The VDR Cracking Test for Solidification Crack Susceptibility on Weld Metals and Its Application to Aluminum Alloys †

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Abstract

A new type solidification cracking test of weld metal has been developed, which was named "continuously variable deformation rate (VDR)" cracking test and then the principle of this cracking test was experimentally comfirmed and the characteristics of this testing method was also examined in details with some weld metals for commercially aluminum alloys.

Moreover, solidification crack susceptibility of filler wires for MIG arc weld metals of Al-Zn-Mg alloy was examined with VDR cracking test and results were compared with those of conventional T-joint cracking test, Main conclusions obtained were as follows; (1) It has been made clear that the VDR cracking test was very useful to evaluate the susceptibility of the initiation and/or propagation of the solidification cracking in the weld metal in actual welding process, because in this cracking test it was possible that the critical deformation rate which was considered to represent simply the properties of the brittleness temperature range was easily obtained by continuously decreasing the deformation rate applied on the solidifying weld metal during welding. (2) The susceptibility of the solidification cracking of commercial filler wires for the MIG arc weld metal of Al-Zn-Mg alloy has been evaluated with the index of the critical deformation rate obtained by the VDR cracking test and which decreased in order of 1070, (5183, 5356 and 7N11) and 4043. These results almost agreed with those in T-joint cracking test.

KEY WORDS: (MIG Welding) (Hot Cracking) (Weldability Tests) (Aluminum Alloys) (Al Zn Mg Alloys) (Solid Filler Wire)

1. Introduction

In order to do the fundamental analysis for the susceptibility of the solidification cracking of the weld metal, it has been strongly pointed out that[1-2] it is very important to obtain the quantitative knowledge about the properties of the brittleness temperature range of the materials during actual welding process, such as the temperature difference, the minimum value of the ductility with it and the shape of the ductility curve against the temperature drop.

Meanwhile, a lots of solidification cracking tests have been proposed and applied for the practical use[3]. However, only a few cracking tests are considered to be successful to obtain quantitatively the properties of this brittle range such as the Trans-Varestraint test[2] and the MVTU test[4]. In former type, the bending strain is applied on the weld metal and in the latter one, the tensile deformation is applied on the weld metal. In each cracking test, however, many specimens are needed to obtain the ductility curve in the brittle range, because for this purpose, the magnitude of the deformation rate is needed to be varied in the wide ranges in each welding bead due to the principle of the each cracking test. This makes these testing processes more troublesome.

Therefore more simple method which is also able to obtain the properties of the ductility curve is needed for the solidification cracking test. On the basis of this demand, a new type cracking test has been developed in this investigation. In this cracking test, the deformation rate applied on the weld metal during solidification is continuously varied from very fast one to zero one during the welding of only one weld bead.

This cracking test developed by the authors, original type of which was proposed by K. B. Bagryanskii et al[5], is named the continuously variable deformation rate (VDR) cracking test and as the index for the evaluation of the solidification crack susceptibility the critical deformation rate for the occurrence or the propagation of the

† Received on March 31, 1979

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solidification cracking is used. It is considered that the critical deformation rate is the most reasonable index to represent the properties of the brittleness temperature range.

In this investigation, firstly, the characteristics of the VDR cracking test developed in this experiment have been examined in details using the some commercial aluminum alloys.

Secondary, in order to make clear the effect of filler wires on the susceptibility of the soilidification cracking in the MIG arc weld metal of Al-Zn-Mg alloy, the critical deformation rate for each filler wire has been examined with the VDR carcking test and these results have been compared with those of T-joint cracking test which is known as one of the most common testing methods among the self-restraint cracking tests.

2. Experimental Procedure and Materials Used

2.1 The VDR cracking test

2.1.1 Principle

In general, during the solidification of most materials and alloys, the solidification temperature range where the liquid and solid coexist is always seen between the liquidus and solidus. In the latter stage of this temperature range, a small quantity of the liquid phase is present in solidified solid, especially in the grain boundary as the shape of film-like. In these conditions, the ductility of the materials is very low and therefore the solidification cracking easily occurs when the strain is applied by the shrinkage during solidification and moreover, in case of welding, by external restraint or deformation caused by parent metal movement due to rapid heat cycle. So that this critical solidification temperature range is called the brittleness temperature range (BTR). Therefore, it is considered that solidification cracking generally occurs when the amount of strain or deformation applied on solidifying metal exceeds the magnitude of the ductility of metals in the BTR.

This concept is simply explained in **Fig. 1**. The condition for solidification carcking are determined by the magnitude of the temperature difference in the BTR, the minimum ductility of the metal (E_{min}) in the BTR and the quantity of deformation of the solidifying metal passing through the BTR which is shown by the three straight lines in Fig. 1.

Then the solidification cracks will form if the magnitude of deformation of the solidifying metal exceeds the ductility in the BTR, for example, the deformation rate for the temperature drop is indicated by the straight line (1) in Fig. 1.

In case of the straight line(3), however, no crack will form in the weld metal because the deformation rate is too slow to intersect the ductility curve in the BTR. Consequently, the deformation rate indicated by the straight line(2) is critical one for the occurrence of solidification cracks. Therefore the critical deformation rate, tanθ in line(2), is the most important index for the evaluation of the solidification crack susceptibility of weld metal during welding. It will be the most reasonable and beneficial testing method for solidification crack susceptibility if the critical deformation rate, CST[2)], is measured with a simple testing.

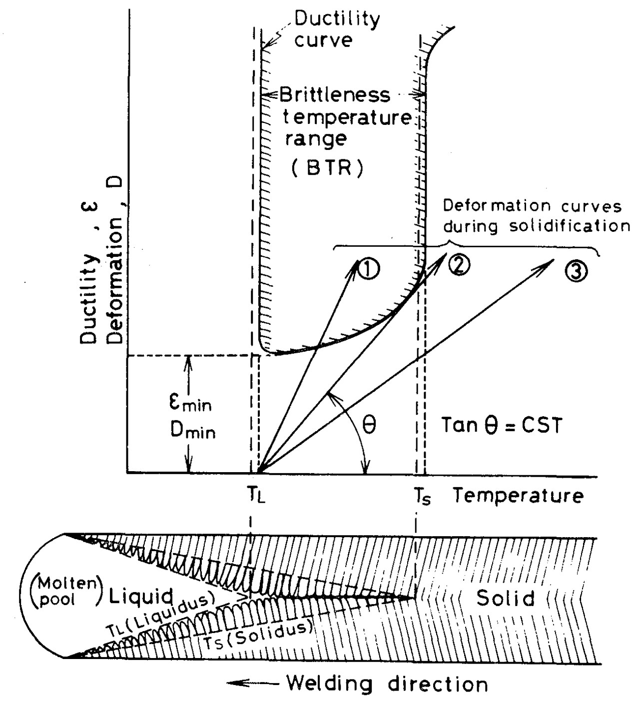

Fig. 1 General explanation for mechanism of solidification cracking of weld metal during welding

Of course the basis on which this theory is developed is that plasitic deformation accumulates throughout the entire brittleness temperature range, starting at its upper boundary.

