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Improvement of weld solidification crack susceptibility of Al-Zn-Mg ternary alloy by low-frequency pulsed GMA (MIG) welding with trial-manufactured Zr-added Al-high-Mg welding wire

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Summary: The grain refinement and solidification crack susceptibility of GMA (MIG) weld metal produced with Al-4.5%Zn–1.2%Mg A7N01 base metal have been successfully improved by a combination of low- frequency switching pulsed GMA welding and a new trial-manufactured Al- 7%Mg welding wire containing added Zr as a microalloying element. The results show a close relationship between the grain size of the weld metal and the crack susceptibility, with a sharp reduction in the crack susceptibility being obtained in weld metal with fine equiaxed grains of 20–30 m dia. The pronounced grain refinement can only be obtained by a combination of low-frequency pulsed GMA welding at a switching frequency of 2.5–50 Hz and trial-manufactured Zr-added Al-7%Mg wire. Little grain refinement is found with Zr-free wire. The paper discusses the relation- ship between grain refinement and the oscillation behaviour of the molten pool due to current pulsation.

Introduction

Despite their high strength, A7N01 and A7003, as examples of Al-Zn-Mg ternary alloys, feature excellent extrudability and natural ageing ability and are therefore extensively used in welded structures to achieve weight-saving in a variety of industrial fields, including railway rolling stock. These alloys, however, basically have a high solidification crack susceptibility, a feature calling for special attention during their fusion welding.[1]

Some of the authors have previously described an investigation of a method for improvement of the solidification crack susceptibility of these alloys,[2,3] have noted the effect of zirconium (Zr) as a microalloying element, and have shown that the grain structure of the weld beads can be refined by suitable addition of Zr and that the solidification crack susceptibility can be appreciably improved.[2] The effective added amount of Zr for this purpose, however, must be around 0.3% or more. To reduce this effective added amount to a practical level, Ref. 3 considers electromagnetic stirring of the molten pool during welding and shows that grain refinement can be promoted by suitable stirring, and that the effective added amount of Zr can be reduced to around 0.2%.

For stirring of the molten pool, the method of current pulsation (pulsed welding process) has long been known, in addition to electromagnetic stirring.[4] For stirring of the molten pool by the pulsed welding process, there is no need for any special facilities, such as the excitation coil in electromagnetic stirring. Stirring can be simply achieved by control of a suitable welding current waveform on a commercial inverter-controlled welder, so that the current pulsation method is extremely effective in practice. To achieve effective stirring of the molten pool by this method, electromagnetic stirring results suggest that it is necessary to use what is known as a low-frequency pulse with a pulse frequency of several Hz to several tens of Hz.[5–7] Conventional pulsed MIG welding is an important process in welding practice, but it is difficult to perform stable arc welding in the low-frequency range of several Hz to several tens of Hz.[8]

Some of the authors, however, have recently developed a new low- frequency pulsed MIG welding process based on alternate switching of two different unit pulse conditions at medium frequencies of around 100 Hz to allow stable arc welding even in the switching frequency range of several Hz to several tens of Hz.[9] In Al alloy applications, some of the authors have found that, under suitable pulsed welding frequency conditions, this method improves the grain refinement of welds and consequently reduces the solidification crack susceptibility.[10] They have also confirmed its effectiveness for void suppression.[11]

On the basis of this experience, the present paper describes how the grain refinement and solidification crack susceptibility of GMA weld metal produced in Al-4.5%Zn–1.2%Mg A7N01 base metal have been successfully improved by a combination of low-frequency switching pulsed GMA welding and a new trial-manufactured Al-7%Mg welding wire containing added Zr as a microalloying element. This is due to the synergistic effect of the Zr-added Al-7%Mg wire being supplied to the molten pool and stirring of the molten pool being induced by current pulsation.

