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Citation	Transactions of JWRI. 1976, 5(2), p. 153-167
Version Type	VoR
URL	https://doi.org/10.18910/3609
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Solidification Crack Susceptibility of Aluminum Alloy Weld Metals (Report I)†

—Characteristics of Ductility Curves during Solidification by Means of the Trans-Varestraint Test—

Yoshiaki ARATA*, Fukuhisa MATSUDA*, Kazuhiro NAKATA** and Ichiro SASAKI***

Abstract

For the purpose of quantitative investigation of solidification crack susceptibility for aluminum alloys, the properties of the ductility curve in solidification range, such as the brittleness temperature range (BTR), the minimum value of ductility within BTR (E_{min}), and the shape of the ductility curve against temperature drop were investigated by Trans-Varestraint test for Al-Mg and Al-Cu binary alloys contained a small amount of Fe and commercially used aluminum alloys of 1xxx, 2xxx and 5xxx types.

The main conclusions obtained are as follows:

(1) *The BTR is gradually increased with an increase of alloying elements, and then is satulated to the temperature difference between liquidus and ternary eutectic temperature irrespective of an increase of alloying elements when the ternary eutectic of Al-Mg-Fe or Al-Cu-Fe system begin to form.*

(2) *The Emin is very low for almost all alloys used with the exception of commercially pure aluminum. There are below zero augmented strain for Al-0.8% Cu and −2% Cu binary alloys and within the range from zero to 0.1% for the other alloys, while within the range from 0.1 to 0.3% for commercially pure aluminum.*

(3) *The minimum in the ductility curve in the BTR is generally observed in the location just behind the liquidus temperature, and then the crack begins to start there during Trans-Varestraint test.*

(4) *The mode of the fractured surface of the solidification crack which is generated by Trans-Varestraint test is gradually changed with a decrease of temperature as a result of a scanning electron microscopic investigation and it could be classified into three types, that is, called type D, type D-F and type F in order of a degrease of temperature from the near liquidus temperature to the temperature of lower limit of the BTR.*

1. Introduction

A great deal of researches have been carried out on solidification cracking of aluminum and its alloys[1]. As a result, the effect of composition in material on solidification crack susceptibility has been cleared qualitatively.

In general, for the fusion welding of most alloys, there is a low ductility temperature range during solidification at the behind the weld puddle. It is considered that the solidification cracking occurs in this low ductility range, when thermal and external strains exceed the minimum ductility value for cracking of weld metal during solidification.

Concequently, authors believe that, in order to investigate the solidification crack susceptibility, it is important to clear the properties in this low ductility range, such as the brittleness temperature range, the minimum value of ductility within it and the shape of ductility curve against temperature drop.

However there is few investigation about the properties of low ductility range on aluminum and its alloys[2),3),4)]. Therefore it has been not cleared so far how the kind and the amount of the alloying elements effect on the properties of this low ductility range.

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The reason in the above is considered that there is few quantitative testing method to investigate the properties of the solidification ductility curve during actual welding, so far.

However, in order to investigate the properties of solidification brittleness temperature range, the authors think that the Trans-Varestrain test[5] would appear to be the most successful method at the present.

Concequently, the authors adopt, in this study, the Trans-Varestraint test as the evaluation method of solidification crack susceptibility of aluminum and its alloys.

By using the Trans-Varestraint test, the effect of amount of alloying elements on the properties of the ductility curve in solidification brittleness temperature range was investigated on Aluminum-Magnesium (Al-Mg) and Aluminum-Copper (Al-Cu) binary alloys, which are the fundamental systems of commercially used aluminum alloys. Moreover, the properties of ductility curves of Al-Mg and Al-Cu binary alloys were compared with those of the various commercially used aluminum alloys.

Meanwhile, it is few, so far, the investigations on fractography of the surface of the solidification crack[6], especially on aluminum and its alloys. However it is very important to investigate them from the viewpoints of not only the morphology of the fracture surface of solidification crack but also the segregations of element and eutectic products. The solidification cracking dosely related to the kind and the amount of the liquid phase remaining during solidification. Fortunately the solidification crack which is opened by a large strain in the Trans-Varestraint test during welding has a fractured surface for a wide temperature range along the weld bead from near liquidus temperature to low temperature. Therefore it is much easy to investigate the correlation between the fracture mode of the crack surface and the temperature.

So that, on the fractured surface of solidification crack occurred by the Trans-Varestraint test, the morphology and the chemical compositions were investigated by means of a scanning electron microscope with a X-ray spectrometer.

2. Materials Used and Experimental Procedures

2-1 Materials used

The materials used are Al-Mg and Al-Cu binary alloys and commercially used aluminum alloys. Chemical compositions of materials used are shown in Table 1 and 2.

The Al-Mg and Al-Cu binary alloys, Mg or Cu content of which was varied from about 0.5 to 5%, respectively, were made experimentally. Contents of impurities were degreased as much as possible, but only Fe element was contained about 0.2% which is a ordinary value in commercially used aluminum alloys. In Al-Mg binary alloys, the alloy whose Mg content is about 10% is the commercially used aluminum alloy for casting purpose. After the melting and casting, the Al-Mg and Al-Cu binary alloys were rolled to 6mm in thickness and then heat treatment was performed at 350°C for 3 hours for the normalizing.

Next, among of commercially used aluminum alloys, 1070 is the commercially used pure aluminum alloy, and 5005, 5052, 5154 and 5083 are the Al-Mg system alloys and 2017, 2024 and 2219 are the Al-Cu system alloys.

All of the materials were used under annealed condition.

2-2 Experimental procedure

2-2-1 Methods of cracking test and evaluation of test results

For the solidification cracking test, the Trans-Varestraint test was used. In regard to the principle and the detail of

Table 1 Chemical compositions of Al-Mg and Al-Cu binary alloys used.

Material	Designation	Chemical composition (wt%)								
		Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	B
Pure Al	1	<0.01	0.06	0.15	<0.01	<0.01	<0.01	<0.01	<0.01	–
Al-Mg binary alloys	2	<0.01	0.06	0.15	<0.01	0.51	<0.01	<0.01	<0.01	–
	3	<0.01	0.06	0.15	<0.01	0.99	<0.01	<0.01	<0.01	–
	4	<0.01	0.06	0.15	0.01	1.72	<0.01	<0.01	<0.01	–
	5	<0.01	0.06	0.15	0.02	3.03	<0.01	<0.01	<0.01	–
	6	<0.01	0.06	0.14	0.01	4.88	<0.01	<0.01	<0.01	–
	7	<0.01	0.06	0.07	<0.01	9.72	<0.01	<0.01	0.09	0.004
Al-Cu binary alloys	A	0.45	0.06	0.13	<0.01	<0.01	0.01	<0.01	<0.01	–
	B	0.84	0.06	0.15	<0.01	<0.01	0.01	<0.01	<0.01	–
	C	2.05	0.06	0.18	0.01	0.02	0.01	<0.01	<0.01	–
	D	3.00	0.07	0.19	0.01	0.02	0.01	<0.01	<0.01	–
	E	4.96	0.07	0.22	0.01	0.04	0.03	<0.01	<0.01	–

Table 2 Chemical compositions of commercially used aluminum alloys used.

Material	Chemical composition (wt%)								
	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Zr
1070-0	0.02	0.10	0.33	<0.01	<0.01	<0.01	<0.01	0.04	–
5005-0	0.04	0.10	0.53	<0.01	0.86	<0.01	<0.01	0.02	–
5052-0	0.01	0.09	0.29	0.01	2.60	0.01	0.20	–	–
5154-0	0.02	0.11	0.25	0.06	3.50	<0.01	0.23	0.03	–
5083-0	0.06	0.13	0.21	0.50	4.00	0.02	0.20	0.03	–
2017-0	4.09	0.27	0.27	0.48	0.48	0.02	0.01	0.01	–
2024-0	4.54	0.13	0.29	0.62	1.50	<0.01	<0.01	0.04	–
2219-0	6.32	0.08	0.11	0.33	<0.01	0.04	<0.01	0.04	0.14

practical use of the Trans-Varestraint test, one of the authors has reported previously[5].

The testing specimen is a square plate of 100 mm in width and 6 mm in thickness. Each specimen was fixed on the bending block by two bolts in distance of 80 mm.

The augmented strain applying on the specimen surface was measured by a strain gage sticked on specimen surface and a strain meter. Then, the measured values of augmented strain were adopted as the augmented strain on actual cracking test.

A conventional TIG arc melt run weld (AC) was done with welding current: 230A (180A for only alloy 7), arc voltage: 18V and welding speed: 100 mm/min.

In actual welding of cracking test, welding traverse was started after enough size of the molten pool was made so that the weld bead width was being kept a constant about 10mm.

