Research Article

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Microstructure and mechanical properties of 2060 Al–Li alloy welded by alternating current cold metal transfer with high-frequency pulse current

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Abstract: Al–Li alloy has been widely used in the aerospace field owing to its high strength and low density. In this study, alternating current cold metal transfer (AC CMT) along with a high-frequency pulse current technique was used to weld a 2060 Al–Li alloy using an ER5356 wire. The effect of pulse frequency on the arc shape, microstructure, and mechanical properties of the welded joints was examined, and mechanical performance testing was conducted. The results revealed that the arc diameter, arc length, and arc volume showed a trend of increasing first and then decreasing with an increase in the pulse frequency and reached their peak values when the pulse frequency was 50 kHz. Coupling the welding process with a high-frequency pulse resulted in grain refinement, which was attributed to the stirring action of the arc force. Both the porosity levels and grain size decreased with increasing frequency. When the pulse frequency was 70 kHz, the porosity level was the lowest, and the grain size was refined to 24.1 μm . The tensile

strength of the welded joints also increased with the pulse frequency, and a maximum tensile strength of 249 MPa was observed at 70 kHz.

Keywords: high-frequency, AC CMT, 2060 Al–Li alloy, arc characteristics, mechanical properties

1 Introduction

Owing to the advantages of low density, excellent resistance to stress corrosion cracking, and enhanced mechanical properties such as high strength and good fracture toughness, Al–Li-based alloys are widely used in aircraft and aerospace structures. Compared with the previous second generation of Al–Li alloys, the third generation of Al–Li alloys has displayed superior mechanical behavior in terms of strength and hardness and improved weldability with lower anisotropy. This could be attributed to the chemical composition of third-generation Al–Li alloys, which have a lower content of Li and an increased content of Cu, Zr, and Mn [1,2]. Nevertheless, there are still some issues with Al–Li alloys during welding, such as weld metal porosity and cracks [3]. Studies have shown that the use of appropriate filler materials and preparation of high-quality weld surface are good methods for reducing the weld defects of Al–Li alloys [4]. Therefore, the strength of Al–Li weld joints can be greatly improved by choosing appropriate filler materials and effective welding parameters. Mousavi and Sabzi [5] studied the effect of pouring temperature and the surface angle of vortex casting on the microstructural evolution and mechanical properties of 7050 Al–3wt% SiC composite. Mechanical property measurements showed that the yield strength, hardness, and fracture toughness of the composite were increased by increasing the pouring temperature and reducing the surface angle during vortex casting.

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Effective methods for the welding of Al–Li alloys include laser beam welding (LBW) using high-energy beams and friction stir welding (FSW) using solid-phase connections [6–8]. LBW offers several advantages such as a lower heat application than conventional arc welding and a reduction in porosity and cracks during the welding process. Different Al–Li alloys (2060 and 2198) were laser-welded without the addition of filler materials [9,10]. The effects of welding parameters on the formation of welded joints, microstructure evolution, solute segregation, porosity, and their relationship with the mechanical properties of the joints were studied. This research has found that reducing welding heat input can effectively prevent grain coarsening, while reducing porosity and thermal cracking tendency, thereby improving joint performance. Liu et al. [10] further studied the influence of the microscopic morphology of different regions on the mechanical properties of welded joints and found that the microhardness distribution corresponds to the grain morphology distribution. The average microhardness at the center of the weld was the smallest because the grain size at the center of the weld was the largest. In addition, Cu and Mg segregation occurred during the welding process, which reduced the strength of the weld. However, Al–Li alloys have high reflectivity for laser beams, and alloying elements with lower melting points evaporate. The radiation of FSW is extremely small, the welded joints are flawless, and there is no need for chamfering when welding thick plates. Solutions have also been found for the three main problems associated with FSW, which are back support, weld thinning, and small hole defects [11]. Furthermore, refill friction stir spot welding (RFSSW) is a new technique for joining metal structures [12], which is used to connect thin aluminum elements; the welded joint exhibits good performance when the welding parameters are appropriate. The current research focus is to explore other efficient welding technologies to meet the requirements of low-cost production of Al–Li alloy products.