Table 1 Chemical compositions of base metals and welding wires used

Material		Chemical composition (mass%)									Remarks
		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	
Base metal	A7N01	0.07	0.16	0.09	0.48	1.13	0.20	4.50	0.03	0.13	3mmt
	A5083	0.14	0.19	0.04	0.67	4.57	0.13	0.01	0.03	—	
Welding wire	A5356	0.05	0.14	0.01	0.09	4.82	0.10	Tr	0.09	—	1.6mm diam.
	A5183	0.07	0.15	0.01	0.55	4.81	0.08	0.01	0.06	—	
	7Mg	0.08	0.17	Tr	0.12	7.22	0.11	0.01	0.07	—	
	7MgZr	0.05	0.17	Tr	0.12	6.60	Tr	0.09	0.01	0.25	

Materials used and experimental method

Materials used

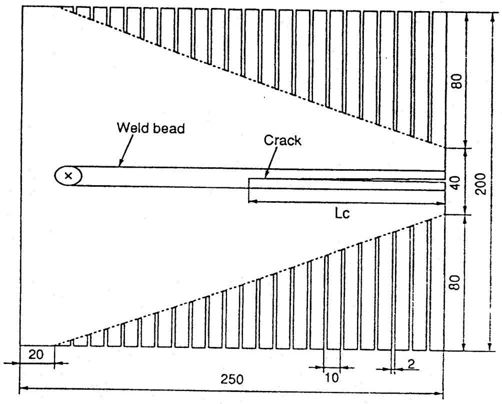
The base metal mainly used in the solidification cracking tests was A7N01. The reference base metal used was A5083, an Al alloy for welded structures for which extensive results are currently available. The welding wires used were commercial Al-5%Mg wire (A5356) generally used at present for A7N01 as well as trial-manufactured Al-7%Mg wire (7Mg wire) and 7MgZr wire obtained by addition of 0.25%Zr to the latter, both having higher Mg contents than A5356. Commercial A5183 was used for A5083. The base metal plate thickness and welding wire diameter were 3 and 1.6 mm respectively. Table 1 lists their chemical compositions. The reason for application of trial-manufactured Al-7%Mg alloy was that the solidification crack susceptibility of Al-Zn-Mg ternary alloys decreases with an increasing Mg content.[12–14]

Weld solidification crack test method

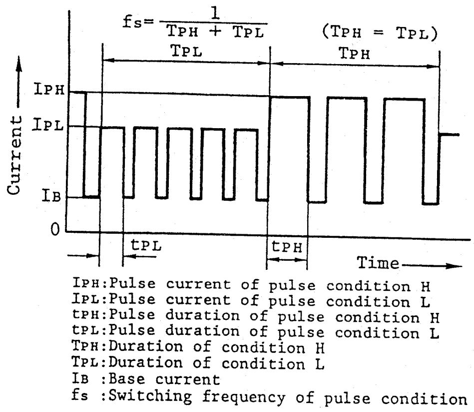
As previously reported,[10] the solidification crack susceptibility of pulsed MIG welds was evaluated by the modified Houldcroft cracking test. As distinct from the conventional Houldcroft cracking test, this test method is intended to increase the plate rigidity by making the slit shallower as welding progresses, to control the rotating deformation of the specimen so that the molten metal is cracked under tension, and to arrest crack propagation.[15,16] The conventional Houldcroft cracking test can only be applied to low-speed welding up to 300 mm/min at most, whereas the modified Houldcroft cracking test can also be employed for higher-speed welding.[16] The solidification crack susceptibility is then determined by the value (%) obtained through division of the crack length by the specimen length of 250 mm. Figure 1 shows the specimen geometry. Since A7N01 has a high solidification crack susceptibility, however, the specimen plate width is greater than previously reported. SEM observations were also used to verify that the cracks initiated by this test method were always solidification cracks.

Low-frequency pulsed MIG welding process

Figure 2 gives a schematic illustration of the voltage and current waveforms used during low-frequency pulsed MIG welding in the present investigation. The method adopted was intended to ensure periodic switching of two unit pulses (a combination of the pulse current value I_P and pulse width t_P) within the one pulse/one droplet range under stable welding droplet transfer conditions.[9] In what is known as conventional pulsed welding, only each individual unit pulse is used.



