Evaluations of Ductility Characteristics and Cracking Susceptibility of Al Alloys during Welding†

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Abstract

The ductility characteristics of solidifying weld metal between liquidus and solidus temperatures during welding has been measured by artificial-restraint cracking tests, namely the Trans-Varestraint test and the Slow Bending type Trans-Varestraint test. Minimum augmented strain to cause cracking, εmin, brittleness temperature range (BTR) and critical strain rate for temperature drop (CST) were selected as criteria representing ductility characteristics and to evaluate weld solidification crack susceptibility. In addition, solidification crack susceptibilities of 16 kinds of commercial Al alloys have been evaluated qualitatively by self-restraint type cracking tests. Correlation between test results, criteria representing ductility characteristics and metallurgical factors were discussed. CST is the most suitable criterion to evaluate the weld solidification crack susceptibility of Al alloys, because crack susceptibility decreases monotonically with increasing CST. εmin and BTR are also important criteria to show the threshold at which crack susceptibility begins to increase steeply. Among the metallurgical factors, dihedral angle of eutectic products in the grain boundary and grain size showed close correlations with crack susceptibility.

KEY WORDS: (Ductility) (Solidification crack) (Al alloy) (GTA welding) (Cracking test) (Dihedral angle) (Grain size)

1. Introduction

Cracking tests are grouped into two types, self-restraint type and artificial-restraint type[1,2]. In the former cracking is induced by the strain or deformation caused by the expansion and/or shrinkage of test specimen during welding. It is therefore difficult to control quantitatively the strain imposed on weld metal. Thus, the susceptibility of solidification cracking is evaluated using qualitative criteria. However, by using this type of cracking test, important results for practical use can be obtained by testing under the same conditions as practical welding work.

In the latter the artificially-applied strain can be controlled quantitatively. Thus cracking susceptibility can be evaluated absolutely by using quantitative criteria such as minimum augmented strain to cause cracking (εmin), critical strain rate for temperature drop (CST), and brittleness temperature range (BTR), which are representative of the ductility characteristics of weld metal during solidification.

Therefore it is very important for practical welding work and for fundamental considerations to make clear the mutual correlationship between self-restraint type and artificial-restraint type cracking tests.

A number of studies have examined the susceptibility for solidification cracking of Al alloys by using self-restraint and artificial-restraint cracking tests. However, these are few studies[3-11] about ductility characteristics of solidifying weld metal between the liquidus and solidus during the welding of Al alloys. Correlation between ductility characteristics and the results of self-restraint tests have rarely been discussed. [12]

Therefore, in this study the correlation between ductility characteristics of weld metal during welding obtained by the artificial-restraint cracking test and cracking susceptibility evaluated by the self-restraint test have been studied. In addition the effect of metallurgical factors have been discussed.

2. Experimental Procedures

2.1 Materials Used

Chemical compositions of commercial Al alloys used are listed in **Table 1**. Plate thickness is 2 or 6 mm.

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Table 1 Chemical compositions of Al alloy base metals A2219.

Material		Chemical composition (mass%)											Treatment condition
		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	V	B	
Base metal	A1070	0.13	0.33	0.02	Tr	Tr	Tr	Tr	0.02	-	-	-	H112
	A1100	0.12	0.53	0.13	0.02	0.01	Tr	0.02	-	-	-	-	H112
	A2017	0.53	0.19	3.89	0.62	0.55	0.11	0.05	0.02	-	-	-	T6
	A2219	0.06	0.16	6.05	0.26	Tr	Tr	0.01	0.04	0.14	0.09	-	T87
	A2024	0.13	0.24	4.60	0.64	1.65	0.01	0.11	0.01	-	-	-	T6
	A3003	0.19	0.60	0.15	1.12	0.01	Tr	0.02	0.01	-	-	-	H112
	A5005	0.10	0.53	0.04	Tr	0.86	Tr	Tr	0.02	-	-	-	H112
	A5052	0.06	0.13	0.01	0.02	2.54	0.21	Tr	0.01	-	-	-	H112
	A5154	0.11	0.25	0.02	0.06	3.50	0.23	Tr	0.03	-	-	-	H112
	A5083	0.14	0.19	0.04	0.67	4.57	0.13	0.01	0.03	-	-	0.0012	H112
	A6063	0.45	0.18	0.02	0.02	0.55	0.02	0.01	0.01	-	-	-	T5
	A6N01	0.54	0.18	0.23	0.04	0.65	0.01	0.02	0.01	-	-	-	T5
	A6061	0.71	0.16	0.18	0.03	0.97	0.08	0.03	0.02	-	-	-	T5
	A7N01	0.09	0.16	0.10	0.43	1.17	0.22	4.57	0.02	0.12	-	-	T5
	A7003	0.08	0.16	0.11	0.14	0.70	0.09	5.50	0.02	0.15	-	-	T5
	A7075	0.10	0.19	1.64	Tr	2.62	0.19	5.62	0.02	-	-	-	T6

2.2 Self-Restraint Cracking Tests

The following 4 cracking tests are used as self-restraint tests for Al alloys. Shape and dimension of these test specimens are shown in **Fig.1**

(1) Ring-casting cracking test

A test alloy about 60g in weight is melted in a carbon crucible under argon shielding (1L/min flow rate) and cast at a pouring temperature of 750°C into a ring-shape steel mold preheated at 50°C. After cooling in an atmosphere of argon, the length of each crack observed is measured on the surface of the ring-cast alloy as shown in Fig. 1(a) and total crack length, LT is selected as the criterion for crack susceptibility.

(2) GTA weld crater cracking test

A fully-penetrating weld crater of about 10 mm in diameter is made on a specimen as shown in Fig. 1 (b) by a spot welding with gas tungsten arc at 100A AC, 18V arc voltage and 15L/min of argon shielding gas. Total crack length, LT, is measured on the weld crater surface and a cracking ratio of LT to the weld crater diameter is selected as the criterion for crack susceptibility.

(3) Houldcroft type cracking test

A fully-penetrating bead-on-plate weld bead is made on a specimen as shown in Fig. 1 (c) by gas tungsten arc without filler wire at alternating arc current : 100A, arc voltage:18V, welding speed: 300 mm/min and argon shielding gas: 15L/min. Centerline cracking usually occurs in the weld bead at the starting edge of the specimen and propagates as welding advances. The percentage ratio of crack length to a specimen length of 150 mm is selected as the cracking ratio.

