Solidification Crack Susceptibility of Aluminum Alloy Weld Metals (Report III)†

— Effect of Straining Rate on Crack Length in Weld Metal —

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Abstract

The effect of the straining rate and the augmented-strain on the length of solidification crack occurred in the weld metal has been investigated theoretically and experimentally by means of the Slow Bending Speed (SB) Trans-Varestraint cracking test for four aluminum alloys, that is, 5052-o, 5154-o, 5083-o and 2017-o.

For the prediction of the crack length occurred in the weld metal, the equations was theoretically derived under some assumptions.

As a result of comparing the calculated values of the crack length with the actual values, it was proved that there was a good agreement between them.

1. Introduction

In the actual welding process, it is generally considered that the weld metal during solidification is strained with various levels of the straining rate and the strain even in the same alloy due to the differences in welding condition and a degree of restraint. Also, some experimental results supporting the idea as described above have been reported[1),2)].

Therefore, for evaluating the solidification crack susceptibility of weld metal, it is necessary to reveal the effect of straining rate on the solidification crack susceptibility, that is, the brittleness temperature range (BTR), cracking threshold required to cause cracking (ε_{min}) and the morphology of cracking.

Nevertheless, only a few investigations on the effect of straining rate on the solidification crack susceptibility, so for, have been attempted by using some cracking tests, for example, tensile strain type solidification cracking test[3),4),5)] and Mulex hot cracking test[6)]. Therefore, the effect of the straining rate on the solidification crack susceptibility has not always been clear.

On the other hand, in the previous reports[7)], the authors developed a new cracking test, namely Slow Bending Speed (SB) Trans-Varestraint test on the basis of Trans-Varestraint test and then, the effect of the straining rate on the ε_{min} has been investigated for various aluminum alloys. As a result, it has been clear that the ε_{min} changed with the straining rate for some aluminum alloys. Moreover, it has been expected that the morphology of solidification crack occurred in the weld metal should be affected by the straining rate.

Consequently, in this investigation, the theoretical analysis has been done on the relations between the crack length and the straining rate and augmented-strain under some assumptions. Then, the effect of straining rate on the morphology of solidification cracking, especially the crack length is examined in the weld metal of four aluminum alloys by using the SB-Trans-Varestraint cracking test. The experimental results have been also compared with those of the theoretical analysis.

2. Theoretical Consideration for Effect of Straining Rate on Crack Length in Weld Metal

In the fusion welding process with a moving heat source, the BTR moves together with the travel of the weld puddle. So, the crack will be lengthen in length along weld center when the augmented-strain is being applied exceeding the cracking threshold. The length of the crack is also considered as an important factor for solidification crack susceptibility as the width of

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the BTR and the cracking threshold. Therefore, the calculation of the crack length in the weld metal with various straining rate and augmented-strain has been done under some assumptions.

Figure 1 illustrates a model for the calculation of

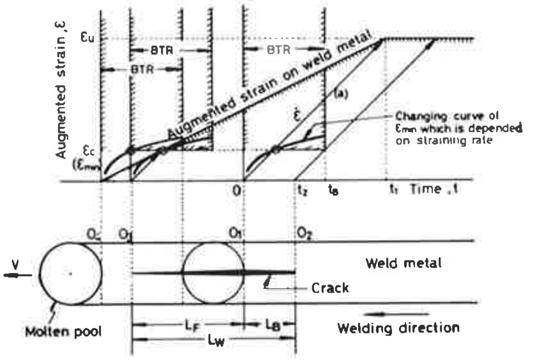


Fig. 1 Illustration of model for calculation of crack length

the crack length and qualitatively shows the relation between the crack length and the changing curve of cracking threshold which is depended on straining rate and augmented-strain applied on the weld metal. A weld puddle is moving with a welding speed of V from right to left side in Fig. 1 and the BTR is also moving together with the weld puddle.

The characteristic of solidification cracking threshold curve of the material is assumed as follows:

As shown in Fig. 1, the width of the BTR is t_B, which can be exchanged to the temperature difference by using a cooling curve in the weld metal[8], that is, t_B=BTR/Mean Cooling Rate, and a cracking threshold (ε_{min}) in the BTR increases as the decrease of the temperature as shown by the bold line because the cracking threshold of aluminum alloy weld metals were useally inclined to increase with a decrease of straining rate in the lower temperature zone of the BTR[9].

