rate which is conducted from inclination of the deformation curve between the end of puddle and the tip of crack is also much higher at A than at B. After larger deformation occurred at A for the start of the welding, the crack in bead was initiated as shown in Fig. 15, but, as soon as the welding advanced, the tip of the crack quickly went near the end of puddle. Then, at B where the deformation rate

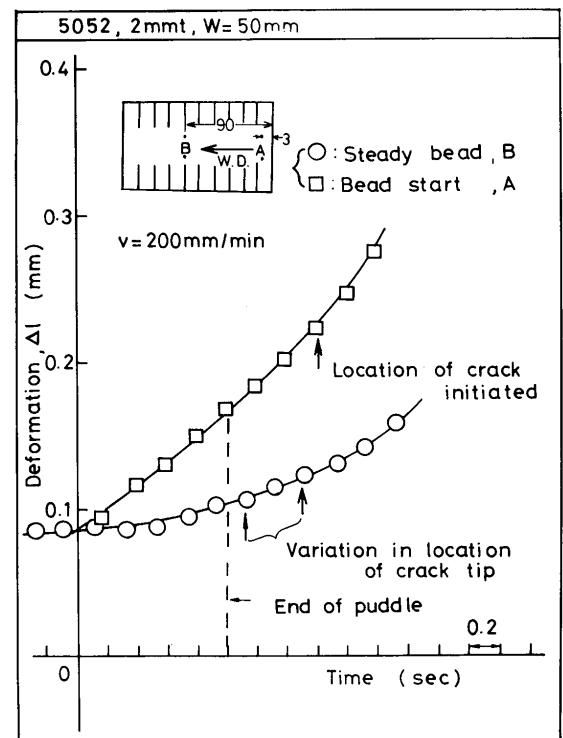


Fig. 15 Comparison of deformation characteristics at bead start with at steady-state bead.

is lowered considerably but the crack is still continued, the crack tip is moving continuously with a little variation in its location because of the intermittent crack. From Fig. 15, it is considered that high deformation rate and large deformation are required for crack initiation and after the crack initiated the crack is continued for propagation by small quantity of deformation. It is suggested, therefore, that there is a considerable difference in the minimum ductility required for initiation and propagation of cracking.

In general the deformation rate in expansion is the highest near the weld start of the specimen edge in the cracked bead, and, as welding advanced inward, it is gradually decreased and finally is changed to negative (contraction) when the crack was stopped. The location of the crack tip behind the end of weld puddle is also varied with the advance of welding. The location is close to the end of molten puddle near the weld start excepted that at the moment of crack initiation but is gradually delayed as welding advances inward and the deformation rate decreases. This means that the temperature near the crack tip in the weld metal is higher in crack of high deformation rate and is lower in that of low deformation rate in general.

Nextly the authors have investigated the size and shape of Houldcroft-type cracking test using the results investigated in the above. The relations between actual specimen width, W , and the deformation rate (deformation speed) at the end of weld puddle measured at point B in Fig. 2 are shown for welding speed of 200 to 1000 mm/min using 5052-O 2mm thick sheet in Fig. 16. White, black and half-black marks respectively indicate that the crack continued, did not occur and just stopped at the measuring point B. The results told us that in the range more than 70 mm in W the deformation speed is always decreased with an increase in the specimen width and reached to a constant, but less than 50 mm in W the different type in the deformation speed occurs in the cracked weld beads in high and low welding speed.

For the latter the deformation speed is decreased with a decrease in W in low welding speed as 200 and 300 mm/min in this investigation for aluminum alloy of 2 mm thick sheet, while that is increased in high welding speed as 750 and 1000 mm/min. The facts in the above are so important to investigate the solidification cracking test of thin sheet. Houldcroft-type cracking test is widely known as a test method to evaluate the solidification crack susceptibility of metal. This specimen has the shape that W is decreased with an advance of welding as shown in Fig. 17 (1)⁶. Then the susceptibility to solidification cracking of metal is evaluated by the comparison of the crack length in weld bead. From the results in Fig. 16 it is suggested for Houldcroft type test specimen that this test

is available only for the test specimen less than 50 mm in W_1 in Fig. 17 and test welding speed less than about 300 mm/min in aluminum alloy 2 mm thick sheet because the deformation speed of the cracked bead is decreased with an advance of welding and finally the crack can stop at some critical deformation speed.

That is to say, Houldcroft type test specimen is available in case of narrow specimen and low welding speed. This agreed with the result that the crack susceptibility of Al-Mg alloys could not be evaluated distinctively with Houldcroft type specimen in case of welding speed more than 360 mm/min (15 ipm)⁷.

Therefore for high welding speed and/or wider specimen the test specimen for solidification crack susceptibility is better in the shape that W is increased with an advance of welding. An example of these test specimens is shown in Fig. 17 (2) which was proposed for aluminum alloy by Ando et al⁸.

Besides some different specimen shapes will be proposed hereafter for other thin metals and alloys for the evaluation of solidification cracking.

5. Conclusions

In order to confirm the mechanism of solidification cracking which was previously investigated by one of the authors, the moving characteristics of the weld edges near the end of molten puddle during welding has been investigated for aluminum alloys by a new measuring method using a motor driven 35 mm camera.