In this study, the two criteria are used to evaluate the test results. One is the minimum augmented strain required to cause cracking, E_{min} and the other is the maximum crack length, L_{max}, which is the length of the longest crack generally formed at the weld center as shown in Fig. 1 and which shows the size of the brittleness temperature range, BTR.

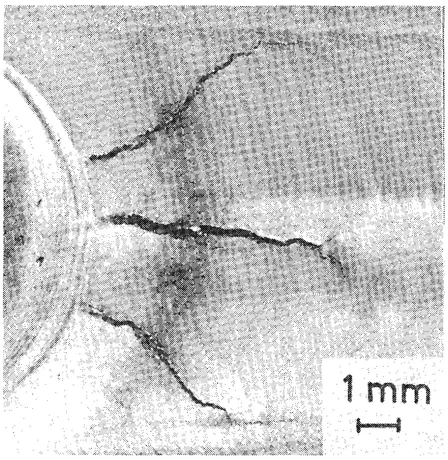


Fig. 1 General appearance of solidification crack by the Trans-Varestraint testing.

The brittleness temperature range is decided by a combination of the maximum crack length and the temperature distribution along the axis of weld bead center, which was measured with a 0.5 mm dia. W + 6% Re/W + 26% Re termocouples.

2-2-2 The thermal analysis of alloys

The liquidus temperature (T_L) and the bulk solidus temperature (T_S) of the alloys used were measured by a thermal analysis in order to determine the melting properties of the alloys which relate to the brittleness temperature range.

Each sample was melted in an electric furnace of argon atmoshphere, and the cooling curve was measured with a chromel/Alumel themocouples (0.5 mm diam.) and a self-balancing pen-writing recorder.

2-2-3 Method of the fractography of the solidification crack

The scanning electron microscope was used for the fractography of the solidification crack of commercially used aluminum alloys.

As the same time, the compositions of the segregated produsts existing on the fractured surface were analyzed with a X-ray dispersive spectrometer.

2-2-4 Measurement of the amount of eutectic products

For Al-Mg and Al-Cu binary alloys, the amount of the eutectic products formed in weld metal was measured with the point counting method[7], which is performed by an optical microscope with an eyepiece with 400 points of intersection mesh. The magnification for the observation is x1000 and the number of the observation area is 100.

For the point counting method, the area fraction of the eutectic products is designated as follows:

$$A = \frac{\Sigma N}{N_O \times f} \times 100\ (\%) \quad (1)$$

where, A is a area fraction of eutectic products (%), N_O is the number of points of the intersection in observed area (in this study, N_O is 400), N is the total number of points of the intersections located on the eutectic products and f is the number of observed area (in this study, f is 100).

3. Result and Discussion

3-1 The minimum augmented strain, E_{min} and the maximum crack length, L_{max}

The effects of the augmented strain on the maximum crack length are shown in Fig. 2(a) and (b) for Al-Mg and Al-Cu binary alloys, respectively, and in Fig. 3(a) and (b) for commercially used aluminum alloys.

The cracks occurred at 0.3% but did not occur at 0.1% of augmented strain for alloy 1 (pure aluminum) and 1070 (commercially pure aluminum). So that, the E_{min} required to cause cracking is within the range from 0.1% to 0.3%. For the other alloys, the cracks occurred at 0.1%, then the E_{min} for these alloys is less than 0.1% augmented strain.

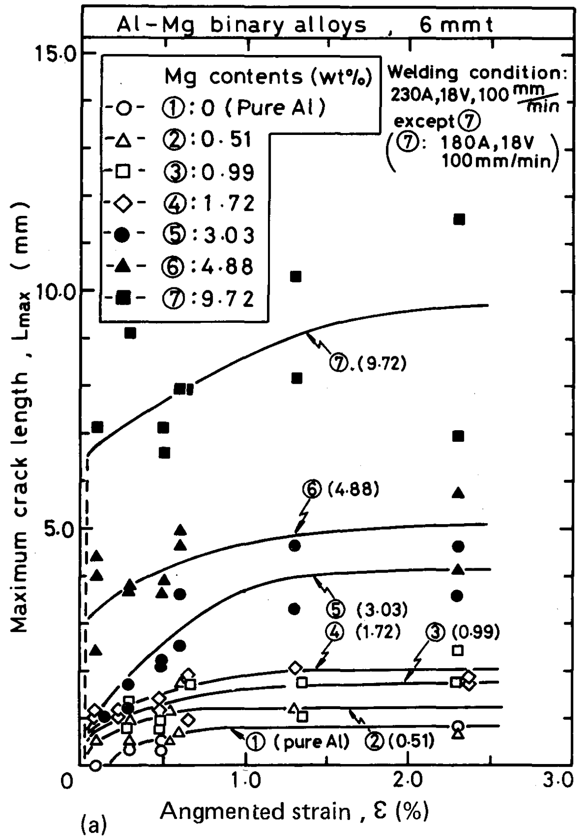
Each curve in Fig. 2(a) for Al-Mg binary alloys is increased to the satulated value with an increase of the augmented strain. Moreover, the satulated value of the L_{max} is increased with an increase of Mg contents though the data showed a considerable scattering. This tendency is similar for the commercially used Al-Mg system alloys in Fig. 3(a).

On the other hand, in Al-Cu alloys, the variation in the L_{max} was very small with augmented strain as shown in Fig. 2(b) and Fig. 3(b). That is to say, more than 0.2% to 0.5% augmented strain the L_{max} shows the satulated value for each alloy. Moreover, from Fig. 2 (b), the satulated value of the L_{max} increased as Cu content was increased to about 2%, but increasing the Cu content over than about 2%, the L_{max} was almost satulated to a constant value from 3.5 to 4.5 mm in length.

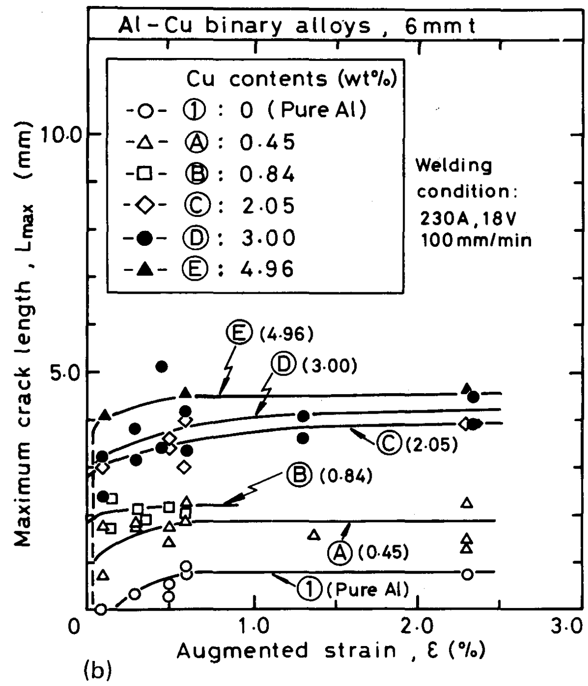
Meanshile, for commercially used Al-Cu system alloys as shown in Fig. 3(b), the tendency of the satulated value of the L_{max} was largely different. The reason in the above is discussed in the later 3.3.

The appearances of cracking in the weld bead are shown in Fig. 4, 5 and 6 for Al-Mg, Al-Cu binary alloys and commercially used aluminum alloys, respectively.

Among those alloys, in alloys B and C containing about 0.8% and 2.0% Cu, respectively, solidification cracks often occurred in the bead without external strain. It means that these alloys are much susceptible to crack in comparison with the other alloys, and show cracking in the weld bead caused by the thermal strain only. For

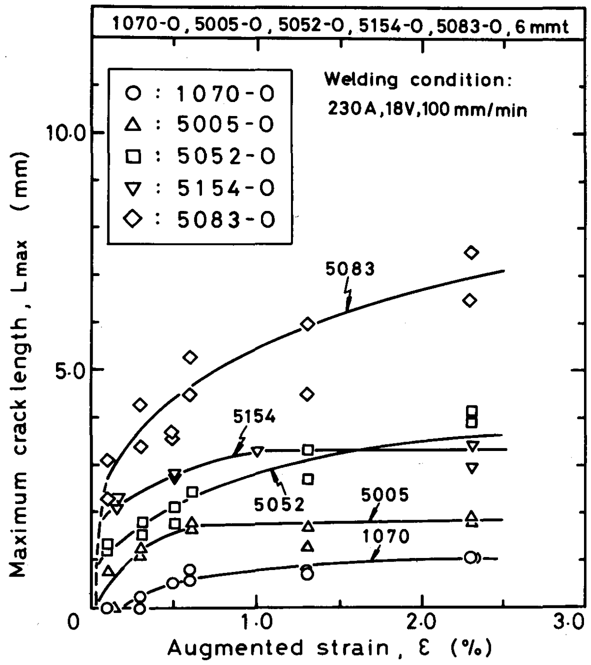


(a)