Recent studies on arc welding have demonstrated the positive effect of impulse current and frequency in grain refinement during the solidification of the weld region in aluminum alloys. For instance, the grain size was reduced with a higher pulse current frequency in an arc welding process [13,14]. During alternating current (AC) arc welding, the coupling of a high-frequency and moderate pulse current frequency has significant effects on the solidification process of the molten metal [8]. This has often resulted in improved mechanical properties of weld joints. Researchers have demonstrated that the issue of porosity can be effectively addressed by implementing AC arc welding. A reasonable adjustment of the time ratio of the EN phase and the EP phase in AC arc welding has resulted in a reduction in porosity and grain size [15]. Moreover, optimizing the AC arc welding parameters has been proven to have a positive effect on the metallurgical characteristics of the weld metal [16].

In the recent past, there have been several advancements in gas metal arc welding processes (GMAW). Cold metal transfer (CMT) is a type of GMAW (Figure 1) with substantial benefits, such as maintaining a “controlled heat” during the welding process. In this automated welding process, there is minimal heat due to a short circuit that controls (i.e., retracts and advances) the welding filler material [17]. Therefore, the arc introduces heat for a brief period, resulting in a spatter-free material transfer and a smooth weld. This unique characteristic (i.e., controlled heat input) makes this an ideal technique for welding Al–Li alloys. In addition, the CMT welding process has several advantages, such as a narrow welding thermal zone, and uniform welding seam. Moreover, it can effectively clean the oxide film while welding aluminum alloys [17].

Therefore, this study chose a new process that combines high-frequency pulse current with an AC CMT welding process to weld aluminum–lithium alloys. This process has been used to weld 2198 Al–Li alloy and has achieved good results. When the appropriate process

Figure 1: CMT droplet transition [17].

parameters were selected, grain refinement of the welded joint was obvious [16]. Research on the excellent combination of AC CMT and high-frequency pulse current for welding 2060 Al–Li alloy can provide a reference for the preparation of aerospace structural parts.

2 Experiment

The welding set-up houses two parallel independent power systems (i.e., CMT advanced power supply and high-frequency power supply) that are connected to a welding torch. Therefore, there is a single arc during the welding process that combines the AC CMT with a high-frequency pulse current (Figure 2) [16]. There are diodes in the circuit of the high-frequency power supply in parallel with CMT power supply. The diode has the characteristics of unidirectional current, so two parallel power supplies will not interfere with each other. A photograph of the welding system is presented in Figure 3. This welding system is composed of a KUKA robot and its control cabinet, Austria Fronius CMT Advanced 4000R AC CMT welding machine, and a high-frequency power supply. The peak current of the high-frequency pulse was 30 A, the duty ratio was 50%, and the frequency range selected in the current study was 20–80 kHz. In accordance with the CMT welding database, the optimal welding parameters (i.e., without coupling high-frequency current welding) of the welding wire were chosen (Table 1).

The base metal was an Al–Li alloy (2060-T8) plate ($135 \times 95 \times 2$ mm). Filler wire of ER5356 with a 1.2 mm diameter was used. The Mg content in the ER5356 filler wire can play a vital role in dispersion strengthening due to the precipitation of the $\beta(\text{Al}_3\text{Mg}_2)$ phase in the Al alloy [18]. Therefore, ER5356 filler wires were chosen to weld the 2060 plate. In addition, a comparison of the

Figure 3: Photograph of the welding system.

performance of ER5356- and ER4043-filled 2060 Al–Li alloy welding joints shows that ER5356 welding wire has better performance than ER4043 in reducing pore distribution, and it is not conducive to the generation of pores in terms of wire composition [19]. The chemical compositions of the 2060-T8 Al–Li alloy and filler material ER5356 are shown in Table 2. Photographs of the welded plates are shown in Figure 4.

Unlike conventional welding methods, the AC CMT current and voltage have unique characteristics in both the EP and EN phases [20]. The characteristics of the EP and EN phases of the AC CMT during welding are shown in Figure 5. During the EP phase, the cations hit the surface of the workpiece and molten pool, which can quickly clean the oxide film on the surface of the workpiece. Moreover, the arc is more divergent, the workpiece

Figure 2: The experimental set-up of AC CMT advanced supply coupled with high-frequency power supply: (a) AC CMT advanced supply and high-frequency generator and (b) welding torch [16].

