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Ductility characteristics of commercial aluminium alloys between liquidus and solidus temperatures during welding and evaluation of weld solidification cracking susceptibility

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Summary: This paper describes an investigation of the ductility characteristics of solidifying weld metal by external restraint solidification cracking tests, i.e. the Trans-Varestraint test and slow-bending Trans-Varestraint test. The minimum augmented strain necessary for crack initiation (ε_{min}), brittleness temperature range (BTR), and critical strain rate for temperature drop (CST) are selected from the ductility characteristics as criteria for evaluation of the weld solidification cracking susceptibility.

The solidification cracking susceptibility of 16 types of 1000–7000 series commercial aluminium alloys is also qualitatively evaluated by self-restraint solidification cracking tests, i.e. the ring casting test, GTAW crater test, Houldcroft test, and fan-shaped test.

The grain size of the weld metal, the dihedral angle of eutectic products at the grain boundaries and the amount of eutectic products are also measured as metallurgical factors.

The correlation between the results obtained in the self-restraint cracking tests and the criteria adopted for the ductility characteristics and metallurgical factors are discussed. CST is the most suitable criterion for evaluation of the weld solidification cracking susceptibility of Al alloys, because the crack susceptibility monotonically decreases with an increasing CST. ε_{min} and BTR are also important criteria for indication of the threshold at which the crack susceptibility begins to increase sharply. When $\varepsilon_{min} > 0.22\%$ and BTR $< 43\,^{\circ}$C, Al alloys show very low solidification cracking susceptibility.

Among the metallurgical factors, the dihedral angle and grain size are well correlated with the solidification cracking susceptibility, whereas the amount of eutectic products is not.

Introduction

Cracking tests are broadly classified into the self-restraint cracking test and externally augmented strain (displacement) cracking test depending on the mechanism of crack initiation and propagation.[1] The former is a method of crack initiation based on the strain (displacement) associated with elongation and shrinkage of the material itself, whereas the latter is a method of induced crack initiation based on the external application of a tensile strain (displacement) or bending strain (displacement) to the material. The former makes it virtually impossible to exercise quantitative control over the strain (displacement) applied to the material, so that evaluation of the solidification cracking susceptibility is performed relatively using qualitative indices, such as e.g. the crack length, crack number, cracking ratio, etc. Since tests can be run under actual welding conditions, however, results important for practical applications can be obtained. The latter, on the other hand, permits an absolute evaluation using quantitative indices representing the ductility characteristics of the weld metal in the solid/liquid temperature range, such as e.g. the critical amount of strain (displacement) necessary for crack initiation, the critical strain (displacement) rate, the crack initiation temperature range, etc. However, it is extremely important both fundamentally and experimentally to clarify the correlation between both sets of cracking test results.

The weld solidification cracking susceptibility of Al alloys has so far been well researched and documented in the literature for both self-restraint cracking tests and externally augmented strain cracking tests.[2–6] The literature, however, contains little research relating to the ductility characteristics of the weld metal during welding in the solid/liquid temperature range,[7–16] with the correlation between both sets of results of the self-restraint cracking tests and externally augmented strain cracking tests being especially little studied.[17]

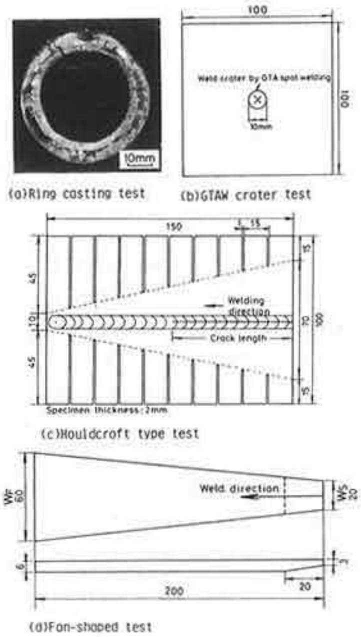
This paper therefore describes an investigation of the correlation between the self-restraint cracking test results and the ductility characteristics of the weld metal during welding as determined by externally augmented strain cracking tests and also discusses the relationship with the metallurgical factors of the weld metal.

The weld solidification cracking susceptibility of 1000–7000 series commercial aluminium alloys is first qualitatively and quantitatively evaluated by each solidification crack test method. Based on the self-restraint cracking tests, a qualitative comparison is made using indices such as e.g. the crack length, crack number, and a cracking ratio based on the latter. Based on the externally augmented strain cracking tests, a quantitative comparison is also made using indices such as e.g. the critical amount of strain (displacement) necessary for crack initiation, the critical strain (displacement) rate, and the crack initiation temperature range. On the basis of the results obtained during evaluation of the weld solidification cracking

Table 1 Chemical composition of Al alloy base metals

Alloy base metal	Chemical composition (mass %)											Treatment condition
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	V	B	
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

susceptibility by these cracking test methods, the weld solidification cracking susceptibility of commercial Al alloys is discussed from an overall perspective with reference to macro/mirostructural observations of welds, fracture surface observations, the results obtained during solidification temperature measurements by thermal analysis, etc. The present research effort represents a fundamental evaluation of the weld solidification cracking susceptibility of commercial Al alloys with filler-free base metal chemistries.



1 *Self-restraint cracking test specimens.*

Experimental method

Sample alloys

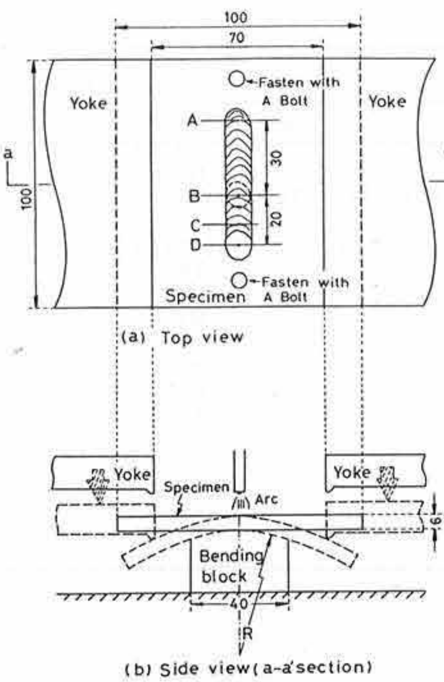
Table 1 lists the chemical compositions of the Al alloy base metals used in the solidification cracking tests. They are all commercial Al alloys with a plate thickness of 2–6 mm.