According to this concept for the occurrence of solidification cracking, if the deformation rate is continuously changed from the very fast deformation rate as shown by straight line(1) to the slow one as shown by the straight line(3) during welding, the critical deformation rate can be easily obtained. On the basis of this, a new cracking test has been developed, that is, the continuously variable deformation rate (VDR) cracking test. This type of cracking test was originally developed by K. B. Bagryanskii[5)] but the characteristics of their testing apparatus were not clearly explained and applications of this carcking test have been little reported, so far.

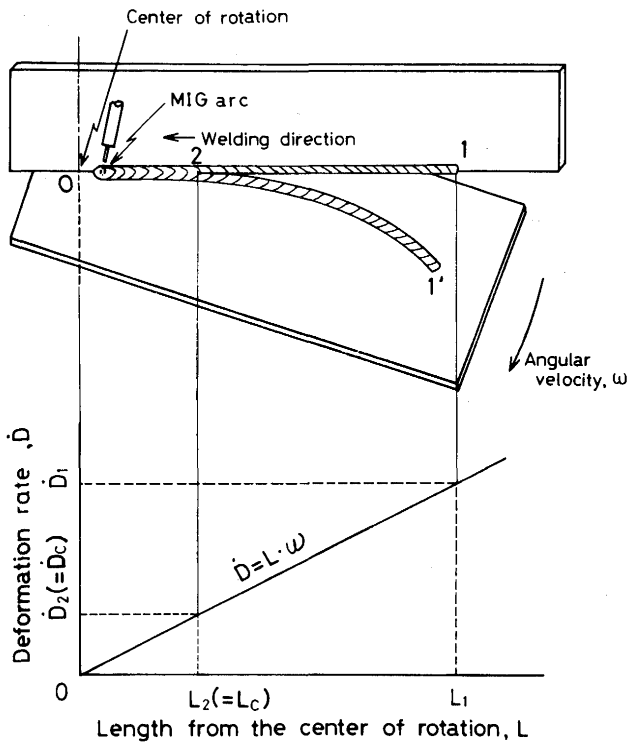

Fig. 2 Principle of the VDR cracking test, that is, variation of applied deformation rate of weld metal during the VDR cracking test

Simplified explanation of the principle of the VDR cracking test is shown in **Fig. 2**. The specimens are arranged to form the T-joint as shown in the upper figure in Fig. 2. The vertical member is fixed and horizontal member is rotated by a constant angular velocity around the center of rotation, O. The fillet welding with MIG arc is carried out from the point (1) toward the center of the rotation, O, during the rotation of the horizontal member. Then the weld metal is deformed with various rate of deformation in accordance with the distance from the center of rotation, L_1 to L_2, which are shown by the next equation,

$$\dot{D} = L \times \omega \qquad \cdots\cdots\cdots (1)$$

where, $\dot{D}$ is the deformation rate (mm/sec), L is the distance from the center of rotation (mm) and ω is the angular velocity (rad/sec).

This relation is represented in lower figure in Fig. 2. It is apparent that the deformation rate decreases straight with a decrease of L and then reaches to zero at the center of rotation. Thus, in the VDR test the deformation rate with which the weld metal is deformed can be continuously varied in the wide range during only one pass welding.

Now, at the starting point of the MIG arc welding which is represented as point (1) in Fig. 2, the deformation rate is enough fast to occur the solidification crack because the L_1 is large enough. Then during the welding toward the center of rotation, the crack propagates in the weld metal during solidification just behind the moving molten puddle. Finally, because of the decrease of the deformation rate, the propagation of the solidification crack is stopped at the critical position, that is, point(2) in Fig. 2 whose distance from the center of rotation is $L_2=L_c$. Then, the critical deformation rate is obtained by the equation(1) as $\dot{D}_c=L_c \times \omega$. This critical deformation rate is essentially in accordance with that represented by the straight line(2) in Fig. 1. Therefore, the solidification crack susceptibility of the weld metal can be evaluated by using this critical deformation rate as an index under a same welding condition.

2.1.2 Apparatus

General appearance of the VDR cracking test apparatus developed in this investigation and its close-up view showing specimens are shown in **Fig. 3(a)** and **(b)**,

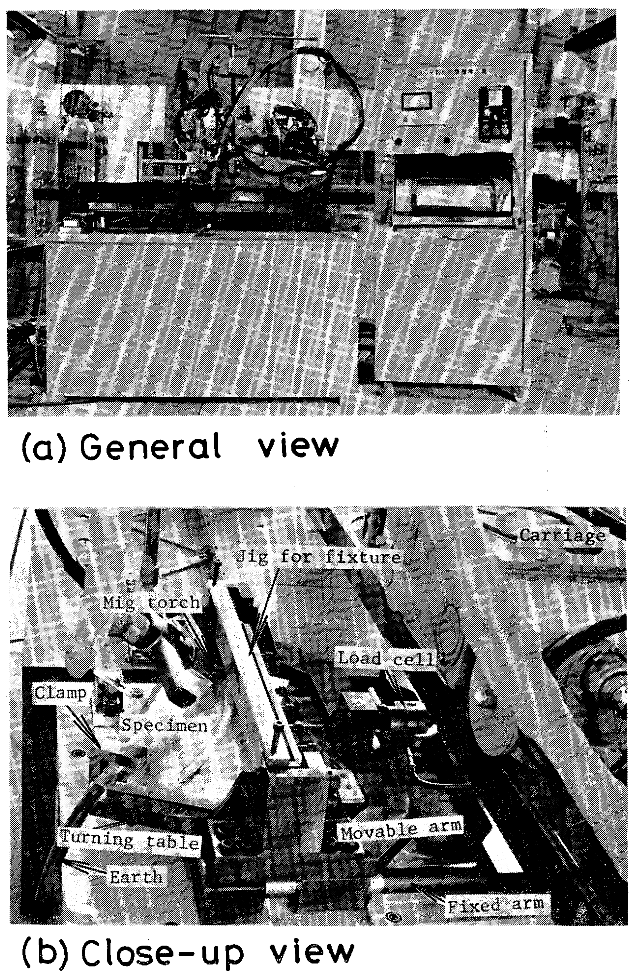

Fig. 3 View of the VDR cracking test apparatus

respectively and also simplified sketch is shown in **Fig. 4**.

