Assessment of Solidification Cracking Test for Aluminum Alloy Welds†

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Abstract

In order to investigate the desirable weld cracking test method for aluminum alloys in practical purposes, some cracking tests such as modified Houldcroft test, T- and Lap-fillet tests, GMA weld crater cracking test and so on have been applied for the welding of 7N01 and other aluminum base alloys with commercial and tentative filler wires. Then, each cracking test method was evaluated from the viewpoints of discrimination of crack susceptibility, reappearance of cracking index, practicability and economical situation of test. Among them, the authors recommended the modified Houldcroft test and GMA weld crater cracking test for GMA weld bead and weld crater cracking test, respectively. This experiments have been done in cooperation with the work of international cooperative program in Nonferrous Working Group in commission IX of IIW.

KEY WORDS: (Solidification cracking) (Cracking test) (Aluminum alloys) (GTA welding) (GMA welding) (Solid filler wire)

1. Introduction

Solidification cracking occurred in weld bead and crater is one of the most serious problems in the welding of aluminum alloys. Therefore in order to evaluate the susceptibility to solidification cracking of weld metal, many cracking test have been developed and used in many countries[1] so for. However there were only a few studies[2,3] unfortunately in respect to the evaluation of cracking tests methods using the some base and welding filler materials. Recently, the demand that the common solidification cracking test methods should be established is internationally required, especially in the field of aluminum alloy welding.

Therefore, the purpose of this report is to obtain the basic informations about various weld solidification cracking test methods performed with GTA and GMA weldings using various base metals and filler wires of aluminum alloys. The self-restrained cracking test, such as modified type Houldcroft test[4], T-fillet and Lap-fillet tests[3] and GMA weld crater cracking test[5] were used as weld solidification cracking test methods to be evaluated.

Ring-cast cracking test[5,6] was also used to compare the susceptibility of solidification cracking in welds and castings.

As base metals, 7N01 Al-Zn-Mg alloy is mainly used in comparison with 1100 industrial pure Al, 5083 Al-Mg-Mn and 6000 series Al-Mg-Si alloys with commercial and tentative filler wires.

The second purpose is to investigate the effects of minor elements for grain refinement such as zirconium (Zr), titanium (Ti), and boron (B) on crack susceptibilities of weld bead and crater of 7N01 alloy using the above test methods, because this alloy is much more susceptible than those of 5083 alloy. For this purpose, tentative Al-Mg alloy filler wires with Zr or Ti with B were made.

As a result each cracking test method was evaluated from the viewpoints of discrimination of crack susceptibility, reappearance of cracking index and practicability and economic situation of test.

This experiments have been done in cooperation with the work of international cooperative program in Nonferrous Working Group in commission IX of IIW.

2. Experimental Procedure

2.1 Materials used

Base metal used is mainly 7N01 (Al-4.5%Zn-1.2%Mg) alloy. In comparison with 7N01, 1100 (industrial pure aluminum), 5083 (Al-4.5%MgMn) and Al-Mg-

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Table 1 Chemical compositions of base metals and filler wires used

Material		Chemical composition (wt%)										Plate thickness or wire dia. (mm)
		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	B	
Base metal	1100-O	0.11	0.57	0.13	0.01	0.01	Tr	0.01	0.01	–	–	6
	5083-O	0.14	0.19	0.02	0.61	4.58	0.12	0.01	0.01	–	–	6,12,30
	7N01-T5	0.06	0.18	0.07	0.47	1.11	0.21	4.36	0.02	0.16	–	6,12,30
	6061-T5	0.55	0.14	0.14	0.02	0.95	0.09	0.07	0.01	–	–	6
	6082-T5	0.96	0.27	0.03	0.55	0.89	0.02	0.04	0.02	–	–	6,30
	6N01-T5	0.78	0.19	0.02	0.20	0.52	0.01	0.06	0.02	–	–	6,12
	6005A-T5	0.76	0.21	0.01	0.20	0.46	Tr	0.06	0.02	–	–	10
Filler wire	1100	0.20	0.48	0.10	Tr	–	–	Tr	–	–	–	1.6
	5554	0.10	0.16	0.01	0.70	2.67	0.10	0.01	0.09	–	–	1.6
	5183	0.08	0.16	0.01	0.68	5.08	0.07	Tr	0.08	–	–	1.6
	5183TiB	0.10	0.19	0.01	0.60	4.87	0.08	0.02	0.07	–	0.0018	1.6
	5356	0.05	0.14	0.01	0.09	4.82	0.10	Tr	0.09	–	–	1.6
	5356TiB	0.06	0.14	Tr	0.11	4.88	0.09	Tr	0.11	–	0.002	1.6
	7N11	0.08	0.33	0.01	0.39	3.87	0.19	1.43	0.05	0.01	–	1.6
	6MgZr*	0.05	0.17	Tr	0.12	6.60	Tr	0.09	0.01	0.25	–	1.6
	6MgTiB*	0.03	0.16	Tr	0.12	6.34	Tr	0.09	0.07	–	0.004	1.6
	7Mg*	0.08	0.17	Tr	0.12	7.22	0.11	0.01	0.07	–	–	1.6

* Tentative filler wire

Si 6000 series alloys such as 6061, 6082 and 6N01 are also used. 6N01 is a tentative alloy in Japan. Plate thicknesses of these alloys are 6, 10, 12 and 30 mm. As welding filler wires for GTA and GMA welding methods, 1100 (industrial pure Al), 5554 and 5356 (Al-Mg), 5183 (Al-MgMn) and 7N11 (Al-Zn-Mg) commercial filler wires and 5356TiB, 6MgTiB, 6MgZr and 7Mg tentative filler wires are used. Chemical compositions of base metals and filler wires used are listed in **Table 1**.

In addition, experimentally made Al-2%Zn-3%Mg alloy sheets with 2 mm in thickness containing minor elements of Zr and Ti+B, the chemical composition of which corresponds to that of the weld metal of 7N01 base metal with 5356 filler wire, are also used to examine the effects of minor elements on solidification cracking in castings and weld beads. Chemical compositions are shown in **Table 2**.