Table 1: Process parameters for AC CMT welding

Wire brand	Arc voltage U/V	Welding current I/A	Welding rate $v/(cm\ min^{-1})$	Gas flow rate $q/(L\ min^{-1})$	EP:EN
ER5356	9.8	90	70	20	10:10

Table 2: Composition of the base metal Al–Li 2060 and ER5356 filler wire (wt%)

	Cu	Li	Zn	Mn	Mg	Si	Fe	Al
2060	4.2	0.9	0.45	0.5	1.1	0.05	0.01	Bal.
ER5356	0.05	—	0.05	0.15	5.0	0.1–0.2	0.1–0.2	Bal.

generates more heat as a cathode, and the temperature of the molten pool is higher. In addition, the transition period is longer than that of the EN phase. During the EN phase, the welding wire as the cathode generates more heat. Therefore, the welding wire melts faster, the transition period is shorter than in the EP phase, and the arc shrinks more. Compared with the EN phase, the arc is divergent during the EP phase, the workpiece produces a large amount of heat, and the arc burns for a longer time, which is not conducive to reducing the heat input. Thus, the EP phase affects the welding quality of the aluminum–lithium alloy [21]. Consequently, the EP phase coupled with a high-frequency pulse current was used in this study to improve the arc characteristics.

The surfaces were carefully prepared before welding. This involved cleaning the oxide films on the butt using a steel wire brush and scraper (thickness at least 0.15 mm) to effectively eliminate the pores. Acetone was used to remove oil and water stains. Flat welding with a set arc guide plate and an arc receiving plate were used, along with high-purity (99.99%) argon gas for shielding purposes. The microstructures of the weld joints were characterized using a Zeiss optical microscope. The samples were subjected to metallographic preparation techniques (i.e., mount, ground, and polished) and later etched using Keller's reagent (95% H_2O + 2.5% HNO_3 + 1.5% HCl + 1.0% HF , %vol). Vickers microhardness tests were performed on the cross-sectional area of the weld joints at a load of 200 gf for a dwell time of 15 s. The hardness tester was a THV-1MD automatic turret digital microhardness tester. The samples for tensile testing were wire-cut using a wire-rod electronic discharger in accordance with ISO 4136:2001 tensile standards (Figure 6). The tensile tests were performed at a speed of $1\ mm\ min^{-1}$ at room temperature using a SANS CMT5204 electronic universal test machine.

Figure 4: Welded plates made with different frequencies: (a) 0 kHz, (b) 40 kHz, (c) 50 kHz, (d) 60 kHz, and (e) 70 kHz.

Figure 5: The characteristics of EP phase and EN phase of AC CMT: (a) AC CMT current and voltage, (b) arc morphology of different phases of AC CMT, (c) AC CMT current waveform coupled with high-frequency pulse current, and (d) AC CMT voltage waveform coupled with high-frequency pulse current.

3 Results and discussions

3.1 Morphological characteristics of arc

During welding, the morphology of the arc while using the filler wire ER5356 was analyzed (Figure 7). With the addition of a high-frequency pulse current, there was a significant drop in the arc length (Figure 8(b)). However, the arc burning period did not change. This could be ascribed to the AC CMT welder control system, which

uses the arc voltage signal as the feedback signal. Based on the arc voltage in the control system, the wire feeding system responds by either withdrawing or feeding the wire [22]. For example, when the control system detects that the arc voltage is zero (or below a threshold value), the wire feeding system starts to withdraw the wire. In contrast, when the arc voltage increases above a critical value, the wire feeder begins to feed the wire. Therefore, when a high-frequency pulse current was added, the arc voltage was increased, and the filler wire was drawn back. This resulted in an increase in the dry elongation

Figure 6: Schematic representation of the tensile sample (all dimensions are in mm).

and a reduction in the arc length. As seen in Figure 8(b), adding the high-frequency pulse initially lowers the arc length at 20 and 30 kHz, then increases it to near the 0 kHz value for higher frequencies, with a maximum of 6.9 mm at 50 kHz. The above phenomenon could be attributed to the following reasons: (a) the arc voltage has been used as a feedback quantity to control wire movement and (b) the frequency of the coupling high-frequency pulse current is much greater than the change frequency of the welding current and voltage. Therefore, the high-frequency current applied to the AC CMT arc was calculated using the root-mean-square (RMS) value. The RMS value I_e can be determined using the following equation:

$$I_e = I_p D \quad (1)$$

where I_e is the effective value of pulse current, I_p is the peak pulse current, and D is the pulse current duty cycle.