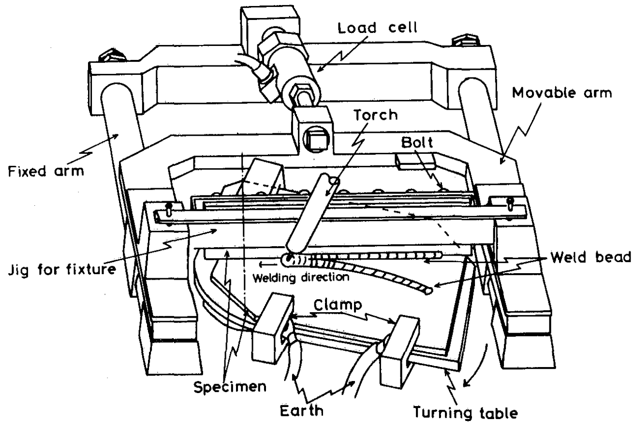

Fig. 4 Simplified sketch of the VDR cracking test apparatus

As shown in Fig. 4, the VDR cracking tester mainly consists of next five components, that is, a turning table, a jig for fixture of specimen, a movable arm, fixed arms and a load cell. The turning table is turned by a constant angular velocity by the electric moter and can be varied continuously to the maximum, 0.0363 rad/sec. In the VDR test, the T-joint fillet welding is mainly used in this experiment but a lap-joint fillet welding and butt welding in modified type are also applicable. A horizontal member of T-joint specimens is fixed on this turning table by three clamps and also welding earthes are. On the other hand, a vertical member is fixed to jig by bolts for preventing the deformation of specimen and this jig is also fixed to a movable arm.

In actual crack testing process, it is very important to judge the time when the solidification crack stops its propagation. In this apparatus a load augmented to the weld metal, which is demanded to initiate and propagate the solidification crack, is measured during cracking test by the load cell mechanically connected to the vertical member by a jig and a movable arm. When solidification crack is stopped, the load measured increases abruptly because the welding is still continued forward. Since this increase in the load is afraid to cause the forced fracture of welded specimen, the rotation of turing table is stopped at a desired value of the measured load. This value is named the setting load for stop of testing, that is, P_s.

The load measured and angular velocity of turning table are recorded by self-balanced pen-writing recorder.

As a welding method, the fillet welding by **MIG** arc has been used in this experiment. The joint configulation and the arrangement of the specimen and welding torch are shown in **Fig. 5**. A gap of the root is set to a constant value of 2mm.

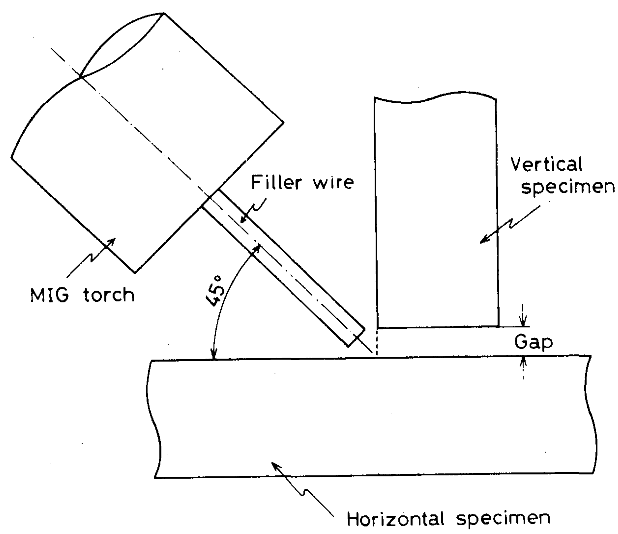

Fig. 5 Joint configuration and arrangement of specimen and welding torch in the VDR cracking test

Table 1 Chemical compositions of materials used

Material		Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Zr
		Chemical composition (wt. %)								
Base metal	1100-O	–	0.10	0.30	–	–	–	–	0.03	–
	5052-O	0.01	0.08	0.27	0.02	2.57	0.01	0.17	0.02	–
	5083-O	0.02	0.15	0.19	0.64	4.49	–	0.11	0.01	–
	7N01-T4 (A)	Tr	0.07	0.14	0.42	1.15	4.78	0.22	0.02	0.20
	7N01-T4 (B)	Tr	0.08	0.18	0.29	2.0	4.2	–	0.02	0.16
Filler wire	1070	0.01	0.08	0.16	–	–	–	–	–	–
	4043	0.10	5.4	0.21	0.02	0.01	0.01	–	0.02	–
	5183 (A)	0.01	0.10	0.19	0.601	4.87	0.02	0.08	0.07	–
	5183 (B)	0.01	0.07	0.16	0.69	5.0	Tr	0.08	0.07	–
	5356 (A)	0.01	0.06	0.19	0.14	4.95	0.01	0.11	0.11	–
	5356 (B)	Tr	0.06	0.12	0.14	5.2	Tr	0.12	0.12	–
	7N11	0.01	0.06	0.12	0.34	4.15	1.96	–	0.07	–

The dimensions of the horizontal and vertical members are 160mm in width and 320mm in length and also 60mm in width and 330~450mm in length, respectively. The thickness of the specimen is 10~15mm for each member.

2.2 Materials used

The materials used in this experiment are commercial aluminum alloys. The chemical compositions of these materials are listed in **Table 1**. Among them, 1100 is commercially used pure aluminum, 5052 is aluminum-magnesium(Al-Mg) and 5083 is aluminum-magnesium-manganese (Al-Mg-Mn) alloys and 7N01 is aluminum-zinc-magnesium(Al-Zn-Mg) alloy. As filler wire 1070 is commercially pure aluminum, 5356, 5183 and 7N11 are Al-Mg, Al-Mg-Mn and Al-Mg-Zn alloys, respectively. The diameter of those filler wires is 1.6mm. 7N01 and 7N11 were defined in Japan Industrial Standard.

