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Beneficial effects of low-frequency pulsed MIG welding on grain refinement of weld metal and improvement of solidification crack susceptibility of aluminium alloys: Study of low-frequency pulsed MIG welding

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Introduction

Various methods for grain refinement of aluminium alloy weld metal have been previously investigated, e.g. by magnetic stirring in TIG welding,[1-5] and using vibration and stirring of the molten pool by pulsed arc welding.[6] These methods have been suitably validated, and practical applications are in progress. Attempts to achieve grain refinement by combination of MIG welding with the above-noted techniques, however, have not been successful because of the problems noted below.

First, when MIG welding is combined with magnetic stirring, the need to equip the welding torch or base metal back surface with an excitation coil sets limits on the range of operating conditions for MIG welding. Induction of an external magnetic field also destabilises droplet transfer and leads to heavy spattering.

In an investigation of grain refinement by pulsed arc welding, some of the authors[7] have adopted a pulse current waveform in which the pulse current is based on the welding current in the spray transfer zone and the background current on the welding current in the short-circuit transfer zone. They have also used welding wire containing a trace amount of an element intended to promote grain refinement, such as Zr, Ti, or B. The authors have further demonstrated the effectiveness of this approach.

Depending on the welding conditions applied, however, this method is limited in terms of the pulse frequency range over which the arc conditions can be varied and stability maintained, as by TIG welding. That is to say, when the foregoing pulsed MIG welding process is used, if the welding current is varied within a period (low frequency) longer than the time constant of wire fusion, the arc length is prone to unstable fluctuations.[8] For this reason, the effect of pulsed MIG welding on grain refinement in the low-frequency range below 20 Hz is beyond the current range of experimental investigation. Moreover, when sheet-like specimens of the type used in Houldcroft tests are employed, welding at a low current within the range from several tens of A to around 100 A is performed, so that the range of conditions within which the pulse frequency can be set is extremely narrow and cannot be properly investigated. On the other hand, in the first report of this study,[9] the authors have developed a low-frequency pulsed MIG welding process in which the arc conditions can be arbitrarily varied within an acceptable droplet transfer range. They have further described the oeprating principle and effectiveness of this process.

To overcome the problems facing application of low-frequency pulsed MIG welding, the present paper describes the effect of the welding current waveform conditions on weld metal grain refinement of aluminium alloys, together with an investigation of the beneficial effect of grain refinement on solidification crack susceptibility.

Experimental method

Materials used

The base metal in these experiments was commercial 3 mm thick Al-Mg alloy (A5052). The welding wire was commercial 1.6 mm dia Al-Mg alloy wire (A5356-WY). Table 1 lists their chemical compositions. The welding wire contained 0.11% Ti for grain refining.

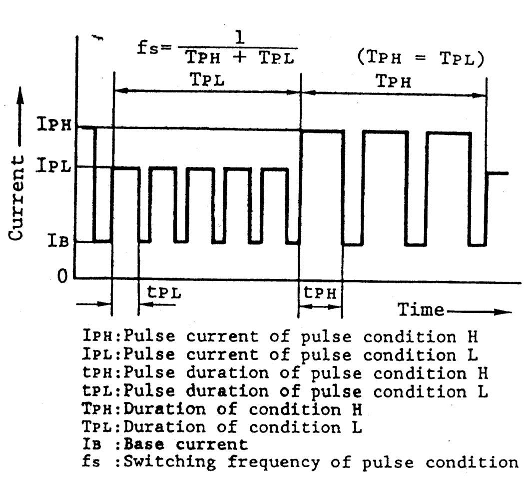
Low-frequency pulsed MIG welding

Low-frequency pulsed MIG welding is performed by an inverter-controlled welding power source able to perform periodic switching of two unit pulse conditions in the current waveforms shown in Fig. 1. This switching function applied within the appropriate unit pulse condition range (of pulse current value I_P and pulse amplitude t_P) over which pulse-synchronised projection transfer is possible.

