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Cracking Study of Aluminum Alloys by the Variable Tensile Strain Hot Cracking Test*

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Abstract

In order to investigate mainly the effect of augmented strain and strain rate on the solidification cracking of weld metals, the Variable Tensile Strain hot cracking test apparatus was newly produced. In this paper, four types of aluminum and their alloy sheets were examined by this test apparatus. From these results, it was confirmed that this apparatus was suitable for evaluation of crack susceptibility of sheet metals because of its applicability of variable tensile strain and strain rate on weld beads during welding.

From the relation between strain rate and crack length, it was found that there was a threshold value of strain rate for crack initiation and the crack length decreased, reached a constant value, with an increasing strain rate.

Comparing the test materials, it was ascertained that solidification cracking was susceptible in order of A 2024, 5083 5052 *and* 1050 *metals.*

1. Introduction

There have been proposed many methods to perform hot cracking tests for a long time, and each of them is going to be used extensively according to its aim and test condition. For example, one of the authors introduced the methods of hot cracking test and their practical use in Japan, requested by the Second Commitee of IIW[1].

Though several testing methods have been offered one after another now the Varestraint test by Savage[2] and the Trans-Varestraint test by Senda and Matsuda[3] are widely being adopted for many studies or tests, which yield us good results. These methods are gradually clarifying the factors to the growing mechanism and the effectiveness of solidification cracking of weld metals, in carbon steel and other alloys[3,4].

In addition to these methods, there is the Angle Expanding Type Fillet weld cracking test[5] which is sometimes adopted as hot cracking test and it belongs to the bending load type. On the other hand, we can find only a few studies about tensile strain type solidification cracking test up to this time. Among them, the Baumann Technical College Test firstly developed by Russian investigators[6,7], is very convenient for quantitative examination of solidification cracking susceptibility by use of various rates of tensile loading. Recently, Nakata and Nishiura[8] offered the idea of a tensile restraint hot cracking test which can change tensile deformation given to weld metals according to degrees of restraint. They examined mainly the relation between welding variables and solidification cracking.

Now, in this report, to make clear mainly the effect of strain rate which has little been examined, systematic experiments on solidification cracking of weld metals of aluminum alloys have been performed using the Variable Tensile Strain hot cracking test apparatus, which can vary arbitrarily augmented strain and strain rate.

2. Test Apparatus and Method

The Variable Tensile Strain hot cracking test apparatus which was assembled on trial is able to examine hot cracking occurring in weld metals by loading swiftly the testing materials with optional strain and strain rate. The mechanism of this apparatus is shown in Fig. 1. It consists of air cylinder, gear box, motor and restraining jig. The main system is as follows.

At first, a specimen ⓢ is fixed by a restraining jig ⓙ. Though an air cylinder ⓑ is stopped in its movement by the stopper ⓐ, when a motor ⓜ begins transmitting its revolution to the stopper ⓐ through an electromagnetic clutch, this stopper moves in the direction that the arrow points to; then the cylinder pushes a lever ⓒ and the specimen receives tensile load, with the restaining jig, because of revolution around a hinge point ⓟ. But after revolving to some extent, the lever is stopped by the stopper ⓓ, so the specimen naturally ceases to move in the desirable displacement.

Therefore, the displacement can be changed optionally in 0∼1.5 mm range and 0.15 mm interval by moving the location of the stopper ⓓ. Moreover, the strain rate can be changed in 0∼0.13 sec range extensively, by controlling the moving speed of the stopper ⓐ with a reduction gear and a variable motor in a gear box ⓖ.

Test sheets are cut off to a specimen of 70×100 mm size. This specimen is completely fixed by bolts to the jig fitted with sharp edges on its back surface. In this case, the restraining distance is set at 50 mm. A single bead weld is performed without the addi-