3. Results and Discussions

3.1 Fundamental experiment for the VDR cracking test

3.1.1 Decision of setting load

A typical example for the variation of the load measured during the VDR cracking test is shown in **Fig. 6** for the weld metal of 1100 base metal with 1070 filler wire. The horizontal axis in Fig. 6 indicates the lapse time from the start of cracking test. An abrupt increase in the load observed at about 27 sec and latter corresponds to the stop of the propagation of solidification cracking. In the VDR cracking test the rotation of the turning table is automatically stopped to prevent the welded specimen from the forced fracture caused by the rotation of the turning table when the magnitude of the load reaches a setting load, P_s. In **Fig. 7** the relationship between the setting load for the stop of testing, P_s, and the critical deformation rate, $\dot{D}_c$, is shown for the weld metal of 1100 base metal with 1070 filler wire and 5083 base metal with 5183 (A) filler wire. Judging from the result of Fig. 7, the $\dot{D}_c$ is almost independent to P_s values from 50 to 350kg for 1100 base metal. This means that the forced fracture has not occurred at any P_s value up to 350kg. This fact was actually comfirmed by the observations of the cracking surface near the tip of solidification crack with scanning electron microscope.

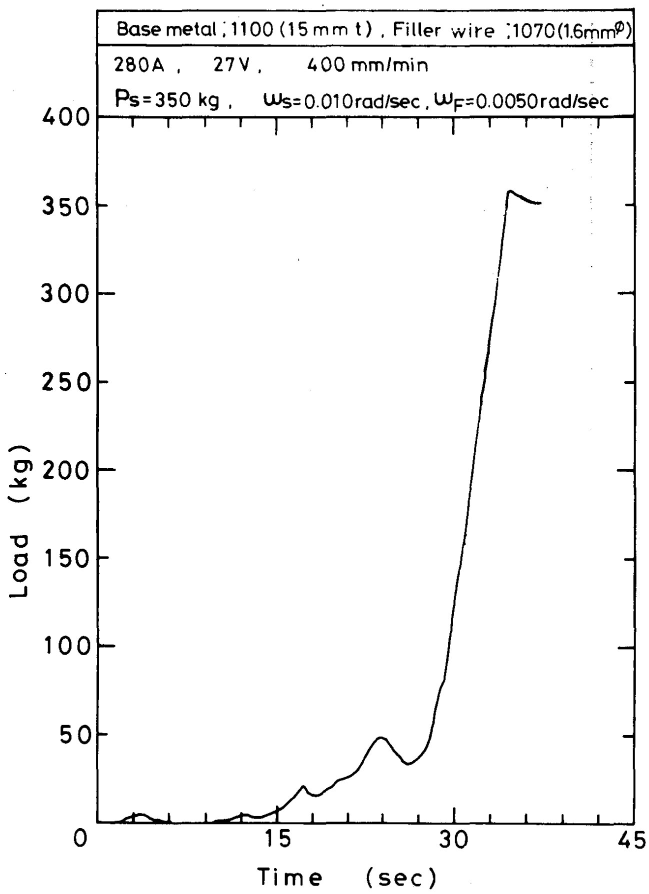

Fig. 6 An example of variation of load measured during the VDR cracking test: 1100 base metal with 1070 filler wire

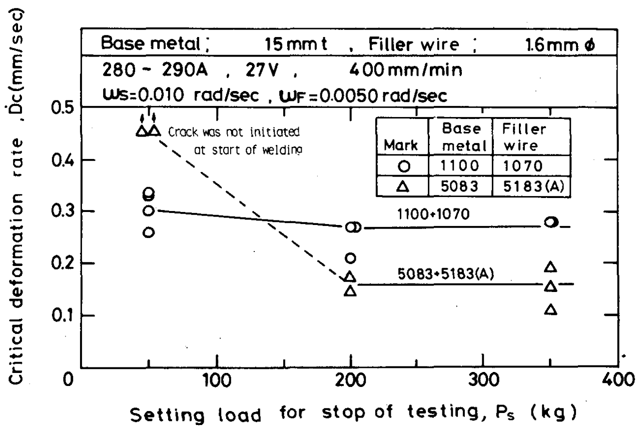

Fig. 7 Effect of setting load for stop of testing on critical deformation rate, $\dot{D}_c$

On the contrary, in case of the materials possessing the higher tensile strength, such as 5083 weld metal with 5183 filler wire, when the P_s was 50kg, the solidification crack did not occur even at the starting point of welding. So that the cracking test could not be performed at 50kg of P_s value. Increasing the P_s from 200 to 350kg, however, solidification crack easily occurred and $\dot{D}_c$ measured was almost constant. According to these results it is recommended that the most adequate value of the P_s is 200 to 350kg.

3.1.2 Selection of optimum angular velocity

As is known from the principle of the VDR cracking test, it is necessary that the solidification crack is certainly initiated and then propagated at the starting point of the welding. Therefore, the occurrence of the solidification cracking in the weld metal at the starting point on the welding has been examined with various angular velocities, ω_s from 0.0025 to 0.020 rad/sec in order to determine the optimum angular velocity to initiate and propagate the solidification crack with certainty.

The starting point of the welding was decided to 270mm in length away from the center of rotation because of a limit of the specimen size and ability of testing apparatus. The distance between the starting point and center of rotation is, however, desirable to be as long as possible not only in order to initiate and propagate the solidification crack at the starting point with certainty, but also in order to increase the accuracy in evaluation of susceptibility of solidification cracking. On the contrary, there is a strong requirement for the cracking test that the quantity of materials needed to evaluate the susceptibility of solidification cracking should be as little as possible. Due to this demand, small specimen size is more desirable. Therefore, there is a limit in the distance between the starting point and center of rotation due to the specimen size.

