Effect of linear energy on the properties of an AL alloy in DPMIG welding

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Effect of linear energy on the properties of an AL alloy in DPMIG welding

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Abstract. The effect of different linear energy parameters on the DPMIG welding performance of AA1060 aluminium alloy is studied in this paper. The stability of the welding process is verified with a Labview electrical signal acquisition system, and the microstructure and tensile properties of the welded joint are studied via optical microscopy, scanning electron microscopy and electrical tensile tests. The test results show that the welding process for the DPMIG methods stable and that the weld beads appear as scales. Tensile strength results indicate that, with increasing linear energy, the tensile strength first increases and then decreases. The tensile strength of the joint is maximized when the linear energy is 120.5 J / mm.

1. Introduction
At present, the manufacturing industry is concerned with the light weight, strengthen and toughness, and accuracy properties of materials. Due to their excellent overall performance, including light weight; high abrasion corrosion and shock resistance; and capacity for reuse, aluminium alloys have been widely applied in industries such as transportation, shipping and aerospace [1]. Because of this wide application of aluminium alloys combined with continual increases in their processing requirements, the welding of aluminium alloy has become the focus of many studies, and new advanced welding methods, such as DPMIG, CMT, EWM-Cold Arc, friction stir welding, and hybrid laser welding, have appeared. The DPMIG method is characterized by high price/performance ratios, beautiful welds, wide gaps between joints, relatively low porosity, grain refinement, low crack sensitivity, and so it has drawn much attention [2].

For DPMIG welding, the single-frequency MIG(PMIG) is modulated by a low-frequency pulse to form a high-frequency pulse waveform. Double-pulse welding uses a low-frequency impulse to modulate the peak current and peak time, with a higher frequency controlling the droplet transition pulse. The influence of low pulse frequency on the molten pool morphology and weld microstructure was studied in [3], and the results illustrated that the weld forming was closely related to the low frequency. In particular, the larger the low frequency, the smaller the grain microstructure of the weld. Thus, it is thought that the low frequency is a key factor in DPMIG welding. In [4], the DPMIG method was used to weld aluminium alloy AA7075-T651, which was then subjected to a two-stage artificial ageing heat treatment. It is found that the hardness of the weld softening zone was greatly improved and that the mechanical properties of the welding joints were significantly improved, after heat treatment. In this study, the effect of welding energy input on the morphology and mechanical
properties of welds produced by the DPMIG method was studied to determine the optimal line energy and guide practical operation.

2. Experimental method

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The original base metal was aluminium alloy AA1060, and dimensions 300 ×150 ×3 mm³. The plate butt welding was conducted using a digital welding power NBC500, with an ER4043 welding wire of diameter 1.2mm. High-purity (99.99% concentration) argon was used as a shielding gas, and the chemical components of the base material are listed in Table 1. Relevant welding parameters are shown in Table 2. After the welding was completed, the two ends of the weld were cut out 30 mm by spark discharge wire cutting machine. Three tensile specimens and one metallographic specimen were sectioned from the vertical weld on each test plate, according to GB/T228-2002 standard, "metallic materials tensile testing at ambient temperature". The tensile test was conducted on an AG-IC type electronic universal testing machine, with a tensile rate of 1mm/min. The tests were repeated for a total of three trials, and the reported tensile strength is simply the average of the results. In addition, an MeF-3 type optical microscope and PHIL IPS-XL30 type scanning electron microscope were used to observe the microstructure of the section of the welding joint.

Table 1. Chemical compositions of AA1060 and ER4043

| Ingredient | Si  | Fe  | Cu  | Mn  | Ti  | Mg  | Zn  | Al  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| AA1060     | 0.25| 0.35| 0.05| 0.03| 0.15| 0.03| 0.05| margin |
| ER4043     | 4.5-6.0| <0.60| <0.30| <0.15| <0.15| <0.20| <0.10| margin |

Table 2. Welding process parameters

| Sample | Welding current(A) | Welding voltage(V) | Welding speed(mm·s⁻¹) | Linear energy(J·mm⁻¹) |
|--------|--------------------|--------------------|------------------------|-----------------------|
| A      | 90                 | 20                 | 10                     | 162                   |
| B      | 93                 | 20                 | 10                     | 168                   |
| C      | 96                 | 20                 | 10                     | 173                   |
| D      | 99                 | 20                 | 10                     | 178                   |
| E      | 102                | 20                 | 10                     | 184                   |
| F      | 105                | 20                 | 10                     | 189                   |

3. Results and discussion

The weld appearance under different line energies is shown in Figure 1. As the line energy was increased from 162J mm⁻¹ to 189 J mm⁻¹, the weld forming was better, the "fish-scale" pattern was clear and regular, there were no defects (such as undercut, collapse and welding penetration), and there was less spatter. These results suggest that the whole welding process was stable.
Figure 1. Weld appearance under different linear energies