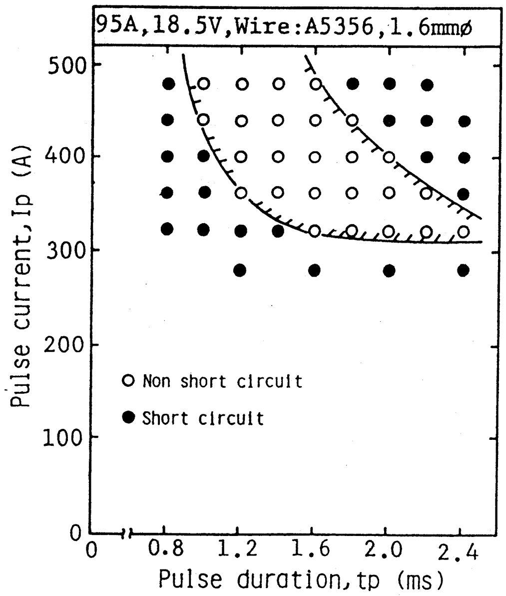
Figure 2 presents the results obtained for the appropriate unit pulse condition range at a wire diameter of 1.6 mm by high-speed video photography and waveform analysis[10] (described below). These results suggest that, as previously reported, there is a wide range of appropriate unit pulse

Table 1 Chemical composition of materials used

Materials		Chemical compositions (wt%)							
		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Base metal	A5052	0.10	0.27	0.02	0.02	2.40	0.21	0.01	-
Filler wire	A5356	0.08	0.14	0.01	0.10	5.16	0.09	0.01	0.11



1 *Low frequency pulsed current waveform and its notation.*

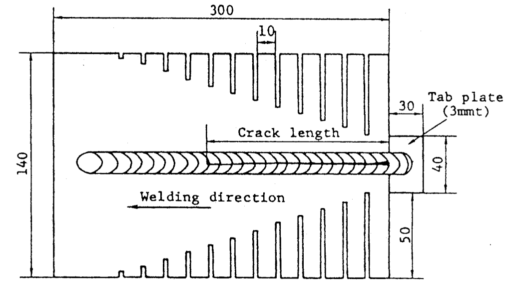


2 *Appropriate pulse conditions in pulsed MIG welding for aluminium alloy.*

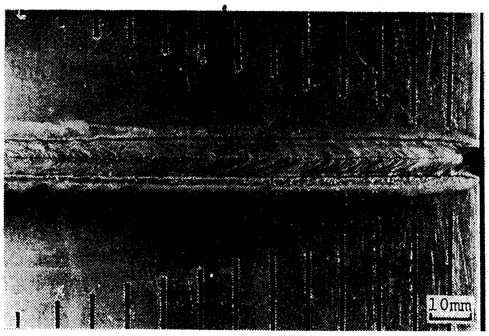
Table 2 Waveform conditions

Pulse condition H
Pulse current, IPH : 360-480A
Pulse duration, tPH: 1.6-2.2ms
Pulse condition L
Pulse current, IPL : 360A
Pulse duration, tPL: 1.2ms
Switching frequency, fs: 2.5-50Hz
Base current, IB: 30A

conditions within which satisfactory welding droplet transfer can be obtained even at a wire diameter of 1.6 mm. Within the appropriate unit pulse condition range marked by the hatching in this diagram, the two periodically switched unit pulse conditions (pulse condition L and pulse condition H) are selected, as shown in Table 2. The base current value I_B in each unit pulse condition was always set at 30 A, and the switching frequency f_s of the unit pulse conditions ranged between 2-50 Hz. By conventional pulsed MIG welding without any switching of the unit pulse conditions, bead-on-plate welding was performed under pulse condition L (at pulse frequency f = 115 Hz).



3 *Shape and dimension of modified Houldcroft test specimen (specimen thickness : 3 mmt).*



4 *Appearance of weld bead showing cracking.*

Solidification cracking tests

Figure 3 shows the geometry of the modified Houldcroft test specimen. Welding was performed from the deep to shallow side of the slit in this specimen.[11,12] The welding conditions applied under the pulsed current waveform conditions indicated above were an average welding current I_{av} of 95 A, an average arc voltage E_{av} of 18.5 V, and a welding speed v of 40 cm/min. By this means, it was possible to produce a weld with uniform penetration from the start of welding to completion.