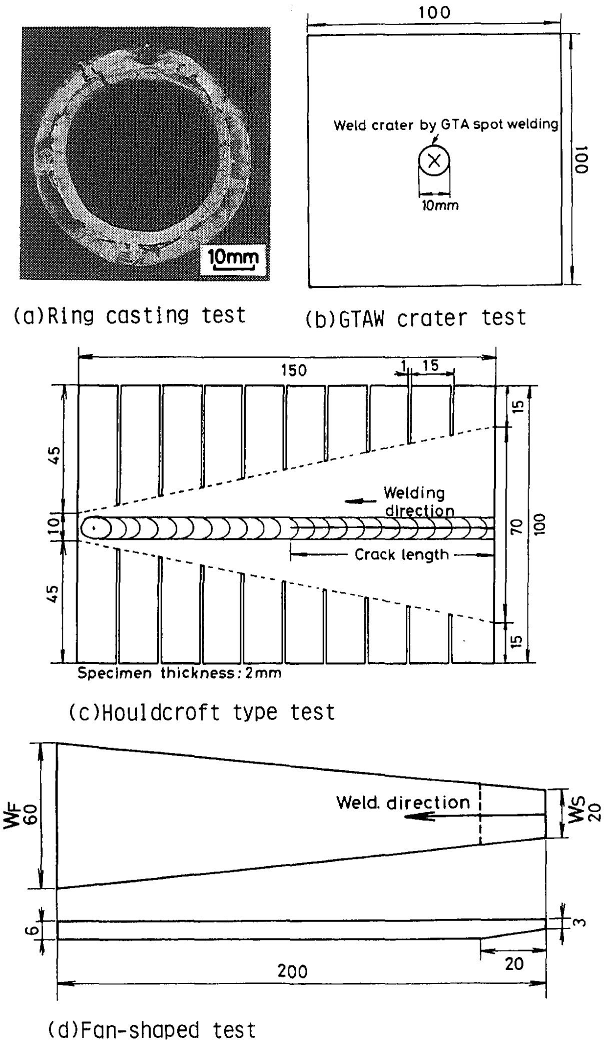

Fig. 1 Self-restraint cracking test specimens.

(4) Fan-shaped cracking test [13]

This test specimen has a peculiar style as shown in Fig. 1 (d) and is suitable for a high speed processes, namely, for electron beam welding. The specimen width increases as welding advances, which is the inverse of the Houldcroft type of specimen. A fully-penetrating weld bead is made on a specimen by bead-on-plate electron beam welding without filler metal at 40kV of accelerating voltage, 100cm/min of welding speed, with defocused beam of 1.40 ab parameter (work distance/beam focussing distance) under a vacuum atmosphere of 1.33×10^{-2} Pa. Beam current is selected from between 70 to 85 mA for each Al alloy. The percentage ratio of a centerline crack to specimen length of 200 mm is selected as the criterion of cracking ratio.

2.3 Artificial-Restraint Cracking Tests

Following 2 cracking tests are used as artificial-restraint cracking test as shown in Fig. 2.

(1) Trans-Varestraint test [4, 14]

Fig. 2 shows a schematic representation of a small specimen type Trans-Varestraint test. Bead-on-plate gas-tungsten arc welding is carried out at 230A in alternating current, 18V, 100mm/min and 15L/min in argon shielding gas. The minimum augmented strain to cause cracking, εmin, and brittleness temperature range (BTR) are obtained as criteria representing the ductility characteristics of the solidifying weld metal.

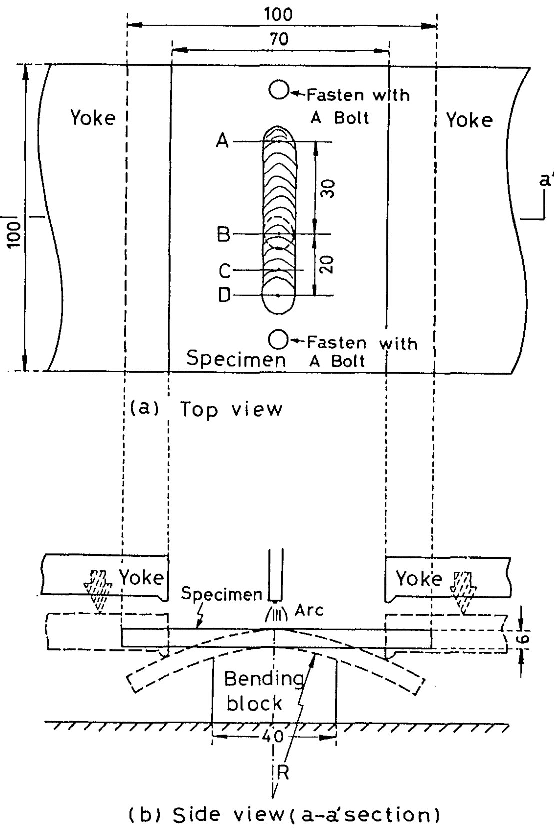

Fig. 2 Schematic illustration of small type Trans-Varestraint test apparatus.

(2) Slow Bending type (SB) Trans-Varestraint test [15]

In practical welding work, the strain rate imposed on the weld bead is estimated to be much lower than that in the Trans-Varestraint test, because the measured values of strain rate imposed on the weld bead during GTA welding of A5052 thin sheet ranged from 0.6 to 5.3%/s[16]. So, in this test, strain rate augmented on weld metal is varied by changing the bending speed of the test specimen in the same cracking tester as Trans-Varestraint test shown in Fig. 2 under the same welding conditions. The critical augmented strain to cause cracking, εc, for different strain rates, the critical strain rate to cause cracking, εc, and the critical strain rate for temperature drop (CST) are selected as criteria representing the ductility characteristics of solidifying weld metal.

2.4 Thermal Analysis and Thermal Distribution in the Weld Bead

Liquidus temperature (TL), nominal solidus temperature (Ts) and/or eutectic temperature (TE) of Al alloys were determined with thermal analysis equipment by measuring a cooling curve of Al alloy melted in a carbon crucible in a electric furnace under argon atmosphere by using Pt/Pt-13% Rh thermocouple of 0.5mm diameter. The thermal distribution curve of a weld bead was obtained by inserting a W-5%Re/W-26%Re thermocouple of 0.25mm diameter into the molten weld pool and measuring a cooling curve during welding. This thermal distribution curve is utilized to obtain BTR and CST.

2.5 Macro- and Microstructural Analysis

Macro- and microstructures of weld metal were revealed by electrolytic etching in 2% HBF4 water solution after mechanical polishing. One hundred contact angles of eutectic products in grain boundaries were measured for each alloy on micrographs printed with x 1500 magnification. These data were arranged in a cumulative curve and a dihedral angle θD representing contact angles of eutectic products was selected as the contact angle at 50 cumulative percent. The amount of eutectic products in weld metal was measured by point counting method using 400 intersections mesh on micrographs of 100 sheets for each alloy. Mean grain size of microstructure of weld metal (GSM) was measured with line intercept method on micrographs of x 45 to x

180 magnifications. The length of a test line is 500 to 2000 μm and the number of test lines is 100 (10 lines x 10 micrographs). In the case of columnar grains, the mean width was measured as GSM on the center of weld bead.