Solidification cracking tests

Self-restraint cracking tests

Various self-restraint cracking test methods are employed for Al alloys, such as e.g. the ring casting test most appropriately used for evaluation of solidification cracking susceptibility during casting,[3] the GTAW crater test used for evaluation of the solidification cracking susceptibility of weld craters, the Houldcroft test most appropriately used in practice for evaluation of the solidification cracking susceptibility of weld beads in light-gauge materials, and the fan-shaped test newly developed for evaluation of the solidification cracking susceptibility of electron beam welds.[18] Figure 1 shows their respective specimen geometries.

The ring casting test is described below.[19] Around 60 g molten Al alloy melted in a graphite crucible using an electric furnace (argon gas atmosphere, flowrate 1 l/min) is cast in a mild steel ring-shaped mould (preheated at 50 °C) at the prescribed temperature (750 °C). After air cooling to room temperature, the lengths of the cracks found over the whole surface of the ring-shaped ingot released from the mould are measured, with the total value (total crack length) being used to evaluate the crack susceptibility. The GTAW crater test and Houldcroft test are not described in any great detail here, since they are fully detailed in a previous paper.[14] The indices respectively used here for evaluation of the cracking susceptibility, however, are the cracking ratios, i.e. the value (%) obtained through division of the total length of cracks initiated on the weld crater surface by the crater diameter (around 10 mm) and the value (%) obtained through division of the the length as far as the arrest tip of cracks propagating from the onset of welding by the specimen length (150 mm). In the fan-shaped test, unlike the Houldcroft test, bead-on-plate welding is performed from the narrow to wide side of the plate width. This approach enables the plate stiffness to be increased by extending the plate width, the rotational deformation of the specimen acting to crack the weld metal to be controlled, and the crack thereby to be arrested.[20,21] These specimen geomet-



2 *Small type Trans-Varestraint test apparatus.*

ries are used in electron beam welding and laser beam welding that generally involve welding at a higher speed than in arc welding.[18] Constant welding conditions were adopted: an acceleration voltage of 40 kV, welding speed of 100 cm/min, and ab = 1.4. To obtain a fully penetrated bead, the beam current was set at 70–85 mA depending on the alloy being tested. The evaluation was performed using the cracking ratio, i.e. the value (%) obtained through division of the the length as far as the arrest tip of cracks propagating from the onset of welding by the specimen length (200 mm).

Externally augmented strain (displacement) cracking tests

The solidification cracking susceptibility of the base metal was quantitatively evaluated by two types of bending externally augmented strain cracking tests (Trans-Varestraint and SB Trans-Varestraint tests).

1 Trans-Varestraint test

Figure 2 outlines the test method.[22] In the present investigation, small-sized specimens were tested under fully reversed bending. The minimum augmented strain necessary for crack initiation (ε_{min}) and the crack initiation temperature range (brittleness temperature range, BTR) were adopted as indices for evaluation of the solidification cracking susceptibility. Welding was performed by TIG (AC) bead-on-plate welding. The welding conditions were: 230 A, 100 mm/min, 18 V, and argon shielding gas (15 l/min).

2 SB Trans-Varestraint test

In the Trans-Varestraint test, the augmented strain rate has an extremely high value, although the strain rate applied to the weld is stated to be slowed somewhat during actual welding.* In the present investigation, the bending strain rate variable type (slow-bending type, SB) of Trans-Varestraint test[24] was therefore used. The same type of cracking test machine was used in the Trans-Varestraint tests shown in Fig. 2. The augmented strain rate can be varied through adjustment of the falling speed of the bending yoke. At a constant augmented strain rate, the critical amount of augmented strain of crack initiation ε_c is determined through stepwise variation in the amount of augmented strain, and the ductility characteristics of the material within BTR are evaluated. The critical augmented strain rate of crack initiation $\dot{\varepsilon}_c$ is also determined through stepwise variation in the augmented strain rate at a constant amount of augmented strain. In this case, the critical strain rate for temperature drop (CST) in relation to the temperature change due to assembly of temperature distribution curves at the weld bead centre during welding is determined. The welding conditions were the same as in the Trans-Varestraint test.

Thermal analysis and weld bead temperature distribution measurement methods

The liquidus temperature T_L, nominal solidus temperature T_S, and eutectic temperature T_E were determined by a thermal analysis. An upright electric furnace was used, and melting and solidification of the material (around 25 g) were performed in a graphite crucible in an argon gas stream. Cooling curves were measured with a 0.5 mm dia. Pt/Pt-13%Rh thermocouple.

The temperature distribution curves of the weld beads during welding involved a 0.25 mm dia. W-5%Re/W-26%Re thermocouple being directly inserted into the weldpool from its surface during TIG arc welding, the determination being made from the cooling curves then obtained.