Table 2 Chemical compositions of Al-2%Zn-3%Mg alloys with and without Zr or Ti+B

Specimen No.	Chemical composition(wt%)				
	Mg	Zn	Zr	Ti	B
1	3.0	2.0	-	-	-
2	3.0	2.0	-	0.007	0.0015
3	3.0	2.0	-	0.024	0.0047
4	3.0	2.0	-	0.038	0.0078
5	3.0	2.0	0.08	-	-
6	3.0	2.0	0.21	-	-

2.2 Cracking test methods and welding conditions

2.2.1 Modified Houldcroft test

In the previous report[7], the authors reported that the ordinary type Houldcroft test specimen was only valuable in case of low welding speed as 300 mm/min or less for 2 mm thick Al sheet and also the reverse shaped-type to Houldcroft specimen was recommended in case of higher welding speed. Accordingly, in this experiment the modified type of Houldcroft test specimen, which was recommended in previous report[4,7] was used for GTA and GMA weldings for 2 mm and 6 mm thick specimens. **Figure 1** shows the shape and dimension of test specimen for GTA and GMA weldings in a same figure.

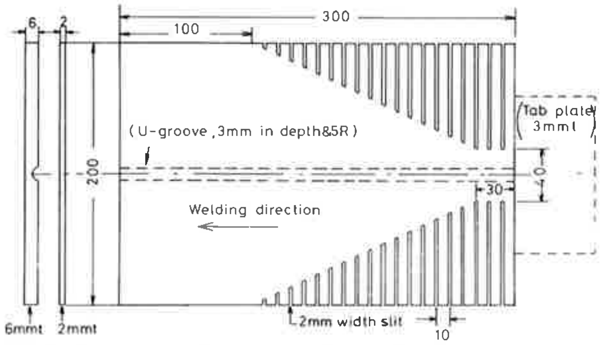


Fig. 1 Shape and dimension of modified Houldcroft test specimen for GTA and GMA weldings

In case of GTA welding, DCRP in argon gas shielding and DCSP in helium gas shielding were used for 2 mm and 6 mm thick specimens, respectively. Welding conditions of current and speed were selected to make a full-penetrated weld bead. They were 350 mm/min-95A and 750 mm/min-140A in case of 2 mm thick specimen. In case of 6 mm thick specimen welding speed was a constant value of 200 mm/min and welding currents were varied from 150 to 200A in accordance with base metals and filler wires.

Test specimen was set on a copper backing plate with a ditch and was restrained under two roller bearings not to make angular deformation of specimen during test welding in case of 2 mm thick sheet, but not restrained in case of 6 mm thick plate. Welding starting point was decided to be 5 mm apart inside from a specimen edge. As soon as the specimen edge was fully melted by the arc to its whole thickness, the arc was began to proceed with a constant welding speed and at the same time filler wire was provided with a constant feeding rate of 600 mm/min for 6 mm thick specimen, though there was not used for 2 mm thick specimen. Higher feeding rate than 600 mm/min made an undesirable weld bead with an irregular shape of bead surface. In order to minimize the scattering in test data as small as possible a transistor-generated welder with a constant current arc charactaristic was used.

In case of GMA welding, in order to make full-penetrated weld bead from the start zone of weld bead as specimen edge, U-groove of 3 mm in depth was made in advance on the specimen surface along the center of the specimen as shown in Fig. 1.

In addition to this, a tab plate of 3 mm in thickness was also prepared attaching to the specimen edge to provide the starting point for GMA welding. Welding was started on this tab plate and continuously advanced on test specimen through U-groove with a constant welding speed of 400, 600 or 800 mm/min. Commercial pulse GMA welder which generates a pulsed current of 60 Hz in frequency and 60A in pulse current on base current was used in order to obtain a stable arc even with low welding current of about 200A using 1.6 mm dia. of filler wire. Welding current which is represented by an average value in this pulsed welder was selected to be 185–275A to make a full-penetrated weld bead for each welding speed and also for each combination of base metal and filler wire.

In both cases of GTA and GMA weldings, crack susceptibility of weld bead was represented by the ratio of crack length to whole length of weld bead of 300 mm.

2.2.2 *T-fillet test*

The shape and dimension of T-fillet test specimen with tapered clearance and a jig for fixture of test specimen are shown in **Fig. 2(a)**, **(b)** and **(c)**. The tapered clearance with 3 mm gap in maximum and zero in minimum was made by two methods according to the previous report[9]; one is that an insert metal of 3 mm in thickness was inserted between the vertical and horizontal test peices at the one end of test specimen as shown in Fig. 2(a) and another was that the root of the vertical test plate was machined into a tapered shape as shown in Fig. 2(b). Test specimen were tightly fixed by the L-shaped steel jig during test welding as shown in Fig. 2(a) and (b). Of course, ordinary T-fillet test specimen with restraining weld beads as shown in Fig. 2(c) was used in comparison with the jig restraint test specimens. Welding condition of three large restraining weld beads was 270A and 400 mm/min using 5356 wire.

Test weld by conventional GMA welding was done from the specimen end with a 3 mm gap to another end with zero gap. Plate thickness and diameter of filler wire are 12 mm (partly 10 mm) and 1.6 mm, respectively. Welding speed was varied from 400 to 1500 mm/min, but higher welding speed than 800 mm/min it became very difficult to make smooth weld bead because of the existence of the root gap.

2.2.3 *Lap-fillet test*

The shape and dimension of the test specimen is shown in **Fig. 3**, which was introduced in the previous report[3]. Four test weld beads longitudinal to the specimen were evaluated for weld crack susceptibility under four restraining weld beads transverse to the specimen. In advance of test welding the restraining beads were welded in T1 to T4 seams by conventional GMA welding with 270A–400 mm/min using 1.6 mm dia. 5356 filler wire. Test weld beads were done on four grooved fillet seams of W1 to W4 under the same welding condition presetting.

