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Investigation on Double Wire Metal Inert Gas Welding of A7N01-T4 Aluminum Alloy in High-Speed Welding

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Abstract: Four-millimeter thick A7N01-T4 aluminum alloy plates were welded by double wire metal inert gas welding (DWMW) in high welding speeds, ranging from 1100 to 1250 mm/min. The results show that a sound joint could be obtained at a high speed of 1200 mm/min using DWMW. The weld zone (WZ) in the joint showed a dendritic structure of equiaxed grains, and in the fusion zone (FZ), the microstructure existed as a fine equiaxed crystal structure about 100 μm in thickness. In the WZ adjacent to the FZ, elongated columnar crystal structure distributed along to the interface, and coarse microstructure in the heat affected zone (HAZ) were found, showing a typical rolling texture. The main precipitates in the WZ were assumed to be Fe-enriched phases, and Mg- and Zn-enriched phases. Tensile fracture generally occurred in the WZ adjacent to the FZ with a decrease in ductility, and it was consistent with the results of the microstructure analysis and hardness profile. The mean ultimate tensile strength and elongation of specimens were 302 MPa and 4.5 %, respectively.

Keywords: double wire metal inert gas welding, aluminum alloys, high-speed welding

Introduction

7xxx aluminum alloy is an Al-Zn-Mg-(Cu) alloy with good extrusion performance and high strength [1–4], and it has become the main alloy of large thin-walled, high-precision

solid and hollow profiles for aerospace and transportation vehicles [3, 5, 6]. At present, the fusion joining methods used in 7xxx aluminum alloy welding mainly include metal inert gas (MIG) welding, laser welding and laser-arc hybrid welding [5, 7–13].

MIG welding process has the advantages of simple operation, low welding process cost, and good gap tolerance [5, 10]. For MIG welding of 7xxx aluminum alloy, Yang et al. fabricated 4-mm A7N01 plates at a welding speed of about 420 mm/min [14]. Similarly, Potluri et al. reported that 1.6 mm 7005 plates were successfully joined together by pulsed-current MIG welding at 203 mm/min [15]. Above investigations indicated clearly that MIG welding is not suitable for the requirement of high efficiency, and due to the low energy density, it imposes many problems such as burn through, large heat input, and distortion [5, 10, 16]. Laser welding, because of its concentration of energy density, high welding speed, high precision, low heat input, and flexibility, becomes a novel technical method for 7xxx alloy welding [9]. Detailed experiment and analysis were carried out by Katayama et al. on the effect of CO₂ laser welding conditions on porosity formation during high-speed welding [8]. Also, a study of the feasibility of laser welding of AA7075-T6 showed that this method is highly susceptible to porosity [17], which indicates that the application of laser welding in practice still remains a technological challenge, due to its high reflectivity of aluminum to light, the keyhole instability, vaporization of zinc and/or magnesium, and high cost of equipment shortcomings [18]. Laser-hybrid welding, as a relatively new fusion welding method, has been considered to be a promising precision joining technique which has a high-energy utilization and welding speed [5]. Hu et al. successfully welded A7075 plates by laser-gas metal arc welding, achieving a full penetration at a travel speed of 6 m/min [19]. However, a number of researchers have presented that due to the complicated operation and the demanding synergic effect between the two heat sources, its wide applications are limited [20–22]. According to above analyses, to expand its available applications, providing a low cost and high

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welding efficiency method to weld A7N01P has become a more pressing problem [5, 8, 10].

Double wire MIG welding (DWMW) simultaneously provides heat energy to one molten pool, and it can directly perform welding process without preheating, change the heat distribution, improve the deposition rate, and effectively avoid various other relative disadvantages. As it can attain a higher welding productivity and ameliorate the welding formation in practice, DWMW has attracted extensive attention at present [23–28]. A lot of work has been reported that steel joints with a high performance could be obtained at a high welding speed by DWMW [23, 26–28], but the investigation of DWMW on aluminum alloys is scarce in the literature [24].

In this paper, DWMW using ER 5356 filler wire was applied to A7N01P welding, aiming to improve the welding efficiency at a low cost. In addition, the microstructure and mechanical properties of the weld joints were analyzed. Furthermore, the relation between welding speeds of aluminum alloy plates with different thicknesses and welding technologies was discussed in order to provide the guidance for the industrial applications of DWMW.