Macro/microstructural observations and analytical method

The macrostructural and general microstructural observations were made by anodic oxidation of the specimens in Barker's solution (2% HBF_4 aqueous solution) after mechanical polishing (with up to # 1200 emery paper) and buff polishing (with 0.3 μm alumina). The cathodes were made of commercially pure Al plate (A1070). Energising was performed at a voltage of 20–250 V for 30 sec to 2 min depending on the alloy being tested. The macrostructural observations were made with polarising illumination using anodically oxidised materials. The amounts of eutectic products crystallised in the weld metal were measured by the point counting method using an optical microscope after anodic oxidation.[25] An eyepiece with a mesh of 400 intersecting points (to JIS specifications), × 1000 magnification, and 100 fields of view was used. Determination of the dihedral angle θ of

* *At the strain rate due to rotational deformation during two-dimensional bead-on-plate welding of light-gauge materials, provided that the bead width has the target spacing, actually measured values of up to around 0.6–5.3 %/sec for A5052 (Ref. 22) and up to around 2.1–3.8 %/sec for ferrous materials[23] are reported.*

the eutectic products in the weld metal involved the dihedral angle of the eutectic products crystallised at the grain boundaries being measured on optical micrographs (×1500 printing magnification). The angle with a cumulative value of 50% as determined from the cumulative curves was adopted as the dihedral angle θ_D (Ref. 26). The number of measurements of θ performed per sample was 100. The mean grain size GS_M was also measured by the line segment method on polarised light optical micrographs (×45–180 printing magnification).[25] The test line length was adopted as that where the number of included grains was at least > 10 (500–2000 μm), the number of samples used here being 10. For the columnar crystals considered, GS_M was determined using the columnar crystal width. The measurement positions were at the weld bead centre where the grains are larger.

Quantitative comparative investigation of weld solidification cracking susceptibility of commercial Al alloys

To unify the numerical values of the various indices used to evaluate the solidification cracking susceptibility during the self-restraint tests, the relative cracking ratio CR_R (%) was here defined for convenience. That is to say, this parameter – taking 100% to be the cracking ratio of the alloys showing the maximum cracking ratio in the solidification cracking tests – represents the percentage value obtained through division of the cracking ratios of alloys other than the latter by this maximum value, being given by equation [1] as:

$$CR_R = CR/CR_{max} \times 100\ (\%) \qquad [1]$$

where CR_R: relative cracking ratio, CR_{max}: maximum cracking ratio obtained in the solidification cracking tests (the cracking ratio of the alloys showing the maximum cracking ratio), CR: the cracking ratios of the different alloys tested in the solidification cracking tests.

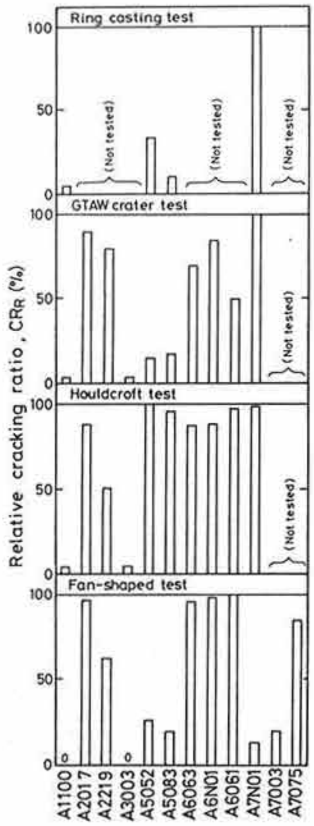
Figure 3 summarises the CR_R values of the alloys tested in the solidification cracking tests. The CR_R values of the alloys are broadly in agreement irrespective of the cracking test employed except for one area. That is to say, 1000 series alloys and A3003 show much smaller CR_R values in all the tests. A5052 and A5083, which are Al alloys used for welded structures, also have low CR_R values in any test other than the Houldcroft test. 2000 and 6000 series alloys, however, have high CR_R values in all the tests. A7N01 has the highest value of all in all tests other than the fan-shaped test. As described below, however, the results obtained in the fan-shaped test suggest that there is some possibility of A7N01 having its solidification cracking susceptibility reduced to much the same level as that of A5083 under the effect of the fine equiaxed nature of its grain structure.

Evaluation of ductility characteristics in solid/liquid temperature range during welding

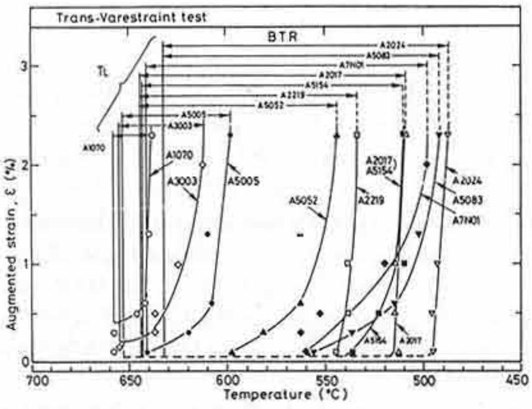
Ductility characteristics of commercial Al alloys

To make a quantitative evaluation of the solidification cracking susceptibility of the weld metal, it is necessary to determine the ductility curves of the alloys in the solid/liquid temperature range at the back of the weldpool during welding. Figure 4 shows the ductility curves in the solid/liquid temperature range of the weld metal produced during TIG arc welding of various commercial Al alloys as determined by the Trans-Varestraint test. The upper limit temperature of the ductility curves is the liquidus temperature T_L of each alloy. Table 2 lists the ε_{min} and BTR values of the alloys as determined from this diagram. The same tabulation also includes the $\dot{\varepsilon}_c$ and CST values determined by the SB Trans-Varestraint test described below.

Commercial Al alloys can be broadly classified into three groups depending on the magnitude of ε_{min}. The



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



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

Table 2 Values of ε_{min}, BTR, ε_c and CST

Alloy	Trans-Varestraint test ε_{min} (%)	Trans-Varestraint test BTR(°C)	SB Trans-Varestraint test ε_c (%/s)	SB Trans-Varestraint test 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

high-ε_{min} group covers A1070 and A3003, with ε_{min} having values as high as around 0.4% (> 0.3% and < 0.5%) and around 0.22% (> 0.15% and < 0.3%) respectively. Other alloys, however, with the exception of the 6000 series, each have much lower values of around 0.05% (> 0% and < 0.1% (the lowest externally augmented strain in these tests)). Each 6000 series alloy also has an externally augmented strain of 0%, i.e. cracks are initiated in the bead only. The foregoing results most notably suggest that, in these tests, the ε_{min} differences between the alloys are ambiguous except for those with high ε_{min} values. This is due to the fact that these tests envisage an extremely fast augmented strain rate of 5.7 %/sec.