1 *Shape and dimension of modified Houldcroft type cracking test specimen.*



2 *Low-frequency pulsed current waveform and its notation.*

Under oscillation of the molten pool during pulsed welding, stirring inside the molten pool may be expected to occur. This oscillation is caused by fluctuation of the arc force, which is reportedly proportional to the peak current value.[8] The research objectives pursued imply that it is desirable to have a large difference in the peak current values of the two unit pulses. If this difference is too large, however, it is conversely impossible to perform

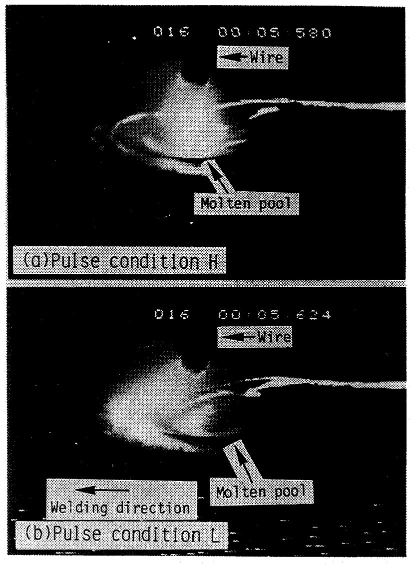
Table 2 Low frequency pulsed welding conditions

Pulse condition L(I_{PL} : 360A, t_{PL} : 1.2ms)
Pulse condition H(I_{PH} : 400A, t_{PH} : 2.0ms)
Base current, I_B : 30A
Switching frequency, fs : 0-50Hz
Average welding current, I_{av} : 95A
Average arc voltage, E_{av} : 19V
Welding speed, v : 400mm/min
Shielding gas : Pure Ar, 25l/min

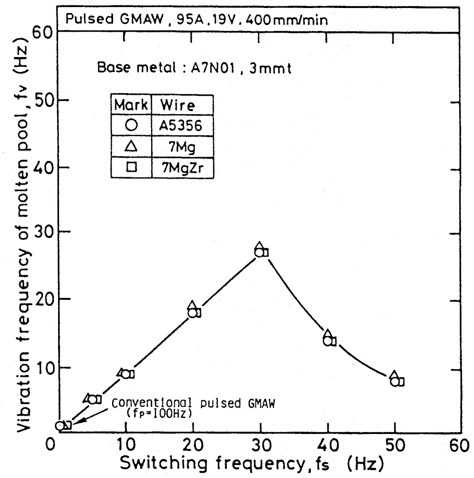
stable welding. For this reason, a detailed preliminary investigation was performed, with the low-frequency pulsed welding conditions listed in Table 2 being set. The conditions of an average welding current I_{av} of 95A, average voltage E_{av} of 19 V, and welding speed v of 400 mm/min were adopted to obtain complete two- dimensional beads in the 3 mm thick crack specimen. From among available unit pulse conditions satisfying the latter, tabulated unit pulse conditions H and L were selected to allow a large difference in I_P and stable unit pulse switching. The unit pulse switching frequency f_s was varied between 0–50 Hz. Switching frequency $f_s = 0$ Hz corresponds to conventional pulsed welding under unit pulse condition L or H.

Method for dynamic observations of oscillation of molten pool surface

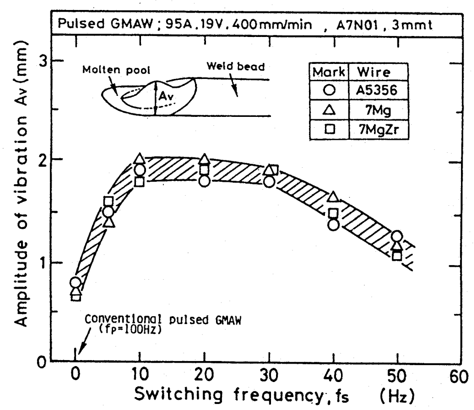
As previously reported,[10] the oscillation patterns of the molten pool surface during low-frequency pulsed GMA welding were photographed with a high-speed video camera (500 frames/sec) from an angle of around 15o from the horizontal with xenon lamp back-lighting. Figure 3a and b respectively show the oscillation patterns of the molten pool surface under unit pulse conditions H and L. During the period of pulse condition H, the molten pool surface becomes concave, conversely becoming convex during the period of L. The difference in this vertical motion of the molten pool surface during one period was measured on a monitor display, this value being adopted as the apparent amplitude. The oscillation frequency was also simultaneously measured.