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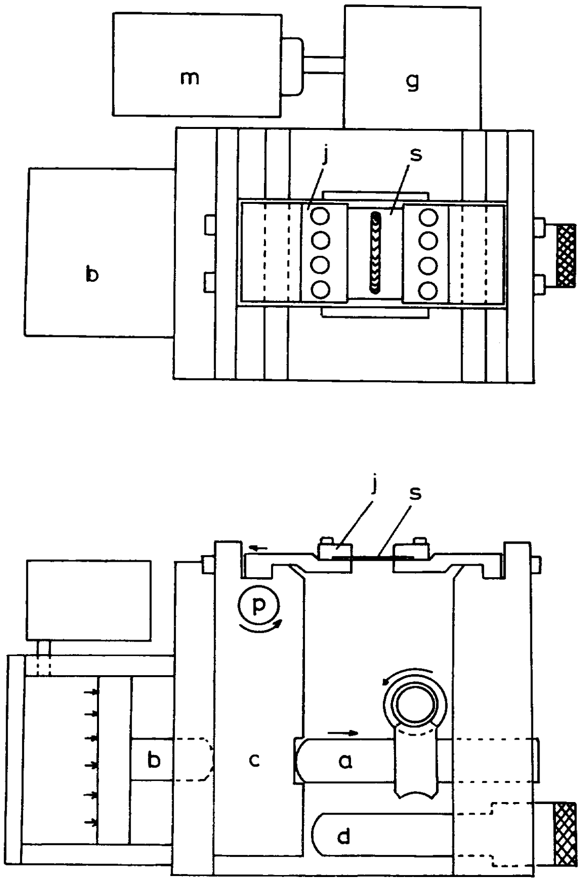


Fig. 1 Test apparatus.
a: stopper b: air cylinder c: lever d: stopper
g: gear box j: jig m: motor p: hinge point s: specimen

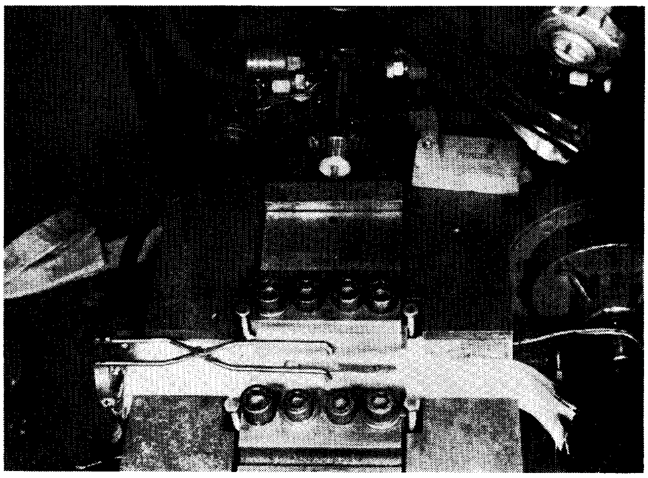


Photo. 1 Test apparatus and scissors type strain meter used.

tion of filler metal using a tungsten-inert gas (Tig) welding machine. A test bead is laid about 80 mm along the longitudinal centerline, and just when the weld arc reaches the center of the specimen, an optional tensile strain is applied quickly to the weld bead by an electromagnetic switch with a given strain rate.

The displacement applied to the specimen can be measured not only by a differential transformer set on the upper side of the lever ⓒ, but also continuously during welding by a penrecorder, using a scissors-type strainmeter made of a phosphorous bronze clip gage put into two small holes located at a distance of 20 mm across a weld bead on each specimen, as shown in Photo. 1.

3. Test Materials and Test Condition

One commercially pure aluminum and three aluminum alloy sheets of 2 mm thick were selected for test materials. Table 1 shows their chemical compositions. A 2024 (Al-Cu) belongs to the duralumin type and is said to be comparatively susceptible to cracking. A 5052 and A 5083 (Al-Mg) excel in corrosion resistance, and recently A 5083 has been applied widely to shipbuilding or pressure vessel.

The surface of a specimen cut to a size of 70 × 100 mm was polished with a wire brush, and degreased by acetone. A glass wool was laid under the specimen and was fixed together with it to the jig. The welding conditions are AC current 95∼105 Ampere, arc voltage 14 Volt and welding speed 300 mm/min but 170 mm/min for A 1050 metal. These were decided as the conditions suitable for melting the sheet specimen to full thickness and forming a nice back bead, by the preliminary experiment.