The results are shown in **Fig. 8** whose vertical axis

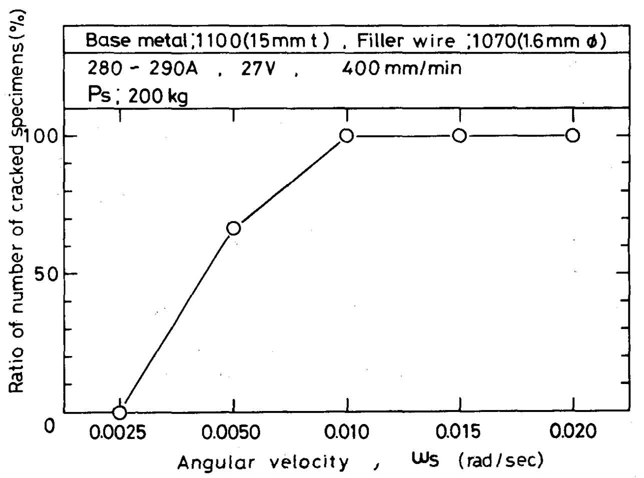

Fig. 8 Effect of angular velocity on ratio of occurrence of solidification crack at start of welding

indicates the ratio of the number of cracked specimen against that of all specimens examined. As materials, a combination of 1100 base metal with 1070 filler wire has been used because of its lowest susceptibility of solidification cracking. As shown in Fig. 8, it is apparent that in order to initiate the solidification crack with certainty, the ω_s is needed to be more than 0.010 rad/sec, which corresponds to a deformation rate of 2.70 mm/sec.

If the more accurate evaluation of the solidification crack susceptibility of the weld metal is required, the critical crack length, L_c is more desirable to become as long as possible. For this purpose, the ω_s is necessary to be as small as possible in accordance with the principle of the VDR test. Consequently, the value of 0.010 rad/sec is recommended as the most adequate angular velocity at the starting point of the welding for aluminum alloys. At this value of the ω_s, the solidification crack was certainly initiated and propagated at the starting point of the welding for all the combinations of the base metals and filler wires used.

Moreover, in order to enlarge the L_c, next method has been used in this experiment. The angular velocity is changed from that at the starting point, ω_s, namely, 0.01 rad/sec, to more small value, that is, final angular velocity, ω_F during cracking test when the molten pool reaches the point of about 200mm as shown in **Fig. 9**. Figure 9 shows

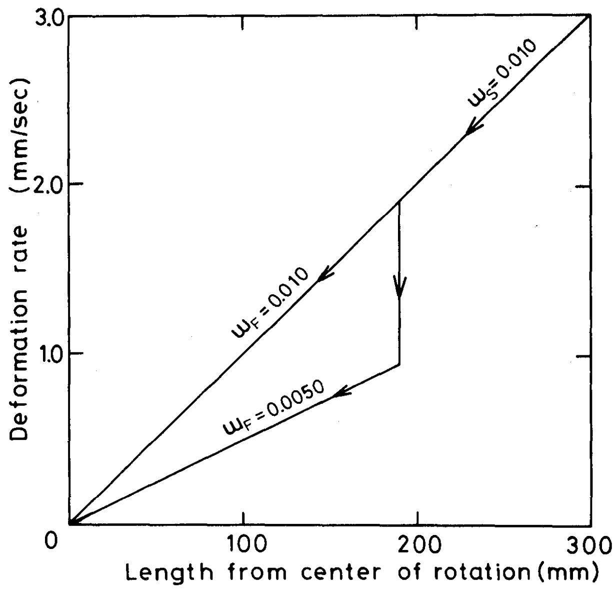

Fig. 9 A typical example for variation of angular velocity in the VDR cracking test

a typical example of the change in the angular velocity from 0.01 rad/sec of ω_s to 0.005 rad/sec of ω_F. In slower angular velocity than 0.004 rad/sec of ω_F, the propagation of the solidification crack was mostly stopped as soon as the change in the angular velocity. Therefore, it seems that the optimum angular velocity for evaluation of susceptibility of solidification cracking in aluminum alloy weld metals is about 0.005 rad/sec.

3.1.3 Effect of angular velocity on critical deformation rate of weld metal

According to the principle of the VDR test, the $\dot{D}_c$ should be constant against the variation of the angular velocity, but on the contrary, the critical crack length, L_c should be inversely proportional to the angular velocity, under the same welding condition. In order to comfirm above discussions, the relation between the L_c or $\dot{D}_c$ and the angular velocity has been examined for three kinds of combinations of base metal and filler wire.

Figures 10 and **11** show the effect of the angular velocity on the L_c and the $\dot{D}_c$, respectively. In Fig. 10, it is apparent that the L_c decreases with the increase of the angular velocity in each weld metal. Next, in Fig. 11, the values of the $\dot{D}_c$ for each weld metal is considered to be kept to almost constant value against the angular velocity more than 0.005 rad/sec for 1100 and 5083 base metals, that is, 0.25 and 0.18 mm/sec, respectively and more than 0.0035 rad/sec for 5052 base metal, that is, 0.06 mm/sec, though in more slow angular velocity than above values, the $\dot{D}_c$ is likely to increase as the decrease of the angular velocity in case of the base metals of 1100 and 5052, or in case of 5083 base metal the propagation of solidification cracking was stopped as soon as the change of the angular velocity.