3 *Typical oscillation pattern of molten pool, A7N01/MgZr, $f_s = 30$ Hz.*



4 *Relation between switching frequency and vibration frequency of molten pool.*



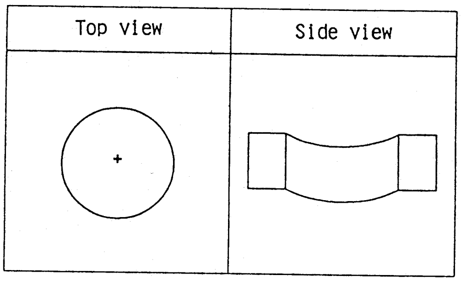
5 *Relation between switching frequency and amplitude of vibration of molten pool surface.*

Experimental results and discussion

Oscillation of molten pool during low-frequency pulsed GMA welding

Figures 4 and 5 show the relationship between the oscillation frequency of the molten pool surface f_v, its apparent amplitude, and f_s for A7N01 base metal and A5356, 7Mg, and 7MgZr wires.

Figure 4 initially shows that, up to $f_s = 30$ Hz, the oscillation frequency of the molten pool surface f_v virtually coincides with f_s and that the molten pool oscillates synchronously with f_s. At a higher switching frequency, however, f_v also decreases with an increasing f_s, with f_v decreasing to around 9 Hz at $f_s = 50$ Hz. This relationship between the molten pool oscillation and pulse frequency also shows much the same trend irrespective of the wire type. Figure 5 showing the amplitude suggests that, when $f_s = 0$ Hz, i.e. during conventional pulsed MIG welding, the molten pool gently oscillates at around 0.5 Hz, though the amplitude is small. In low-frequency pulsed GMA welding, however, the amplitude sharply increases with an increasing f_s, becoming saturated at a virtually constant value in the 10–30 Hz range. This value is 2.6–2.9-



6 *Oscillation mode in a fully penetrated molten pool.*

fold greater than in conventional pulsed welding. Beyond this level, however, the amplitude asymptotically decreases with an increasing f_s. Even at 50 Hz, however, the amplitude is 1.5–1.7-fold greater than in conventional pulsed welding, with low-frequency pulsed GMA welding still exerting an effect. These results also show much the same trend irrespective of the wire type.

The foregoing results suggest that, in the low-frequency pulsed GMA welding process adopted in this investigation, more vigorous molten pool oscillation can be produced than in conventional pulsed MIG welding under the pulsed welding conditions listed in Table 2.

Since the maximum oscillation is obtained at $f_s = 10$–30 Hz and f_s and f_v virtually coincide in this frequency range, this indicates that this frequency range corresponds to the natural oscillation frequency of the molten pool. Reference 8 has already described a detailed analysis of molten pool oscillation during pulsed welding. The following simple relation can be used to estimate the natural oscillation frequency of the molten pool in the oscillation mode pertaining to the production of complete two-dimensional beads (Fig. 6): (Ref. 17)

$$f = 1.08\ (\gamma/\rho h)^{1/2}/D \qquad [1]$$

where:
f: natural oscillation frequency, γ: surface tension of molten metal, ρ: density of molten metal, h: plate thickness (thickness of molten pool), D: diameter of molten pool.