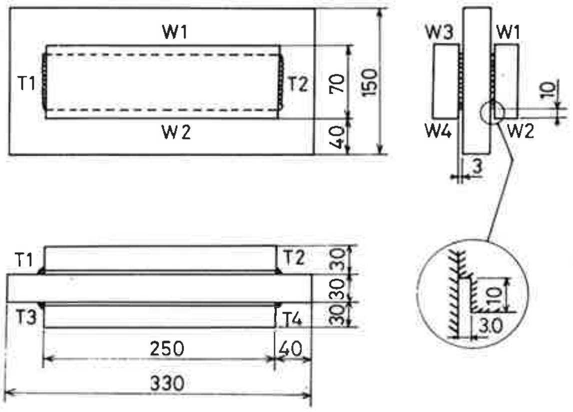


Fig. 3 Shape and dimension of Lap-fillet test specimen

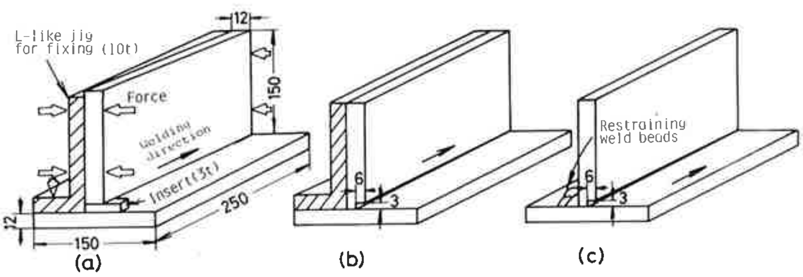


Fig. 2 Shape and dimension of T-fillet test specimens

The crack susceptibility of the test weld beads was evaluated as the ratio of total-length of four weld beads excluding craters. Welding condition of test welding was selected in two welding conditions of 280A–28V and 300A–29V with welding speeds of 300, 400, 500 and 600 mm/min. Higher welding speed than 600 mm/min, it became difficult to make a smooth weld bead because of the existence of 3 mm root gap.

2.2.4 Weld crater cracking test

The shape and dimension of the test specimen is shown in **Fig. 4**, which was introduced in the previous

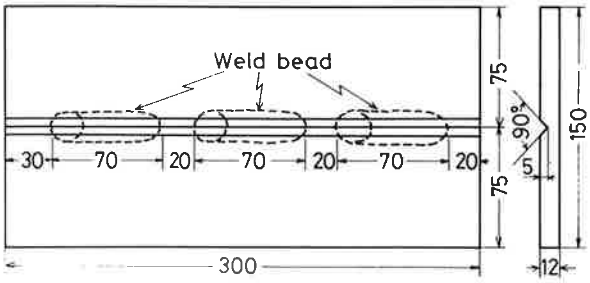


Fig. 4 Shape and dimension of GMA weld crater cracking test specimen

report[5]. Three short weld beads of about 70 mm in length were discontinuouly made on a V-grooved specimen of 12 mm thick plate. The crater cracking susceptibility was represented by the ratio of the total-length of cracks observed on the surface of each weld crater of longitudinal length of each weld crater. Mean value of these ratios for three weld craters was adopted as the crater cracking index in this experiment. Welding conditions were 270A of welding current and 200, 400 and 600 mm/min of welding speed.

2.2.5 Ring-cast cracking test

In order to compare the cracking susceptibility in casting with those in weld bead or weld crater, ring-cast cracking test was performed using the mold for ring-castings as shown in **Fig. 5**.

Pouring temperature of test alloy was 750°C and preheating temperature of mold was 50°C. Crack susceptibility was represented by the total-length of cracks observed on the whole surface of test specimen casted. Effect of minor elements on crack susceptibility of tentative Al-2%Zn-3%Mg alloys was also investgated in order to compare with result obtained by means of modified Houldcroft test.

3. Cracking Test Results

3.1 Crack susceptibility in weld bead

3.1.1 Modified Houldcroft test

(1) GTA welding

Effect of minor element such as Zr or Ti+B on crack susceptibility was investigated by using modified Houldcroft test specimen of Al-2%Zn-3%Mg alloy of 2 mm in thickness with low and high welding speeds of 350 and 750 mm/min in DCRP, respectively. Test results are shown in **Fig. 6** in relation between crack susceptibility and contents of Zr and Ti+B, where Ti+B content of abscissa represents only the content of Ti in Ti+B content and that of B is almost equal

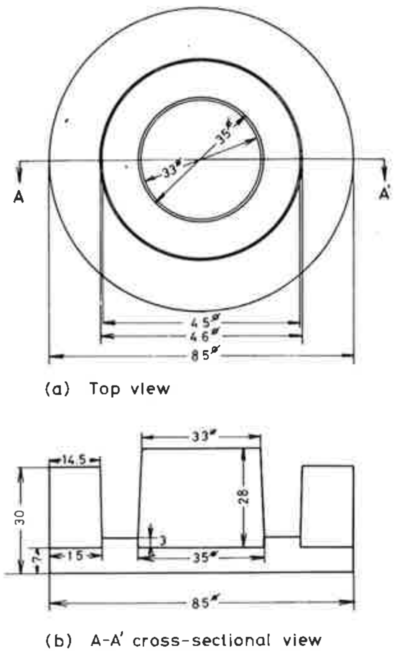


Fig. 5 Shape and dimension of mold for ring-cast cracking test

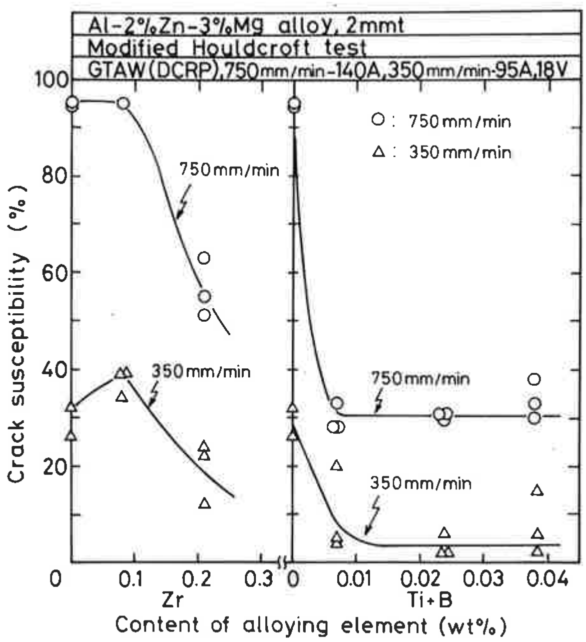


Fig. 6 Effects of Zr or Ti+B additions on weld crack susceptibility evaluated by modified Houldcroft test

to one fifth of Ti content.