The main conclusions obtained are as follows;

- (1) The moving characteristics of weld edges was quantitatively measured by accuracy of 0.01 mm with the new camera method. Moreover the end of puddle and the tip of crack were simultaneously taken into the same film. This was much convenient to investigate the location and behaviour of the crack tip behind the end of puddle.
- (2) The moving characteristics of weld edges near the end of puddle showed expansion in case of cracked bead and contraction in case of crackless bead for the full penetration bead of 2 mm thick aluminum alloy sheet. These experimental results were qualitatively agreed with the predicted results.
- (3) Increasing welding speed and decreasing width of specimen, hardness of specimen and thickness of specimen the amount of deformation at the end of puddle was increased. The results could be explained by the degree of rigidity.

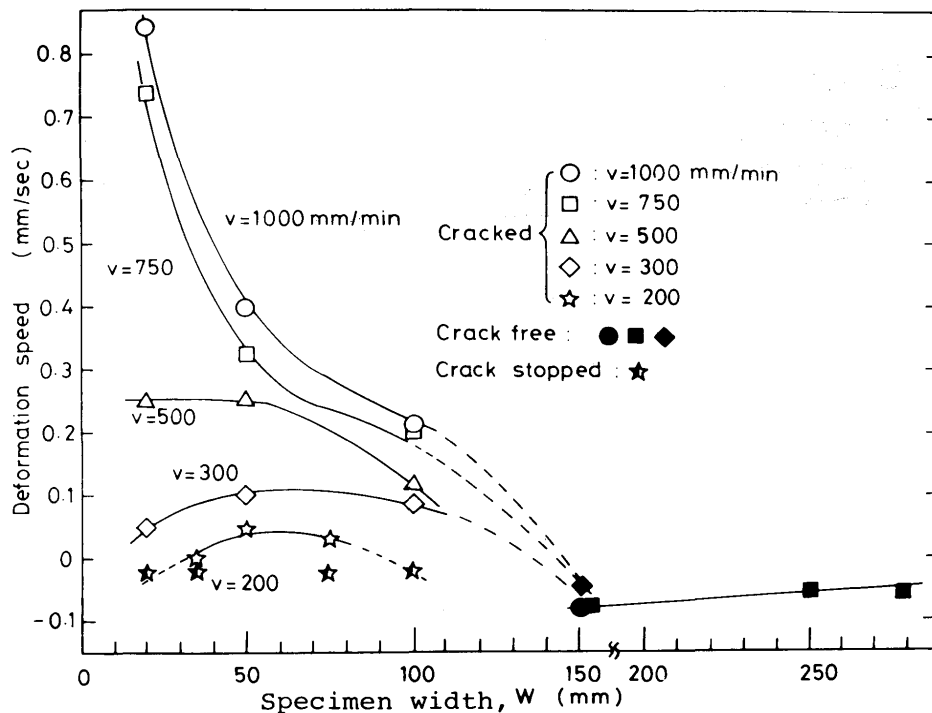


Fig. 16 Relation between specimen width and deformation speed at trailing end of weld puddle for weld bead at different welding speed.

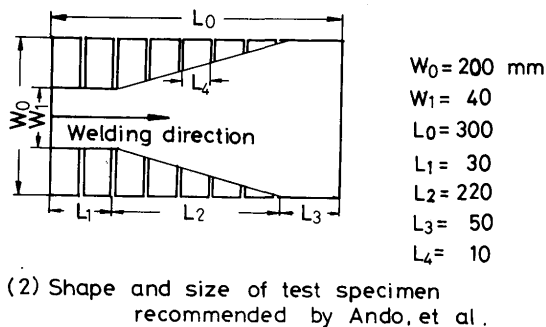
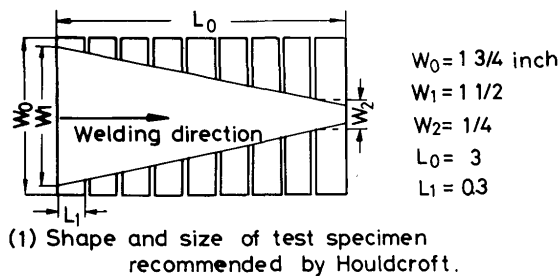


Fig. 17 Examples of shape and size for cracking test specimen used for evaluation of solidification crack susceptibility of Al alloy thin sheet.

- (4) In case of high welding speed more than 750 mm/min, the deformation rate was obviously increased decreasing the specimen width. However, in low welding speed less than 300 mm/min, the rate was reversely decreased decreasing the specimen width less than 50 mm.
- (5) The amount of deformation and the deformation rate was higher in the weld start at specimen edge than in the steady-state weld at the middle of specimen. Moreover the minimum ductility required to cause cracking was higher in the initiation of crack at the specimen edge than in the propagation of crack in the steady-state bead.
- (6) The shape of test specimen in Houldcroft type hot cracking test is valuable in case of low welding speed (i.e. up to about 300 mm/min for 2 mm thick aluminum sheet). In cases of high welding speed the reverse shape to Houldcroft type specimen, which is widened in width as welding advances, was recommended from this experimental investigation.

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