A real molten pool has the shape of a slender ellipse in the direction of welding progression, and the molten pool shape is little changed by the wire type or pulse frequency. Its minor axis and major axis respectively average 9.3 mm (8–10 mm) and 13.1 mm (12–15 mm). The minor axis/major axis ratio averages 1.42 (1.3–1.5). Determination of the diameter of an equivalent circle gives a mean value of 10.7 mm (9.8–11.6 mm). The specimen plate thickness used here was 3 mm. In MIG welding, however, since filler material was supplied by wire, the molten pool thickness h averaged 6.1 mm (6.0–6.5 mm). For calculation of f by equation [1], the molten pool form factors noted above were used. The molten pool during arc welding of Al alloys was assumed to be superheated normally at 800–1000 °C with a maximum of around 1200 °C.[8,18] The values of γ and ρ used were those applicable to pure Al at 660–1200 °C.[19] Table 3 lists the calculated results. This tabulation suggests that the calculated natural oscillation frequency basically ranges between 20–30 Hz, which is the range within which oscillation most readily occurs. This range virtually coincides with the frequency range showing the most vigorous oscillation as determined in Fig. 5. These results suggest that the molten pool oscillation during low-frequency pulsed MIG welding as used in this investigation is basically controlled by the natural oscillation phenomena of the molten pool.

Grain refinement of weld metal by low-frequency pulsed GMA welding

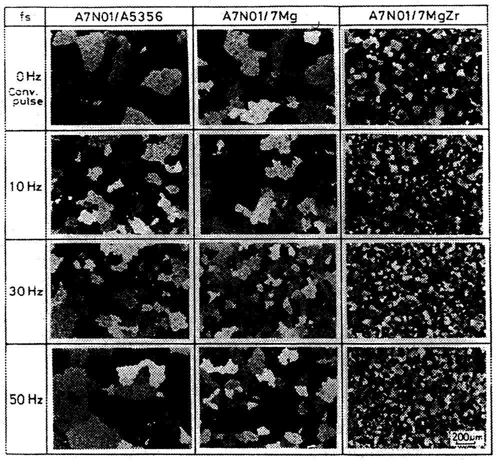
Figure 7 shows typical microstructures of the weld beads produced with each wire in relation to f_s. In all cases, application of a low- frequency pulse leads to grain refinement, this effect being especially pronounced for 7MgZr where the weld bead as a whole consists of fine equiaxed grains irrespective of f_s.

Figure 8 shows the relationship between the mean grain size and f_s. This diagram shows that, when A5356 and 7Mg wires are used, the mean grain size strongly depends on f_s. That is to say, the mean grain size asymptotically decreases with an increasing f_s, being minimised at $f_s = 30$ Hz. It thereafter asymptotically increases with an increasing f_s, approaching the value found during conventional pulsed welding. Even at $f_s = 50$ Hz, however, it is

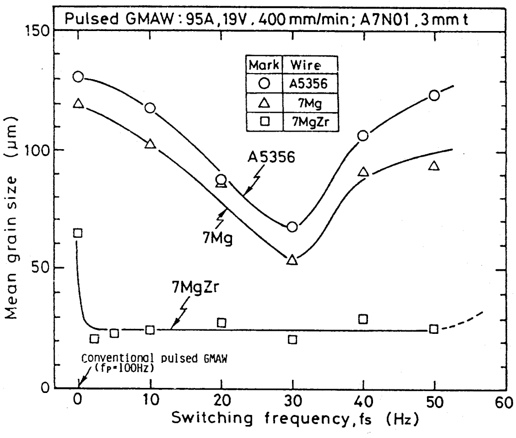
Table 3 Calculated oscillation frequency of pure Al molten pool at different temperatures and diameters of molten pool

Temperature of molten pool (°C)	Density of molten metal ρ (kg/m^3)	Surface tension of molten metal γ (N/m)	Thickness of molten pool h (mm)	Diameter of molten pool D (mm)	Oscillation frequency f (Hz)
660	2385	0.914	6.1	9.3*	29
				10.7**	26
				13.1***	21
800	2346	0.865	6.1	9.3	29
				10.7	25
				13.1	20
1000	2290	0.795	6.1	9.3	28
				10.7	25
				13.1	20
1200	2234	0.725	6.1	9.3	27
				10.7	24
				13.1	19