According to equation (1), the RMS value of the pulse current is only related to the peak value of the pulse current I_p and duty cycle D , and has very little correlation with the high-frequency current frequency. If, I_p and D remain unchanged, the RMS value of the pulse current remains unaffected. If the average impedance and the voltage imposed on the arc are assumed to be constant, then the arc length should remain unchanged with the addition of the high-frequency pulse current (Ohm's law) [22]. However, the results show that the arc length changes according to the frequency of the high-frequency impulse current. This also indicates that the average arc impedance follows the same trend as that of the arc length, which first decreases and then increases. This arc impedance is determined by the degree of arc ionization (i.e., the number of carriers) [23]. This clearly shows that high-frequency pulse currents of different frequencies have multiple effects on the degree of ionization of the arc. With an increase in the pulse frequency, the degree of arc ionization and density of the conductive ions increased, whereas the arc impedance decreased. The maximum ionization degree was observed for a particular frequency range (50–70 kHz), followed by a sharp drop at higher frequencies [24]. This could be ascribed to the limited excitation response of the arc plasma to the impulse energy. The energy response and transmission of the arc as a heat source are suppressed by energy excitation with very high frequencies. This leads to the failure

Figure 7: Arc forms at different frequencies.

Figure 8: Arc characteristics versus frequencies: (a) arc diameter, (b) arc length, and (c) arc volume.

of the immediate transmission of conductive ions and an increase in the arc impedance. When the welding current changes from the base current to the peak current, the anode current density forms a voltage spike. The leading edge of the pulse voltage also has a spike, and the duration of this high voltage does not change with the frequency. At this time, the arc voltage is in an unsteady state, which can be maintained for a period of time. This shows that there is a transition process when the pulsed arc changes from one stable state to another. The time of this transition does not change with frequency; it is a characteristic of the arc itself. Because the arc can be controlled in an unstable state at high frequency, the stiffness of the arc, the energy density, and the power all increase, which is the cause of the high-frequency effect [24].

3.2 Porosity in weld joints

Hydrogen pores are one of the main problems in the welding of Al–Li alloys. Al–Li alloys are rich in active metallic elements such as Mg and Li, which promote the formation of oxidation layers after high-temperature processing. These oxide layers absorb moisture from the

Figure 9: Comparative study on the porosity level and microstructure at weld joints made with different frequencies: (a and f) 0 kHz, (b and g) 40 kHz, (c and h) 50 kHz, (d and i) 60 kHz, and (e and j) 70 kHz.

surrounding environment during welding. Consequently, the hydrogen atoms can enter the molten pool, leading to the formation of hydrogen pores because hydrogen solubility is higher in the liquid state than in the solid. The presence of pores can be detrimental to the strength and quality of weld joints. Therefore, it is necessary to investigate the relationship between weld material porosity and the corresponding welding parameters. Welding samples coupled with high-frequency pulse

current were chosen for the porosity investigation as they had a better appearance with no weld defects, no obvious deformation of plates, and clear and continuous fish scales.

Figure 9 shows the occurrence of porosity in the Al–Li weld joints. In the absence of a coupled high-frequency pulse, the pores are not evenly distributed. For example, pores of different sizes are observed in the center, fusion line, and edge of the weld (Figure 9(a)). When coupled with a high-frequency current, the number of pores in the center of the weld is comparatively small, and most of the pores are concentrated along the fusion line and the edge of the weld. During the welding process, a high-frequency electrical pulse flows through the molten pool formed by a pulsation-induced electromagnetic field of a certain intensity. Under the action of a pulsed induction electromagnetic field, the molten pool is affected by a strongly pulsed electromagnetic force. For a given cross-section of the hemispherical molten pool, there is a circulating flow driven by an electromagnetic force that originates at the center of the surface and then flows downward. The pores in the molten pool are effectively concentrated at the edge of the liquid metal hemisphere by stirring and then move away. Hence, the pores were distributed around the edge of the weld and along its centerline during the solidification process. The above phenomenon showing the flow direction of the liquid metal under stress in the molten pool is shown in Figure 10 [25,26].