Fig. 2 shows the relationship between displacement measured by a differential transformer and strain by a clip gage during welding. There is a comparatively linear relationship between them, but their inclinations of lines are somewhat differnt in each material. The length of actual crack was measured with an opti-

Table 1 Chemical composition of test materials (%)

JIS Code	Cu	Mn	Mg	Cr	Al
A 1050	—	—	—	—	<99.50
A 2024	4.5	0.6	1.5	—	93.4
A 5052	—	—	2.5	0.25	97.25
A 5083	—	0.67	4.39	0.12	95.82

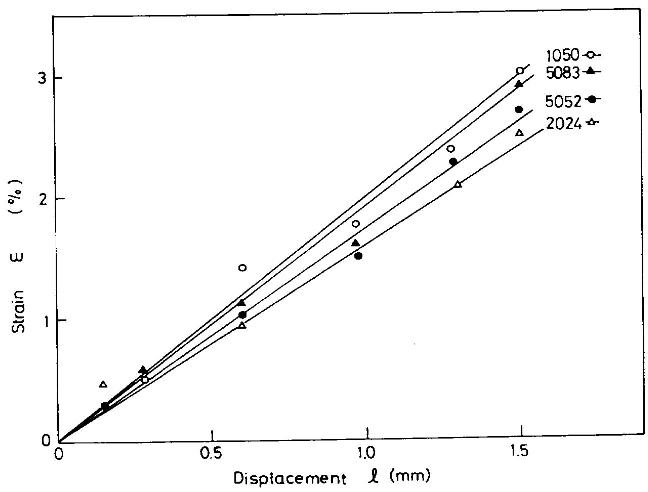


Fig. 2 Correlation of displacement measured by a differential transformer and strain by a clip gauge.

cal microscope of low magnification, then maximum crack length or total crack length was obtained respecitively.

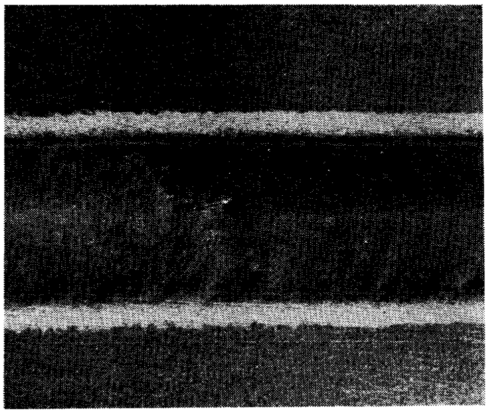
4. Test Results

1) Relation between augmented strain and cracking

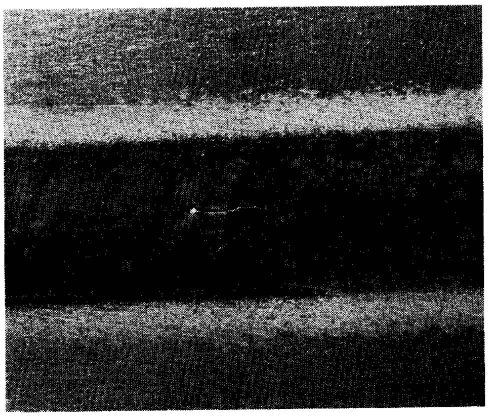
In this test, solidification cracking was formed vertically to the solidification line of weld puddle under the arc, when tensile strain acted on the specimen. Photo. 2 shows the form of cracking which appeared in A 5052 metal for two of different augmented strains. There are one bold crack in central portion and other fine cracks around it. Photo. 3 shows the crack which cocurred in A 2024 metal. The crack extended continuously to the end of the weld bead because of its greater susceptibility to cracking.

Fig. 3 illustrates the change of total crack length Lt against augmented strain, and Fig. 4 shows also a maximum crack length Lm in case of set the strain rate at 0.046/sec. Both crack lengths become greater with an increase of augmented strain, but these are saturated to a constant value after exceeding a certain strain. This saturated value of maximum crack length seems to be related to the brittleness temperature range (BTR) which has been already shown by Senda and Matsuda[3] in their Trans-Varestraint test.