*Short diameter
**Equivalent diameter
***Long diameter



7 Relation between macrostructure of A7N01 weld bead and switching frequency with different wires.



8 *Effect of switching frequency on mean grain size of A7N01 weld bead with different wires.*

still lower than the value found during conventional pulsed welding. On the other hand, when 7MgZr is used, Fig. 7 suggests that there is already some grain refinement by conventional pulsed welding. In low-frequency pulsed GMA welding, major grain refinement takes place across the $f_s = 2.5$–50 Hz range. The mean grain size here always falls to 20–30 μm dia., being around 1/2 the value at $f_s = 30$ Hz where most grain refinement is found when A5356 and 7Mg wires are used. This value is also equivalent to that of the fine equiaxed grains obtained by addition of a large amount of Zr as previously reported[2,3] and the value obtained by electromagnetic stirring.[3]

Table 4 lists the Mg, Zn, and Zr contents of the weld beads. The contents of these elements are little changed

Table 4 Mg, Zn and Zr content of A7N01 weld bead with different switching frequency and wires

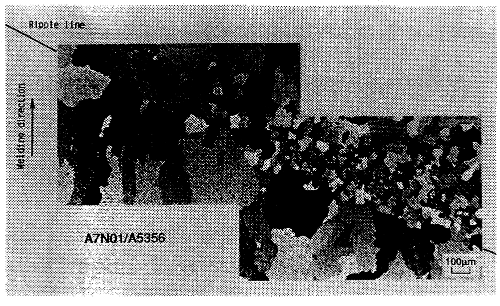
Welding wire	fs (Hz)	Chemical composition (mass%) Mg	Zn	Zr
A5356	0	2.6	2.4	0.07
	30	2.6	2.4	0.07
7Mg	0	3.3	2.5	0.07
	30	3.5	2.4	0.07
	50	3.2	2.4	0.08
7MgZr	0	3.3	2.4	0.18
	10	3.4	2.2	0.18
	30	3.3	2.4	0.18
	50	3.5	2.1	0.18

depending on f_s in both conventional pulsed welding and low-frequency pulsed MIG welding when any wire is used. This suggests that the change in the mean grain size due to f_s with each wire is not caused by a change in the composition depending on f_s, but depends on oscillation of the molten pool as previously described. With regard for the fact that there is no change in the molten pool oscillation depending on the wire type, the difference in the degree of refinement due to the wires is considered to depend on the Zr and Mg contents in the weld bead. A comparison of A5356 and 7Mg initially shows that the latter with a higher Mg content gives greater refinement. This is attributable to an increase in compositional supercooling with an increasing Mg content.[20] The refining capacity of Mg, however, is relatively low, and the mean grain size in this case exhibits a distinct frequency dependence as shown in Fig. 8. That is to say, grain solidification nuclei are vigorously formed during the sharp temperature change associated with the hot metal flow at the solidification front, giving a grain growth process during steady hot metal flow.[5–7]

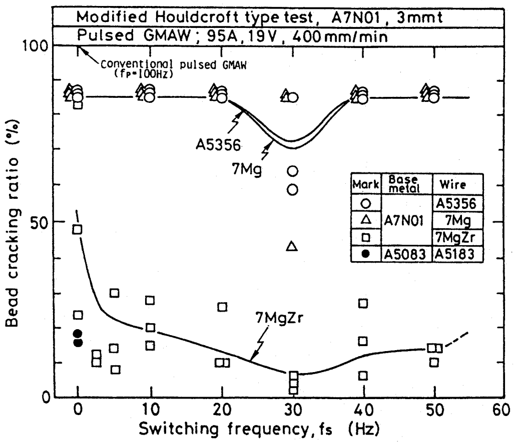
In low-frequency pulsed GMA welding used in this investigation, the former occurs during unit pulse switching and the latter during each unit pulse period. This accordingly leads to the formation of weld bead refinement bands corresponding to f_s. At a constant welding speed, the number of refinement bands per unit bead length also increases with an increasing f_s, so that refinement also progresses with f_s. This assumes, however, that f_s is within the natural oscillation range. If f_s is above this range, the effect of molten pool oscillation conversely decreases, and the stirring effect declines, so that there is a decrease in the refinement effect itself. There is thus an optimum f_s for grain refinement.[5–7]

Figure 9 shows the discontinuous weld bead structure found when A5356 wire is used. This picture shows suppression of the growth of the columnar crystals which grow from the bottom of the photograph along the ripple line considered to indicate heavy fluctuation of the solidification conditions. This leads to the local formation of fine equiaxed grains with a size of several μm to several tens of μm. Because of the insufficient amount of Zr in the weld bead here, however, the number of fine equiaxed grains formed is also insufficient, and this does not result in grain refinement of the weld bead as a whole.