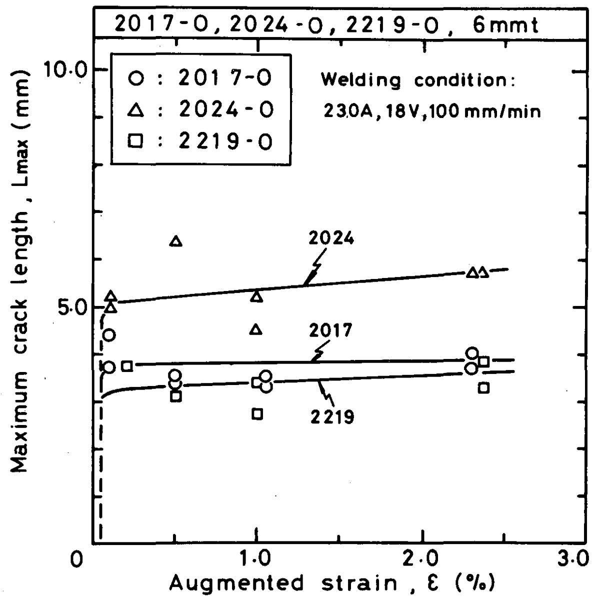


(b)

Fig. 2 Maximum crack length vs. percent augmented strain for weld metals of Al-Mg and Al-Cu binary alloys.



(a) Al-Mg system alloys



(b) Al-Cu system alloys

Fig. 3 Maximum crack length vs. percent augmented strain for weld metals of commercially used aluminum alloys.

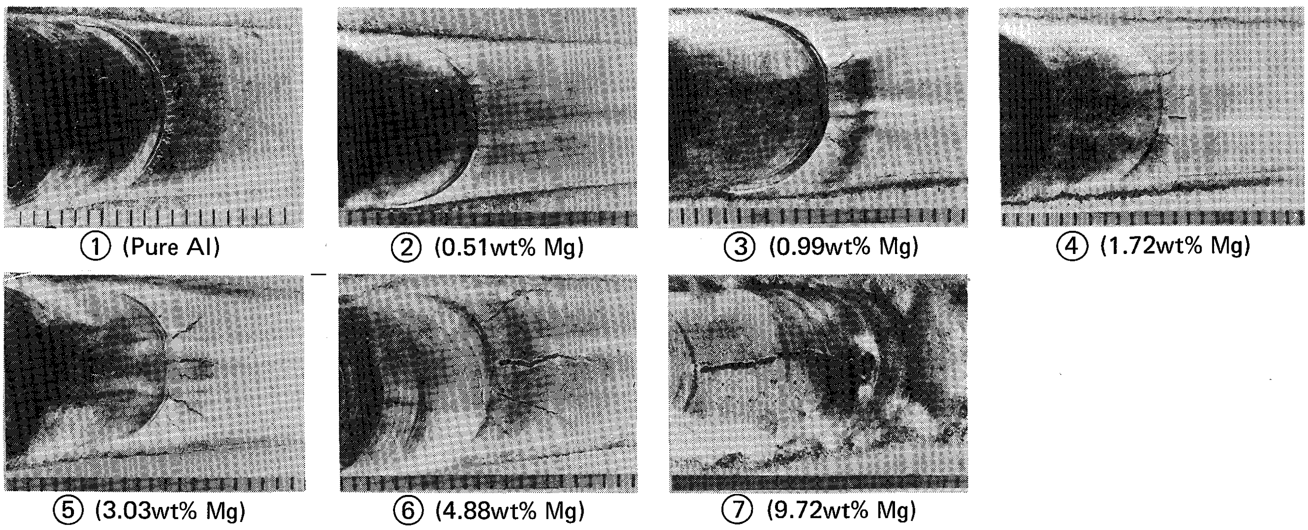


Fig. 4 Appearance of solidification crack on Trans-Varestraint tested specimen for Al-Mg binary alloys.

these alloys, the Lmax was decided with the same way as the other alloys, that is, when the strain was applied during welding, the cracks occurred not only just behind weld puddle in the instance of straining but also in the lower temperature zone of the weld bead. Then the former crack was adopted to the decision of the Lmax.

3-2 Fractography of solidification cracks

On the Trans-Varestraint test, a solidification crack occurs instantaneously over the whole range of the brittleness temperature range, so that, it is possible to obtain the relation between the metallurgical mode of the fractured surface and the temperature, when the temperature during welding is measured along the weld metal.

Therefore, in this study the fractured surface of the solidification crack occurred by the Trans-Varestraint test was observed with a scanning electron microscope for commercially used aluminum alloys.

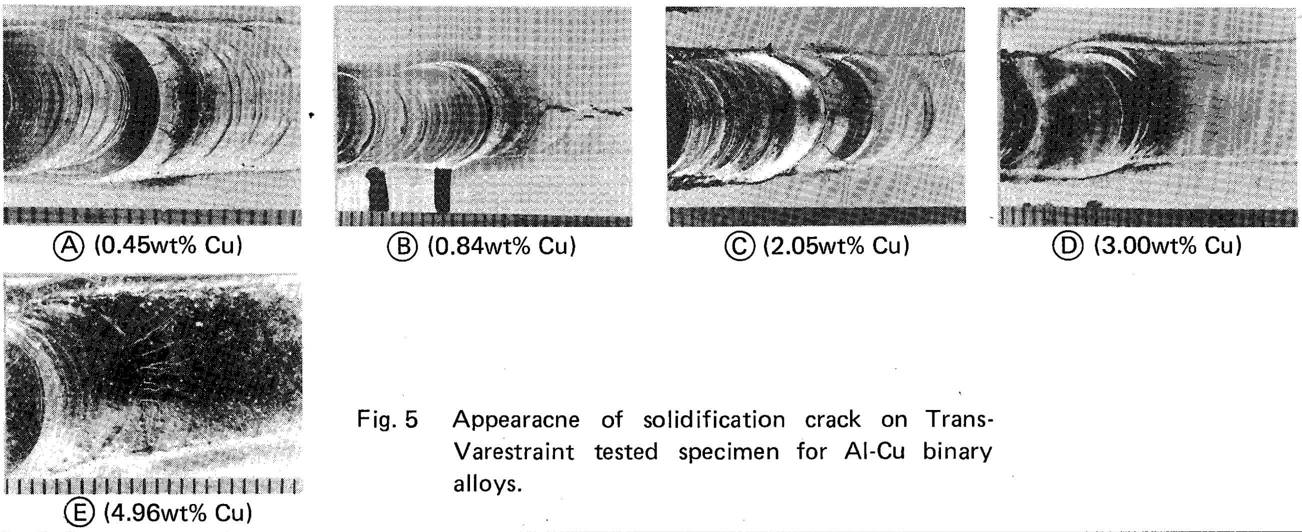


Fig. 5 Appearacne of solidification crack on Trans-Varestraint tested specimen for Al-Cu binary alloys.

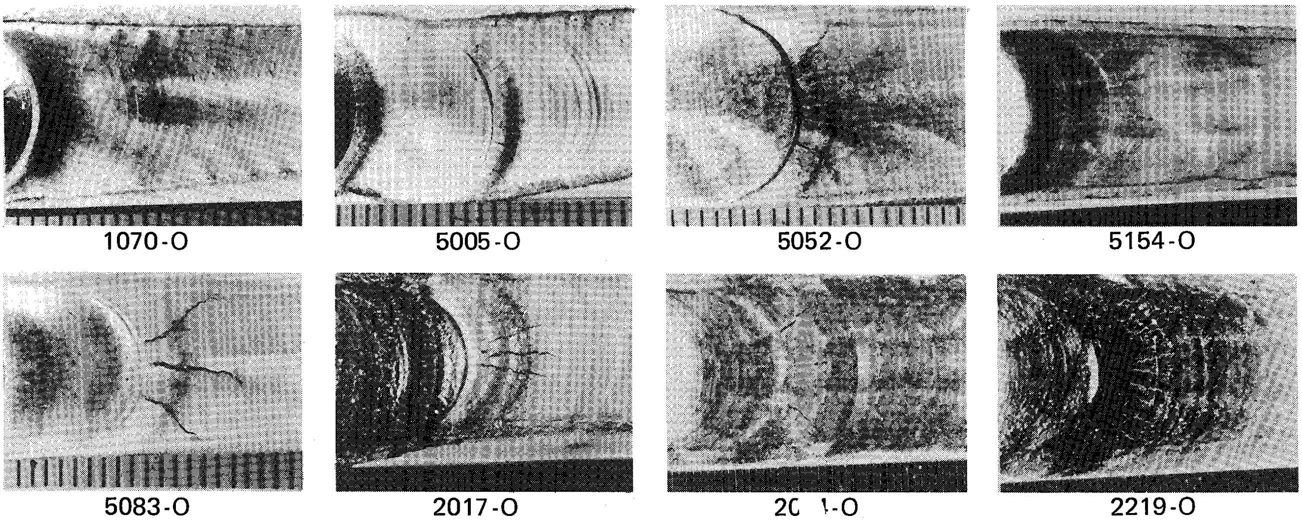


Fig. 6 Appearance of solidification crack on Trans-Varestraint tested specimen for commercially used aluminum alloys.