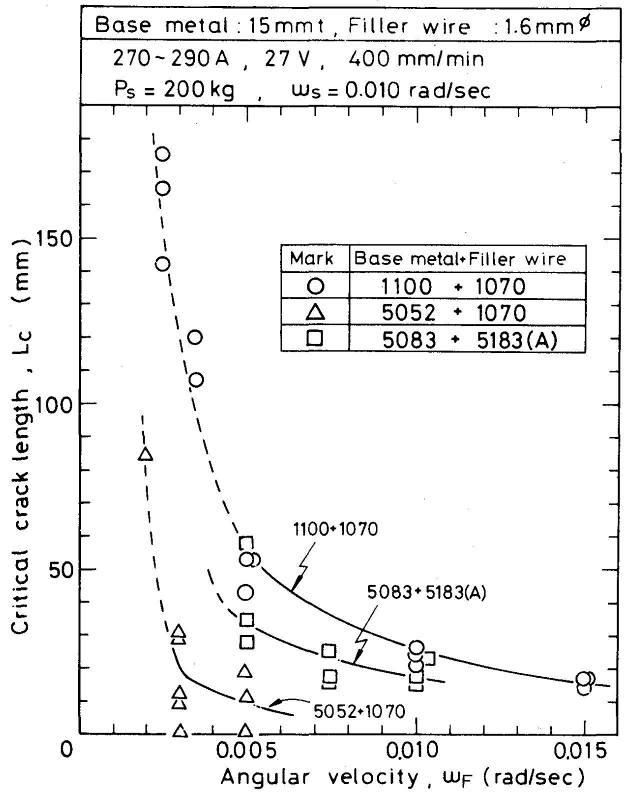

Fig. 10 Relation between angular velocity and critical crack length

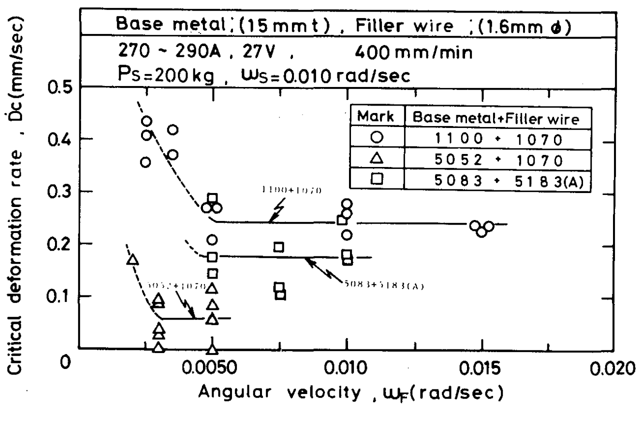

Fig. 11 Relation between angular velocity and critical deformation rate for propagation of solidification cracking in various weld metals of commercial aluminum alloys

Judging from these results, it is considered that these experimental results about the relation between the angular velocity and the L_c or $\dot{D}_c$ almost agree with those estimated by the principle of the VDR test except in case of very slow angular velocity.

Meanwhile, it seems that increase of the $\dot{D}_c$ value in very slow angular velocity is due to that the deformation rate augmented to weld metal around molten puddle become much slower as the decrease of angular velocity, because this decrease in deformation rate seems to increase the chance of the healing of the solidification cracking which will lower the susceptibility of solidification cracking.

Moreover, as to the susceptibility of the solidification cracking of the weld metals used, it increases with following order, which is inverse order of the $\dot{D}_c$, that is, 1100 base metal with 1070 filler wire, 5083 base metal with 5183(A) filler wire, 5052 base metal with 1070 filler wire. These tendencies are considered to agree very well with the fact generally known in actual welding process.

3.1.4 Effect of welding speed on critical deformation rate

Figure 12 shows the relation between welding speed

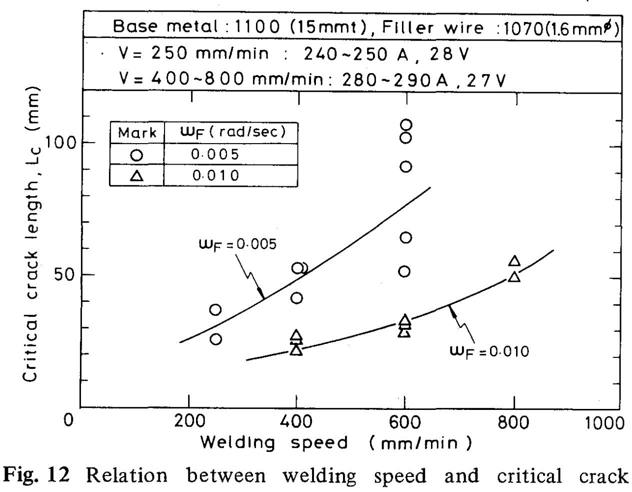

Fig. 12 Relation between welding speed and critical crack length, L_c

and critical crack length, L_c in the weld metal of 1100 base metal with 1070 filler wire against two levels of the angular velocity, that is, 0.005 and 0.01 rad/sec. In Fig. 12, the L_c increases with welding speed for each angular velocity, though the values of the L_c against 0.005 rad/sec is larger than those against 0.01 rad/sec.

As to the $\dot{D}_c$, in **Fig. 13**, the values of the $\dot{D}_c$ increased as the increase of welding speed and were almost the same in the same welding speed even for different angular velocities, though data were farely scattered at the welding speed of 600 mm/min. This increase in the $\dot{D}_c$ is explained by the decrease in the width of the BTR in length caused by the increase in cooling rate due to the increase of welding speed under a constant deformation rate.

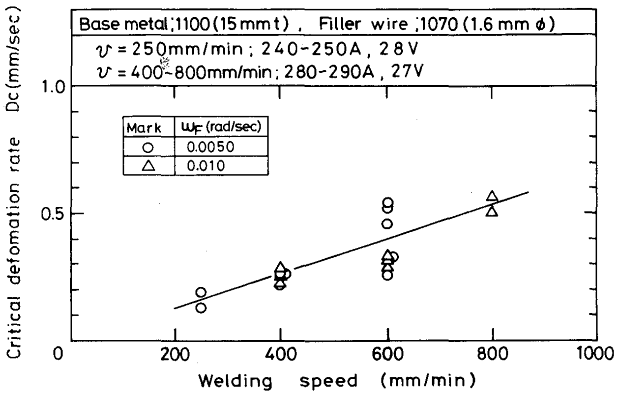

Fig. 13 Relation between welding speed and critical deformation rate for weld metal of 1100 base metal with 1070 filler wire

3.1.5 Cracking mode of solidification cracking during the VDR cracking test

In order to make clear the crack propagation mode of solidification cracking, the direct observation of the tip of propagating crack has been performed with the aid of 35mm camera with filming rate of 5 frame/sec.

Figure 14 shows the typical photographs showing the propagating solidification cracks together with weld puddle and MIG torch. Their simplified sketches are also shown under each photograph. The propagation mode of solidification crack is classified into almost three types as shown in Fig. 14. They were named type A, B and C, respectively.