3. Self-Restraint Cracking Test Result

In order to compare the test results obtained by different types of cracking test, a relative cracking ratio (CRR) is defined by following equation (1),

$$CRR = CR/CRmax \times 100\ (\%) \qquad (1)$$

Where CRR: relative cracking ratio, CR: cracking ratio of each alloy, CRmax: maximum cracking ratio in each cracking test. In the case of the Ring-casting test, CR is replaced with LT.

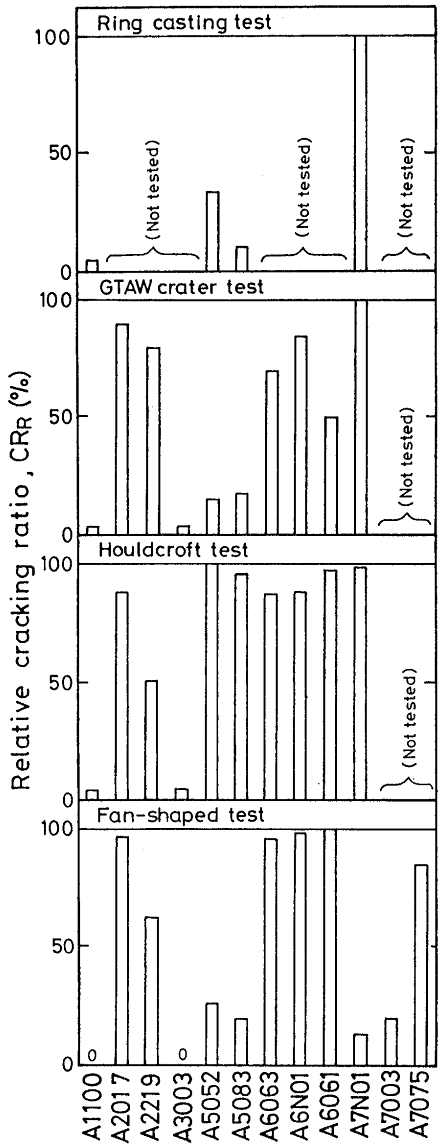

Fig. 3 Relative cracking ratio, CRR of commercial Al alloys evaluated by self-restraint cracking tests.

Table 2 List of εmin, BTR, εc and CST.

Alloy	Trans-Varestraint test		SB Trans-Varestraint test	
	ε_{min}(%)	BTR(°C)	$\dot{\varepsilon}_c$(%/s)	CST(%/°C)
A1070	0.4(0.3-0.5)	20	5.0	3.75
A1100	0.4(0.3-0.5)	20	-	-
A2017	0.05(0-0.1)	135	0.15	0.35
A2219	0.05(0-0.1)	110	0.50	0.66
A2024	0.05(0-0.1)	145	-	-
A3003	0.22(0.15-0.3)	43	-	-
A5005	0.05(0-0.1)	55	-	-
A5052	0.05(0-0.1)	100	0.64	1.19
A5154	0.05(0-0.1)	130	0.70	0.81
A5083	0.05(0-0.1)	140	0.47	1.18
A6063	0	93	-	-
A6N01	0	143	-	-
A6061	0	128	-	-
A7N01	0.05(0-0.1)	143	0.15	0.44

-:Not determined

Fig. 3 shows collectively the CRR of alloys in each cracking test, though not all alloys were tested. Similar results for CRR for each alloy were obtained independent of the type of cracking test. 1000 series and A3003 alloys, showed very low CRR values, independent of the cracking test. A5052 and A5083 which are typical weldable constructional alloys showed low CRR values in most cracking tests except the Houldroft type test. On the contrary 2000 and 6000 series alloys showed very high CRR values independent of the cracking test. A7NO1 showed high CRR values, except in the Fan-shaped test, but showed very low CRR due to the grain refinement as shown in Fan-shaped test results.

4. Evaluation of Ductility Characteristics of Solidifying Weld Metal during Welding

4.1 Ductility Characteristics of Commercial Al Alloys

In order to evaluate quantitatively the solidification crack susceptibility of a weld metal, it is very important to obtain the ductility curve of solidifying weld metal adjacent to a weld pool during welding. **Fig. 4** shows the ductility curves of solidifying weld metal between TL and TS during GTA welding evaluated by the Trans-Varestraint test. The higher temperature boundary of a ductility curve corresponds to the TL of each alloy. εmin and BTR were obtained from these ductility curves and are listed in **Table 2**. In addition $\dot{\varepsilon}$c and CST in Table 2 were obtained by SB-Trans-Varestraint test. Judging from the values of εmin, commercial Al alloys can be grouped into 3 categoree, A1070, A1100 and A3003 showed about 0.4% and 0.22% for εmin, respectively, which are much larger than the others. 2000, 5000 and 7000 series alloys showed a low εmin, about 0.05%. εmin of 6000 series alloys cannot be obtained because of cracking in weld metal without artificial augmented strain. Thus it is

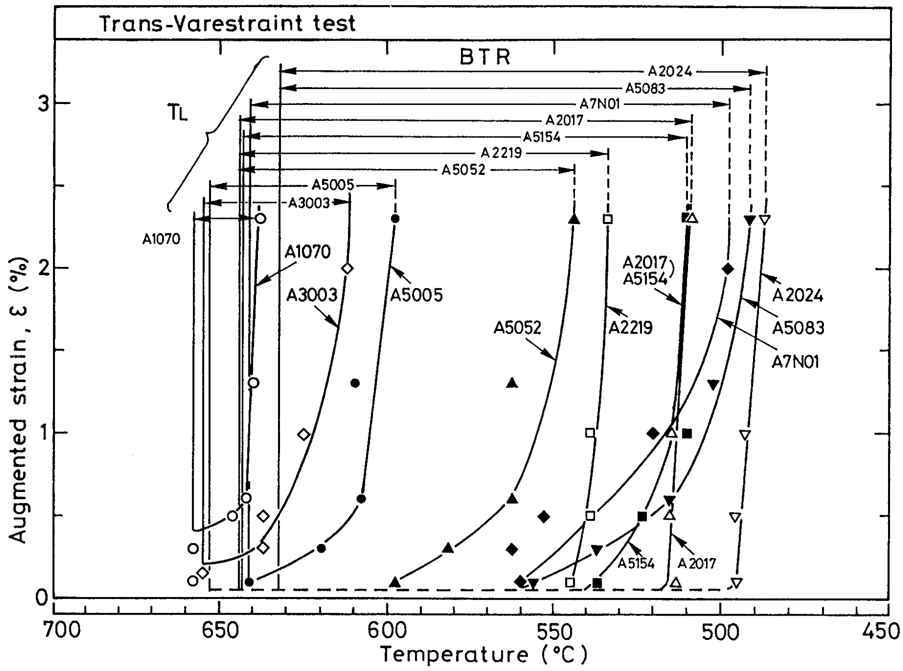

Fig. 4 Ductility curves of commercial Al alloys evaluated by Trans-Varestraint test.

difficult to make clear the difference in εmin between each alloy by using the Trans-Varestraint test except A1070, A1100 and A3003 with very high εmin. This is considered to be due to the high strain rate, about 5.7%/s, in the Trans-Varestraint test. On the contrary, the difference in BTR between each alloy is clear as shown in Table 2. A1070 showed the narrowest BTR, but A7NO1 showed the widest. The BTR of the 5000 series alloys increased with increasing Mg content of the alloy. Most of the 2000 series alloys showed a wide BTR but A2219 showed a comparatively narrow BTR.