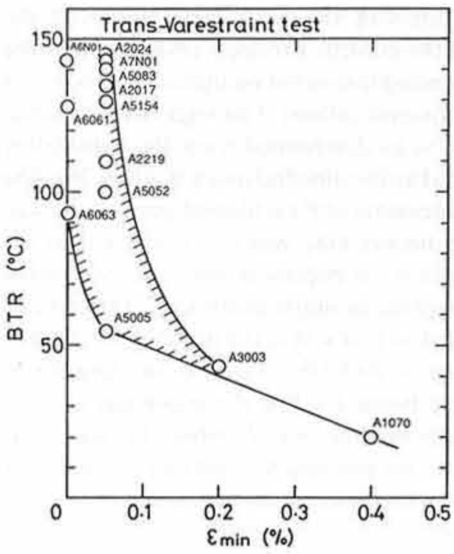
On the other hand, the BTR differences between the alloys are clearly defined. A1070 shows the narrowest BTR value. For Al-Mg alloys, BTR increases with an increasing Mg content. Among 2000 series alloys, the BTR of A2219 is relatively narrow and large elsewhere. The BTR of A7N01 has a wide value among these alloys.

Figure 5 shows the relationship between the BTR and ε_{min} of the alloys. This diagram suggests that BTR tends to get narrower with an increasing ε_{min} and that both factors are poorly correlated.

Reference 22 generally finds that the solidification cracking susceptibility falls with a larger ε_{min} and narrower BTR. Based on the foregoing results, the following is obtained when the solidification cracking susceptibility of the alloys is evaluated first by the magnitude of ε_{min} and then by the value of BTR at the same ε_{min} level.

{A1070 < A3003} ≪ {A5005 ≪ (A5052, A2219) < (A5154, A2017, A7N01, A5083, A2024)}≪ {A6063 < (A6061, A6N01)}

A1070 and A3003 are found to have a high ε_{min} as well as an extremely narrow BTR, so that their solidification cracking susceptibility is heavily depressed. By contrast, all 6000 series alloys have an extremely low ε_{min} as well as a wide BTR, so that their solidification cracking susceptibility is much enhanced. These results are also consistent with those found during welding production. A2219 with a relatively narrow BTR is generally fusion-weldable,



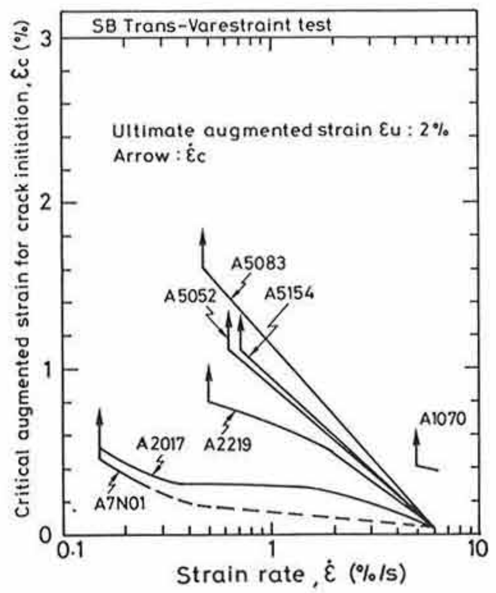
5 *Relation between BTR and ε_{min} for commercial Al alloys.*

whereas the other 2000 series alloys with a wide BTR cannot be fusion-welded. These results are consistent with those found during welding production. The solidification cracking susceptibility of A7N01 is regarded as being of the same order as that of A2017 when judged from the perspective of BTR width. On the other hand, A5083, for which most experience has been gained among Al alloys intended for welded structure applications, has a fairly wide BTR, being conversely judged to have a high solidification cracking susceptibility, which is inconsistent with the results found during welding production. This implies that the solidification cracking susceptibility cannot always be accurately evaluated by the BTR width alone, an important factor being the magnitude of ε_{min} within BTR, as described below. By the Trans-Varestraint test, however, the augmented strain rate is extremely high, and strict solidification application conditions apply, so that, for Al alloys, except for alloys with an extremely low solidification cracking susceptibility, such as commercially pure Al, it is difficult to clarify the differences between the alloys.

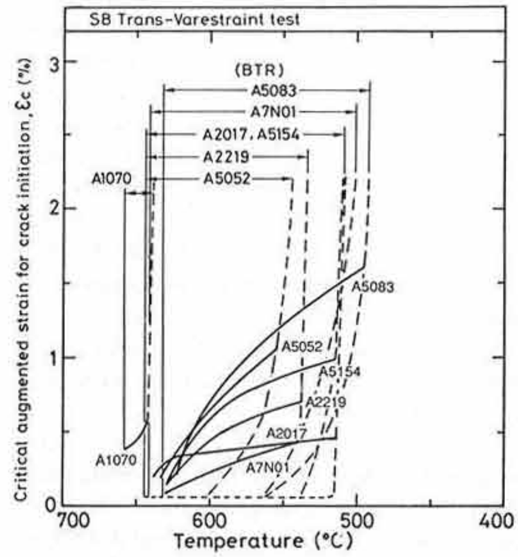
The ε_{min} values of the alloys were therefore determined when the Trans-Varestraint test was run by a method involving variation in the augmented strain rate, i.e. by the SB Trans-Varestraint test. The test was run for alloys extensively used in practice in welded structures. A2017 was used as a reference alloy having a BTR value much the same as that of A7N01.

Figure 6 shows the relationship between the augmented strain rate $\dot{\varepsilon}$ with an ultimate augmented strain of 2% and the critical augmented strain for crack initiation ε_c. Also marked here by the arrows is the critical augmented strain rate for crack initiation $\dot{\varepsilon}_c$. The fastest $\dot{\varepsilon}$ and an $\dot{\varepsilon}_c$ at 5.7 %/sec are the (ε_{min}) values used in the Trans-Varestraint test. For 5000 series alloys and A2219, ε_c increases with a decreasing $\dot{\varepsilon}$, there being an especially sharp increase in 5000 series alloys, including A5083. A2017 and A7N01, however, exhibit a small increase in ε_c.