Here, in case of A 2024 metal as the figure shows, crack lengths began growing again rapidly after passing a small flat part of the curve. This may be explained as follows: the crack grew or spread sporadically after straining, because of the greater cracking susceptibility of the metal. In case of A 2024 metal, therefore, this small flat part was regarded conveniently as maximum crack length associated with brittleness temperature range. These values are



(a)



(b)

Photo. 2 Appearance of cracking in A 5052 metal. Augmented strain : (a) 2.5 %, (b) 3.6%

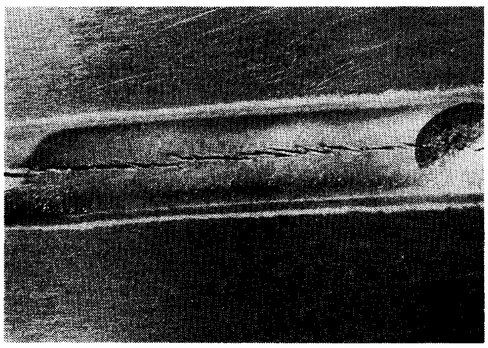


Photo. 3 Appearance of cracking in A 2024 metal. Augmented strain 2.0%.

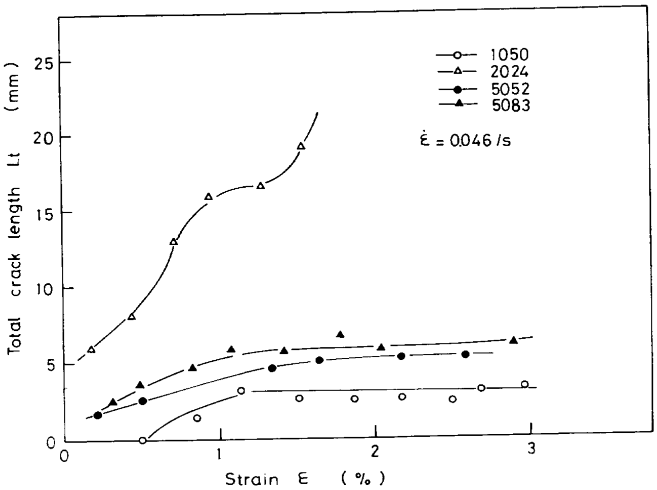


Fig. 3 Relation between total crack length and augmented strain.

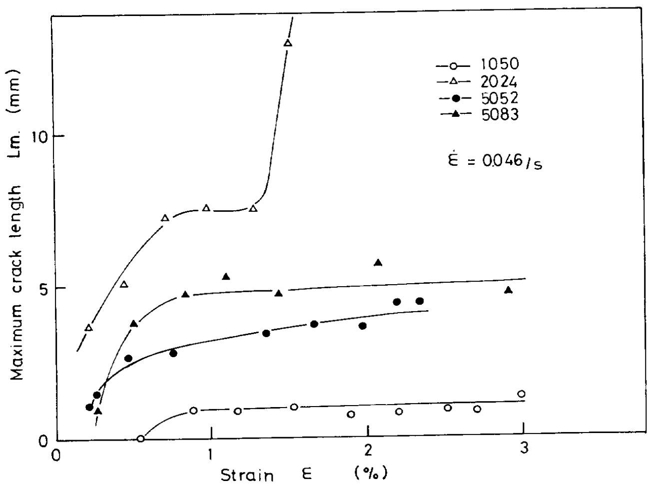


Fig. 4 Relation between maximum crack length and augmented strain

Table 2 Summary of weld cracking criteria obtained by the test.

JIS Code	$\bar{L}_{max}$ (mm)	BTR (°C)	CST (10^{-5}/°C)	ε_{min} (%)	$\dot{\varepsilon}_{min}$ (10^{-3}/s)	$\dot{\varepsilon}_{p}$ (10^{-3}/s)	
A 1050	0.9	50	15.0	0.5	10	—	(ε=2.82)
A 2024	7.5	205	2.0	≃0	—	—	
A 5052	4.4	120	4.8	0.2	2.5 1.9 1.5	3.5 3.3 3.2	(ε=2.82) (ε=1.7) (ε=1.0)
A 5083	5.0	175	3.5	0.2	2.0 2.2	2.5 4.0	(ε=2.3) (ε=1.7)

$\bar{L}_{max}$: Staturated value of maximum crack length
BTR : Brittleness temperature range
CST : Critical strain rate for temperature drop
ε_{min} : Minimum augmented strain for cracking
$\dot{\varepsilon}_{min}$: Minimum strain rate for cracking
$\dot{\varepsilon}_{p}$: Strain rate at peak value of maximum crack length

given in Table 2 as $\bar{L}_{max}$.