The weld metal is began to be strained with a constant straining rate ($\dot{\varepsilon}$) as shown in (a) line in Fig. 1 at the instant when the end of the weld puddle reaches to the point O_1 and, when the augmented-strain reaches to the cracking threshold $\varepsilon_c(\varepsilon_{min})$, the cracking should occur within the range from point O_1 to O_2, that is, the lowest temperature boundary of the BTR.

Then, straining is stopped when the augmented-strain reaches to the ultimate value (ε_u), where $\varepsilon_u > \varepsilon_{min}$. At this time, the end of the weld puddle reaches to the point O_4.

According to the idea as described above, the crack will occur between O_2 and O_3 where the augmented-strain reaches to ε_c. In this circumstances the crack occurred can be divided into two parts, one exists behind the end of the weld puddle at the point O_1 where the straining began and another exists at the front of it, which are named as "back crack" and "front crack", respectively.

The weld puddle moves forward with the distance of $V\cdot(\varepsilon_{min}/\dot{\varepsilon})$ until the augmented-strain reaches to ε_{min} because the time required to reach to ε_{min} is given by $(\varepsilon_{min}/\dot{\varepsilon})$. Therefore, in the right hand of the point O_1, the length of back crack corresponds to the one excluding $V\cdot(\varepsilon_{min}/\dot{\varepsilon})$ from the width of the BTR, $(V\cdot t_B = l_B)$. Consequently the length of back crack (L_B) is given by the next equation:

$$L_B = V\left(t_B - \frac{\varepsilon_{min}}{\dot{\varepsilon}}\right) = l_B - V\cdot\frac{\varepsilon_{min}}{\dot{\varepsilon}} \qquad (1)$$

Moreover, the length of front crack (L_F) in the lower figure in Fig. 1 extends from point O_1 to O_3 where augmented-strain is just equal to the ε_{min} and is far from O_4 in distance of $V(\varepsilon_{min}/\dot{\varepsilon})$. Where, the length of O_1O_4 corresponds to the distance which weld puddle can move during the time ($=\varepsilon_u/\dot{\varepsilon}$) required to reach to ε_u with a constant straining rate. Therefore, the length of front crack, L_F is given by the next equation:

$$L_F = V\cdot\frac{1}{\dot{\varepsilon}}(\varepsilon_u - \varepsilon_{min}) \qquad (2)$$

Consequently, the whole length of crack, L_W is given by the following equation:

$$L_W = L_B + L_F = V\cdot\left(t_B + \frac{\varepsilon_u - 2\varepsilon_{min}}{\dot{\varepsilon}}\right) \qquad (3)$$

Where ε_{min} : Cracking threshold required to cause cracking (%)
$\dot{\varepsilon}$: straining rate (%/sec)
ε_u : ultimate augmented-strain (%)
t_B : time corresponding to the width of the BTR, BTR/Mean Cooling Rate (sec)
l_B : length of crack corresponding to the BTR occurring at a simultaneous straining rate (mm)
V : welding speed (mm/sec)
L_B : length of back crack (mm)
L_F : length of front crack (mm)
L_W : whole length of crack (mm)

From eq. (3), when the ε_u is exceeding the value of $2\varepsilon_{min}$, the whole length of the crack will increase with decrease of $\dot{\varepsilon}$ if the ε_{min} varies little or a little against $\dot{\varepsilon}$. On the contrary, when the ε_u is less than $2\varepsilon_{min}$, L_W will decrease with a decrease of $\dot{\varepsilon}$.

Table 1 Chemical compositions of commercial aluminum alloys used

Material	Chemical composition (wt%)									
	Cu	Si	Fe	Mn	Mg	Zr	Cr	Ti	Zr	B
5052-0	0.04	0.09	0.19	0.01	2.50	0.01	0.15	<0.01	–	–
5154-0	0.02	0.11	0.25	0.06	3.50	0.01	0.23	0.03	–	–
5083-0	0.03	0.10	0.18	0.79	4.44	0.02	0.10	0.02	<0.01	–
2017-0	3.80	0.47	0.43	0.47	0.44	0.11	0.03	0.02	–	–

3. Compareson of Calculated Result with Experimental Result

3.1 Materials Used and Experimental Procedure

3.1.1 *Materials used*

The materials used are 6 mm in thickness of commercially used aluminum alloys. 5052-O, 5154-O and 5083-O are Aluminum-Magnesium (Al-Mg) alloys and 2017-O is Aluminum-Copper (Al-Cu) alloy. Chemical compositions of materials used are shown in **Table 1.** All materials are used under annealed condition.