Each three data coincided considerably and same tendency was clearly seen at both welding speeds. Crack susceptibility is increased as the increase of Zr or Ti+B contents with more than about 0.2% or 0.007%, respectively, independent of welding speed, although high welding speed increased crack susceptibility of weld bead with or without minor elements.

It is considered that these beneficial effects of Zr and Ti+B additions are mainly due to the grain refinement of weld bead macrostructure.

Nextly, commercial aluminum alloys of 6 mm thick plate were tested with GTA welding in DCSP with He-gas shielding with or without commercial and tentative filler wires. Results are shown in **Figs. 7** and **8**. Figure 7 shows crack susceptibilities of commercial

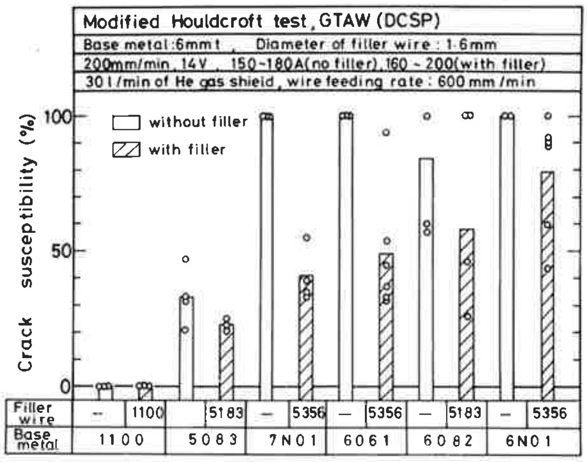


Fig. 7 Crack susceptibilities of weld beads of commercial alloys evaluated by modified Houldcroft test for GTA welding with and without filler wires

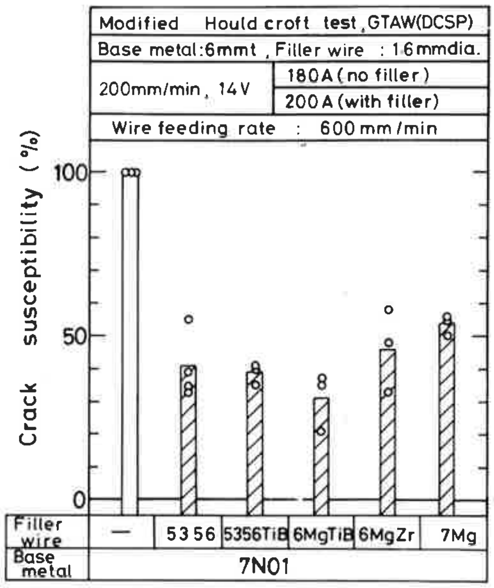


Fig. 8 Effects of filler wires on crack susceptibilities of 7N01 weld bead for GTA welding

base metals welded with or without commercial filler wires. Without filler wire, 7N01 and 6000 series alloy are much more susceptible to cracking than 5083 alloy, and in 1100 industrial pure Al crack is not seen.

Filler wire addition decreases crack susceptibility in each weld bead, though those of 6000 series alloys are not so remarkablly reduced in comparison with 7N01 and 5083 weld beads. The scattering in test data is large in case of 6000 series alloys but is comparablly small in case of other alloys. This is considered to be mainly due to the arc instability during welding for 6000 series alloys even if a transistar-generated welder with a constant current is applied.

Figure 8 shows crack susceptibility of 7N01 weld bead made with tentative wires in comparison with those made with 5356 commercial wire and without any filler wires. 7N01 base metal is much susceptible without filler wire but crack susceptibilites are reduced to 20~50% of that of base metal by the addition of filler wires. However, there are no obvious differences in crack susceptibility with each filler wire, though 6MgTiB wire seems to be slightly less susceptible in average than the others. It is generally known that in case of GTA welding, the dilution of filler wire composition to molten base metal one is very small, that is to say, about 20% in this experiment. Therefore, effect of modification of filler wire composition on weld bead cracking is not likely to appear obviously.

Figure 9(a), **(b)**, **(c)** and **(d)** show typical macrostructures on cross-section of weld bead for 7N01 base metal without filler wire and with 5356, 6MgTiB and 6MgZr, respectively. Feathery crystal is likely to develop in central zone of weld bead especially in DCSP-GTA welding as shown in Fig. 9.

(2) GMA welding

Cracking test was performed with GMA welding by using 6 mm thick modified Houldcroft test specimen with an U-grooved ditch on the specimen and a tab plate for arc start as shown in Fig. 1.

Figure 10 shows test results for commercial base metals with commercial filler wire. Welding speed was a constant value of 400 mm/min, but welding current was varied to make a full-penetrated weld bead of 12–14 mm in width on the top surface and 3.5–4.5 mm on the back surface. The weld beads of 7N01 and 6061 with 5356 wire were much more susceptible than those of 6082 with 5183 and 6N01 with 5356 which showed a less crack susceptibility equal to that of 5083 with 5183 wire. These results didn't coincide with those with GTA welding as shown in Fig. 7 which indicate that 6000 series alloys are much more susceptible than 7N01 even using same