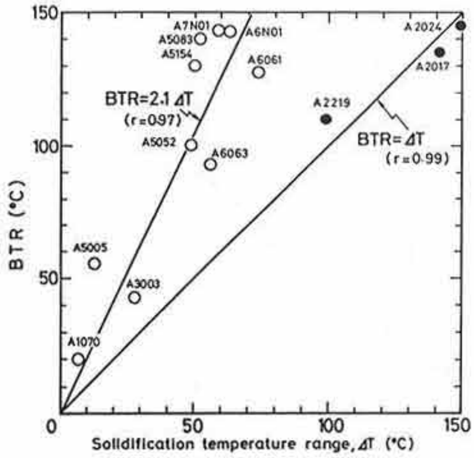
Figure 7 next shows the results presented in Fig. 6 converted to ductility curves within BTR using the temperature distribution curves at the weld bead centre



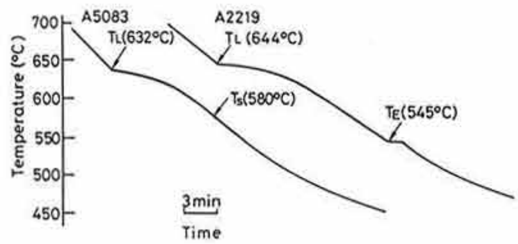
6 *Effect of strain rate on $\dot{\varepsilon}_c$ of commercial Al alloys.*



7 *Ductility curves of commercial Al alloys evaluated by SB Trans-Varestraint test.*



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



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

during welding. The change in ε_c is here shown as a function of the temperature. For Al-Mg alloys, ε_c sharply increases with a falling temperature. A2219 exhibits much the same trend, whereas A2017 and A7N01 show only small degrees of increase. Table 2 described above shows the $\dot{\varepsilon}_c$ values obtained at a constant ultimate augmented strain of 2% and the CST values based on the ductility curves of Fig. 7. The solidification cracking susceptibility is found to decrease with an increasing CST. These alloys are ranked as follows in terms of the solidification cracking susceptibility:

A1070 ≪ (A5154, A5052, A5083) < A2219 < (A7N01, A2017)

This trend is consistent with the results found during welding production. That is to say, 5000 series alloys, including A5083 for which most experience has been gained among Al alloys intended for welded structure applications, have results different from those obtained in the Trans-Varestraint test, with A1070 having a low solidification cracking susceptibility and with 2000 and 7000 series alloys conversely having a high weld metal solidification cracking susceptibility.

Values of $\dot{\varepsilon}_c$ and CST are therefore regarded as being important indices in evaluation of the solidification cracking susceptibility of commercial Al alloy welds. Similar results have also been reported in recent ferrous materials research.[23]

Relationship between BTR and solidification temperature range

Figure 8 shows the relationship between BTR and the solidification temperature range ΔT ($T_L - T_S$ or $T_L - T_E$) determined by a thermal analysis. BTR here tends to increase with the solidification temperature range. For 2000 series alloys, both factors are in virtual agreement, with the following relation being obtained:

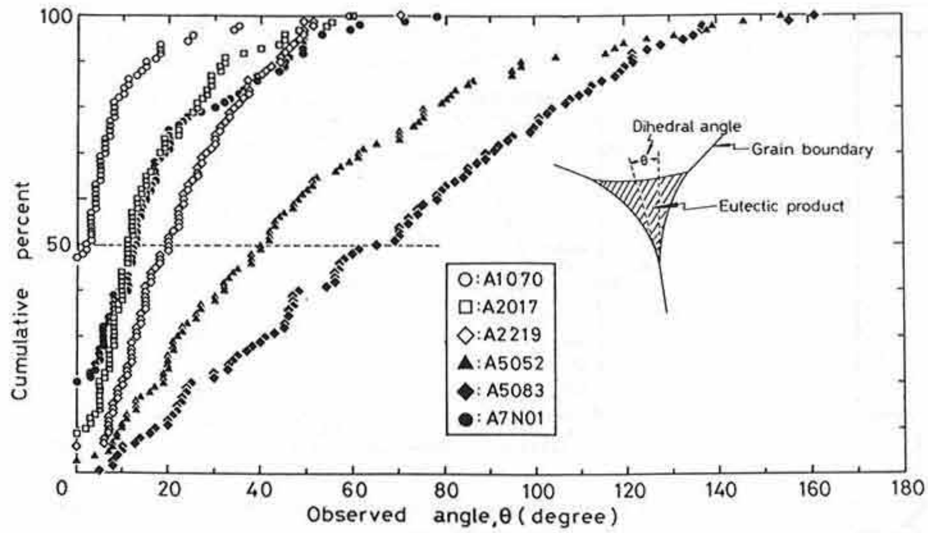
$$BTR = 1.0\,\Delta T,\ (r = 0.99) \qquad [2]$$

For the other alloys, however, BTR has a higher value than ΔT, being expressed by the following relation:

$$BTR = 2.1\,\Delta T,\ (r = 0.97) \qquad [3]$$

where r: correlation coefficient.