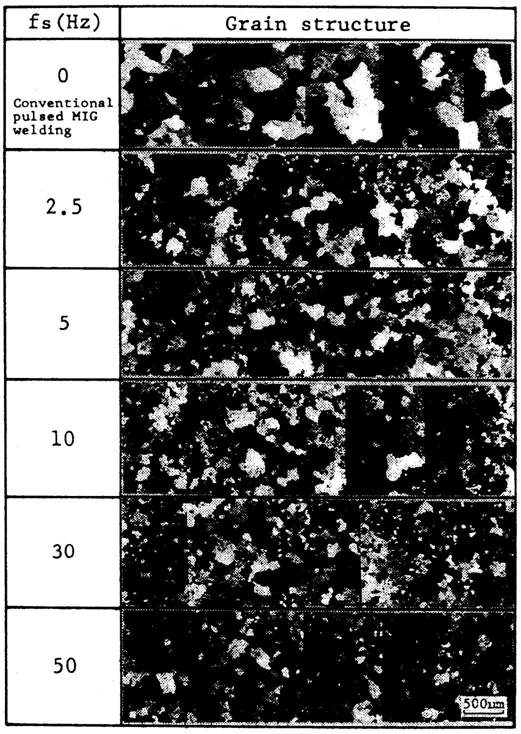
In determination of solidification crack susceptibility, the length of the arrested crack divided by the welding length (%) was used as a means of evaluation.

Macrostructural observations of the weld metal were made at a location 1.5 mm from the base metal surface in the sheet thickness direction using horizontal sections at the bead centre.

Figure 4 shows the appearance of a weld bead obtained in the solidification cracking tests. The cracking produced in these tests is revealed by the macrostructural observations to be intergranular cracking. The fracture surfaces determined by SEM fractography further reveal a dendritic morphology and clearly indicate the cracking to be of solidification cracking type.

Molten pool observations and waveform analysis method

Observations of molten pool vibration and welding droplet transfer were made with a high-speed video camera operating at 500 frames/s and 1000 frames/s using back-lighting with a xenon lamp. To analyse the arc operating point, the welding current waveform and arc voltage waveform were



5 Macrostructural change in weld metal caused by low frequency pulsed MIG welding process with various f_s values.

input to a personal computer via an A/D converter, as previously reported, and the effective value of the welding current I_{eff} and arc voltage E_{eff} were determined.

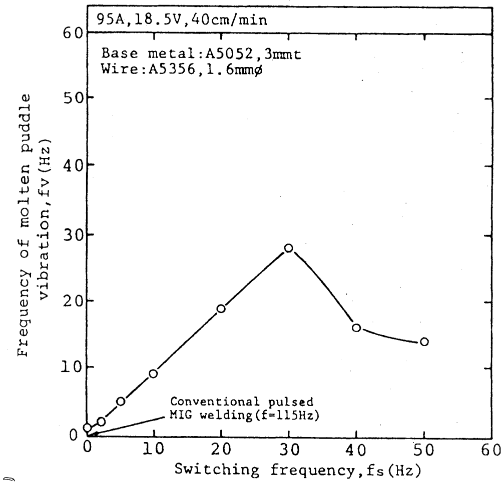
Experimental results and discussion

Effect of f_s on grain refinement and solidification crack susceptibility of weld metal

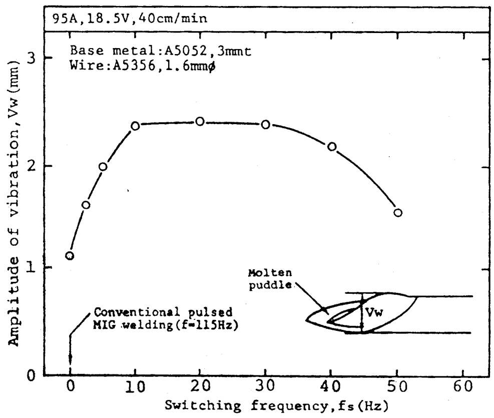
Figure 5 shows the relationship between the weld metal macrostructre and f_s at the weld centre near the location of solidification crack arrest at pulse current waveform settings of pulse condition L, I_{PL} = 360 A, t_{PL} = 1.2 ms, and pulse condition H, I_{PH} = 400 A, t_{PH} = 2.0 ms. At f_s = 0 Hz, i.e. conventional pulsed MIG welding, a coarse-grained structure is obtained (mean grain size 452 μm), whereas, when the unit pulse conditions are switched, fine grains are intermingled with coarse, with the greatest degree of grain refinement being obtained at f_s = 30 Hz (mean grain size of 150 μm). At 50 Hz (mean grain size of 250 μm), however, coarse grains are again intermingled with fine, with a uniformly refined structure no longer being produced.