Fig. 7 shows a typical example of the appearance in the fractured surface in x300 mangification for 1070 commercially pure aluminum. The solidification cracking zone can be obviously distinguished from the non cracking zone by the difference in the mode of the surface, that is, the non cracking zone shows the dimple pattern.

In Fig. 7, the mode of the fractured surface is varied with the variation of the temperature which was higher in the left side. Moreove, the mode can be roughly classified into three types within the cracking zone. That is, in the higher temperature zone near the end of the molten puddle, the primary and the secondary arms of the dendrites, the mode of which was slmost globular, were obviously observed but in the lower temperature zone in the right side, the mode of the secondary arms of the dendrites became indefinite with a decrease of temperature. In the lowest temperature zone in the brittleness temperature range, the secondary arms of the dendrites could not be distinguished and the surface of the primary arms of the dendrites became to be considerably smooth.

In this study, the authors called those modes of the fractured surface as type D and type F for high and low temperature zone, in the brittleness temperature range, respectively, and moreover the intermediate mixed zone of type D and F as type D-F.

On the other alloys of 5052, 5083 and 2017, the same type D, F and D-F modes were seen in the fractured surface but a little difference for each alloys. Fig. 8 shows collectively the type of the mode of the fractured surface for each alloy. In type D, there is no obvious difference among the alloys. However the characteristics in each alloy were distinguished in type F and D-F. That is, in the type F and D-F, the surfaces of the primary arms of 5052 and 5083 were much rough than that of 1070. Moreover type F in 5083 was much flat than that in 5052.

Meanwhile, for 2017, the type D-F mode was conti-

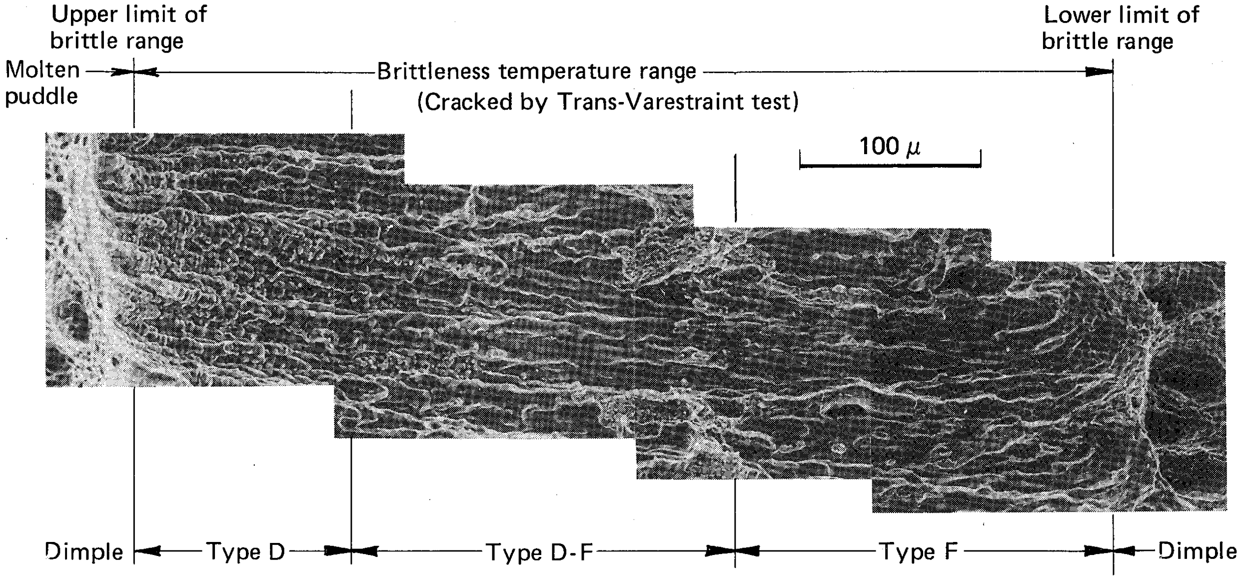


Fig. 7 Variation of mode of fractured surface of a solidification crack along weld center for 1070 commercially used aluminum alloy by Trans- Varestraint testing.

nued until the lowest temperature in the brittleness temperature range and the type F did not be distinguished.

Fig. 9 shows the relation between the mode of the fractured surface and the temperature of it for each alloy. Where, the location of observation for the fractured surface was selected at near the top surface of the weld metal in order to relate the temperature distribution along the weld metal surface. In Fig. 9, the temperature indicated by an arrow showed the bulk solidus temperature measured. The type D was observed only in the zone higher

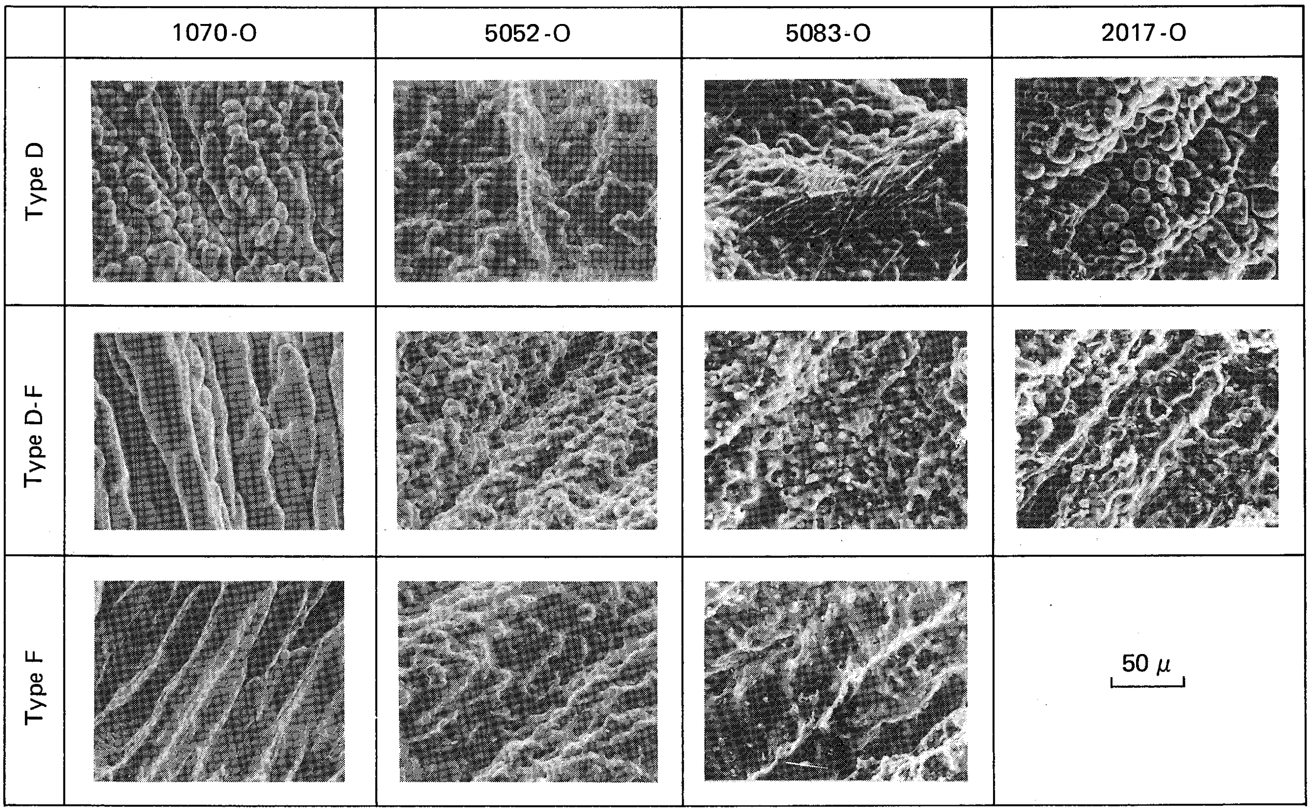


Fig. 8 Typical example for each type of the mode of fractured surface of solidification crack on Trans-Varestraint tested specimen for 1070, 5052, 5083 and 2017 aluminum alloys.