Fig. 5 shows the relation between BTR and εmin. εmin is likely to increase with decreasing BTR, though correlation between them is not clear at small value of εmin. In general, a larger εmin and/or a narrower BTR indicates a lower susceptibility for solidification cracking. Therefore, judging from εmin as the first criterion and BTR as the second criterion if εmin for each alloy is the same level, solidification crack susceptibilities for commercial Al alloys used are ranked in the following order;

(A1070, A1100<A3003)<<{A5005<<(A5052, A2219) < (A5154, A2017, A7NO1, A5083, A2024)} <<A6063 < (A6061, A6NO1)}

A1070, A1100 and A3003 show the extremely low susceptibility for solidification cracking due to a large εmin and a very narrow BTR. 6000 series alloys are judged to be highly susceptible to cracking due to a very

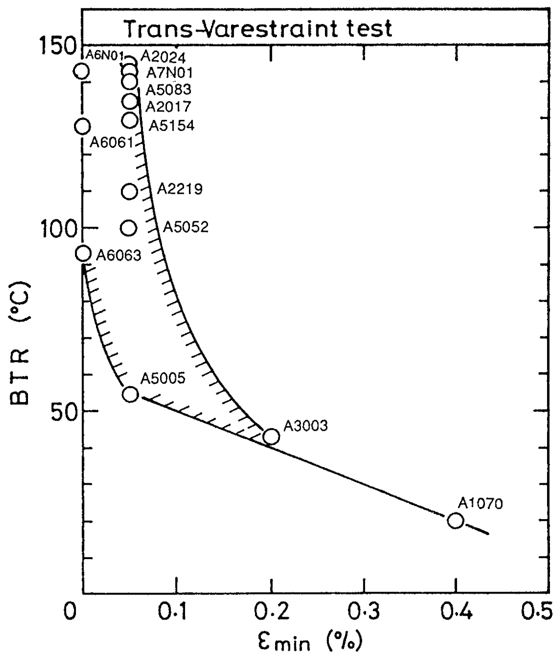

Fig. 5 Relation between BTR and εmin, for commercial Al alloys.

small ε_{min} and wide BTR. A2219, which is weldable in practical use, has a comparatively narrow BTR, but the other 2000 series alloys have wider BTR and are more difficult to weld because of high crack susceptibility. Crack susceptibility of A7NO1 is estimated to be the same level as A2017. These estimated results for crack susceptibility coincide well with the experiences and the results in practical welding work.

BTR of A5083 is wide. This result indicates that the crack susceptibility of A5083 is high. However A5083 is one of the most popular weldable constructional Al alloys. This fact suggets that crack susceptibility is not always decided exactly by BTR only, but ε_{min} in the brittle range is an important criteria to be considered.

By using the Trans-Varestraint test, however, it was difficult to obtain ε_{min} exactly for each alloy except A1070, A1100 and A3003, because ε_{min} was too small to evaluate by the Trans-Varestraint test due to the very rapid strain rate. Therefore, the SB-Trans-Varestraint test with a varying strain rate was utilized to evaluate the ε_{min} for each alloy. **Fig. 6** shows the relation between strain rate, $\dot{\varepsilon}$ and critical augmented strain to cause cracking, ε_c. The results in Fig. 6 indicate a critical strain rate to cause cracking, $\dot{\varepsilon}_c$. ε_c at the maximum $\dot{\varepsilon}$, 5.7%/s corresponds to ε_{min} in Trans-Varestraint test. ε_c of the 5000 series alloy and A2219 increase with decreasing $\dot{\varepsilon}$, especially for the 5000 series alloys. A2017 and A7NO1 showed only a slight increase in ε_c with decreasing $\dot{\varepsilon}$.

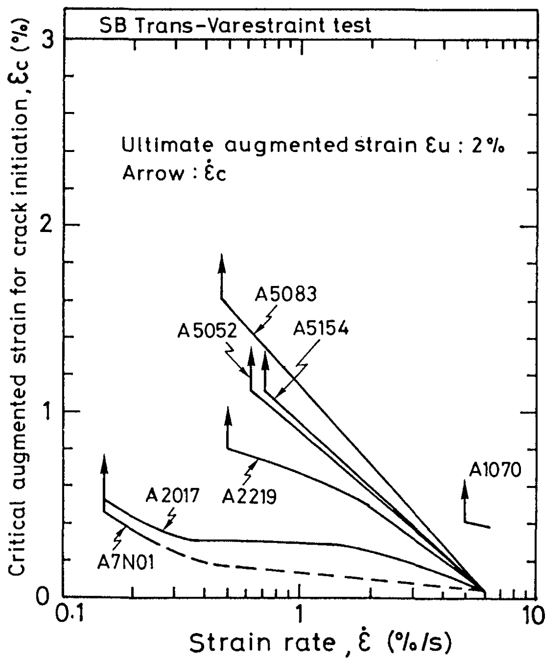

Fig. 6 Effect of strain rate on ε_c of commercial Al alloys.

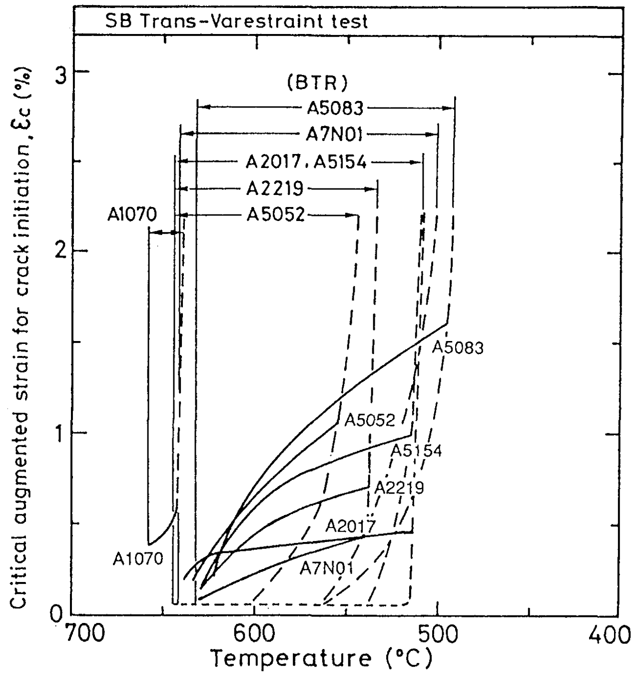

Fig. 7 Ductility curves of commercial Al alloys evaluated by SB Trans-Varestraing test.