3.1.2 *Experimental procedure*

A cracking test used in this experiment is the SB-Trans-Varestraint cracking test[8]. By means of this cracking test, the weld metal during solidification can be strained with various straining rate and the ε_{min} can be evaluated for given straining rate.

The TIG-arc bead-on-plate welding has been carried out in the cracking test with the condition of welding current 230 amp (ac), arc voltage 18 volt and welding speed 100 mm/min. After the cracking test, the lengths of all of the back and the front cracks are measured on the surface of weld metal by means of the micrometer at $\times 6$ to $\times 70$ magnifications.

The maximum length of cracks among them are adopted as the length of each crack, L_B, L_F and L_W.

3.2 Experimental Result and Discussion

3.2.1 *Effect of straining rate on morphology of cracking in SB-Trans-Varestraint tested specimen*

In the high bending speed type Trans-Varestraint tested specimens as described in the previous report[8], the crack occurred behind the end of the weld puddle at the instant when augmented-strain applied. That is, only the back crack occurred but the front crack didn't.

On the other hand, two types of crack, namely the back crack and the front crack, have been appeared in the SB-Trans-Varestraint tested specimens as shown in **Fig. 2** as an example.

The cracks usually appear in the both sides divided by the ripple line which corresponds to the end of weld puddle where the augmented-strain began to be applied.

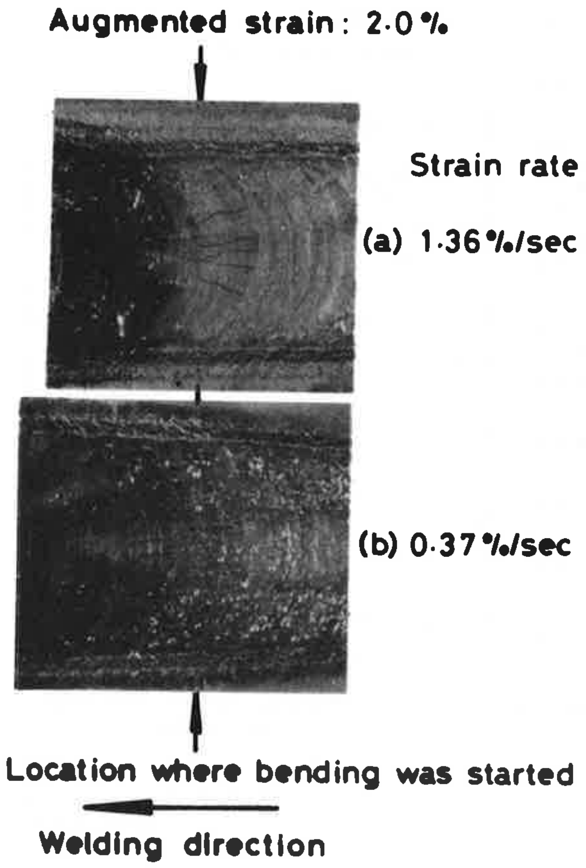


Fig. 2 Appearance of cracking occurred in the SB-Trans-Varestraint tested specimen of 2017-o

These differences in the morphology of the cracking closely depend on the straining rate applied on the weld metal during solidification because the straining rate in the Trans-Varestraint test is fast as about 5.7%/sec or more and this value is much larger than that in the SB-Trans-Varestraint test.

Figure 2 shows the morphology of the cracking in the weld metals of 2017-O for two levels of the straining rate but the augmented-strain is a constant value, namely 2.0%. As the straining rate is comparably fast but slower than that of Trans-Varestraint test, the front crack appears but the length of it is shorter than that of back crack as shown in Fig. 2(a). Then, as the decrease of the straining rate, the length of the front crack becomes longer and, on the contrary the length of the back crack becomes shorter in Fig. 2(b) in comparison with (a).