The foregoing results sugget that a stirring effect is generally produced by molten pool vibration.[7] The following investigations were performed to verify these results.

Figure 6 shows the relationship between the value of f_s set during welding and the frequency of molten pool vibration during high-speed video photography. These data indicate that the frequency of molten pool vibration virtually agrees with f_s up to 30 Hz. At a frequency beyond 30 Hz, however, the frequency of molten pool vibration is no longer able to track f_s and decreases. Figure 7 also shows the relationship between f_s and measurements of the height of molten pool elevation from the base metal surface (taken as indicating the amplitude of molten pool vibration V_W as illustrated in the diagram).



6 Relation between f_s and frequency of molten pool vibration.



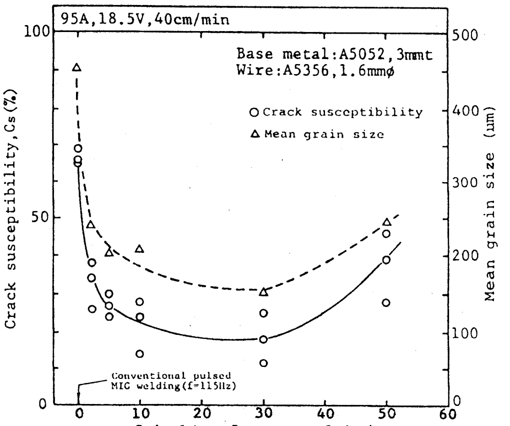
7 Relation between f_s and amplitude of vibration.

In conventional pulsed MIG welding (f_s = 0), zero amplitude is found, whereas, by the proposed welding process, the amplitude increases with an increasing f_s up to f_s = 10 Hz. The amplitude is also maximised between 10-30 Hz, showing a virtually constant value within this frequency range. Resonance between the molten pool vibration and f_s is generally recognised to make a contribution within this frequency range.[13] At a frequency beyond 30 Hz, however, the amplitude again decreases.

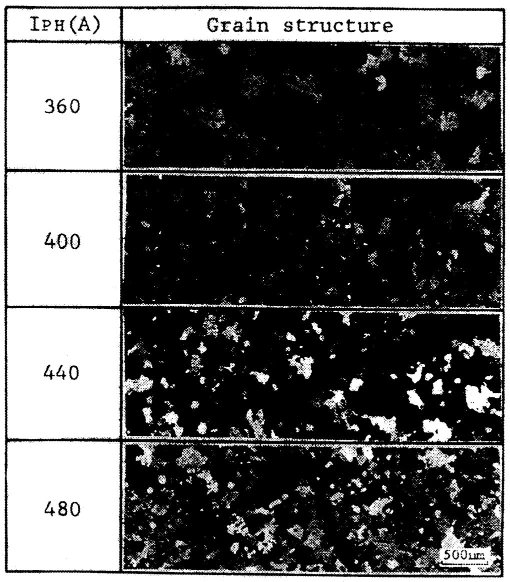
The reasons for a high degree of grain refinement occurring at f_s = 30 Hz are therefore considered to be that the time constant of molten pool vibration for suppresion of grain growth is minimum at 30 Hz, and that the amplitude maintains its maximum value at this frequency, with satisfactory stirring being obtained as far as the weld metal interior to produce uniform grain refinement of the weld metal.

Figure 8 shows the solidification cracking results presented in Fig. 5 in the form of the relationship between f_s and the crack susceptibility. The crack susceptibility shows a value as high as around 70% at f_s = 0 Hz at which a coarse-grained macrostructure is obtained. When switching of unit pulse conditions is performed, however, the crack susceptibility sharply decreases, falling to the region of f_s = 30 Hz with an increasing f_s. At a frequency beyond 30 Hz, however, the crack susceptibility tends to increase, but is lower at f_s = 50 Hz than that obtained by conventional pulsed MIG welding without any switching of unit pulse conditions.

The diagram also shows the relationship between the crack susceptibility and mean grain size, suggesting that, within the decreasing crack susceptibility range, the mean grain size is refined to 150-250 μm and clearly indicating that both factors are correlated.



8 *Effect of f_s on crack susceptibility and mean grain size.*



9 *Macrostructural change in weld metal caused by low frequency pulsed MIG welding process with various I_{PH}.*

This is due to the fact that the strain imposed on individual grain boundaries in the solid/liquid zone is dissipated by grain refinement, causing it to decrease. Under this effect, the ductility in relation to solidification cracking apparently increases,[14] making it difficult for cracking to occur.