Fig. 7 shows ductility curves in the brittle range by converting the abscissa in Fig. 6 from time to temperature by using the cooling curve measured at the central weld bead surface. In the 5000 series alloys and A2219, ε_c increased with decreasing temperature, but A2017 and A7NO1 showed only a slight increase in ε_c. Critical strain rate for temperature drop (CST) can be obtained as the tangent drawn to a ductility curve in Fig. 7 and these are listed in Table 2 along with ε_c at the ultimate augmented strain, 2%.

As a larger CST means lower crack susceptibility, these commercial Al alloys are ranked for crack susceptibility as follows;

A1070<<(A5154, A5052, A5083)<A2219<(A7NO1, A2017)

It is considered that this ranking coincides almost with that in practical welding work. Therefore, in order to evaluate the crack susceptibility of weld metal for commercial Al alloys, ε_c and CST are considered to be very important criteria. The same conclusions were drawn in a recent work about steels [17].

4.2 Correlation between BTR and Solidification Temperature Range

Fig. 8 shows the relation between BTR and solidification temperature range, ΔT (T_L - T_S or T_L - T_E), which was measured by the thermal analysis. BTR increases with increasing ΔT. In the case of the 2000 series of alloys shown with black symbols in the figure, BTR coincides with ΔT, and is represented with following equation,

$$BTR = 1.0\Delta T \quad (r = 0.99) \qquad (2)$$

For the other alloys, BTR for each alloy is larger than ΔT, and following relations is drawn,

$$BTR = 2.1\ \Delta T \quad (r=0.97) \qquad (3)$$

where, r: correlation coefficient.

Thermal analysis results of A2219 and A5083 have different typical patterns as shown in **Fig. 9**. In the case of A2219, an obvious arrest point due to eutectic reaction in the cooling curve appeared and solidification is finished at this eutectic temperature, T_E. Therefore, the lower boundary temperature of the brittle range coincides with this eutectic temperature. On the other hand, obvious eutectic arrest point was not measured in the other alloys as shown in A5083 in Fig. 9. In those cases, nominal solidus temperature, T_s is utilized, (the temperature at which the bulk of liquid solidifies) and is measured as an inflection point in a cooling curve. In a fusion welding process non-equilibrium solidification is occurring due to rapid solidification. This causes remaining liquid to exist at temperature lower than T_s. This also means that the lower boundary of the brittle range is extended to lower temperatures than T_s and thus the BTR is enlarged.

A large difference is also observed in the morphology of fracture surfaces of solidification cracks according to the difference in these correlations between BTR and ΔT [14].

In the case of steels or stainless steels, solidification temperature range is essentially narrow, and phosphorus or sulfur as impurities enlarge the BTR by forming a eutectic with low melting point. In this case, it is possible to narrow the BTR and decrease the crack susceptibility by decreasing the content of these impurities. On the contrary, in Al alloys, major alloying elements, for example copper in Al-Cu alloys, form eutectics with aluminum. This means that BTR of each Al alloy is fixed. Thus, it is difficult to decrease the crack susceptibility by decreasing BTR. Another method to decrease the BTR by controlling the weld metal composition would be the addition of an adequate filler metal. However, even by using filler metal it is difficult in the 2000 series for example, to reduce the BTR to near those of A1070 or A3003. Therefore, a method of improve the crack susceptibility of Al alloys is restricted to the method by increasing the ductility of solidifying weld metal itself in the brittle range, namely the method of increasing ε_{min} and ε_c.

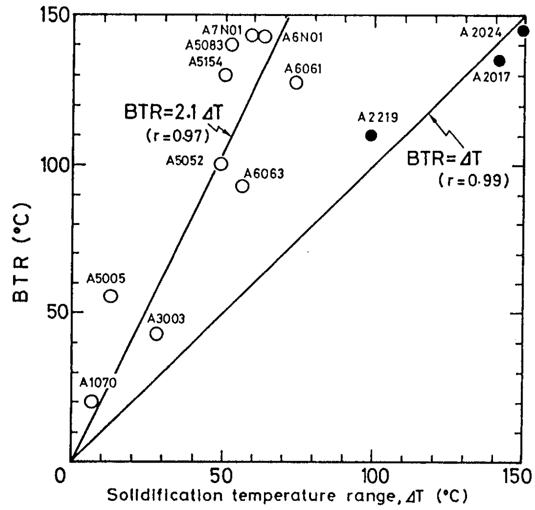

Fig. 8 Relation between BTR and solidification temperature range ΔT measured by thermal analysis.

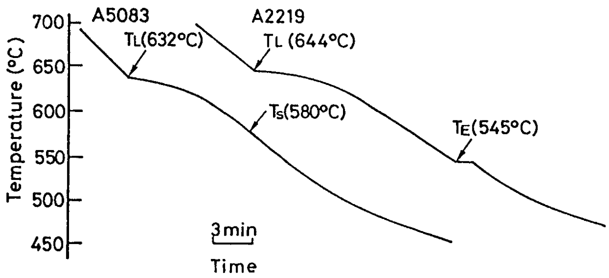

Fig. 9 Typical thermal analysis curves of A5083 and A2219.

4.3 Shape and Amount of Remaining Liquid

Solidification cracking occurs at grain boundaries due to remaining liquid. This means that the shape and amount of remaining liquid in grain boundaries are dominant factors. In this section correlation between CST and these 2 factors is discussed. The shape of remaining liquid in grain boundaries is represented as the dihedral angle, θ_D, of eutectic products in grain boundaries in weld metal. **Fig. 10** shows the cumulative curve of measured contact angles, θ, for each alloy. θ_D is represented by θ at 50 cumulative percent. The θ_D of A5052 and A5083 are 40 and 65 degrees, respectively, which are much larger than those of A1070, A2017, A2219 and A7NO1. θ_D of those alloys are 2, 11, 20 and 13 degrees, respectively.