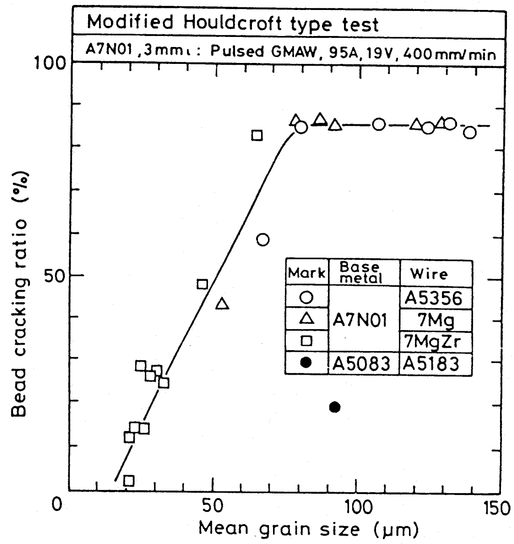
The differences in A5356, 7Mg, and 7MgZr, however, depend on the Zr content. As previously noted, Zr is a powerful grain refining element in Al alloys.[21,22] Paper 3



9 *Macrostructural change showing discontinuous growth caused by the change of soldification condition, A7N01/A5356, $f_s = 0$ Hz.*



10 *Effect of switching frequency on bead cracking ratio of A7N01 weld bead with different wires.*



11 *Relation between mean grain size and bead cracking ratio of A7N01 weld bead with different wires.*

reports that this refining effect is strongly promoted by stirring of the molten pool. The degree of refinement achieved depends on both the Zr content and the degree of stirring, and even slight stirring leads to refinement if the Zr content is sufficiently high.[3] To produce fine equiaxed grains in Al-Zn-Mg ternary alloy welds by low-frequency pulsed GMA welding, Table 4 shows that it is necessary to have a Zr content of 0.18%. This is consistent with the value previously reported for electromagnetic stirring.[3]

The foregoing results suggest that pronounced grain refinement can be achieved in Al-Zn-Mg ternary alloy welds by a combination of low- frequency pulsed GMA welding and trial-manufactured 7MgZr welding wire containing added Zr.

Solidification crack susceptibility of low-frequency pulsed GMA weld metal

The foregoing results indicate that pronounced grain refinement can be achieved in Al-Zn-Mg ternary alloy welds by a combination of low- frequency pulsed GMA welding and trial-manufactured 7MgZr welding wire containing added Zr. An effort was subsequently made to establish, by the modified Houldcroft cracking test, whether the solidification crack susceptibility is improved with grain refinement by the modified Houldcroft cracking test.

Figure 10 shows the relationship between the bead cracking ratio and f_s. In conventional pulsed welding (f_s 0 Hz), A7N01 has a greater bead cracking ratio than A5083/A5183 when any wire is used. This is due to its high solidification crack susceptibility. With 7MgZr, however, some grain refinement is found even in conventional pulsed welding, and, although the corresponding bead cracking ratio fluctuates, it is on average less than for the other wires. Next, when A5356 and 7Mg are used in low-frequency pulsed GMA welding, the bead cracking ratio tends to decrease somewhat at $f_s = 30$ Hz, where grain refinement mostly occurs. At any other f_s value, there is a high bead cracking ratio. When 7MgZr is used, however, heavy grain refinement is found across a wide frequency range of 2.5–50 Hz, and the bead cracking ratio decreases to a value equivalent to or below that of A5083/A5183.