Figure 9 shows typical thermal analysis curves of A2219 and A5083. For 2000 series alloys, there is a distinct eutectic cessation point, this being the temperature at which solidification is completed. For this reason, the lower limit temperature of BTR coincides with the eutectic temperature. For the other alloys as typified by A5083, however, there is no eutectic cessation point. For these alloys, the nominal solidus temperature T_S therefore



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

serves to mark the inflection on the cooling curves indicating where most of the liquid phase has solidified. Because of the fast cooling rate during weld solidification, non-equilibrium solidification generally takes place, with molten liquid being retained down to temperatures lower than T_S corresponding to the solidus during equilibrium solidification.[27] The BTR of alloys other than 2000 series alloys is accordingly extended to temperatures lower than T_S. For 5000 series alloys, because little eutectic is present, it is not possible to determine any eutectic cessation point as the final solidification point corresponding to the lower limit temperature of BTR by the thermal analysis method described above. The differences in BTR and ΔT between 2000 series alloys and others are also reflected in the crack fracture surface morphology.[28]

For ferrous materials and stainless steels, the essential solidification temperature range is relatively narrow, and the low melting point eutectics of impurities – mainly elements such as phosphorus, sulphur, etc – increase the BTR, so that, if the contents of these impurities are reduced, BTR is narrowed, and the solidification cracking susceptibility can be reduced.[29] In Al alloys, however, the principal alloying elements, such as e.g. Cu in Al-Cu alloys, undergo a eutectic reaction with Al to give a virtually fixed BTR value for the respective Al alloys. This means that it is difficult to improve the solidification cracking susceptibility of each individual alloy from the BTR perspective, i.e. to narrow BTR. For actual welds, it is further considered possible to narrow BTR through adjustment of the weld metal composition using appropriate fillers, though it is virtually impossible in practice to narrow the BTR of e.g. A7N01 to the same level as A1070 or A3003. Improvement of the solidification cracking susceptibility of Al alloys is therefore confined to methods intended to improve the ductility within BTR, i.e. to those based on increasing ε_{min} or ε_c.

Metallurgical factors affecting ductility characteristics

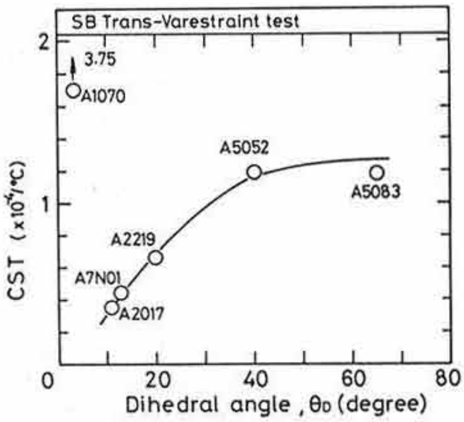
A number of metallurgical factors should be noted as affecting the ductility of Al alloys in the solid/liquid temperature range. With regard to the fact that solidification cracks are initiated by the presence of molten liquid at the grain boundaries, there are basically considered to be two important factors at work here: the morphology of the molten liquid retained at the grain boundaries and its quantity.[30] This section describes an investigation of the relationship between these two factors and CST specified above as an index typifying the ductility characteristics.

The morphology of the molten liquid retained at the grain boundaries is generally represented by the dihedral angle θ_D. In the present investigation, the θ_D values of the eutectic products present at the grain boundaries of weld beads after the solidification cracking tests were measured. The amounts of the eutectic products were also simultaneously measured.

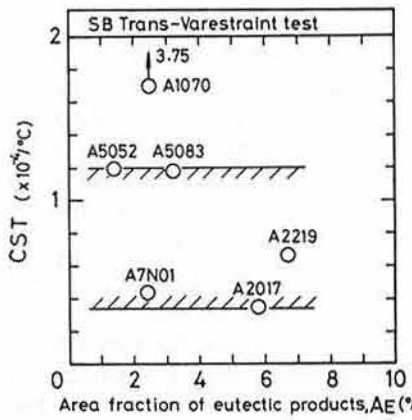
Figure 10 shows an arrangement of the observed θ values of the dihedral angle in the form of cumulative curves. The dihedral angle θ_D is given by θ when the cumulative percentage = 50%. For A5052 and A5083, θ_D has values of 40° and 65° respectively, with θ also being distributed over a wide range of 5–160°. Many values greater than 60° are also found. For the other alloys, however, the θ_D values of A1070, A2017, A2219, and A7N01 are 2°, 11°, 20°, and 13° respectively. In each case, there are also smaller values of θ of less than 60°.

Figure 11 shows the relationship between θ_D and CST. CST and θ_D are well correlated except for A1070. CST increases with an increasing θ_D. It also basically increases linearly up to θ_D = approx. 40°, thereafter tending to become saturated. A1070, despite having a minimum θ_D value of 2°, conversely has an extremely high CST value. This is considered to imply that, when BTR is as narrow as only 20 °C, as in the case of A1070, CST shows a high value regardless of θ_D. Figure 12 subsequently shows the relationship between CST and the fraction of eutectic products, though both factors are not well correlated.

The foregoing results suggest that, except for alloys having an extremely narrow BTR, such as A1070, the ductility of the alloys in the solid/liquid temperature range strongly depends on θ_D, i.e. the morphology of the molten liquid retained at the grain boundaries. The ductility is then found to improve with an increasing θ_D.



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



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

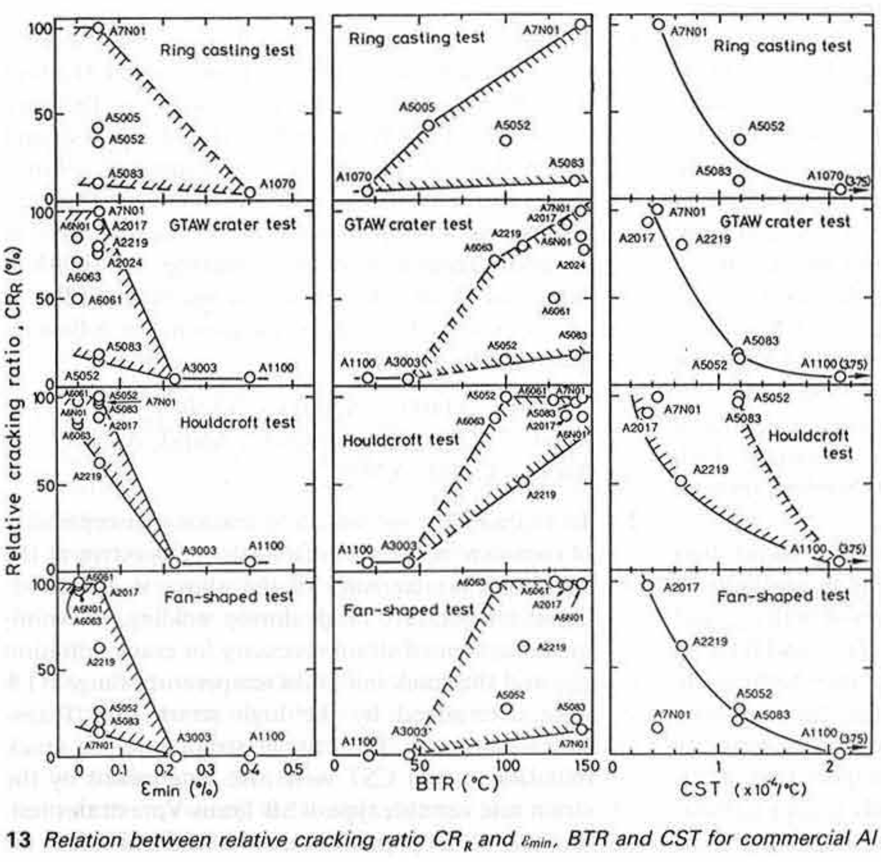
Relationship between self-restraint cracking test results and ductility characteristics of alloys in solid/liquid temperature range