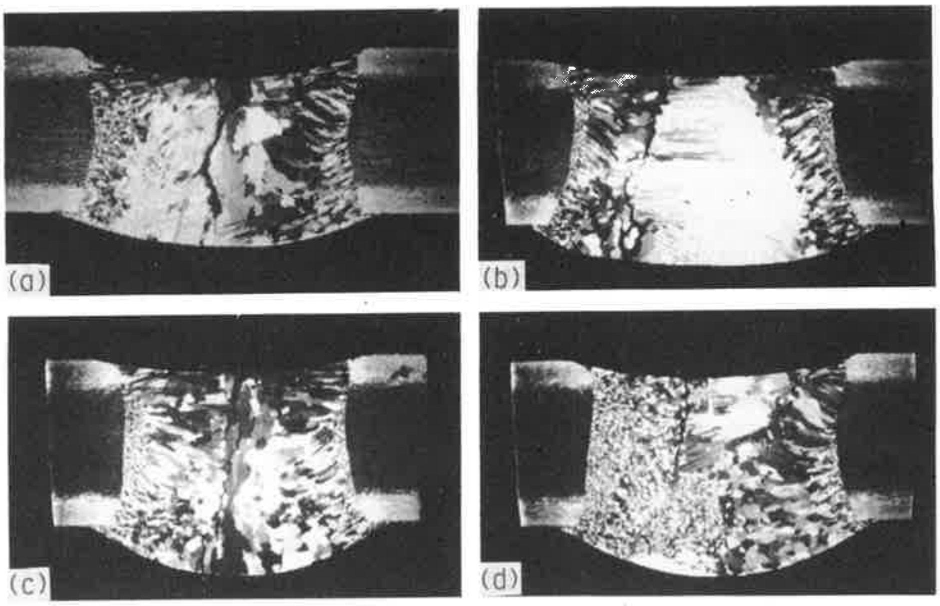


Fig. 9 Macrostructures on cross-sections of 7N01 GTA weld beads; (a) without filler wire, (b) with 5356, (c) with 6MgTiB, (d) with 6MgZr

filler wires for GMA welding. This is considered to be responsible for the difference in the dilution of filler wire in each welding process.

The dilution of filler wire in the weld bead which can be assumed from molten ratio was about 20% in GTA welding and about 60% in GMA welding. 1100 industrial pure Al with 1100 wire was also very low susceptible to cracking.

Figure 11 shows the effects of tentative filler wires on crack susceptibility of 7N01 weld bead in comparison with 5356 filler wire. Crack susceptibility of 6MgZr wire only was less than those of the others which showed almost the same levels. These results were also different a little from those with GTA welding as shown in Fig. 8.

Effect of welding speed on crack susceptibility was investigated for 7N01 base metal with 5356 filler wire with 400, 600 and 800 mm/min. Welding current was varied to make a full-penetrated weld bead of similar size. Test results as shown in **Fig. 12** indicated that crack susceptibility was independent of welding speed within the range of this experiment.

As a result, judging from test results obtained in this experiment, the authors have a favorable im-

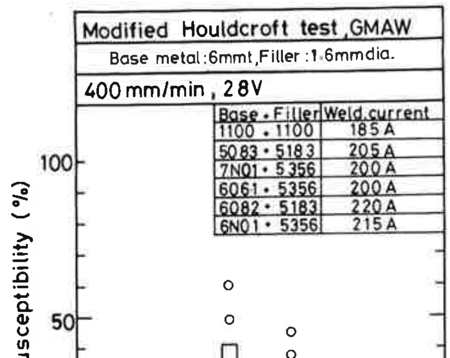


Fig. 10 Crack susceptibilities of weld beads of commercial alloys evaluated by modified Houldcroft test for GMA welding

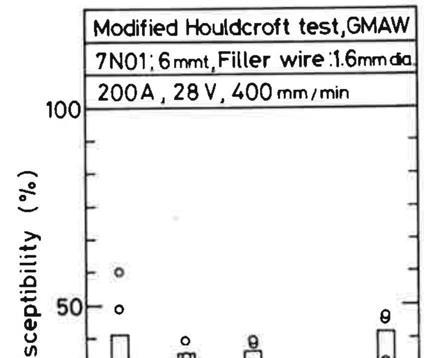


Fig. 11 Effects of filler wires on crack susceptibilities of 7N01 weld bead for GMA welding

pression that the modified Houldcroft test in Fig. 1 is one of the valuable cracking tests to evaluate solidification cracking of weld bead for both GTA and GMA weldings. The favorable points of this test are that the difference in crack susceptibility of weld bead against the effects of the different combination of base metal and filler wires and the modification of filler wire with additional elements is distinguishable and the scattering in data was not so large except of the results in GTA welding (DCSP) of 6000 series alloys, in addition to this, both GTA and GMA weldings are available in this test specimen. Of course the simplicity for preparation of the test specimen and the economy of this test method are excellent because of its simple shape and comparable small dimension of test specimen and also unnecessity of any special jigs or equipments for the test. One problem for this test is a bead-on-plate welding which is different to practical welding joint.

3.1.2 T-fillet test

This type of test method has been utilized most commonly as cracking test for GMA welding so for. At first, three types of T-fillet test specimen as shown in Fig. 2(a), (b) and (c) were examined in order to determine the best test method using 7N01 base metal with 5356 filler wire. Test welds were made with 290A and 25–27V. Welding speed was varied to 400, 600, 800, 1000 and 1500 mm/min. There were, however, no cracks in each welding speed for all test specimens. Therefore the difference could not be distinguished among them. Therefore, test specimen as shown in Fig. 2(a) which is the most simple test specimen among them was used in order to evaluate the crack susceptibility of 7N01 weld bead with 5356, 7N11 and 7Mg wires, 6N01 and 6005A with 5356 wire.

Test results are shown in **Fig. 13**. Only 7N01 weld beads with 7N11 wire cracked at high welding speed than 600 mm/min and crack susceptibility increased with increase in welding speed. On the contrary, there were no cracks even in high welding speed of 1500 mm/min in case of other combinations of base metal and filler wire. 7N11 filler wire is much more susceptible to cracking in 7N01 base metal, so this filler wire is now not utilized in practical purposes.

On the basis of these results, it is considered that T-fillet test is one of the simple tests for a primary distinction but not so suitable cracking test for accurate evaluation between weld metals having a little difference in crack susceptibility because this test is not so sensitive to cracking in weld bead.