Figure 11 shows the relationship between the bead cracking ratio and the mean grain size of welds. Both parameters bear a close relationship. For A7N01, the bead cracking ratio decreases to a value equivalent to that of A5083 when the mean grain size is refined to 20–30 μm. This result is consistent with that obtained in the previously reported investigation of MIG welds with electromagnetic stirring.[3] The fact that A5083/A5183 have a low bead cracking ratio despite their relatively large grain size is due to a difference in the alloy system. As previously reported,[10] improvement of the solidification crack susceptibility by low-frequency pulsed GMA welding may therefore be regarded as being due to grain refinement.

The foregoing results suggest that pronounced grain refinement can be achieved in Al-Zn-Mg ternary welds by a combination of low-frequency pulsed GMA welding and trial-manufactured 7MgZr welding wire containing added Zr and that the solidification crack resistance can thereby be appreciably improved.

Conclusions

The present paper describes how the grain refinement and solidification crack susceptibility of GMA weld metal produced with Al-4.5%Zn-1.2%Mg A7N01 base metal have been successfully improved by a combination of low-frequency switching pulsed GMA welding and a new trial-manufactured Al-7%MgZr welding wire containing added Zr as a microalloying element. This is due to the synergistic effect of the Zr-added Al-7%Mg wire being supplied to the molten pool and stirring of the molten pool being induced by current pulsation. The results obtained may be summarised as follows:

1 In low-frequency pulsed GMA welding involving periodic switching of two unit pulse conditions within the one pulse/one droplet range ensuring stable welding droplet transfer as used in conventional pulsed MIG welding, the molten pool surface becomes concave at the centre during the high peak current period, vertically oscillating and becoming

convex during the low period. This vertical oscillation occurs synchronously up to a switching frequency (unit pulse switching frequency) of $f_s = 30$ Hz. At a higher frequency, however, it conversely decreases without any synchronism being involved. The amplitude of the molten pool surface increases with an increasing f_s, being maximised at 10–30 Hz and having a value 2.6–2.9-fold greater than by conventional pulsed welding. Beyond this f_s level, however, the amplitude asymptotically decreases with an increasing f_s. Even at 50 Hz, however, the amplitude is 1.5–1.7-fold greater than by conventional pulsed welding.

2 In low-frequency pulsed GMA welding of A7N01 base metal with Zr- added Al-7%MgZr wire, pronounced grain refinement is found across a wide frequency range of 2.5–50 Hz, with weld beads as a whole forming fine equiaxed grains with a mean grain size up to 20–30 μm. Even when A5356 and Al-7%Mg wires are used, grain refinement is found, with its degree showing a frequency dependence and most grain refinement taking place at 30 Hz. The degree of grain refinement produced is somewhat lower than when Al-7%MgZr wire is used.

3 The bead cracking ratio of A7N01 MIG welds evaluated by the modified Houldcroft cracking test has a high value in conventional pulsed welding when any wire is used. Even when Al-7%MgZr wire is used, there is little improvement. In low-frequency pulsed GMA welding with Al-7%MgZr wire, however, the bead cracking ratio sharply decreases under any conditions in the 2.5–50 Hz frequency range where pronounced grain refinement is found and falls to a sufficiently low value equivalent to that of A5083/A5183. With the A5356 and Al-7%Mg wire combination, the bead cracking ratio only slightly decreases at 30 Hz where most grain refinement is found.

4 The bead cracking ratio depends on the mean grain size, and, when fine equiaxed grains are formed, the bead cracking ratio linearly decreases with an increasing mean grain size. To achieve a satisfactory reduction in the solidification crack susceptibility of A7N01 weld beads to a value equivalent to that of A5083/A5183, the mean grain size should be reduced to 20–30 μm.

The foregoing results suggest that pronounced grain refinement can be achieved in Al-Zn-Mg ternary at welds by a combination of low-frequency pulsed GMA welding and trial-manufactured 7MgZr welding wire containing added Zr and that the solidification crack susceptibility resistance can thereby be appreciably improved.

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