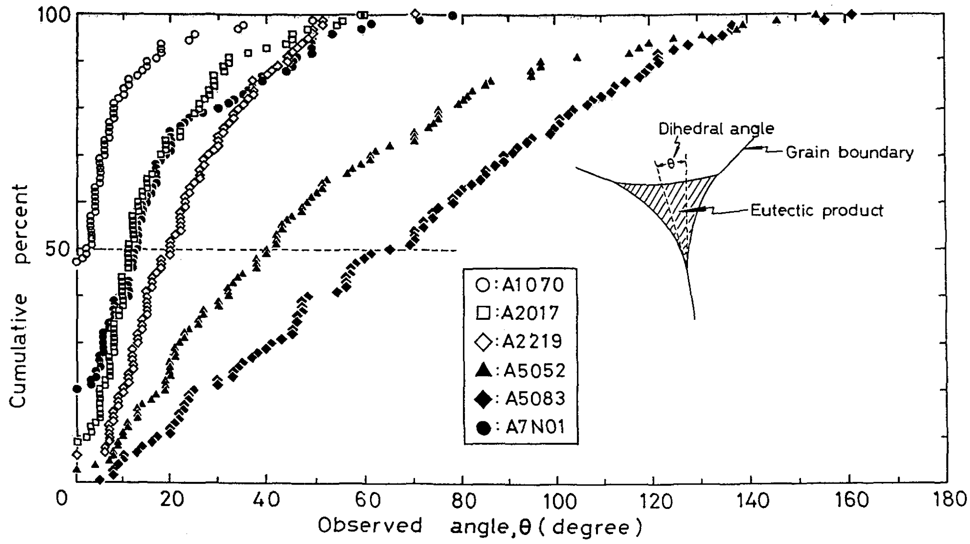

Fig. 10 Cumulative curve of observed dihedral angle of commercial Al alloys.

There is a good correlation between θD and CST, except for A1070, as shown in **Fig. 11**. CST increases linearly up to about 40 degree of θD. Exceptionally, A1070 shows a large CST even with very small θD of about 2 degree. This means that in the case of alloy with very narrow BTR such as 20 degree of A1070, CST becomes largely independent of θD.

Fig. 12 shows the relation between CST and the amount of eutectic products represented by their area fractions. No obvious correlations between them are observed.

Conclusively, it is made clear that the ductility of solidifying weld metal in the brittle range depends much on the shape of remaining liquid in grain boundaries, namely θD and increases as increasing θD except for alloys with very narrow BTR values such as A1070.

5. Correlation between Ductility Characteristics of Solidifying Weld Metal and Self-Restraint Cracking Test Results

εmin, BTR and CST are criteria representing the ductility of solidifying weld metal in the brittle range, and θD and GSM are metallurgical factors affecting the ductility. Correlation between these criteria and metallurgical factors and the relative cracking ratio, CRR, is discussed to clarify the dominant factors affecting solidification cracking susceptibility of weld metal.

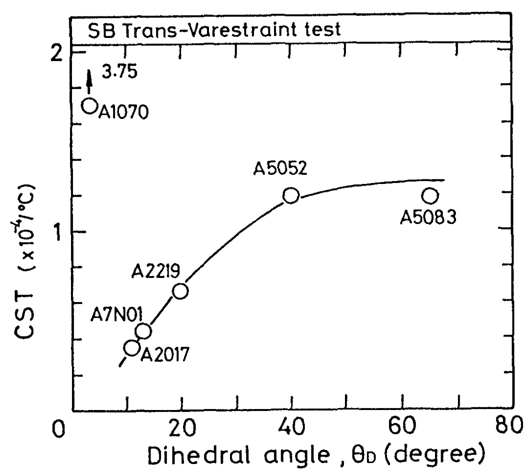

Fig. 11 Relation between dihedral angle and CST measured by SB Trans-Varestraint test.

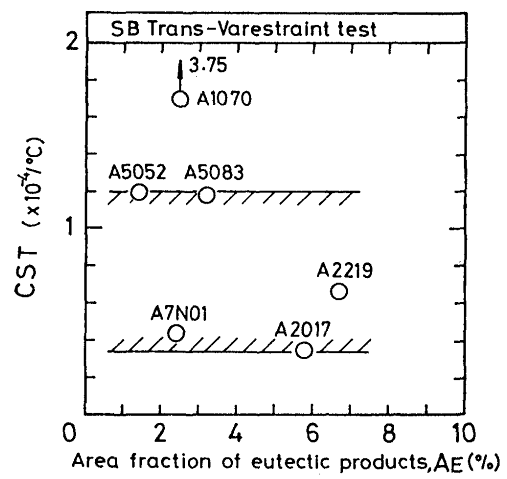

Fig. 12 Relation between area fraction of eutectic products and CST by SB Trans-Varestrain test.