Experimental

The butt welding plates were obtained by a DWMW system (GLC503Quinto-Tandem, CLOOS, Germany) (Figure 1). The DWMW arcs were generated by direct-current torches, at an angle of 90° to the workpiece. The power sources were operated with positive polarity on the wires. Shielding gas was argon with a purity of 99.99 %, flowed at 25 L/min. The distance between the gas nozzle and base metal (BM) was set as 16 mm. The torches were kept

at rest and the workpieces were moved with the moving stages. Welding was carried out by filling the weld groove (Figure 1) in a single pass.

A7N01-T4 aluminum alloy plates, $300\text{ mm} \times 150\text{ mm} \times 4.0\text{ mm}$ in dimension and extruded ER5356 aluminum alloy wire of 1.2 mm in diameter were used as the base workpieces and filler wire, respectively. Chemical compositions of the BM and filler wire are shown in Table 1, and microstructure of the BM is shown in Figure 2. The welding speeds were 1100 mm/min, 1150 mm/min, 1200 mm/min and 1250 mm/min, and the welding parameters of DWMW are shown in Table 2. The two welding torches were defined as the leading arc (L-arc) and the trailing arc (T-arc), respectively (Figure 1).

The testing specimens of weldments were stored at room temperature (275 K) for about 76 days so that they could achieve a sufficient degree of nature aging. For metallographic examination, specimens were sectioned through the center of the joints and parallel to the loading direction. After being mechanically ground and polished, the specimens were etched with Keller's reagent consisting of 2 mL HF, 3 mL HCl, 5 mL HNO_3 and 190 mL H_2O . Microstructure was examined by optical microscope (OM) and LEO Supra 35 scanning electron microscope (SEM) with energy dispersive X-ray spectrometer (EDS).

Hardness profile across weld joint obtained at the welding speed of 1200 mm/min was measured at half the weld thickness with a load of 100 g and a duration of 10 s. Tensile tests were carried out at a constant speed of 1 mm/min on a Zwick/Roell Z050 tester. Transverse oriented tensile specimens at 1200 mm/min were machined, and Figure 3 illustrates the geometry and dimensions of the tested specimens. The weld zone (WZ) was at the center of the specimens, and welding reinforcements on the weld surface were eliminated before conducting the tests. The property values for each condition were calculated by averaging three test results. Additionally, analysis of the fracture location and morphology were performed using the OM and SEM.

Figure 1: Schematic of DWMW process.

Results

High welding speed of A7N01 alloy

Figures 4(a), 4(b) and 4(c) show the weld surfaces which were produced at the speeds of 1100 mm/min, 1150 mm/min, 1200 mm/min, respectively. It could be

Table 1: Chemical compositions of the BM and the welding wire (wt.%).

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
A7N01	≤ 0.3	≤ 0.35	≤ 0.2	0.2–0.7	0.1–2.0	≤ 0.3	4.0–5.0	≤ 0.2	Bal.
ER5356	≤ 0.25	≤ 0.40	≤ 0.1	0.05–0.20	4.5–5.5	0.05–0.2	≤ 0.1	0.06–0.2	Bal.

Figure 2: Micrographs of the BM A7N01-T4.**Table 2:** Welding process settings and parameters.

	Wire feed rate (m/min)	Average voltage (V)	Average current (A)
Leading wire	12.8	22.7	190
Trailing wire	10.8	23.8	162

Figure 3: Dimensions of the sample for performance testing.

observed that the weld surfaces had acceptable visual finishes with satisfactory quality, and no distinct arc interruption occurred could be observed. However, increasing with the welding speed (1250 mm/min), the welding bead became bad (Figure 4(d)). Therefore, according to the advantages of high speed and consistent quality, the DWMW joint obtained at 1200 mm/min was selected for further analysis.

Figure 5 shows the typical cross-section photograph of a DWMW joint, furtherly exhibiting that the full penetration of 4 mm sheets could be successfully realized by DWMW at 1200 mm/min. The welding joint presented three different regions as follows: the WZ, the fusion zone (FZ) and the heat affected zone (HAZ). The macrograph shows a symmetry along the center-line of the weld. The effect of melting and mixing between the filler wire and BM resulted in some differences in microstructure and mechanical properties of each region.