2) Relation between Strain Rate and Cracking

Fig. 5 shows the relations between strain rate and maximum crack length on A 1050, 5052 and 5083 metals, for different augmented strains. From these results, it is found that each metal except A 1050 has the threshold value of strain rate for crack initiation $\dot{\varepsilon}_{min}$ and the strain rate shows a peak value of maximum crack length $\dot{\varepsilon}_{p}$, and moreover, these values differ in each metal. On the other hand, in A 1050 metal, this $\dot{\varepsilon}_{p}$ could not be obtained in spite of selecting rather large strain, because of a comparatively high crack resistance of the metal. Furthermore, in case of A 2024 metal which is the most susceptible to cracking, experiments could not be performed unfortunately on various strain rates.

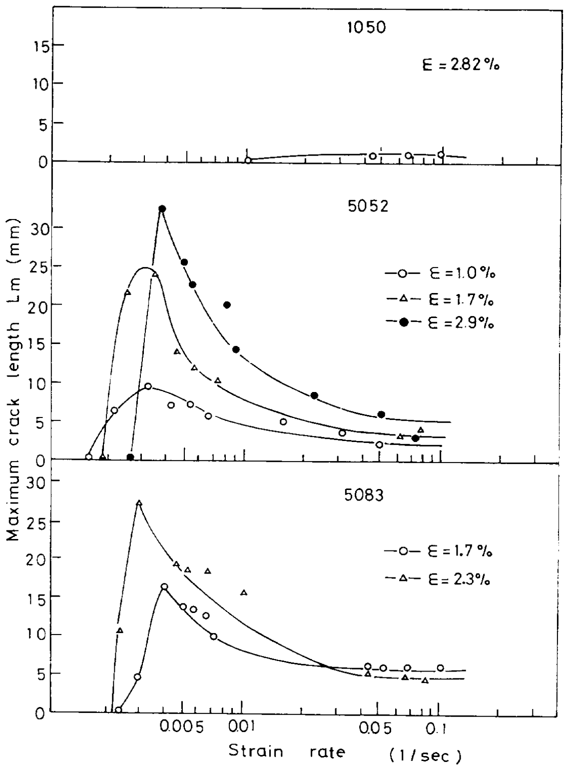


Fig. 5 Relation between maximum crack length and strain rate.

5. Discussions

1) Solidification Brittleness Temperature Range

Fig. 6 illustrates the solidification brittleness temperature range (BTR) of each test metal obtained according to the method of Senda and Matsuda using maximum crack length $\bar{L}_{max}$ in Fig. 4. These curves were given by the following process. That is, liquidus temperature Ta and crack arresting temperature Tb were obtained from thermal cycle curves of weld metal measured on each specimen, and then $T_B=(T_a-T_b)$ set to the brittleness temperature range (BTR) was plotted against augmented strain. Therefore, considering that the more extensive the BTR is, the more susceptible to hot cracking, the cracking tendency of test metals is greater in the order of A 2024, 5083, 5052 and 1050. As expected, A 2024 metal has the most extensive BTR. Therefore, the tangential broken line to the BTR curves in Fig. 6 is apparently the so-called minimum strain rate for temperature drop (CST) shown by Senda and Matsuda[3]. These values obtained on each metal are shown in Table 2. Besides, the minimum strain

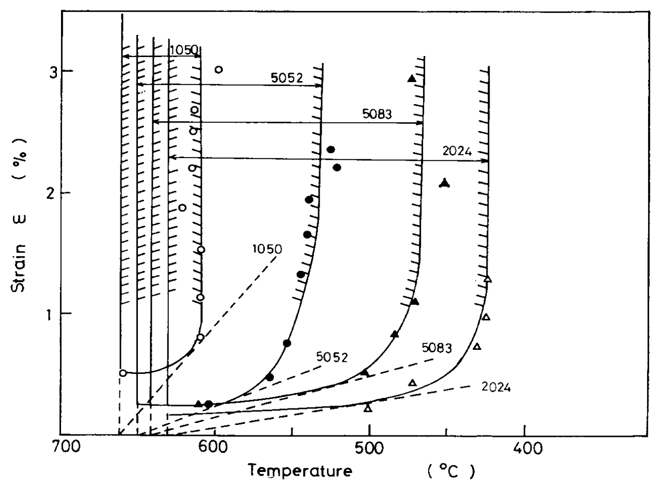


Fig. 6 Solidification brittleness temperature range (BTR) in each test metal.