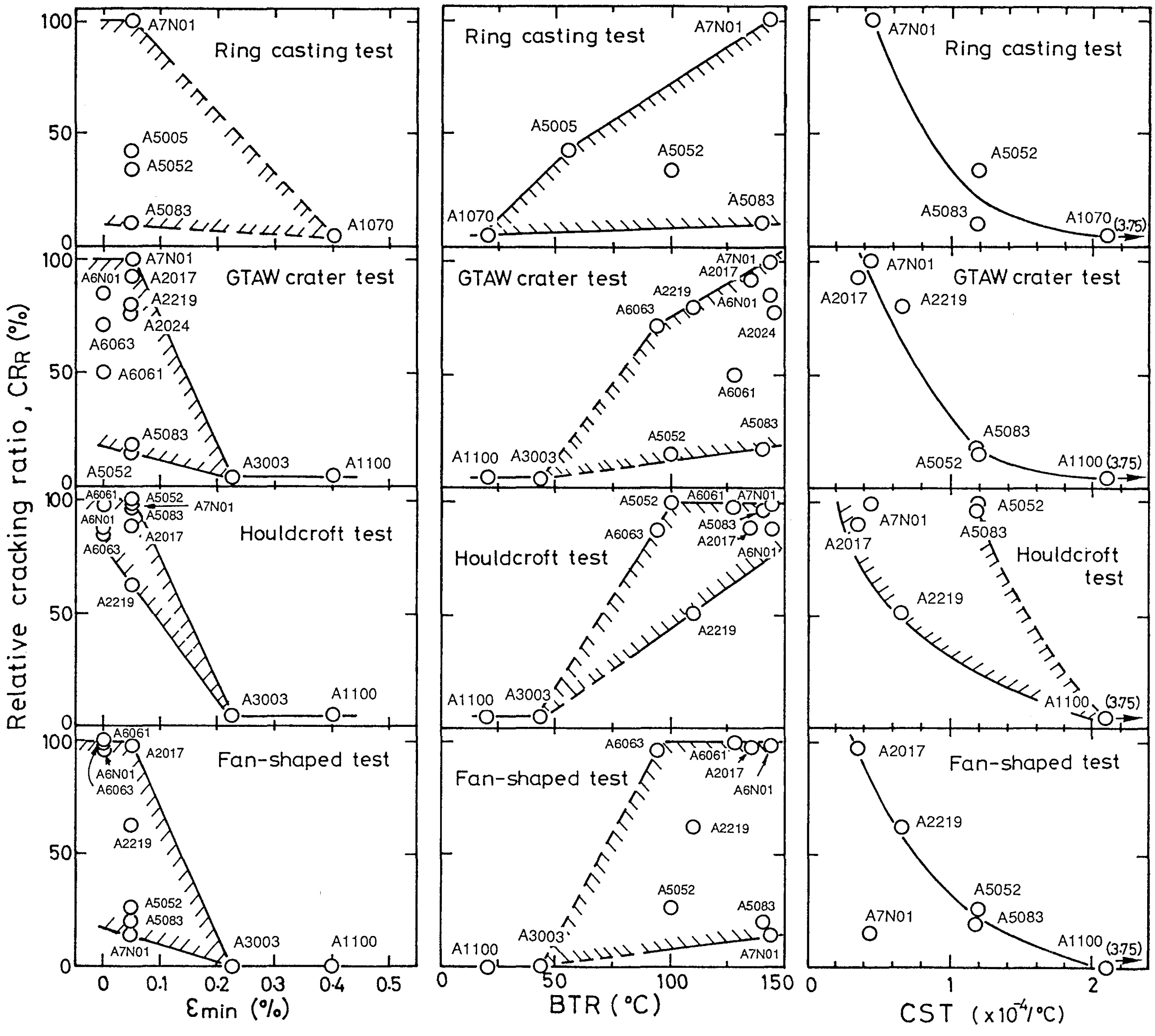

Fig. 13 Relation between relative cracking ratio CRR and εmin, BTR and CST for commercial Al alloys.

At first, **Fig. 13** shows the relations between CRR and the criteria of εmin, BTR and CST for each cracking test. εmin shows an obvious threshold to CRR at 0.2%. At larger εmin than this threshold, CRR showed very low value in any cracking test. As εmin decreased below this threshold, CRR began to increase, but due to large scattering in CRR values, a clear correlation was not observed.

BTR also showed a threshold at about 43 degree. At lower BTR values than this, CRR became very low independent of cracking test type. Increasing BTR beyond his threshold caused an increase in CRR, but also due to large scattering in CRR values, a clear correlation was not observed. CST shows a close correlation with CRR in most cracking tests, except Houldcroft type test, and CRR decreased monotonically as CST increased. Exceptionally, A7NO1 showed low CRR even with small CST. This is considered to due to very small GSM in electron-beam welds of A7NO1.

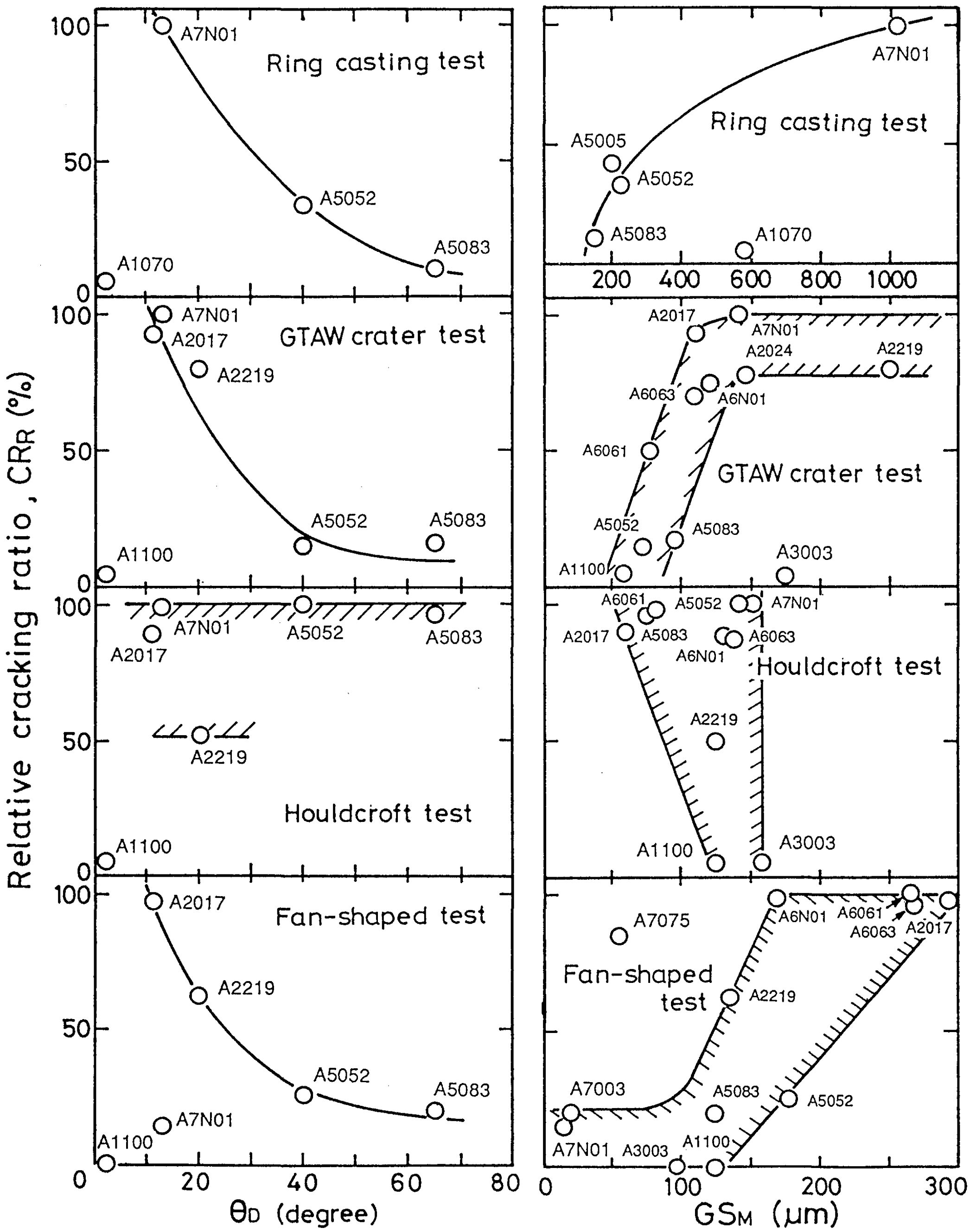

Fig. 14 Relation between relative cracking ratio CRR and θD and GSM.

Fig. 14 shows the relation between CRR and metallurgical factors, GSM and θD. An close correlation is observed between θD and CRR which decreases monotonically with increasing θD, except for Houldcroft type test and 1000 series alloys at each test. 1000 series alloys satisfy the condition required to BTR or εmin in that crack susceptibility is suppressed, to a low level. This is the reason why 1000 series alloys show very small CRR values, even with small θD value in Fig. 14.

A7NO1 in the Fan-shaped test also showed a different result from other alloys. This is due to an extremely small grain size (as shown in the right side figure in Fig. 14), which is frequently observed in weld metal of Zr containing Al alloy in the case of electron-beam welding.