3.1.3 Lap-fillet test

Test results are shown in **Fig. 14(a)** through **(f)** for 7N01, **Fig. 15** for 6082 and **Fig. 16** for 5083 base metals. The weld beads of 7N01 base metal with 5554 wire showed considerable cracking through whole welding speeds. In the weld beads with 7Mg wire a little cracking was also observed. Moreover scattering in crack susceptibility was observed in the weld beads with 6MgZr and 7Mg wires for 600 mm/min of welding speed. In addition crack susceptibilities of the other weld beads were low enough and almost nil through whole welding speeds. High crack susceptibility of 5554 wire is due to its low magnesium content. On the basis of these results, it seems, however, that high

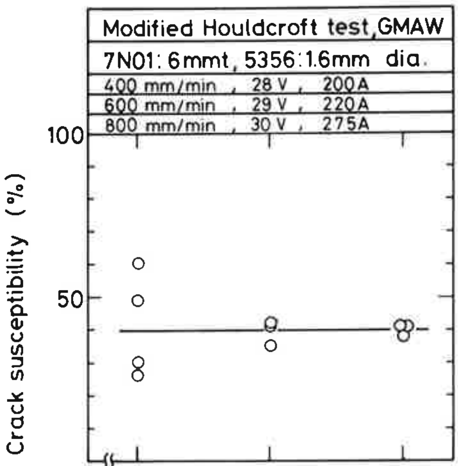


Fig. 12 Effect of welding speed on crack susceptibility of GMA weld beads of 7N01 with 5356 filler wire evaluated by modified Houldcroft test

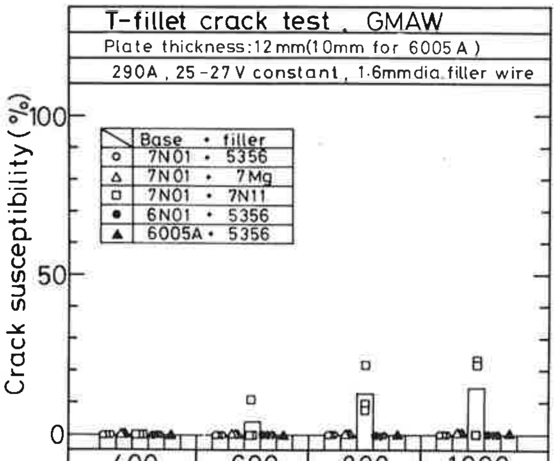
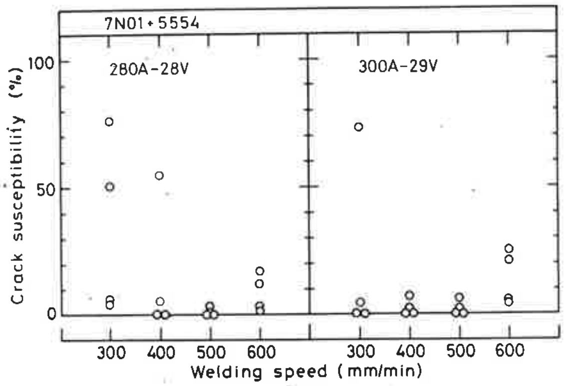
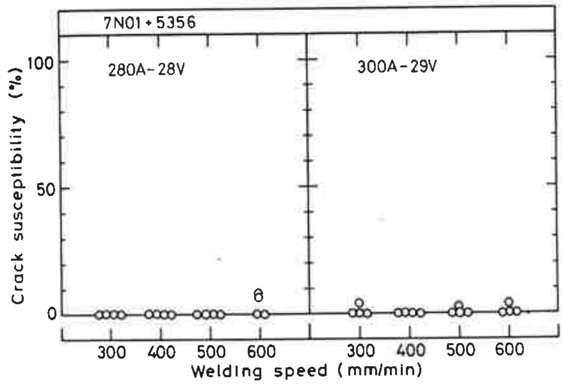


Fig. 13 Crack susceptibilities of GMA weld beads evaluated by T-fillet test



(a)



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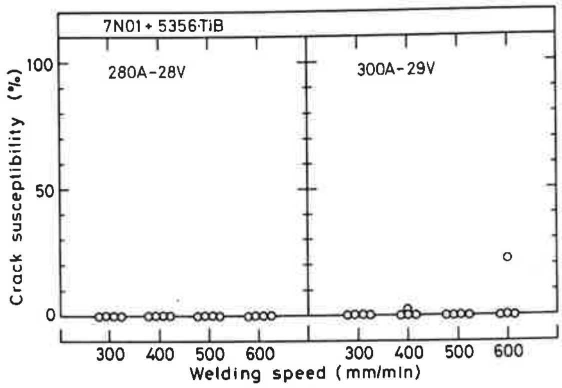
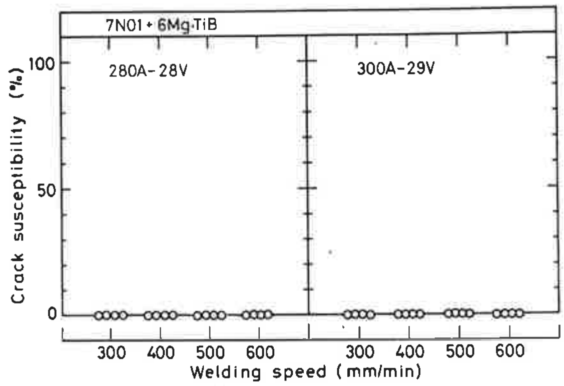
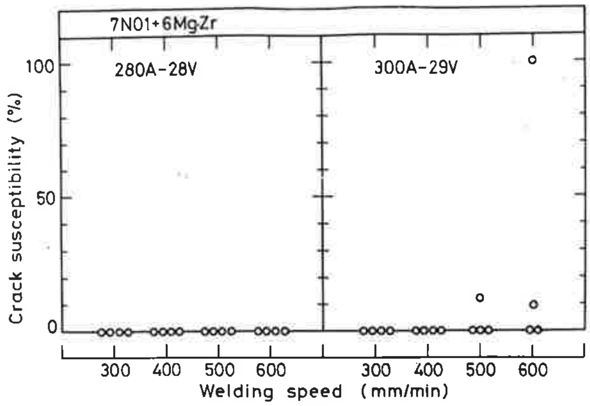


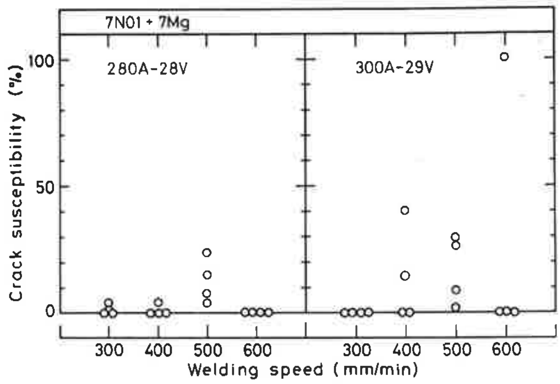
(c)