The fewest pores were seen in the weld joints at a coupling frequency of 70 kHz. The above results clearly show that the porosity of the welded Al–Li alloy was

reduced after the introduction of high-frequency pulse currents.

3.3 Microstructure

The microstructures of the different weld areas and the corresponding effect of high-frequency on grain morphologies are shown in Figure 9(f–j). Han et al. [27] studied LBW in an Al–Li alloy and showed that the microstructure near the fusion line can be divided into several zones, that is, the fusion zone (FZ), equiaxed grain zone (EQZ), partially melted zone (PMZ), and heat-affected zone (HAZ). The grain structure at the weld center without high-frequency pulse current was coarse and equiaxed (Figure 9(f)). The weld microstructure displayed significant grain refinement by using high-frequency pulse currents during the welding process (Figure 9(g–j)). Moreover, there were very few coarse grains, and there was a marked increase in grain refinement for the coupling frequency of 70 kHz (Figure 9(j)). In summary, the weld microstructures displayed grain refinement with an increase in the coupling frequency.

Based on the above observations, an in-depth analysis of the rationale behind the grain refinement was carried out. The original CMT welding current, along with the coupling of the high-frequency pulse current, changes the induced pulsating magnetic field. According to Faraday's electromagnetic induction law, the molten metal at the weld joint produces an induced current, J_e . Owing to the electromagnetic induction, J_e generates a

Figure 10: The flow direction of molten metal under stress.

Lorentz force F under the action of a magnetic field, B . The Lorentz force can be expressed by equations (2)–(4) [28].

$$\vec{F} = \vec{J}_e \times \vec{B}. \quad (2)$$

According to Maxwell's equation,

$$\nabla \times \vec{B} = \mu \times \vec{J}_e. \quad (3)$$

Therefore, it can be inferred that

$$\vec{F} = -\frac{1}{2\mu}(\nabla \times \vec{B}^2) + \frac{1}{\mu}(\vec{B} \times \nabla)\vec{B} = \vec{F}_r + \vec{F}_z, \quad (4)$$

where $\vec{F}$ is the axial force along the direction of the magnetic field (causing vibrations to the molten pool and μ is the permeability), $\vec{F}_r$ is the radial force, perpendicular to the bearing, and $\vec{F}_z$ is the force which produces compression or stretching on the molten pool metal.

In the molten pool, the current flow direction and current density were not completely consistent and uniform. The current density at the weld center was high, whereas the density on the sides was low. Therefore, a pressure difference was formed from the center to the sides owing to the electromagnetic force created by the pulsating magnetic field. In addition, this pressure difference caused forced convection on the molten metal inside the weld. This can flush down some undissolved intermetallic particles (for example, Al_3Zr and Al_3Ti) with high melting points in the FZ and bring them into the pool [29]. Therefore, the number of non-uniform nucleation spots in the weld pool was significantly increased, which could further help in the grain refinement process. Moreover, these forces can produce a shearing effect on the growing dendrites, causing the dendrites to be fractured and dispersed in the weld pool. When the weld metal begins to solidify, the broken dendrites in the weld pool increase the number of crystal nuclei, resulting in the transformation of columnar crystals into equiaxed crystals [30,31].

The current intensity and induced magnetic induction intensity vary with the position in the melt [32]. The contraction force gradient and the velocity difference between the flow groups are formed in the melt, resulting in shear stresses that are given by the following equations [33]:

$$\tau_x = -\eta \frac{\partial V_x}{\partial y} \quad (5)$$

and

$$\tau_y = -\eta \frac{\partial V_y}{\partial x}, \quad (6)$$

where τ_x and τ_y are the shear stresses, η is the viscosity, and V_x and V_y are the melt velocities.