The characteristics of these types are as follows; In

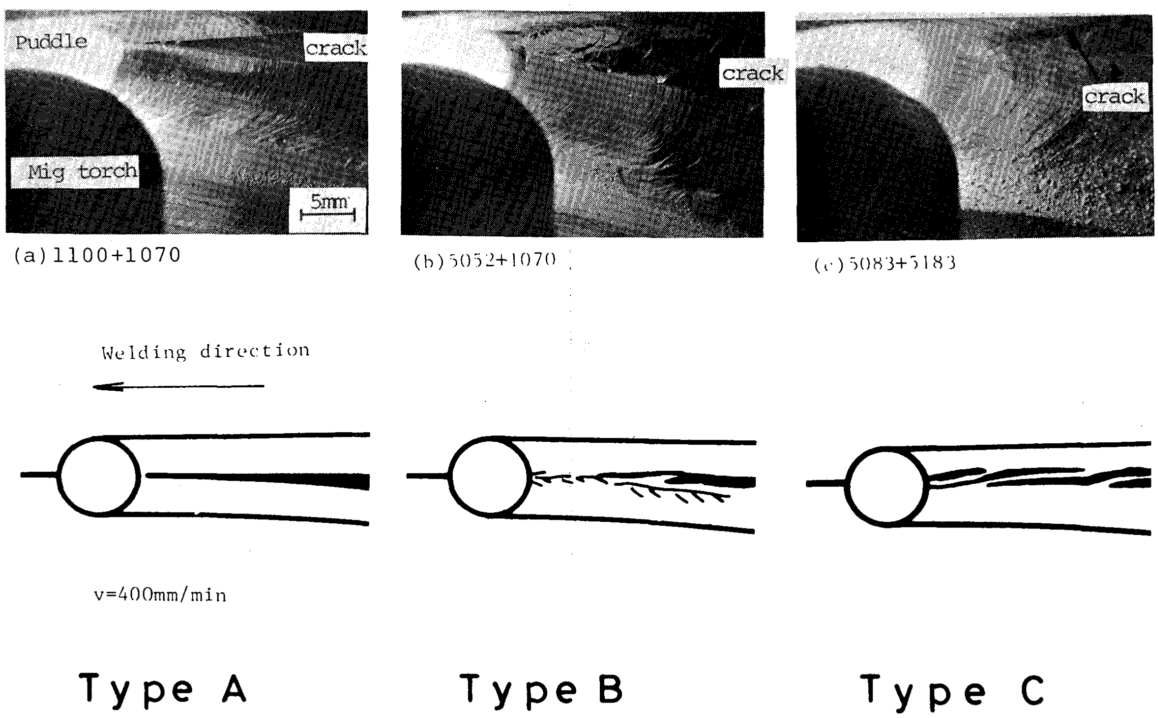

Fig. 14 Typical examples for propagation mode of solidification cracking in weld metals during the VDR cracking test

type A, only one large crack is always observed behind the weld puddle. In type B, macroscopically one large crack is observed but behind the weld puddle many small cracks are always observed at the same time. In type C, macroscopically two large cracks are always observed behind a weld puddle and they are propagating with repeating the initiation and propagation mutually.

It is considered that these differences in the propagation modes of the solidification crack are due to the difference in solidification structure of the weld metal. The type A was observed in the welds using the commercially pure aluminum as the base metal and filler wire, too. In this combination, the solidification structure mainly consists of well developed columnar crystals, especially near the weld central zone columnar crystal is likely to grow straight to the parallel direction of the welding. Therefore crack propagates straight along the grain boundary of these columnar crystals where the magnitude of deformation accumulated is the most. On the contrary, in type B, which was observed in the welds of 5052, 5083 or 7N01 base metals and 1070 filler wire. The weld solidification structure consists of columnar crystals and stray crystals[6] which is likely to appear in the central zone of the weld metal. The solidification crack is considered to initiate and propagate through these grain boundaries at the same time without propagating only through some special grain boundaries, because in case of combinations of these base metals and filler wire the grain boundaries are most susceptible for solidification cracking. On the other hand, type C mode was observed in the welds whose macrosctructure consisted of very small equiaxed crystals.

It seems that the scattering tendency of the $\dot{D}_c$ value obtained by the VDR test, which was comparably low in comparison with those of the index in T-joint cracking test, that is, cracking ratio, as will descrived in 3.2, is related to those propagation modes. That is, the scattering tendency in type A is lower than those in types B and C.

3.2 Evaluation of commercial filler wires on solidification crack susceptibility of Al-Zn-Mg alloy weld metal

The $\dot{D}_c$ values of the weld metals of 7N01(A) and (B) have been obtained by the VDR cracking test against the various commercial filler wires.

MIG arc welding was performed with the welding condition of 260~280 amp of welding current, 27 volt of arc voltage, 400 mm/min of welding speed and 23 l/min of a rate of argon shielding gas.

The $\dot{D}_c$ values obtained are shown in **Fig. 15** for

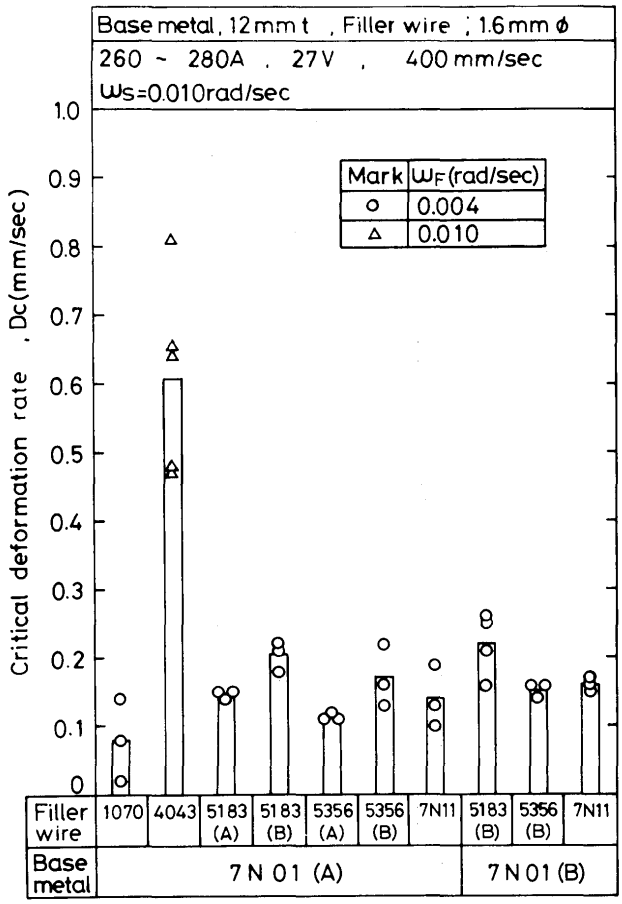

Fig. 15 Critical deformation rate, D_c of Al-Zn-Mg alloy weld metals welded with various filler wires

various filler wires. In Fig. 15, in case of 7N01(A) base metal, $\dot{D}_c$ of 4043 is the highest in all of the filler wires used; that is, about 0.5~0.8 mm/sec, though the scatter in values is considerable. On the contrary, $\dot{D}_c$ for 1070 filler wire is the lowest, that is, lower than about 0.1 mm/sec. Meanwhile, as to the filler wires of 5183(A,B), 5356(A,B) and 7N11, $\dot{D}_c$ values for all filler wires seem to be almost the same, that is, within the range of about 0.1~0.2 mm/sec, though little difference is observed. Moreover, similar tendencies were also observed in the weld metal of 7N01(B).