(d)



(e)



(f)

Fig. 14 Crack susceptibilities of 7N01 GMA weld beads with various filler wires in variation of welding speed and current evaluated by Lap-fillet test

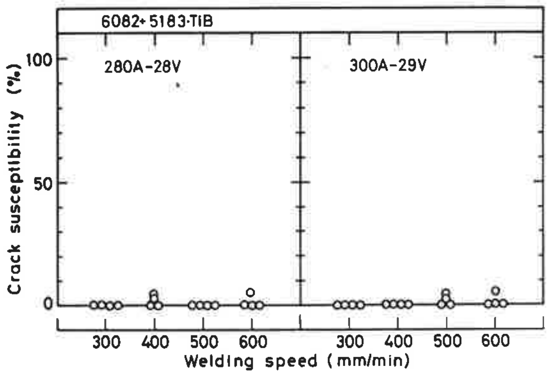


Fig. 15 Crack susceptibilities of 6082 GMA weld beads with 5183TiB filler wire in variation of welding speed and current evaluated by Lap-fillet test

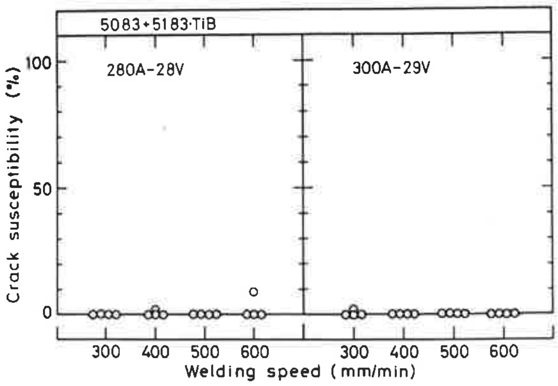


Fig. 16 Crack susceptibilities of 5083 GMA weld beads with 5183TiB filler wire in variation of welding speed and current evaluated by Lap-fillet test

magnesium content of filler wire is not always beneficial for prevention of 7N01 weld bead cracking.

In Lap-fillet test, it is considered that this test is superior to T-fillet test for evaluation of crack susceptibility, but shows a considerable scattering in data as shown in Fig. 14(a), (e) and (f) if cracking occurs in weld bead. Moreover this test is costly for preparation of specimen.

Judging from these results, Lap-fillet test is considered to be not so recomendable for crack susceptibility test in GMA welding.

3.2 Crack susceptibility in weld crater

Cracking susceptibilities in weld crater were shown in **Fig. 17** for GMA welding craters in variation of welding speed of 200, 400 and 600 mm/min for 7N01 base metal with 5554, 5356, 5356 TiB 6MgTiB, 6MgZr and 7Mg filler wires in comparison with 5083 with 5183 filler wire. 7N01 weld crater with commercial 5356 and 5554 wires were much susceptible to cracking in comparison with that of 5083 with 5183. However, 5356 wire added with Ti+B or Zr and higher magnesium wires with or without Ti+B or Zr decreased the crater crack susceptibility of 7N01 base metal. Among them 6MgZr wire shows an excellent effect to reduce the crater cracking. This is mainly due to the grain refinement in weld crater.

Typical examples of general appearances of crater cracking are shown in **Fig. 18** for 7N01 weld craters with 5356, 6MgTi+B and 6MgZr wires. Large Y-shaped crack observed in weld crater with 5356 wire but only a fine crack observed with 6MgZr wire.

As a result of this experiment, the authors think that the crater cracking test method used in this experiment is one of the excellent crater cracking tests because of good discrimination of the difference in

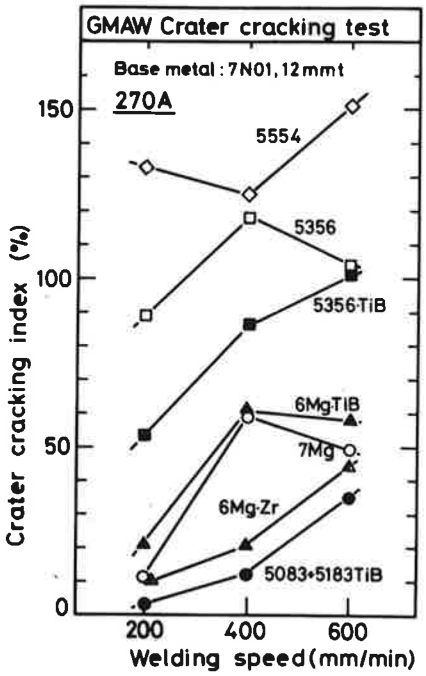


Fig. 17 Crack susceptibilities of 7N01 and 5083 GMA weld craters in variation of welding speed with various filler wires

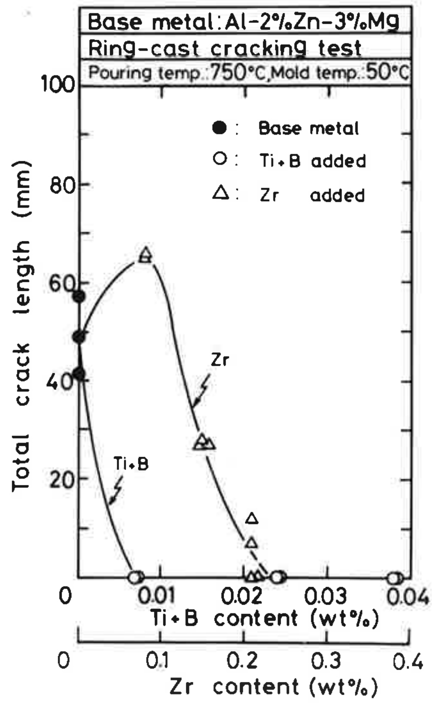


Fig. 19 Effects of Zr or Ti+B additions on crack susceptibilities represented by total crack length in mm evaluated by ring-casting test