Combined with the formula given earlier, it can be seen that τ_x and τ_y in equations (5) and (6) are $\vec{F}_r$ and $\vec{F}_z$ in equation (4). When the shear stresses are sufficiently large, the dendrite or block grains in the melt are sheared into smaller grains and dispersed. These new grains can further nucleate and grow, eventually leading to significant microstructure refinement. It is also important to know that electromagnetic force is the main source of these shear stresses (i.e., a small percentage of the stress may also be due to the impact of the molten pool and arc force). The frequency of the composite currents can be quickly deduced using the electromagnetic formula ($E = -\int_S^0 \frac{\partial B}{\partial t} \cdot ds$). The induced magnetic field produces a greater induced electric field. This can eventually lead to an increased electromagnetic force and a larger shear stress, which can break the coarse grains into smaller ones.

The microscopic analysis clearly shows that the high-frequency pulse current significantly refined the microstructure. The 2060 + ER5356 weld combination yielded grain sizes of 36.6, 28.7, 26.8, 25.9, and 24.1 μm for the corresponding coupling current frequencies of 0, 40, 50, 60, and 70 kHz, respectively. In addition, there may be some variation in the frequency range at which the high-frequency begins to have a significant effect because of the filler wire properties (such as electrical conductivity, viscosity of the molten flow and surface tension).

3.4 Effect of welding parameters on the mechanical properties of weld joints

3.4.1 Microhardness

Microhardness patterns are measured to help understand the mechanical properties of welded joints, which depend on the microstructure [34]. The microhardness measurements are shown in Figure 11. The base metal (BM) was found to have an average microhardness of 146 ± 5 HV, which then drops in the HAZ and is further reduced in the weld zone (WZ). The microhardness pattern across the weld joints is consistent for all the coupling frequencies. The average microhardness is almost the same (70 ± 5 HV) across the center of the weld (Figure 11) for each condition. When the coupling frequency was 70 kHz, the average microhardness of the fusion line was the highest 118 ± 3 HV (i.e., ~74% of the base material). Based on these results, the highest hardness corresponded to the

Figure 11: Hardness distribution on the weld joints with ER5356.

frequency level with the finest grain microstructure. A fine-grained microstructure resulted in improved mechanical properties (e.g., yield strength and hardness). This is in conjunction with the Hall–Petch equation: $\sigma_y = \sigma_0 + K_y d^{-0.5}$ [35,36] (σ_y is the yield strength of the material, σ_0 is the yield strength of the single crystal, K_y is the coefficient of grain boundary effects on strength, and d is the average grain diameter). This formula shows that the yield strength is inversely related to the grain size in welded joints [37].

In general, microhardness is affected by the grain size and the presence of other metallurgical phases. The hardness at the weld center is slightly higher than that of the fusion line (Figure 11). This can be ascribed to the finer grains at the weld center, which were formed by the coupling of high frequencies in the welding process. Moreover, a decrease in grain size leads to an increase in the number of grain boundaries, which are high-energy sites that act as strong barriers against crack propagation [37]. $HV = 0.102 \times \frac{F}{S}$ (where F is the load and S is the indentation size) is used to calculate the hardness values. Indentation is a localized deformation in the metal, which is caused by the movement of dislocations in the metal. It is known that grain boundaries impede dislocation movement. In the case of a smaller grain size, the grain boundary area increases, as do the obstacles to dislocation movement, which results in greater resistance to material deformation. Consequently, the indentation size will be smaller with a higher hardness value.

Moreover, the weld zone is the region with the highest temperature during welding. Therefore, intermetallic particles (2060 + ER5356: $\beta(\text{Mg}_2\text{Al}_3)$, $\theta(\text{CuAl}_2)$, $\text{S}(\text{MgCuAl}_2)$)

would have gathered, grown, and dissolved in the weld zone under the action of the high temperature. Despite significant grain refinement in the weld zone, the hardness value was still lower than that of the BM. The hardness in HAZ was reduced owing to over-aging, dissolution, and growth of the enhanced phase under the action of a high temperature. The heat transferred from the weld area to HAZ is relatively small because of the lower heat input of CMT. Therefore, the second-phase particles in HAZ aggregated and dissolved, but the dissolution was not as significant as in the weld zone. In addition, the BM is in a T8 state (i.e., cold reduction after solution treatment and artificial aging). Therefore, HAZ has a higher hardness than the weld zone but smaller than that of the BM.