Figures 3 and **4** show the effect of the straining rate on the crack length in the weld metal of 2017-O and 5083-O alloys at two levels of the augmented-strain, respectively. In the upper of Fig. 3, 2% of the augmented-strain is much larger than ε_{min}, 0.35% as shown in **Table 2.** Therefore, as the decrease of the straining rate, the L_B becomes shorter but L_F becomes much longer so that the L_W becomes longer as described in Eq. (3).

The cracking disappears when the straining rate depressed under the critical straining rate. On the contrary, in the lower of Fig. 3 the augmented-strain

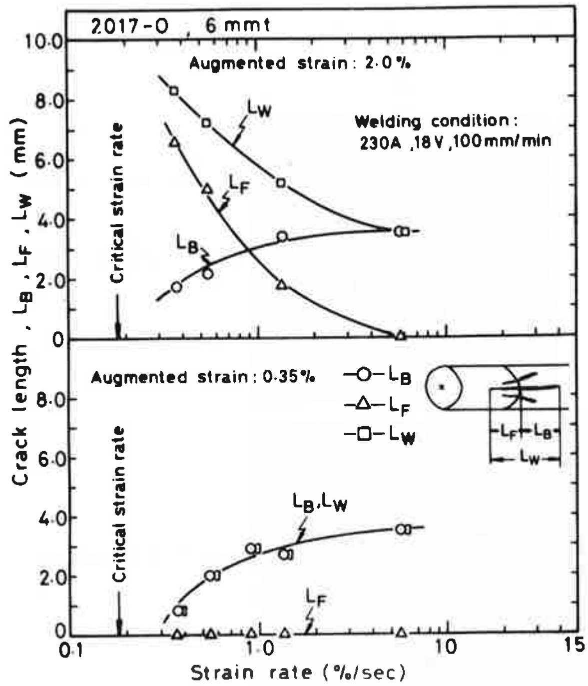


Fig. 3 Relation between straining rate and crack length, L_B, L_F and L_W in the weld metal of 2017-o

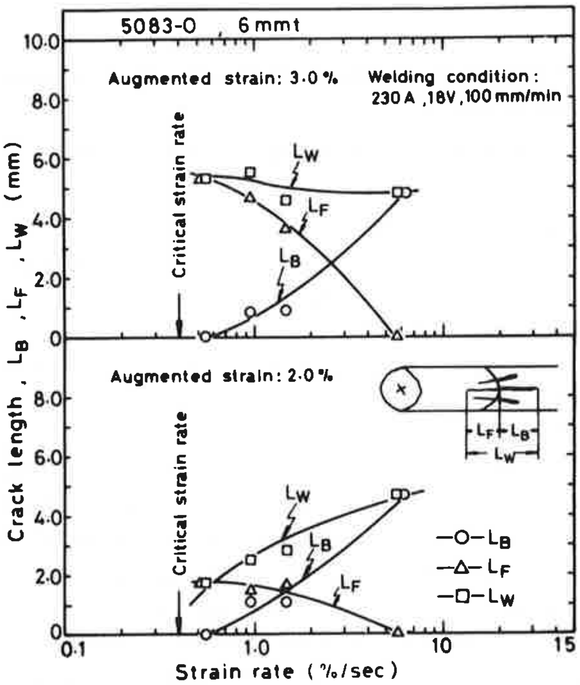


Fig. 4 Relation between straining rate and crack length, L_B, L_F and L_W in the weld metal of 5083-o

Table 2 Summary of values of width of BTR and cracking threshold for various straining rate used for calculation of crack length

Material	Width of BTR* l_B (mm)	Straining rate $\dot{\varepsilon}$ (%/sec)	Cracking threshold** ε_{min} (%)
5052-0	1.6	5.70	0.05
		1.95	0.40
		1.16	0.80
5154-0	1.9	5.70	0.05
		1.74	0.60
		1.37	0.80
		1.10	0.80
		0.77	1.05
5083-0	4.7	5.70	0.05
		1.47	0.80
		0.95	1.28
		0.55	1.50
2017-0	3.5	5.70	0.05
		1.35	0.35
		0.89	0.35
		0.55	0.35
		0.37	0.35