In general, the larger the $\dot{D}_c$ value, the lower the solidification crack susceptibility. So that, the order of the solidification crack susceptibility of filler metals is arranged as the inverse order of the $\dot{D}_c$ value, as follow; 4043, (5183(A,B), 5356(A,B) and 7N11), 1070.

Judging from these results, it is considered that 4043 filler metal, which is Al-5% Si alloy, is the most excellent one in order to decrease the solidification crack susceptibility of 7N01 weld metal. Similar beneficial effect of

4043 has been also reported[7-8] for preventing the solidification cracking in the weld metal of Al-Zn-Mg alloys. The strength and toughness of the weld metal with 4043 filler wire are, however, both too low to the practical use.[7] On the contrary, it is well known that the combination of 1070 filler wire and 7N01 base metal caused a high solidification crack susceptibility of the weld metal such as the combination of 1070 filler wire and 5052 base metal as shown in Fig. 11. Meanwhile, in the case of 5183, 5356 and 7N11 filler wires which are most common for practical use, there is no remarkable difference in solidification crack susceptibility of those filler wires in the VDR cracking test.

Next, T-joint cracking test, which is known as a typical self-restraint cracking test, has been carried out in order to compare with the results of the VDR cracking test.

The test results are shown in **Fig. 16**, where the cracking ratio on the weld metal of 7N01(A) is shown for 4043, 5183(A), 5356(A) and 7N11 filler wires. Among these filler wires it is clear that 4043 is the most excellent one for decreasing the solidification caracking because of its smallest cracking ratio. On the contrary, cracking ratio of others' are much higher than that of 4043 and taking the very large scattering in cracking ratio into consideration they seem to be almost the same value though that of 5183 is slightly higher.

According to the results of T-joint test, it is considered that these tendencies of filler wires for solidification cracking evaluated by T-joint test are considerably similar to those evaluated by the VDR cracking test.

	Welding condition	Filler wire
Restraint Welding	300A, 29V, 400 mm/min	5183(2.4 mm dia.)
Testing welding	280-300A, 26V, 1000 mm/min	5183(A),5356(A), 7N11,4043(1.6 mm dia.)

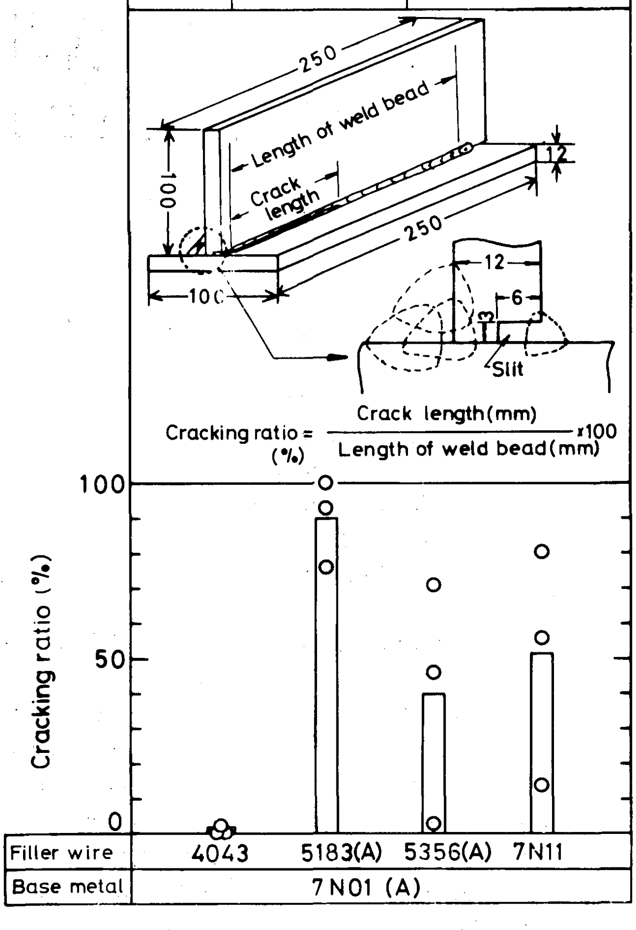

Fig. 16 Cracking ratio in weld metals of 7N01(A) against various filler wires in T-joint cracking test

4. Conclusions

A new type solidification cracking test, that is, continuously variable deformation rate (VDR) cracking test has been developed and then its characteristics for the solidification crack testing method were examined in details, and the principle of this cracking test was experimentally comfirmed with some commercial aluminum alloys. Moreover, solidification crack susceptibilities of filler wires for MIG arc weld metals of Al-Zn-Mg alloy were examined with the VDR cracking test and the results were compared with those of conventional T-joint cracking test. Main conclusions obtained are as follows;

(1) It has been made clear that the VDR cracking test was very useful device to evaluate the susceptibility of the initiation and/or propagation of the solidification cracking in the weld metal in actual welding process because in this cracking test the critical deformation rate which was considered to represent simply the properties of the brittleness temperature range could be easily obtained by continuously decreasing the deformation rate applied on the solidifying weld metal during welding.

(2) The most desirable testing condition for the VDR cracking test was recommended for aluminum alloys. That is, the desirable setting load for stop of testing was about 200kg and the most adequate angular velocity for evaluate the susceptibility of the propagation of the solidification crack was 0.005 to 0.01 rad/sec, though more than 0.01 rad/sec of the angular velocity was needed to initiate and propagate the solidification crack with certainty at the starting point of the welding.

(3) The susceptibilities of the solidification cracking of commercial filler wires for the MIG arc weld metal of Al-Zn-Mg alloy have been evaluated with the index of the critical deformation rate obtained by the VDR cracking test. The susceptibilities are decreased in order of 1070, (5183, 5356 and 7N11) and 4043.

These results almost agreed with those in the conventional self-restraint T-joint cracking test.

Acknowledgement

The authors wish to thank Mr. Khozi KOSHIDA, student of Kinki Univ., for his valuable contributions in this work and also would like to thank Showa Aluminum Co., Ltd, Sumitomo Light Metal Industries, Ltd. and Nippon Light Metal Research laboratory LTD. for their offering materials used in this investigation.

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