3.4.2 Tensile properties of the weld joints

The engineering stress–strain curves and tensile strength of welded joints at different coupling frequencies are presented in Figure 12. The tensile strength of the base material was 490 MPa, and the efficiency of the welded joint was calculated using the following equation [38]:

$$\text{Weld efficiency} = \frac{\text{Ultimate tensile strength of welded joint}}{\text{Ultimate tensile strength of as-received base metal}} \quad (7)$$

Without coupling with the high-frequency pulse current, the tensile strength of the weld joint was 230 MPa, and the minimum joint efficiency was calculated to be

Figure 12: Stress–strain curves and tensile strength of weld joints made with different frequencies: (a) 0 kHz, (b) 40 kHz, (c) 50 kHz, (d) 60 kHz, (e) 70 kHz, and (f) tensile strength.

Figure 13: Samples after fracture: (a) tensile samples and (b) magnified view of fractures.

approximately 46.9%. However, the tensile strength of the weld joints was improved after coupling with the high-frequency pulse current. A frequency of 70 kHz resulted in a superior tensile strength of 249 MPa, with a maximum joint efficiency of about 50.8%. This clearly shows an increase of 19 MPa in the tensile strength of the 70 kHz weld joint above that made without high-frequency pulse current.

Tensile strength is related to the mobility of dislocations in the welded joint. As shown in Figure 9, the grain size of the welded joint was significantly reduced under the coupled high-frequency pulse. The associated grain boundaries have high energy owing to their structural disorder. Therefore, mobile dislocations must possess high amounts of energy to cross the grain boundaries. This is why mobile dislocations accumulate behind the

Figure 14: SEM fractographs of weld joints made with different frequencies: (a and a1) 0 kHz, (b and b1) 40 kHz, (c and c1) 50 kHz, (d and d1) 60 kHz, and (e and e1) 70 kHz.

grain boundaries when they reach them and stop moving. This results in an increase in the dislocation density behind the grain boundaries and finally increases the tensile strength [37].

The weld joint fracture surface characteristics were also studied (Figure 13). From the fracture analysis, it was clear that the fusion line was the weakest link, as all the fracture locations were near the fusion line. From the macroscopic fracture morphology shown in Figure 13(b), there is a slight necking phenomenon (plastic deformation) at the fracture, and the fracture surface was relatively flat and perpendicular to the direction of the tensile load. From the SEM fractographs (Figure 14), the fracture surface shows obvious dimple features and a few tear ridges (Figure 14(a–e)), which indicates a mainly ductile fracture mode. A small amount of tear ridges indicates that the fracture has a tendency for quasi-cleavage fracture [39–41]. Most metals and alloys (especially those with FCC lattice, such as Al–Li alloy) exhibit ductile fracture at ambient temperature. The ductile fracture characteristics under tensile stress include the development of very fine cavities within the necking region, which subsequently connect to form a fine crack that grows to final fracture [42,43]. It can be confirmed that the 70 kHz sample would be more ductile (with more dimples) because of its smaller grain size [44,45]. The coupling high-frequency pulse current had very little effect on the fracture modes of the welding materials.

4 Conclusion

- (1) In general, the arc shape was largely based on the pulse frequencies. In addition, the arc diameter, arc length, and arc volume show a trend of rising first

and then falling with the increase of the pulse frequency and reached their peak values when the pulse frequency was 50 kHz. The peak arc diameter, arc length, and arc volume were 14.5 mm, 6.9 mm, and $1,134 \text{ mm}^3$, respectively.

- (2) In the process of welding 2060 Al–Li alloy with AC CMT coupled high-frequency pulse current, the high-frequency pulse current had a significant effect on the porosity, grain size, and tensile strength of the weld joints.
- (3) The porosity levels and grain size at the weld joints varied depending on the pulse frequencies employed for welding. The porosity levels and grain size both decreased with increasing frequency. When the pulse frequency was 70 kHz, the porosity level was the lowest, and the grain size was refined to $24.1 \mu\text{m}$.
- (4) When using filler wire ER5356 along with the high-frequency effect, there was a significant increase in the tensile strength of the weld joints. For example, a maximum tensile strength of 249 MPa was observed for the weld combination of ER5356 and 70 kHz.

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