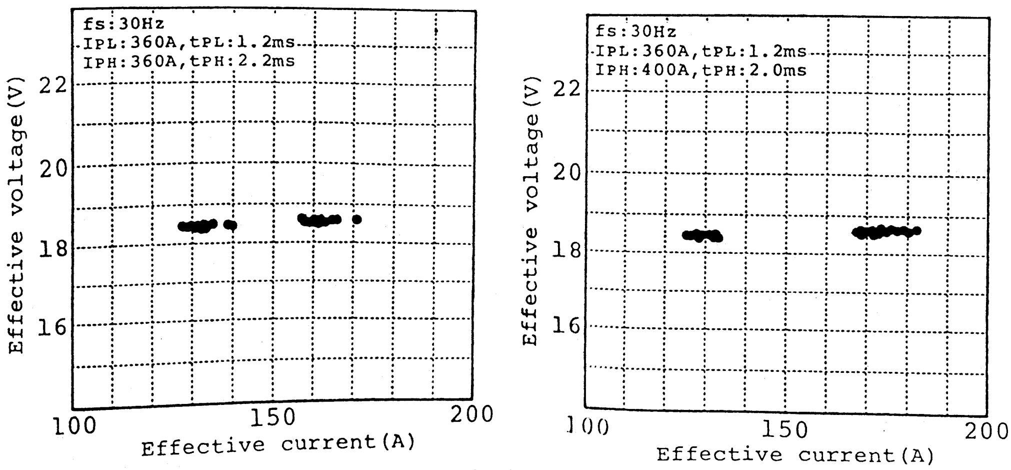
The relationship between f_s and the crack susceptibility in this diagram shows much the same trend as the results previously reported by some of the authors.[7] The present experimental results, however, show the frequency range of crack susceptibility reduction to be wider. This is attributable to the fact that, in the experiments conducted by some of the authors using 7N01 alloy with a high base metal crack susceptibility, there was unsatisfactory crack arrest during simple macrostructural refinement and it was necessary to subject the structure to uniform equiaxed grain refinement.[7] Although A5052 alloy with a relatively low crack susceptibility as used in these experiments has a non-uniform structure, cracks have difficulty in propagating when some degree of grain refinement is performed, so that the range of f_s exerting a beneficial effect on the crack susceptibility is wider.

It can also be confirmed that these results show a good correspondence with grain refinement and that low-frequency pulsed MIG welding beneficialyy affects grain refinement and thereby the solidification crack susceptibility of the weld metal.

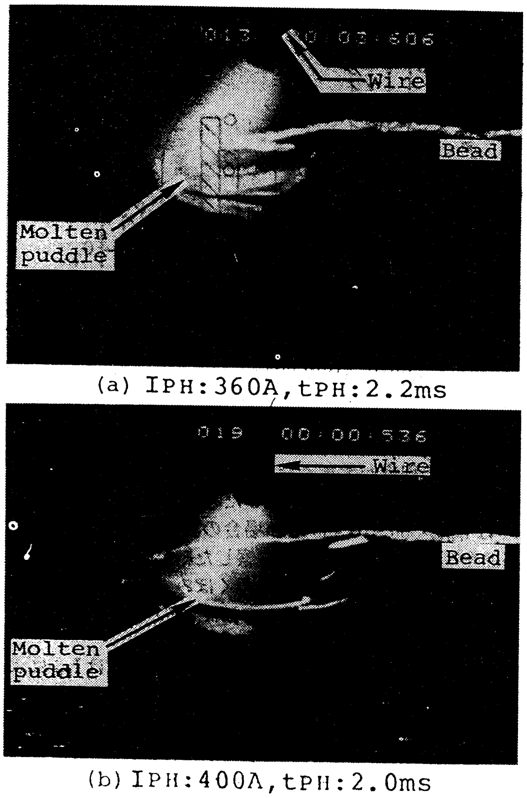
Effect of pulsed welding conditions on grain refinement and solidification crack susceptibility

On the basis of the results presented above, Fig. 9 shows the macrostructural changes in the weld metal found at constant pulse condition L values (I_{PL} = 360 A, t_{PL} = 1.2 ms) during switching at f_s = 30 Hz when I_{PH} in pulse condition H was varied to obtain a constant product of I_{PH} and t_{PH}. It is accordingly found that, when I_{PH} is 360 A, i.e. has the same current value as I_{PL} in pulse condition L, grain refinement takes place, although at a low level (mean grain size 320 μm). When I_{PH} = 400 A, i.e. $I_{PL} < I_{PH}$, however, the degree of grain refinement is more pronounced (mean grain size 150 μm).