* obtained by Trans-Varestraint cracking test
**obtained by SB-Trans-Varestraint cracking test

is 0.35% and equal to the ε_{min}. Therefore the front crack cann't be seen and as the decrease of the straining rate, the L_W becomes shorter together with L_B. In Fig. 4 for 5083-O, the relations between the crack length, L_B, L_F and L_W and the straining rate are shown for 3.0% and 2.0% augmented-strains. There are similar tendencies as those of 2017-O in spite of the large difference in the cracking threshold, that is, the ε_{min} of the wled metal of 5083-O is much larger than that of 2017-O and is inclined to increase as the decrease of the straining rate[9]. At the augmented-strain of 2.0%, the front crack appears since the value of the augmented-strain 2.0% is a little exceeding the ε_{min} of 5083-O in Table 2.

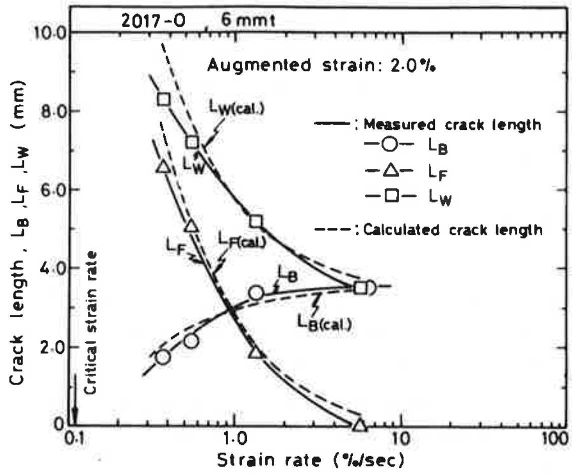
Meanwhile, in regard to the L_W, it is considered that the changes of the L_W against the straining rate are classified into two types with the value of the augmented-strain, that is, one is that the L_W increases as a decrease of the straining rate and the other is that the L_W decreases as a decrease of the straining rate.

As a result of the theoretical analysis, the threshold value of the augmented-strain existing between those two types has been predicted as $2\varepsilon_{min}$. As a result from Figs. 3 and 4, the former type appears at 2.0% and 3.0% augmented-strains for 2017-O and 5083-O, respectively, which are larger than $2\varepsilon_{min}$, that is, 0.05–0.35% and 0.05–1.50% for 2017-O and 5083-O, respectively, in Table 2. On the other hand, the latter type appears at 0.35% and 2.0% for 2017-O and 5083-O respectively, which are nearly equal or smaller than $2\varepsilon_{min}$, though it is different in case of the highest straining rate. Consequently, those changes of the L_W against the straining rate and the augmented-strain are as same as predicted in eq. (3).

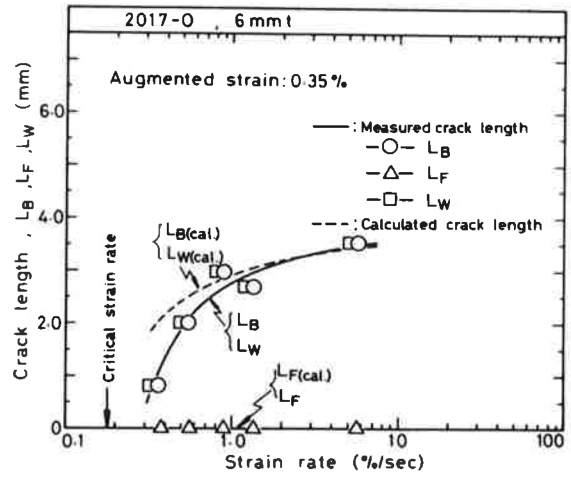
3.2.2 *Comparison of calculated crack length with measured crack length*

Figure 5(a) and **(b)** show the crack length calculated by means of eq. (1), (2) and (3) for comparison with measured crack length in Fig. 3 for 2017-O on the two levels of the augmented-strain, 2.0% and 0.35%, respectively. From these figures, it seems that the dependence of the crack length calculated on the straining rate closely agrees with that of the measured value in any type of crack length.