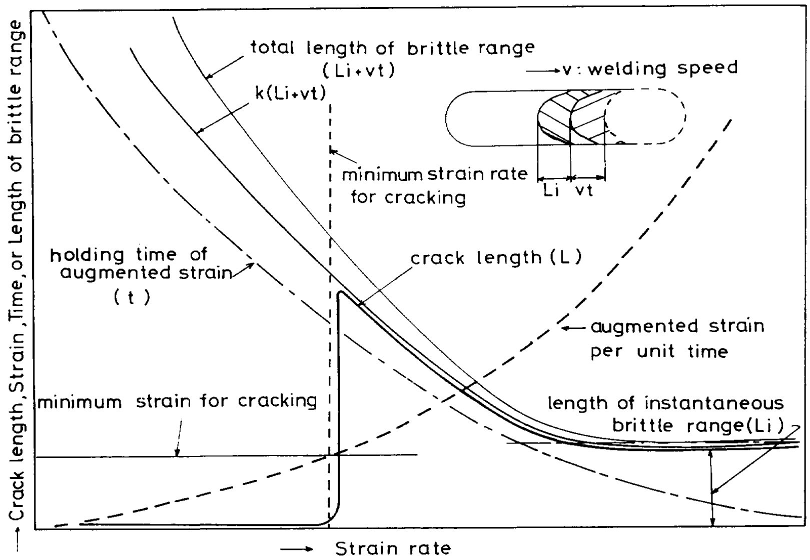


Fig. 7 Qualitative explanation for strain rate dependence of crack length.

rate for cracking $\dot{\varepsilon}_{min}$ explained before is almost considered to have a similar meaning to the CST value.

2) Strain Rate Dependence of Crack Length

Previously in Fig. 5, it was shown that strain rate has the threshold value in crack initiation $\dot{\varepsilon}_{min}$ and the peak value of maximum crack length $\dot{\varepsilon}_p$. These values are also thought to be very important as the criteria for crack susceptibility of each metal. Fig. 7 ilustrates qualitatively the change of augmented strain, holding time, actual crack length and length of instantaneous brittle range with an increasing rate. If the strain rate increased, the augmented strain per unit time added on weld bead swelled like the broken line in Fig. 7, and so the minimum strain rate for cracking could be obtained when the strain exceeded the critical strain for cracking determined for each metal. As the strain rate decreases here, the holding time of augmented strain (t) becomes longer, and the crack length increases because a larger strain over the critical strain for cracking is added to the brittleness temperature range for a long time. Then, the peak value of maximum crack length appears as shown in Fig. 7.

When the strain rate increases exceedingly, the holding time of augmented strain decreases extremely, so the crack length is saturated almost to be equal to the length of instantaneous brittle range Li. It was previously explained that, as the strain rate decreases, the holding time of augmented strain becomes longer, and the crack length (L) exceeds the length of instantaneous brittle range like the thick line in the figure. Therefore, supposing welding speed to be v, the length of brittle temperature range is proved to be (Li+vt) and the actual crack length L is considered to be proportional to (Li+vt) at least in the results showing such tendency as A 5052 metal in Fig. 5.

Figs. 8 and 9 show the comparison between the experimental curve of maximum crack length obtained in Fig. 5 and the curve of total length of brittle

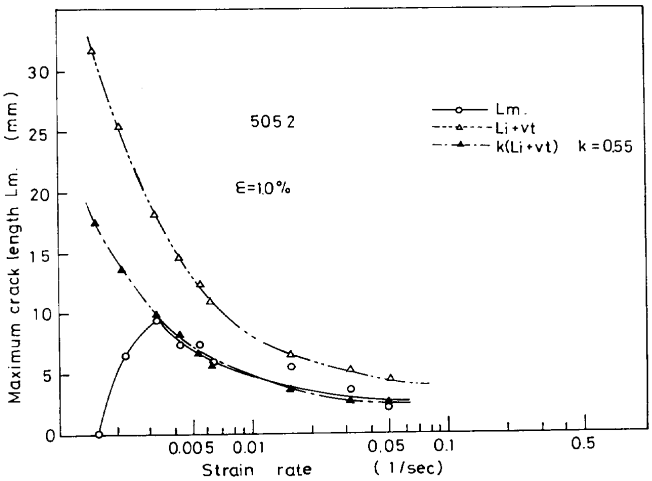


Fig. 8 Approximation of strain rate dependence curve of maximum crack length in A 5052 metal. Augmented strain 1.0%.