As to the relation between GSM and CRR, a close correlation is also observed except for Houldcroft type test results, though not so clear as θD. The reason why the CRR decreases with decreasing GSM is considered to be due to the redistribution of augmented strain on each grain boundary by the grain refinement.

When a crack propagates along a weld centerline,most of the augmented strain on the weld bead is concentrated around the tip of the propagating crack.

Therefore, much more refinement in grain size is required to decrease the concentrated strain on each grain boundary when a large strain is imposed on a weld bead, as the case of Houldcroft type test.

A1070, A1100, and A3003 showed small CRR values independent of GSM . This is due to the same reason as for θD. A7075 is well known as very high crack susceptible alloys, as shown in Fan-shaped test results. This caused large CRR values even at small GSM values.

Consequently, it is made clear that CST, which contains both the factors of BTR and εmin, is the most suitable criterion to evaluate the solidification crack susceptibility of weld metal.

As for εmin and BTR, these are valuable as a criteria showing a threshold at which crack susceptibility begins to increase steeply when εmin and BTR exceed each critical value. However, this also means that beyond a threshold there is no clear correlation between that these critria and crack susceptibility.

Moreover as to metallurgical factors, θD shows a close correlation between crack susceptibility, as CST does. This is apparent from the good correlation between θD and CST. GSM also shows good correlation between crack susceptibility though not as strong as θD in the wide GSM range. However, smaller GSM shows a strong effect on decreasing crack susceptibility.

6. Conclusions

The correlation between ductility characteristics of solidifying weld metal obtained by artificial-restraint cracking tests and the crack susceptibilities evaluated qualitatively by self-restraint cracking tests have been discussed for 16 kinds of commercial Al alloys along with some metallurgical factors of weld metal made with GTA welding without filler metal. Major conclusive remarks are as follows:

(1) As the criterion representing the ductility characteristics of solidifying weld metal during welding, minimum augmented strain to cause cracking, εmin, and brittleness temperature range, BTR, by Trans-Varestraint test with high strain rate and critical strain rate for temperature drop, CST, by variable-strain-rate type Trans-Varestraint test are obtained and listed in Table 2 in this text.

(2) CST is the most suitable criterion to evaluate weld solidification crack susceptibility of Al alloys. The crack susceptibility evaluated by the self-restraint test decreases monotonically with increasing CST independent of alloy types except 1000 series alloys.

(3) εmin and BTR are important criteria to show the threshold at which the crack susceptibility begin to increase steeply, but there is no close correlation between these criteria and the crack susceptibility beyond the each threshold. The crack susceptibility is very low at more than about 0.22% of threshold in εmin and/or less than about 43°C of threshold in BTR.

(4) As metallurgical factors, dihedral angle of eutectic products in grain boundary shows the close correlation with the crack susceptibility, which increases monotonically with increasing dihedral angle. Moreover, dihedral angle shows a close correlation with CST, which increases with increasing dihedral angle. Mean grain size shows a weak correlation with the crack susceptibility over the wide range of grain sizes. The crack susceptibility decreases with decreasing mean grain size. Especially at smaller grain sizes this tendency becomes clear.

References

1) N. M. J. Romijin, " Performance of cracking test on fusion welded aluminum alloys", part II, International Institute of Welding Doc. IX-585-68 (1968).
2) K. Nakata and F. Matsuda, "Recent weld solidification cracking tests and their applications for some commercial aluminum alloys", J. Light Metal Welding & Construction, Vol. 20 (1982) pp.101-111.
3) N. N.Prokhorov, "The technological strength of metals while crystallizing during welding", Welding Production Vol. 9 (1962) pp.1-8.
4) T. Senda, F. Matsuda and G. Takano, "Studies on solidification crack susceptibility for weld metals with Trans Varestraint Test (2)", J. Japan Welding Society, Vol. 42 (1973) pp. 48- 56.
5) K. Ando, S. Nakata, K. Kishida, and Y. Tohei, "Hot deformability of weld metal", J. Japan Welding Society,Vol. 42 (1973) pp. 750-759.
6) J. C.Lippold, E. F. Nippes and W. F. Savage, "An investigation hot cracking in 5083 aluminum alloy weldments", Welding Journal, Vol. 56 (1977) pp.171-178s.
7) H. Tamura, N. Kato, S. Ochiai, and Y. Katagiri, "Cracking study of aluminum alloys by the variable tensile strain hot cracking test", Trans. Japan Welding Society, Vol. 8 (1977) pp. 143-149.
8) W. F.Savage, E. F. Nippes and J. D. Varsik, "Hot-cracking susceptibility of 3004 aluminum", Welding Journal, Vol. 58 (1979) pp. 45s- 53s.
9) F. Matsuda, K. Nakata, "Ductility characteristics of solidifying weld metal of aluminum alloy during GTA welding",. Proc. Intl. Conf. on quality and reliability in welding, Hongzhou, (1984) China, B-11-1 to B11-5.
10) F. Matsuda, K. Nakata, Y. Nishio, K. Tsukamoto and S. Johgan, "Effect of zirconium addition on improvement of solidification crack susceptibility of Al-Zn-Mg alloy weld", Quarterly J. Japan Welding Society, Vol 4(1986), pp.115-120.

11) F.Matsuda, K. Nakata, Y. Nishio, K. Tsukamoto and S. Johgan, " Effect of electromagnetic stirring on improvement of solidification crack susceptibility of zirconium containing Al-Zn-Mg alloy weld", Quarterly J. Japan Welding Society, Vol. 4 (1986), pp.120-125.
12) D. V. D.Torre, "Comparison of cracking tests used for aluminum alloys Part I", International Institute of Welding, Doc. IX-859-73 (1973).
13) F. Matsuda, K. Nakata, "A new self-restraint solidification crack susceptibility test for electron beam welding", Trans. JWRI, Vol. 11,(1983) pp.87-94.
14) Y. Arata, F. Matsuda, K. Nakata and I. Sasaki, "Solidification crack susceptibility of aluminum alloy weld metals (1)", Trans. JWRI, Vol. 5 (1976) pp.153-167.
15) Y. Arata F. Matsuda, K. Nakata, K. Shinozaki, "Solidification crack susceptibility of aluminum alloy weld metals (2)", Trans. JWRI, Vol. 6(1977) pp.91-104.
16) F. Matsuda, K. Nakata, S. Harada, "Moving characteristics of weld edges during solidification in relation to solidification cracking in GTA weld of Al alloy thin sheet", Trans. JWRI, Vol. 9(1980)pp. 225 to 235.
17) S. Tomita, "Quantitative evaluation of solidification brittleness of weld metal during solidification by in-situ observation and measurement", Doctoral dissertation, Osaka Univ. (1988) pp.103-136.