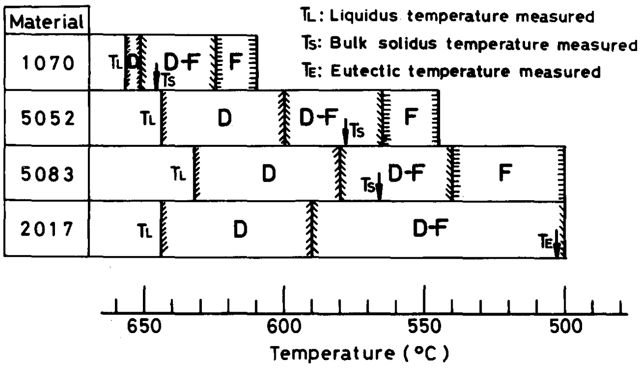


Fig. 9 Variation of mode of fractured surface of solidification crack occurred by Trans-Varestraint test against temperature.

temperature than the bulk solidus temperature measured. On the contrary, the type F was observed only in the zone lower temperature than the bulk solidus temperature measured. Therefore, there is no type F in 2017. Then the bulk solidus temperature measured was located in the type D-F zone, for all alloys.

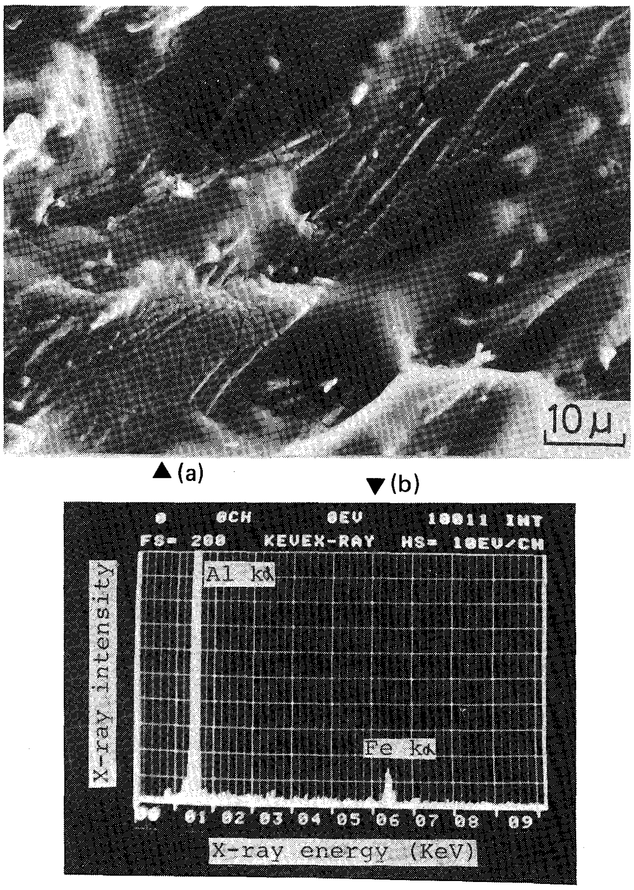


Fig. 10 Appearance of fractured surface, (a), and result of X-ray spectrometric analysis for eutectic products, (b), for type F mode in crack of 1070 weld metal.

Next, it is generally considered that the remaining small amount of liquid in the last stage of solidification is very important for solidification crack susceptibility of alloys[8]. So, the eutectic products formed in the fractured surface were analyzed by X-ray spectometer in the lower temperature zone of the crack. The results were shown in Fig. 10 through 13 for the alloys.

Fig. 10 (a) shows the fractured surface of type F for 1070, in higher magnification, x1500, whose surface was covered with film-like or plate-like eutectic products, and Fig. 10 (b) shows an example of the result of X-ray spectrometric analysis. These eutectic products were mainly composed of Al and Fe elements.

For 5052 shown in Fig. 11 (a), petal-like eutectic products were frequently observed and were composed of Al, Mg and Fe, and Al, Mg and Si elements as shown in Fig. 11 (b) and (c), respectively.

For 5083 as shown in Fig. 12 (a) a deal of small eutectic-particle which was composed of Al, Mg and Si, Al, Mg, Mn and Fe, and Al, Mg, Mn, Fe and Si elements as shown in Fig.12 (b), (c) and (d), respectively, was observed.

Fig.13 (a) shows the lowest temperature zone in the brittleness temperature range for 2017, that is, type D-F, as mentioned before the fractured surface was mostly covered with the mixture of the eutectic products, which were mainly composed of Al, Si, Fe, Mn and Cu, Al and Cu, and Al, Cu, Mg and Si elements as shown in Fig.13 (b), (c) and (d), respectively.

Moreover, for all alloys the eutectic products were usually observed even in the higher temperature zone near the liquidus temperature, that is, in type D, and those were composed of the same system of the elements as

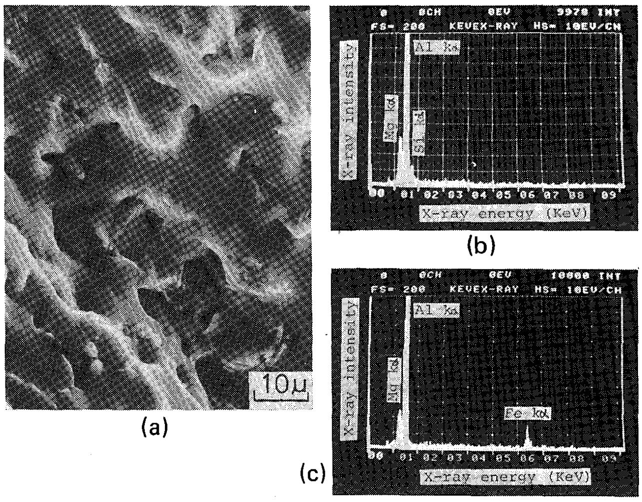


Fig. 11 Appearance of fractured surface, (a), and result of X-ray spectrometric analysis for eutectic products, (b) and (c), for type F mode in crack of 5052 weld metal.

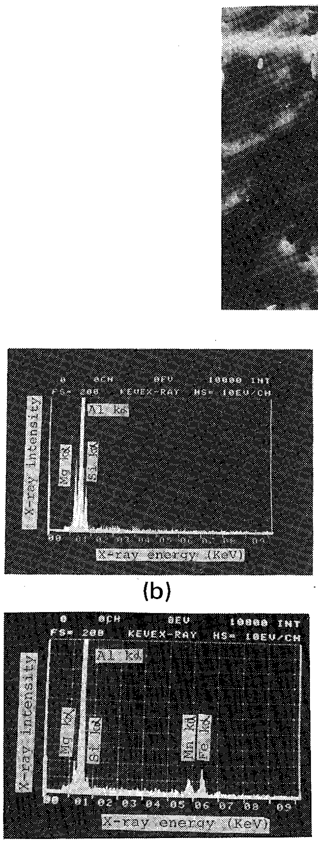


Fig. 12 Appearance of fractured surface, (a), and result of X-ray spectrometric analysis for eutectic products, (b), (c) and (d), for type F mode in crack of 5083 weld metal.

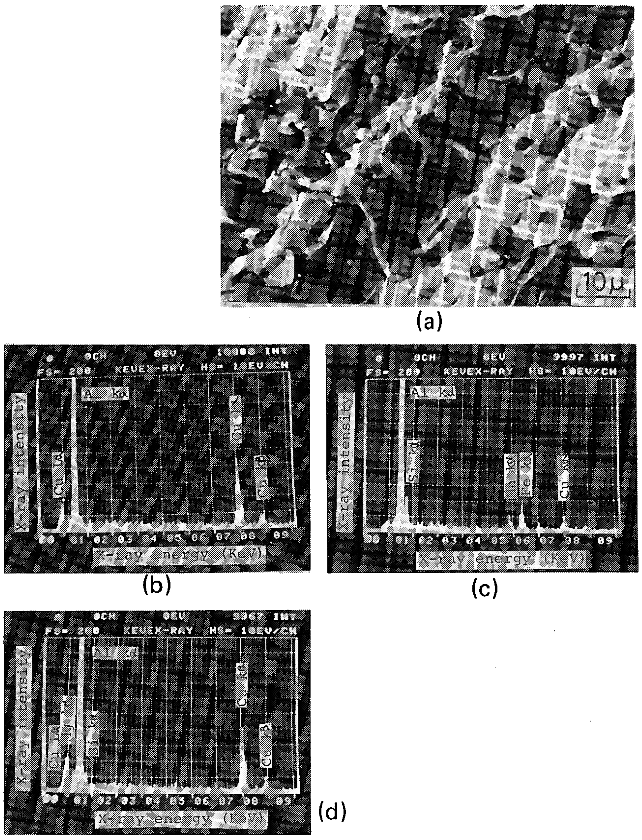


Fig. 13 Appearance of fractured surface, (a), and result of X-ray spectrometric analysis for eutectic products, (b), (c) and (d), for type F mode in crack of 2017 weld metal.

eutectic products in type F for 1070, 5052 and 5083 alloys and type D-F, for 2017 alloy.