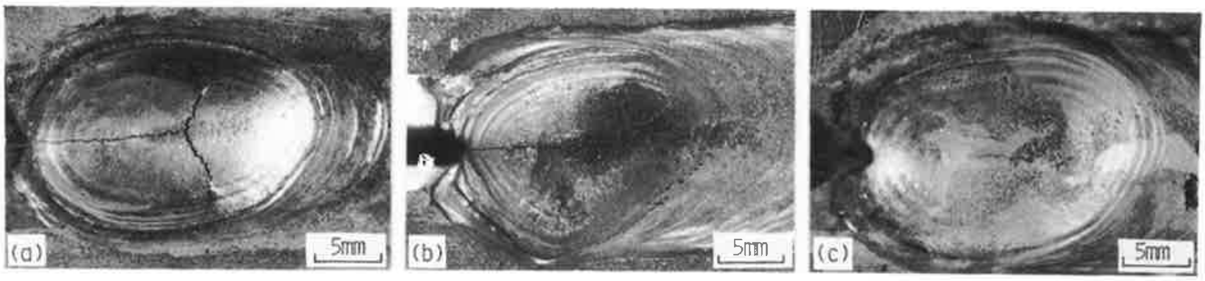


Fig. 18 Appearance of cracking in weld crater at the welding condition of 270A and 400 mm/min; (a) 7N01+5356, (b) 7N01+6MgTiB, (c) 7N01+6MgZr

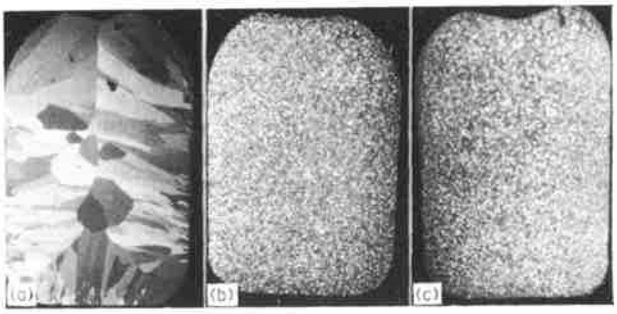


Fig. 20 Macrostructures on cross-section of ring-castings; (a) Al-2%Zn-3%Mg, (b) with 0.2%Zr, (c) with 0.007%Ti+B

crack susceptibility of weld crater, simplicity of test specimen and economy. However in order to minimize the scattering in test data it is necessary to keep the same shape and dimemsion of the groove in specimen preparation and the same welding condition including torch position and angle.

3.3 Crack susceptibility in ring-cast cracking test

Test results of Al-2%Zn-3%Mg alloys with and without Zr or Ti+B were shown in **Fig. 19** which showed the effects of Ti+B or Zr addition on crack susceptibility represented by total crack length in mm. Al-2%Zn-3%Mg alloy without any additions was much susceptible to cracking. The crack susceptibility was remarkably decreased with addition of 0.2%Zr of 0.007%Ti+B.

At the same time, macrostructures were also well refined as shown in **Fig. 20(a)**, **(b)** and **(c)** for no, 0.2%Zr and 0.007%Ti+B additions, respectively. Therefore, the crack susceptibility in the ring-cast cracking test is considered to have a close relation with grain size. These results were also a good agreement with the results obtained by modified Houldcroft test in 3.1.1.

4. Synthetic evaluation of test methods used in this experiment

The feature of cracking test methods used in this experiment were evaluated in **Table 3** with regard to discrimination of the difference in crack susceptibility, reproducibility of cracking data, practicability and simplicity of test method including preparation of specimen and economy of test method.

As a result, the authors think at the present that the modified Houldcroft test used are recommendable as the weld bead cracking test method for GTA and GMA weldings and the weld crater cracking test used in this experiment are also recommendable as a crater cracking test for GMA welding. In addition the ring-cast cracking test is considered to be one of the good cracking tests especially for estimation of the crack susceptibility of weld crater.

5. Conclusions

Some cracking tests for welding bead and crater

Table 3 Result of assessment of cracking tests evaluated in this experiment

Test method	Welding process	Specimen thickness	Discrimination for crack susceptibility	Reproducibility of cracking	Simplicity of test method	Economy of test method
Modified Houldcroft test	GTAW (DCSP)	2 mm	excellent	good	good	excellent
	GTAW (DCSP)	6 mm	good	fair	good	excellent
	GMAW	6 mm	good	good	fair	excellent
T-fillet test	GMAW	12 mm	very poor	fair	fair	poor
Lap-fillet test	GMAW	30 mm	poor	very poor	fair	poor
GMAW crater cracking test	GMAW	12 mm	excellent	good	good	good
Ring-cast cracking test	—	—	excellent	good	fair	good

such as modified Houldcroft test, T- and Lap-fillet tests, GMA weld crater cracking test and ring-cast cracking test have been evaluated using mainly weld bead of 7N01 alloy and partly that of other aluminum alloys with commercial and tentative filler wires.

The main conclusions obtained are as follows;

(1) The features of various cracking tests were evaluated in Table 3 from the viewpoints of discrimination of the difference in crack susceptibility, reproducibility of data tested, simplicity and economy of test method.

(2) On the basis of the cracking test results in this experiment, the authors have recommened as the most practical test method the modified Houldcroft test for weld bead cracking test with GTA and GMA weldings and GMA weld crater cracking test for weld crater cracking test for GMA welding.

(3) Crack susceptibility of Al-2%Zn-3%Mg alloy which is a model alloy of 7N01 GMA weld metal made with 5356 filler wire was reduced by the addition of 0.2%Zr or 0.007%Ti+B in both weld bead and ring-casting. This is considered to be mainly due to the grain refinement in weld bead and casting.

(4) According to the test results of modified Houldcroft test with GMAW and GMA weld crater cracking test, Al-6%Mg added with 0.25%Zr filler wire was considered to the most effective filler wire to reduce the crack susceptibilities of weld bead and weld crater of 7N01 base metal for GMA welding. This is considered to be mainly due to the grain refinement of weld bead and weld crater. However, these results didn't always agree with Lap-fillet test result.

(5) The crack susceptibilities of GTA and GMA weld beads evaluated by modified Houldcroft test didn't always coincide with each other. This is considered to be a large difference in degree of dilution of elements in filler wire existing between both welding processes.

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