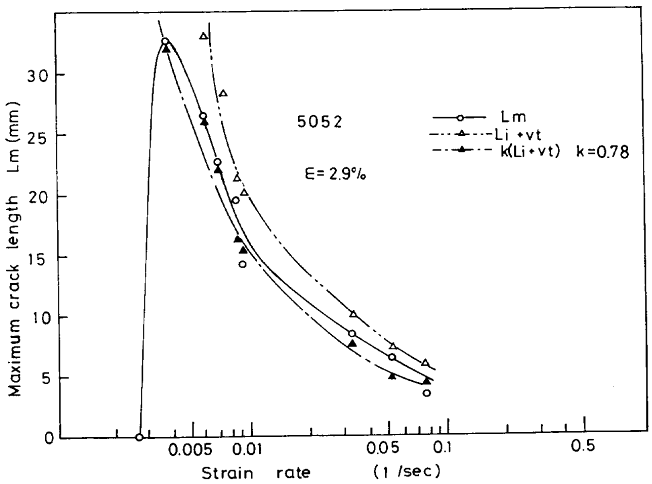


Fig. 9 Approximation of strain rate dependence curve of maximum crack length in A 5052 metal. Augmented strain 2.9%.

range (Li+vt) in A 5052 metal. As both curves seemed to be proportional to each other, so re-plotting by use of a constant k, it was found that the k(Li+vt) curve almost agreed with the experimental curve.

Here, the constant k proved less than 1, and it concerned not only the characteristics of materials such as ductility but also augmented strain, strain rate and welding variables. Therefore, the actual crack length seemed to become smaller than the total length of brittle range predicted from (Li+vt).

Among these factors affecting the constant k, the effect of augmented strain against maximum crack length is illustrated in Fig. 10 for different strain rates in A 5052 metal. In this figure, the curve of the largest strain rate (1) is the same as in Fig. 4. This proved the fact that the maximum crack length increased suddenly with an increasing strain when strain rate became slower than the largest one, as supposed. From this fact, the length of instantaneous brittle range Li in Fig. 7 may be regarded approximately as the saturated value of curve (1) when the strain rate becomes extremely greater in Fig. 10.

The constant k obtained from Fig. 10 was plotted in Fig. 11 against augmented strain. This figure shows that the constant k has, for example, such correlation to augmented strain, and it increases gradually with an increase of strain, and then approaches 1.

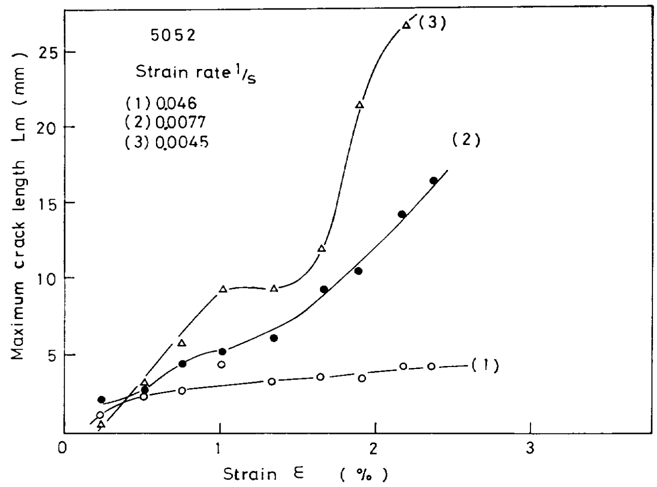


Fig. 10 Change of augmented strain vs. maximum crack length curves with decreasing strain rate in A 5052 metal.