3-3 Ductility curve in brittleness temperature range

In order to decide the brittleness tempeature range, the maximum crack length was changed to the temperature difference by using the temperature distribution curve along the center of weld bead. In this conversion, the temperature in the upper limit of brittleness temperature range was adopted the measured value in 2-2-2 as the liquidus temperature (T_L).

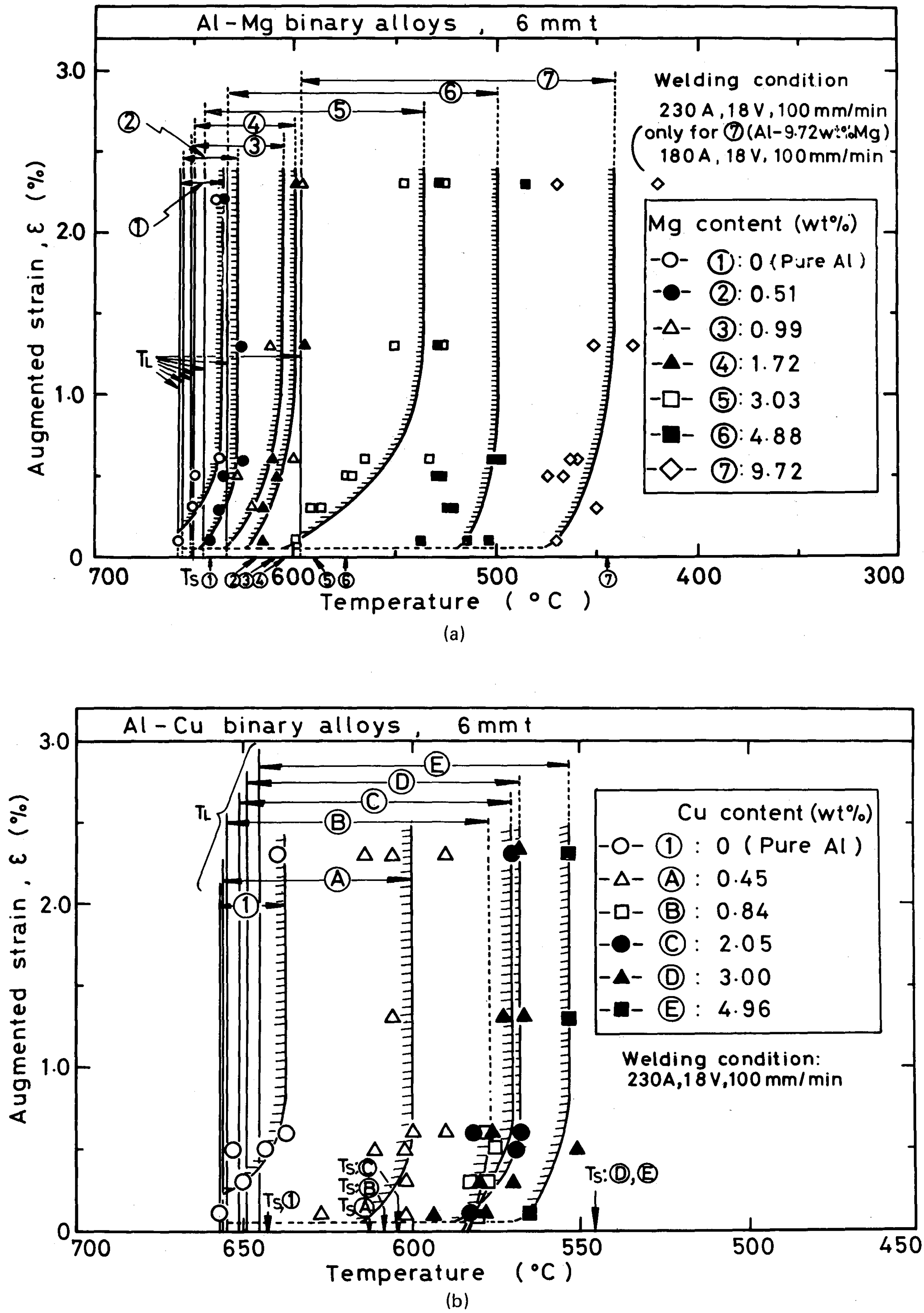
The ductility curves against temperature were shown in Fig.14(a) and (b), for Al-Mg an Al-Cu binary alloys. The ductility dip is shown in the oblique line in the figures. The brittleness temperature range was generally increased for all alloys so far as it satulated with the increase of augmented strain.

This satulated range is called the BTR which is shown as the range with an arrow for each alloy. The BTR is one of the most important index for solifification crack susceptibility.

The temperature in the lower limit of the BTR was lowered as the Mg and Cu contents were increased for Al-Mg and Al-Cu binary alloys, respectively. For Al-Mg binary alloys shown in Fig.14(a), the lower limit of the BTR was lowered little by little from that of alloy 1 (pure aluminum) with an increase of Mg content up to about 1.7% (alloy 4). However, when Mg content was exceeded about 3% (alloy 5), the lower limit was abruptly lowered a great deal. Then it reached about 450°C in alloy 7 (9.7% Mg). This value is almost identical with the eutectic temperature, 450°C for Al-Mg binary alloys[9] and 445°C for Al-Mg-Fe thernary alloys[10].

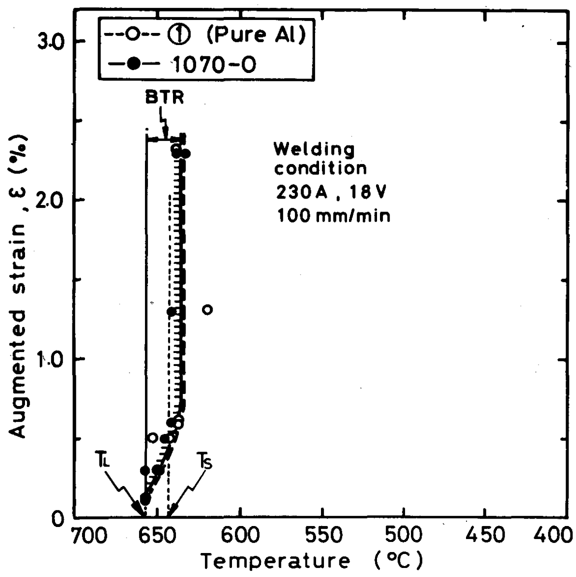
On the other hand, for Al-Cu binary alloys, the lower limit of the BTR in the alloy A whose Cu content is only about 0.5% was abruptly lowered a great deal from that in alloy 1 . Moreover, when Cu content was over about 0.8% (alloy B), the degree of decreasing the lower limit of the BTR became little and the lowest temperature of the BTR was within the temperature range from about 580°C to 550°C for about 5% Cu alloy. This value was identical with entectic temperature, 548°C for Al-Cu binary alloy[9] and 546°C for Al-Cu-Fe thernary alloy[11].

Next, the ductility curve of commercially used

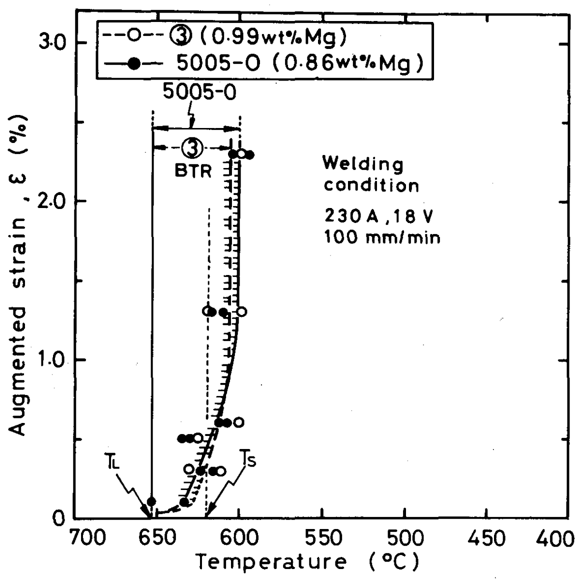


(b)

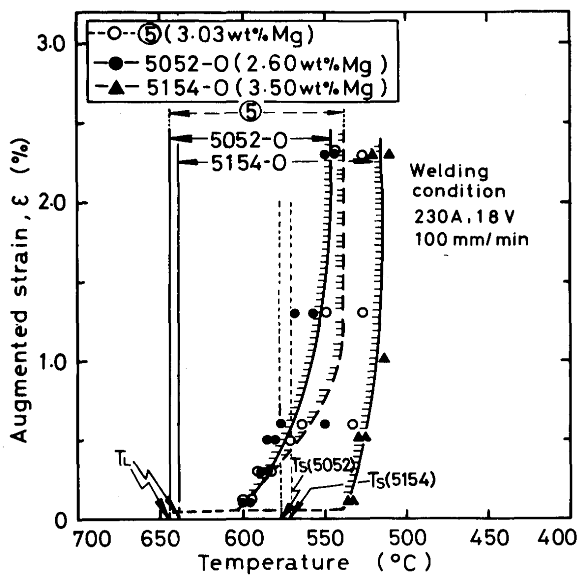
Fig. 14 Representation of properties of ductility curve in solidification brittleness temperature range for Al-Mg (a) and Al-Cu (b) binary alloys.