An effort was here made to examine the correlation between the results obtained during the qualitative evaluation of the solidification cracking susceptibility of commercial Al alloys, with ε_{min}, BTR, and CST as indices expressing the ductility characteristics in the solid/liquid temperature range during welding, and θ_D and GS_M as metallurgical factors affecting the ductility characteristics. The factors affecting the solidification cracking susceptibility are discussed below.

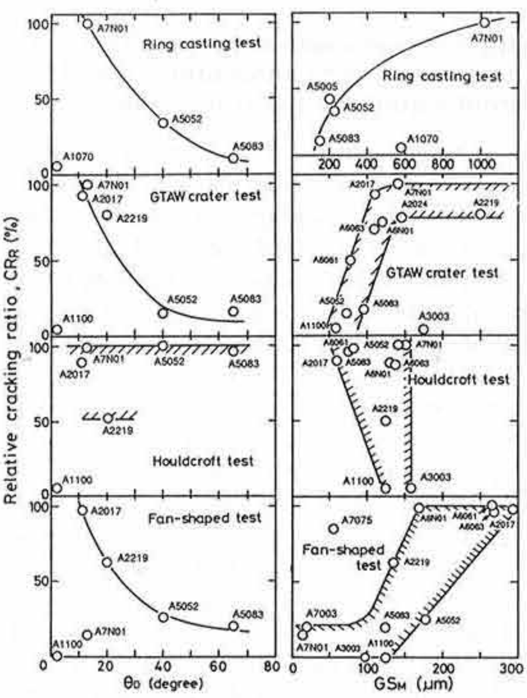
Figure 13 shows the relationship between the CR_R of each cracking test method and ε_{min}, BTR, and CST.

Based on an ε_{min} threshold value of around 0.2%, CR_R has an extremely small value by any cracking test method at an ε_{min} value above the latter. At smaller values, CR_R on the whole increases, though the fluctuation range of its values is extremely large, and both factors are not well correlated. Next, when BTR is narrower than around 43 °C, CR_R shows an extremely small value. Beyond this level, CR_R also on the whole increases, though the fluctuation range of its values is extremely large, and both factors are not well correlated. CST and CR_R, however, are well correlated except in the Houldcroft test. CR_R tends to decrease monotonically with an increasing CST. When tested in the fan-shaped test, A7N01 shows a trend different from that of the other alloys, this being due, as previously noted, to the fact that GS_M is extremely small.

Figure 14 next shows the relationship between θ_D, GS_M, and CR_R as metallurgical factors. θ_D and CR_R are well correlated by any test method except the Houldcroft



13 *Relation between relative cracking ratio CR_R and ε_{min}, BTR and CST for commercial Al alloys.*



14 *Relation between relative cracking ratio CR_R and θ_D and GS_M for commercial Al alloys.*

test, CR_R monotonically decreasing with an increasing θ_D. The 1000 series alloys show a trend different from that of the other alloys because the values of BTR and ε_{min} discussed above satisfy the condition of the solidification cracking susceptibility being extremely low. It is also due to the fact that A7N01 when tested in the fan-shaped test has a much smaller GS_M value than the other alloys. GS_M and CR_R are only weakly correlated except in the Houldcroft test, CR_R also tending to increase with an increasing GS_M. This is attributable to the fact that, under the effect of grain boundary refinement, the strain at the grain boundaries is dissipated, so that the amount of solidification acting on individual grains is reduced. However, it is well-known that, when a crack propagates along the weld bead centre, the bulk of the strain acting on the weld bead becomes concentrated at the crack tip.[31] When such heavy strain concentration is envisaged, as in the Houldcroft test, it appears necessary to have much more rigorous grain refinement than at the grain boundaries to ensure that effective strain dissipation takes place. Unlike the other alloys, 1000 series alloys and A3003 here have a low CR_R despite having a large GS_M. This also occurs for much the same reason as for θ_D described above. A7075 is known to have an extremely high solidification cracking susceptibility. It therefore shows a large CR_R despite having a small GS_M.

The foregoing results suggest that the factor best correlated with the solidification cracking susceptibility is CST, considered as inheriting the features of both ε_{min} and BTR factors. With regard to the effects of ε_{min} and BTR on the solidification cracking susceptibility, they both clearly have significance at the point indicating the threshold value where the solidification cracking susceptibility sharply increases. This fact, however, implies that, if this threshold value is exceeded, there is only a poor correlation with the solidification cracking susceptibility. Like CST, θ_D as a metallurgical factor is well correlated with the solidification cracking susceptibility. This is evident from the good correlation being found between both factors as described above. GS_M is correlated, albeit weakly and, when having an extremely low value, exerts an especially strong effect on the solidification cracking susceptibility.