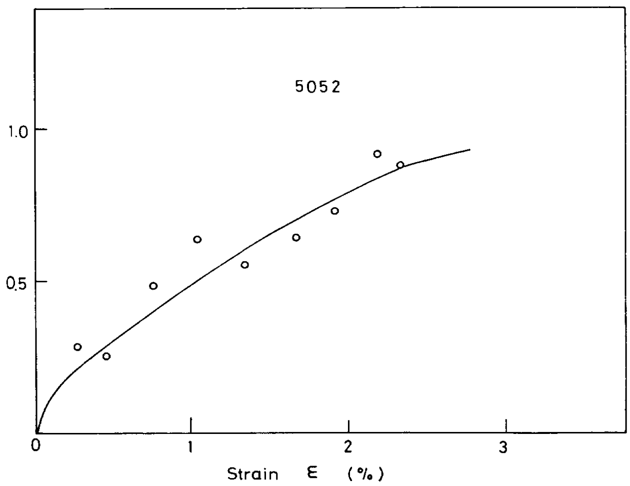


Fig. 11 Relation between the constant k and augmented strain.

3) Comparison of Solidification Cracking Susceptibility

Finally, the test results were summarized in Table 2, comparing the susceptibility of solidification cracking in each aluminum alloy. In case of estimating cracking susceptibility from the saturated value of maximum crack length $\bar{L}_{max}$, the minimum strain for cracking ε_{min}, and the minimum strain rate for cracking $\dot{\varepsilon}_{min}$, it turned out greater in order of A 1050, 5052, 5083 and 2024. This order agreed with the case of comparing by BTR and CST previously. There was, however, not so great difference between A 5052 and 5083 as in comparison by BTR or CST.

It is well-known that A 2024 (24S) metal is very sensitive to cracking[9], and this tendency was shown clearly in this test. In case of A 2024 metal, the cracking was also found in the weld heat-affected zones. These cracks are shown in Photo. 4.

Photo. 5 is an appearance of cracking in A 5083 metal. As indicated, the crack propagates through the boundary of columner structure. A 5083 metal including 4.5 % Mg is the most usefull as structural aluminum alloy, but in this test, its brittleness tempearture range (BTR) was a little more extensive and so its solidification cracking susceptibility seemed

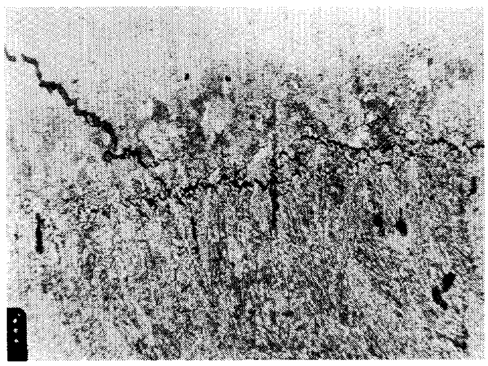


Photo. 4 Heat-affected zone cracking occurring in A 2024 metal.

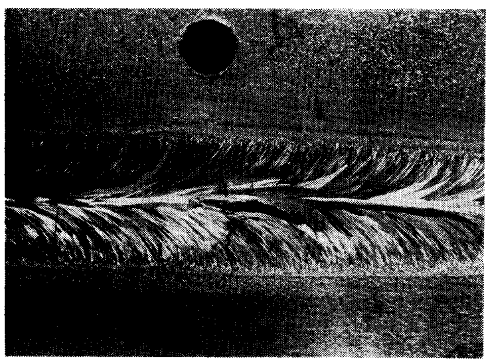


Photo. 5 Crack propagation into columner grain boundaries in A 5083 metal.

to be rather stronger than that of A 5052 metal including 2.5 % Mg.

Recently, aluminum alloys including such grain refining elements as Ti, Zr and Ti-B have been produced for imporving the weldability of A 5083 metal[10].

6 Conclusions

Using the Variable Tensile Strain hot cracking test apparatus assembled by way of trial, is examined mainly the relation among tensile strain, strain rate and solidification cracking tendency of weld metals in one commercial pure aluminum and three aluminum alloys. The main results are summarized as follows:

(1) As the new test apparatus is capable easily and widely of changing the tensile strain and strain rate applied to weld bead during welding, it is found suitable to examine solidification cracking especially in thin sheet metals.

(2) The criteria of solidification cracking susceptibility such as minimum strain for cracking and brittleness temperature range (BTR) were obtained from these results similarly to Varestraint test.

(3) From the relation between strain rate and crack length, it was found that a threshold value of strain rate for cracking existed and the crack length decreased from peak value and approached a saturated value as the strain rate becomes faster.

(4) Comparing the test materials, it may be ascertained that solidification cracking is more liable to appear in order of A 2024, 5083, 5052 and 1050 metals.

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