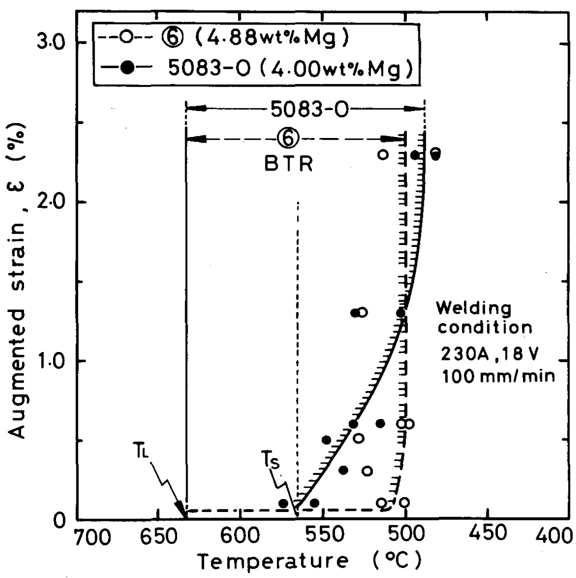
(a) 1070-0



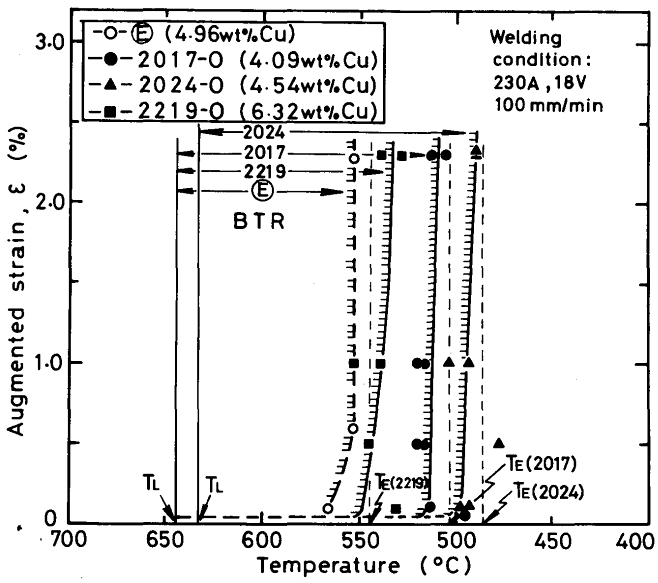
(b) 5005-0



(c) 5052-0 and 5154-0



(d) 5083-0



(e) 2017-0, 2024-0 and 2219-0

Fig. 15 Representation of the properties of ductility curve in solidification brittleness temperature range for commercially used aluminum alloys (broken lines show for Al-Mg or Al-Cu binary alloys)

aluminum alloys were shown in Fig. 15 (a), (b), (c), (d) and (e) in comparison with that of the respective binary alloy. In those figures, the ductility curves drown by a broken line show the Al-Mg and Al-Cu binary alloys, Mg and Cu contents of which were nearly equal to those of commercially used aluminum alloys, respectively.

From Fig. 15(a), (b), (c) and (d), the ductility curves and the BTRs of commercially used aluminum alloys were in general, similar those of Al-Mg binary alloys, respectively, though there is a little difference in the brittleness temperature range at the small augmented strain between 5083 and alloy 6 . That is, the lower limit of the BTR decreased with an increase of Mg contents. Moreover all of the lower limit of the BTR were lower than the bulk solidus temperature measured (T_S) for each alloy. Moreover, the temperature difference between the lower limit and the bulk solidus temperature measured is increased with an increase of Mg content in general.

Next, in Fig. 15 (e), each temperature in the lower limit of the BTR was nearly equal to the eutectic temperature measured (T_E) for commercially used Al-Cu system alloys. The reason why the temperature of the lower limit of the BTR of commercially used aluminum alloys, especially for 2017 and 2024, was lower than that of alloy E (about 5% Cu), is considered that Mg and Mn elements besides Cu are alloyed in these alloys, so that these elements lower considerably the eutectic temperature by forming the complex eutectic system. The BTR and the E_{min} of materials used are collectively shown in Table 3 and 4.

3-4 Effect of alloying contents on BTR

Fig.16 and 17 show the variations of the BTR and the area fraction of the eutectic products occurred with alloying contents for Al-Mg and Al-Cu binary alloys, respectively.

According to the observation of the microstructure of the weld metal with optical microscope (x1000 to x1500), Al-Mg-Fe and Al-Cu-Fe ternary eutectics were observed in the weld metals more than 4.88% Mg and more than 0.45% Cu, respectively. Therefore the oblique line is inserted in each upper figure of Fig. 16 and 17,

In the lower figures of Fig.16 and 17, the broken lines approximately show the temperature difference (T_L-T_E) between the liquidus temperature (T_L) and Al-Mg-Fe and Al-Cu-Fe ternary eutectic temperature (T_E), respectively.

As shown in Fig. 16 and 17, in both systems, the BTR is increased as the alloying content is increased and when it was exceeded the special content, that is, about 5% for Al-Mg and 0.5 to 1.0% for Al-Cu binary alloys, the BTR become a satulated value and come near the temperature difference of the (T_L-T_E).

Table 3 Summary of indices to evaluate solidification crack susceptibility obtained for Al-Mg and Al-Cu binary alloys.

Material	Designation	Mg or Cu content (wt%)	Brittleness temperature range, BTR (°C)	Minimum augmented strain required cracking, Emin (%)
Pure Al	1	0	20	0.1 to 0.3
Al-Mg binary alloys	2	0.51	20	0 to 0.1
	3	0.99	45	0 to 0.1
	4	1.72	50	0 to 0.1
	5	3.03	105	0 to 0.1
	6	4.88	135	0 to 0.1
	7	9.72	145	0 to 0.1
Al-Cu binary alloys	A	0.45	50	0 to 0.1
	B	0.84	80	< 0
	C	2.05	80	< 0
	D	3.00	80	0 to 0.1
	E	4.96	95	0 to 0.1

Table 4 Summary of indices to evaluate solidification crack susceptibility obtained for commercially used aluminum alloys.

Material	Designation	Mg or Cu Content (wt%)	Brittleness temprature range, BTR (°C)	Minimum augmented strain required cracking, Emin (%)
Commercially pure Al	1070-0	0	20	0.1 to 0.3
Al-Mg alloys	5005-0	0.86	55	0 to 0.1
	5052-0	2.60	100	0 to 0.1
	5154-0	3.50	130	0 to 0.1
	5083-0	4.00	140	0 to 0.1
Al-Cu Alloys	2017-0	4.09	135	0 to 0.1
	2024-0	4.54	145	0 to 0.1
	2219-0	6.32	110	0 to 0.1

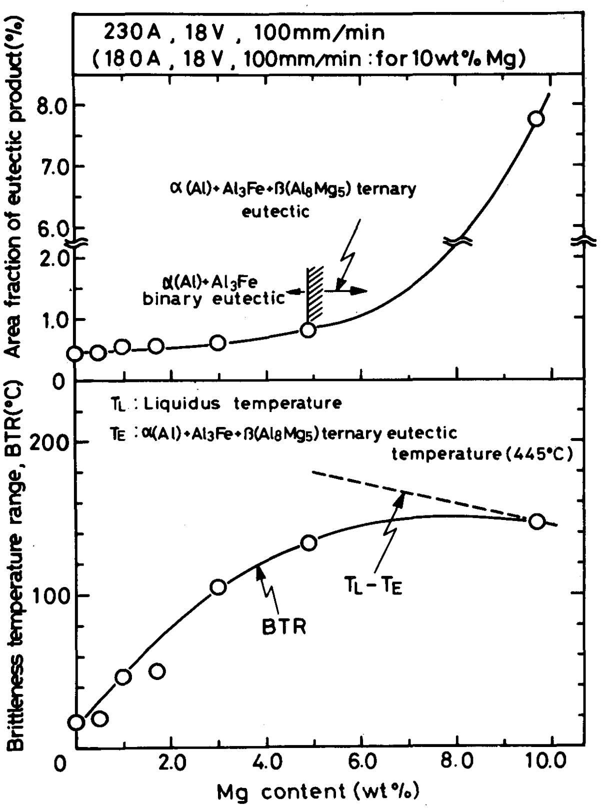


Fig. 16 Brittleness temperature range and area fraction of eutectic products vs. Mg content of Al-Mg binary alloys.