Figure 2 shows the labview current waveforms with different line energies. The strong and weak pulse peak times affected the melting rate of the welding wire, as demonstrated by the small difference between the strong weak pulse peak current and base current. When the single strong and single weak pulse and the pulse frequency were held constant, the change in the number of strong and weak pulses during one DPMIG welding period can alter the welding current. This manifested itself here as a change in the weld heat input. It is clear from Figure 1 that the current amplitudes of the strong and weak pulse train of the DPMIG showed very little change and had better consistency. With increasing line energy, the number of strong pulses increased, and the number of weak pulses decreased during one DPMIG welding period. Different amounts of strong and weak pulses, in addition to welding heat input, affected the energy input in the welding process, thus affecting the oscillation of the molten pool and the grain refinement.

Figure 2. Current waveforms with different linear energies
Figure 3. Microstructure images of welded joints with a line energy of 184 J·mm⁻¹

Figure 3 displays the microstructure of the DPMIG welding joint of aluminium alloy 6061-T6, with a line energy of 184 J·mm⁻¹. As shown in Figure 3 (a), the welding joint was mainly composed of the base metal (Figure 3 (b)), a heat-affected zone (HAZ) (Figure 3 (c)) and a fusion zone (Figure 3 (d)). Moreover, the base metal was mostly dendritic α phase with inter-dendritic eutectic crystals, and black second-phase particles with irregular shape were found evenly distributed in the microstructure of the matrix [5]. Due to rapid heating, melting and solidification during the welding process, a typical dendritic crystal microstructure was observed in a solid state in the fusion zone of the DPMIG welding joint. Compared with base metal and fusion zone, the HAZ shows obviously coarsened grains, and the strengthening phase precipitated in a coacervated manner at the grain boundaries, which was caused by significant welding heat shock in the HAZ.

Surface scanning X-ray EDS microanalysis was carried out in the area of the melted zone of the jointed welded with a line energy of 184 J·mm⁻¹. The distribution of elements (Al, Mg and Si) in this area is shown in Figure 4. Figure 5 plots the tensile strength of the DPMIG welding joint as a function of line energy. The tensile strength of the welding joints was 92.35 MPa, 95.90 MPa, 101.02 MPa, 93.88 MPa, 91.80 MPa and 92.35 MPa for line energies of 162 J·mm⁻¹, 168 J·mm⁻¹, 173 J·mm⁻¹, 178 J·mm⁻¹, 184 J·mm⁻¹ and 189 J·mm⁻¹, respectively. With increasing welding heat input, the tensile strength of the DPMIG welding joint first increased and then decreased. When the line energy was 173 J·mm⁻¹, the tensile strength of the joint was at a maximum of 101.02 MPa, which is 75.4% of the tensile strength of the base metal AA1060. However, when the line energy was 184 J·mm⁻¹, the tensile strength of the joint was at a minimum of 91.80 MPa, which is only 68.5% of the tensile strength of the base metal AA1060.

Figure 4. Distribution of elements (Al, Mg and Si) of welded joints with a line energy of 184 J·mm⁻¹
Figure 5. Effect of linear energy on tensile strength of welded joints

During the tensile test, the samples fractured in the HAZ, suggesting that the weakest location of a DPMIG welding joint is the HAZ. To study the tensile fracture mechanism of the welding joint, the tensile fracture surfaces of the samples with different line energies were observed by scanning electron microscopy. As shown in Figure 7, when the line energies were 162 J·mm\(^{-1}\), 184 J·mm\(^{-1}\) and 189 J·mm\(^{-1}\), there were more pores near the joint fracture. However, when the line energies were 168 J·mm\(^{-1}\), 173 J·mm\(^{-1}\) and 178 J·mm\(^{-1}\), there were no pores near the joint fracture. This demonstrates that line energy significantly affects the pore distribution in the welding joint. The regions annotated A and B in Figs. 5(A) and 5(C), respectively, were magnified and are shown in Figure 6. Obviously, pores with different sizes were found distributed throughout the A zone. There were some dimples as well as more cleavage planes formed by tearing fibres and steps around dimples, suggesting that the mechanism for fracture in the joint was a mixture of plasticity and toughness. The B zone shows many irregular dimples with tiny pores randomly distributed around them. Inclusions or second-phase particles are observed at the bottom of dimples, demonstrating that the joint underwent ductile fracture.
4. Conclusion
DPMIG welding can utilize the alternation of strong and weak pulse trains to enhance the stability of the welding and reduce splatter. Moreover, the appearance of the weld was beautiful and displayed the regular "fish-scale" pattern.

The line energy significantly affected the tensile strength of the DPMIG welding joint. The maximum value of the tensile strength was 101.02MPa for a linear energy of 173J·mm⁻¹. This is 75.4% of the tensile strength of the base metal AA1060.

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