Conclusions

To gain a qualitative and quantitative understanding of the solidification cracking susceptibility of Al alloy welds, this paper describes an evaluation of Al alloys by different solidification cracking test methods. Various commercial Al alloys in the 1000–7000 series range were mutually compared. A qualitative comparison was made using the indices of the crack length, crack number, and cracking ratio determined in self-restraint cracking tests. The quantitative comparison was made using the indices of the critical amount of solidification for crack initiation, the critical strain rate, and the crack initiation temperature range determined in externally augmented strain cracking tests. On the basis of the results obtained during evaluation of the solidification cracking susceptibility by these cracking test methods, the weld solidification cracking susceptibility of commercial Al alloys is discussed from an overall perspective with reference to macro/microstructural observations of welds, fracture surface observations, the results obtained during solidification temperature measurements by thermal analysis, etc. The present research effort represents a fundamental evaluation of the weld solidification cracking susceptibility of commercial Al alloys with filler-free base metal chemistries. The results obtained may be summarised as follows:

1 The results obtained during evaluation of the solidification cracking susceptibility of commercial Al alloys by self-restraint cracking tests, such as the ring casting test, GTAW crater test, Houldcroft test, and fan-shaped test, suggest that, with some exceptions, there is some degree of solidification cracking susceptibility relationship that the alloys broadly have in common regardless of the cracking test method employed. That is to say, within the range of the Al alloys examined in this investigation, the following qualitatively applies:

   (A1070, A1100, A3003) ≪ {(A5083, A5052) < A5005)} < {(A2219) < (A2017, A6063, A6N01, A6061, A7N01, A7075)}

2 To evaluate the solidification cracking susceptibility of commercial Al alloys from the perspective of the ductility characteristics of the alloys in the solid/liquid temperature range during welding, the minimum augmented strain necessary for crack initiation ε_{min} and the crack initiation temperature range BTR were determined by the high strain rate Trans-Varestraint test. The critical strain rate for crack initiation ε_c and CST were also determined by the strain rate variable type of SB Trans-Varestraint test. Table 2 in this paper lists these numerical values for

commercial Al alloys.

3 Commercial Al alloys can be broadly classified into three groups depending on the magnitude of ε_{min}. The high-ε_{min} group covers A1070 and A3003, with ε_{min} having values as high as around 0.4% and around 0.22% respectively. Next come the 2000 series, 5000 series, and A7N01 with around 0.05%. All 6000 series alloys have 0%. The ε_{min} differences between the alloys are ambiguous except for A1070 and A3003.

4 The BTR values of commercial Al alloys show distinct differences depending on alloy. The BTR values of A1070 and A3003 are as low as only 20 °C and 43 °C respectively. Those of the other alloys, however, are much higher, ranging between around 90–145 °C.

5 A virtually positive proportional relationship is established between BTR and the solidification temperature range ΔT (temperature difference beteween the liquidus temperature T_L and the nominal solidus temperature T_S or the eutectic temperature T_E) determined by a thermal analysis, being expressed by the following equation. That is to say, for 2000 series alloys for which the eutectic temperature can be accurately measured:

$$BTR = 1.0\ \Delta T, \text{ (correlation coefficient } r = 0.99)$$

For the other alloys:

$$BTR = 2.1\ \Delta T, \text{ (correlation coefficient } r = 0.97)$$

6 For A5083 and A5052, the critical strain rate for crack initiation in the solid/liquid temperature range determined by the strain rate variable type of SB Trans-Varestraint test sharply increases with a decreasing strain rate. For 2000 series alloys, the degree of increase is small, and A1070 shows very little increase at all.

7 The basic relationship of the critical strain rate for crack initiation CST of commercial Al alloys as determined from the susceptibility characteristics obtained by the SB Trans-Varestraint test is as follows within the range of Al alloys examined in this investigation:

A1070 ≪ (A5083, A5154, A5052) ≪ A2219 > (A2017, A7N01)

8 When the dihedral angle θ_D of the eutectic products at the grain boundaries of weld metal was measured as a metallurgical factor affecting the solidification cracking susceptibility, typical Al alloys such as A1070, A2017, A2219, A5052, A5083, and A7N01 were found to have θ_D values of 2°, 11°, 20°, 40°, 65°, and 13° respectively. θ_D and CST are also well correlated, except for A1070 which has an extremely narrow BTR, CST monotonically increasing with an increasing θ_D.

9 An effort was made to examine the correlation between the results obtained during the qualitative evaluation of the solidification cracking susceptibility of commercial Al alloys, ε_{min}, BTR, and CST as indices expressing the ductility characteristics in the solid/liquid coexistence temperature range during welding, and θ_D and GS_M as metallurgical factors affecting the ductility characteristics. The results obtained here may be summarised as follows:

a) The factor best correlated with the solidification cracking susceptibility is CST. Except for 1000 series alloys, the solidification cracking susceptibility tends to decrease monotonically with an increasing CST irrespective of alloy type.

b) ε_{min} and BTR both clearly have significance at the point indicating the threshold value where the solidification cracking susceptibility sharply increases. The solidification cracking susceptibility shows an extremely low value when ε_{min} is more than around 0.22% and BTR is less than around 43 °C.

c) If this threshold value is exceeded, however, there is only a poor correlation between these factors and the solidification cracking susceptibility.

d) Like CST, θ_D as a metallurgical factor is well correlated with the solidification cracking susceptibility, which monotonically decreases with an increasing θ_D.

e) GS_M is correlated, albeit weakly, with the solidification cracking susceptibility, which also tends to increase with an increasing GS_M.

10 When tested by the fan-shaped test, A7N01 – despite its ε_{min}, BTR, and CST solidification cracking susceptibility indices each implying an extremely high solidification cracking susceptibility – in fact shows an extremely low solidification cracking susceptibility of the same order as that of A5083. This suggests that, because of the extremely fine equiaxed structure giving a GS_M value as low as 14 μm, its solidification cracking susceptibility can be improved to the same level as that of A5083.

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