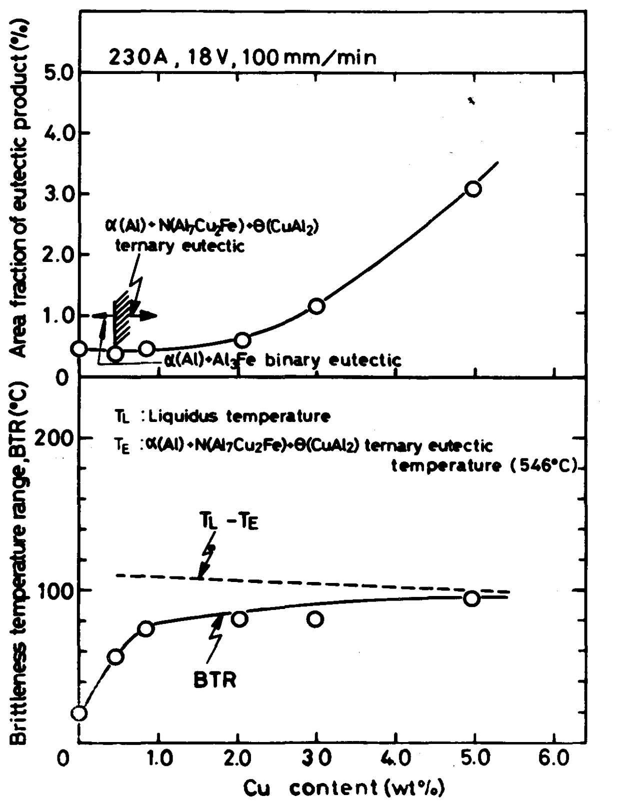


Fig. 17 Brittleness temperature range and area fraction of eutectic products vs. Cu content of Al-Cu binary alloys.

Consequently, the BTR considerably increased near the alloying contents at which the ternary eutectic begins to form, and as the amount of the eutectic products is increased with an increase of alloying element, the BTR is inclined to satulated to the temperature difference of the (T_L-T_E). Then the BTR is finary reached to the (T_L-T_E) at the alloying contents of about 10% Mg for Al-Mg and 5% Cu for Al-Cu binary alloys.

Meanwhile, when the ternary eutectic is formed in the alloy, it is considered that the BTR of the alloy would be reached to the (T_L-T_E). However, as the results from Fig. 16 and 17, the BTR did not reach to the (T_L-T_E) in case of alloy A (about 0.5% Cu) and alloy 6 (about 5% Mg) in which the ternary eutectic begins to form. The reason is considered that there is too little the eutectic products to increase the BTR for these alloys.

3-5 Effect of alloying contents on Emin

As the result from Table 3, the Emin in alloy 1 and 1070 was the higtest of those alloys used, that is, 0.1 to 0.3%. For Al-Mg binary alloys and commercially used Al-Mg system alloys, the Emin was low as 0 to 0.1% and did not vary with Mg content. On the other hand, for Al-Cu binary alloys, the Emin was varied with Cu content. That is, the Emin of 0.84 to 2.05% Cu-Al alloys was less than 0% augmented strain, while the Emin of the other alloys which contain the upper and lower Cu elements are 0 to 0.1%. As described previously, for these alloys of Emin less than 0%, the solidification cracks occurred with only the thermal strain caused by the bead-on-plate welding without any externally augmented strain.

3-6 BTR and Emin as the indices of solidification crack susceptibility

It is generally considered that the solidification crack susceptibility of the alloy is strongly depended on the BTR and Emin as well as CST which was defined by one of the authors[5] as the inclination of tangent to the ductility curve from liquidus temperature. In general, the wider the BTR and the lower the Emin, the much the crack susceptible for solidification cracking of weld metal in alloy. So for as the BTR is concerned, the BTR is increased with an increase of alloying content in aluminum alloys. Therefore from this point it seems that the solidification crack susceptibility is increased with alloying contents.

Meanwhile, the Emin of the aluminum alloys used was generally too low to measure by the trans-Varestraint test in this investigation except pure aluminum. Therefore it is difficult to decide the CST from these data obtained. The authors can understand that pure aluminum and commercially pure aluminum are the least susceptible to the solidification crack of the alloys used from the BTR and E_{min}, and the aluminum alloys of 0.84 to 2.05% Cu are the most susceptible to among the Al-Cu alloys used from the E_{min}. However the authors can not arrange the other alloys in order of crack susceptibility from this investigation.

It is also generally known, however, that the solidification crack susceptibility is the most at the specified value of alloying contents and becomes smaller at the upper and lower alloying contents of the specified alloy. This critical value of alloying contents is said about 0.5 to 2% Mg for Al-Mg[1] and about 0.5 to 3% Cu for Al-Cu binary alloys[12].

So that, it is suggested that only the BTR does not always decide the solidification crack susceptibility of aluminum alloys and the combination of the BTR and the E_{min} is needed to decide that.

Furthermore, the authors think that in order to investigate the value of the E_{min} clearly, the bending speed of the Trans-Varestraint test should be reduced to that of the actual welding process, and that the E_{min} and BTR in this investigation represent the values in case of the highest in the augmented strain rate. These investigations will be discussed in the later reports.

4. Conclusion

In this study, the properties of the ductility curve in the brittleness temperature range were investigated for Al-Mg and Al-Cu binary alloys and commercially used aluminum alloys by using the Trans-Varestraint test. Moreover, the properties were discussed from the viewpoint of metallographic investigations. Moreover, the fractrography of the surface of solidification crack was also treated.

The main conclusions obtained are as follows:

(1) The brittleness temperature range (BTR) during solidification was increased with an increase of alloying elements for Al-Mg and Al-Cu binary alloys used. The lower temperature of the BTR was lowered with an increase of alloying elements and reached to each ternary eutectic temperature of Al-Mg-Fe and Al-Cu-Fe systems at the contents of 10% Mg for Al-Mg and 5% Cu for Al-Cu binary alloys, respectively.

(2) The amount of eutectic products formed in the weld metal whose Mg and Cu contents were more than about 5% and 0.5%, respectively, was increased with an increase of each element for Al-Mg and Al-Cu binary alloys, respectively.

(3) The minimum value of ductility (E_{min}) in the BTR was within the range of 0.1 to 0.3% augmented strain for commercially pure aluminum, and was not varied with a variation of Mg content and was within 0 to 0.1% for Al-Mg binary and commercially used Al-Mg alloys, and was within 0 to 0.1% for 0.45, 3.0 and 5.0% Cu containing Al-Cu binary alloys and commercially used 2017, 2024 and 2219 alloys. While for Al-Cu binary alloys with about 0.8 to 2% Cu content, E_{min} was estimated less than 0% augmented strain, that is to say, the solidification cracks occurred in the bead-on-plate weld metal without augmented strain.

(4) The properties of the ductility curve in the BTR for the commercially used pure and Al-Mg system alloys, 1070 and 5005, 5154 and 5083 were nearly corresponding to those of pure and Al-Mg binary alloys, Mg content of which was almost the same. However, for commercially used Al-Cu system alloys, especially in 2017 and 2024, the BTR was wider than that of Al-Cu binary alloy with almost the same Cu content. It is considered that there are same additional other elements as Mg and Mn besides Cu in 2017 and 2024 alloys which lower the temperature of the lower limit of the BTR.

(5) The mode of the fractured surface of the solidification cracks occurred by the Trans-Varestraint test was varied with a decrease of the instantaneous temperature when cracks occurred and there are classified to three types in mode, that is, called type D, type D-F and type F. In the type D, which was observed at the higher temperature of the BTR, the primary and the secondary arms of the dendrite were obviously distinguished on the surface. However, in the type F, which was observed at the lower temperature of the BTR, the secondary arms of the dendrite was no longer indistinguishable and the surface of the primary arm was considerably flat on the surface. The type D-F was the intermediate mode between type D and type F. Furthermore, the type F was observed only in the zone below the bulk solidus temperature measured.

(6) So far as the solidification crack susceptibility is concerned, it is considered that the commercially pure aluminum and pure aluminum are superior to the other alloys used from the viewpoints of the BTR and the E_{min} and 0.84 to 2% Cu-aluminum alloys are inferior to the other Al-Cu alloys used from the E_{min}. However the other alloys could not be arranged in order to crack susceptibility because of very low value of the E_{min}. Moreover it was suggested that the width of the BTR does not always correspond to the

crack susceptibility in case of aluminum alloys.

Acknowledgement

The authers would like to thank Dr. Toshiyasu Fukui, Sumitomo Light Metal Ind., Ltd. for his offering of the materials and his useful discussion.

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