Figure 6 also shows the comparison of the calculated crack length with the measured one on various levels of the straining rate and the augmented-strain for 5052-O, 5154-O, 5083-O and 2017-O. The data used for calculation, that is, the BTR and ε_{min} for various straining rates are listed in **Table 2.** There are considerably good agreements between calculated and



(a)



(b)

Fig. 5 Comparison of measured crack length with calculated crack length in weld metal of 2017–o

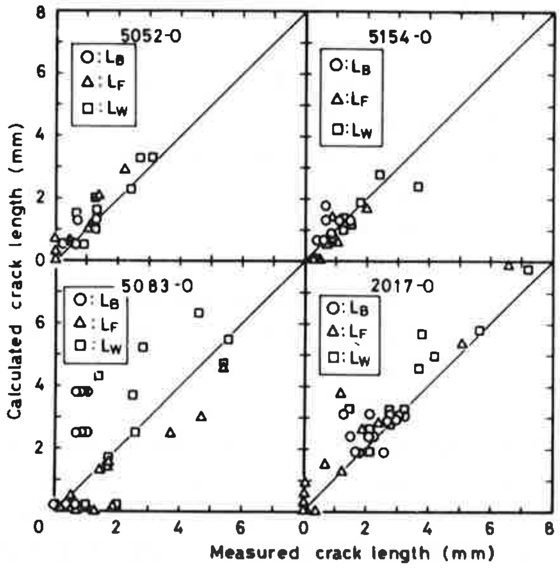


Fig. 6 Comparison of measured crack length with calculated crack length in weld metals of 5052–o, 5154–o, 5083–o and 2017–o

measured values of three types of crack length, namely L_B, L_F and L_W, in each alloy. In regard to 5083-O a little scattering is, however, seen between them, especially in L_B. The reason is that the back crack is not likely to extend to the lowest limit of the temperature in the BTR in spite of the assumption of the prediction eq. (1).

From the result of Figs. 5 and 6, however, the length of the crack occurring in the weld metal can be considerably predicted quantitatively by taking the movement of the BTR together with weld puddle into consideration when the weld metal is strained with a constant value of the straining rate during welding by a moving heat source.

4. Conclusions

The effects of the straining rate and the augmented-strain on the length of solidification crack occurring in the weld metal have been examined theoretically and experimentaly by means of the SB-Trans-Varestraint cracking test for four aluminum alloys.

The main conclusions obtained are as follows:

(1) For prediction of crack length occurring in the weld mteal, the equations are theoretically derived under some assumptions, which are shown as follows:

$$L_B=V\left(t_B-\frac{\varepsilon_{min}}{\dot{\varepsilon}}\right)$$

$$L_F=V\cdot\frac{\varepsilon_u-\varepsilon_{min}}{\dot{\varepsilon}}$$

$$L_W=V\left(t_B+\frac{\varepsilon_u-2\varepsilon_{min}}{\dot{\varepsilon}}\right)$$

where L_B : length of back crack (mm)

L_F : length of front crack (mm)

L_W : whole length of crack (mm)

ε_{min} : cracking threshold required to cause cracking (%)

$\dot{\varepsilon}$: straining rate (%/sec)

ε_u : ultimate augmented-strain (%)

t_B : time corresponding to the width of the BTR (sec)

V : welding speed (mm/sec)

(2) In the SB-Trans-Varestraint cracking tested specimen, the two types of the crack, that is, "back crack" and "front crack" occur in the weld metal rearward and forward of the ripple line where the strain begins to be applied. The back crack locates behind the ripple line and the front crack locates forward the ripple line.

(3) The length of the back crack increases with an increase of the straining rate, then satulated to the maximum crack length obtained by the Trans-Varestraint test on any augmented-strain.

As the augmented-strain is enough larger than the cracking threshold which is given for material, the length of the front crack increases with a decrease of the straining rate. On the contrary, as the augmented-strain is not enough larger than that of the cracking threshold, the length of the front crack decreases together with the whole length of crack with a decrease of the straining rate.

(4) From a result of comparing the calculated values of the crack length with the actual values for three types of crack, that is, L_B, L_F and L_W occurred in the weld metals of 5052-O, 5154-O, 5083-O and 2017-O, there is a good agreement between them, though a little scatter is seen for 5083-O.

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