The reason for this difference in degree of grain refinement despite the product ($I_{PH} \times t_{PH}$) of pulse condition H



10 *Relation between I_{eff} and E_{eff} in each cycle of unit pulse.*

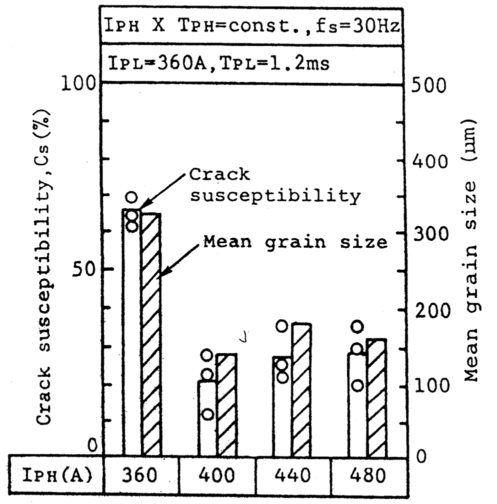


11 *Comparison of molten pool between I_{PH} = 360 A and I_{PH} = 400 A.*

being constant at an identical fs is considered below. Figure 10 shows the changes in the effective values of the welding current and arc voltage during unit pulse condition switching at f_s = 30 Hz and under pulse conditions I_{PH} = 360 A and 400 A. This diagram suggests that, despite switching of unit pulse conditions, the effective value of the arc voltage is unchanged but the effective value of the welding current sharply changes. The degree of change is greater at I_{PH} = 400 A than at I_{PH} = 360 A. An experimental investigation of TIG welding,[15] however, shows that the arc power also increases with an increasing effective value of the welding current, and this is also considered to be much the same for MIG welding. It is therefore considered that, because of the major change in the effective value of the welding current due to the introduction of a difference between I_{PL} and I_{PH} and because of the associated major change in the arc power, molten pool vibration is more vigorous, resulting in a difference in the contribution to grain refinement. Figure 11 compares the molten pool vibration conditions as observed by high-speed video photography at I_{PH} = 360 A and 400 A. A comparison of the molten pool depression found during pulse condition H reveals that the depression is deeper and the degree of vibration greater at 400 A than at 360 A.

The observations presented in Fig. 9 further appear to suggest that much the same degree of grain refinement is obtained irrespective of I_{PH} when $I_{PH} \geq 400$ A. This implies that grain refinement is satisfactorily performed by some degree of molten pool vibration. Within the presently adopted experimental range, satisfactory grain refinement is considered to be achieved at I_{PH} = 400 A.

Figure 12 compares the mean grain size and crack susceptibility corresponding to the macrostructures in Fig. 9. A



12 *Effect of I_{PH} on crack susceptibility and mean grain size.*

high crack susceptibility is found at I_{PH} = 360 A, whereas, when $I_{PH} \geq 400$ A, the crack susceptibility under grain refinement is always lower, confirming that these crack susceptibility improvement effects relate to grain refinement.

Conclusions

To overcome problems in application of low-frequency pulsed MIG welding, the present paper describes the effect of the welding current waveform conditions on weld metal grain refinement of commercial Al-Mg alloys, together with an investigation of the beneficial effect of grain refinement on the solidification crack susceptibility. The results obtained may be summarised as follows:

1. Molten pool vibration and stirring are produced by low-frequency pulsed MIG welding, and the weld metal of commercial A5052 Al-Mg alloy is refined. In particular, uniform grain refinement is found to occur at a unit pulse condition switching frequency of 30 Hz.
2. Under switched unit pulse conditions, the pulse current value strongly affects grain refinement. That is to say, grain refinement is promoted by introduction of a difference in the pulse current value of this unit pulse condition.
3. Grain refinement shows a good correspondence with the results of solidification crack susceptibility tests using modified Houldcroft specimens. Grain refinement as described under **1** and **2** is found to have a beneficial effect on the solidification crack susceptibility of the weld metal.

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