Microstructure of the joints

Figure 6(a) shows the optical microstructure of the WZ in a DWMW joint. It could be clearly observed that, the central zone showed a dendritic structure of equiaxed grains, which dramatically altered the rolled microstructure of the BM (Figure 2), and had different grain orientations. The grain boundaries were large and the eutectic structure at the grain boundary was short and distributed heterogeneously (Figure 6(b)). The composition of the WZ was further investigated by SEM. The results show that some large precipitates distributed along grain boundaries. In addition, a few finely dispersed precipitates were also observed in this zone (Figures 7(a) and 7(b)). EDS analysis revealed that the large precipitate was consisted of 84.27at.% Al, 8.64at.% Fe, 3.49at.% Mg, 2.19at.% Zn, and 1.42at.% Mn (Figure 7(c)), and was therefore assumed to be α -Al phases with Fe-enriched precipitates. The composition of small precipitates in the WZ adjacent to the FZ was further identified by EDS, and the results showed that contents of Mg and Zn elements of small precipitates were higher than that of α -Al phases (Figures 7(d), 7(e) and 7(f)), so they may be Mg- and Zn-enriched precipitates.

The micrographs of the FZ, HAZ, fine equiaxed crystal zone and columnar crystals are clearly distinguished in Figure 6(c). In the FZ, the microstructure existed as a fine equiaxed crystal structure about 100 μ m in thickness (Figure 6(d)). In the WZ adjacent to the FZ, elongated columnar crystal structure distributed along to the

Figure 4: Appearances of butt weld seams under different welding speeds: (a) 1100 mm/min, (b) 1150 mm/min, (c) 1200 mm/min and (d) 1250 mm/min.

Figure 5: Cross-sectional overview of a DWMW A7N01P joint (1200 mm/min).

interface. The columnar crystal structure toward the fusion center grew up around 300 μm width along the FZ boundaries.

Coarse microstructure in the HAZ was found showing a typical rolling texture (Figure 6(c)). It was more clearly to identify as a predominantly discontinuous equiaxed dendritic structure in the HAZ produced by DWMW (Figure 6(d)). The grain size was larger than that in the BM. In the HAZ of the DWMW joint, there was a partially melted structure of about 150 μm width. The region (Figure 6(d)) adjacent to the partially melted zone presented no evidence of excessive grain growth, dissolution or coarsening of second phase particles attributed to over-heating. The BM is characterized by a typical rolled structure (Figure 2). The elongated grains were formed in a pancake shape with their interfaces or grain boundaries parallel to the rolling plane

and the BM was comprised of aluminum solid solution (white phase) and precipitates (black phase) dispersed in grain boundaries and grains.

Mechanical properties

Figure 8 is the hardness profile of the DWMW joint, and the white dotted line (Figure 5) represents the testing location. It should be noted that the WZ had a minimum hardness of only ~ 90 HV for the DWMW joint. Fracture generally occurred in the WZ adjacent to the FZ with a decrease in ductility, and there was no obvious necking around the fracture (Figure 9). This behavior was consistent with the results of the microstructure analysis and hardness profile.

Static tensile nominal stress-strain curves of the weld joints are also examined to correlate the microstructural behavior (Figure 10). The mean ultimate tensile strength and elongation were 302 MPa and 4.5 %, respectively.

The fracture surface exhibits no obvious porosity, slag inclusion and other defects (Figure 11(a)). As shown in Figures 11(b) and 11(c), fracture was consisted of equiaxed dimples of different sizes. The larger dimple size was about 15 μm and the smaller was about 3 μm , showing a quasi-cleavage-like fracture characteristic.

Figure 6: Micrographs of a DWMW A7N01P joint (1200 mm/min): (a) WZ and (b) its high magnification; (c) FZ and (d) its high magnification.

Discussion

Microstructural evolution

DWMW, at a high welding speed, experiences a rapid cooling process, so its solidification characteristics are a little different from that of the traditional MIG welding process.

Upon cooling, solidification of the FZ took place first at the partially melted or solid grains along the fusion boundary (i.e. at the solid-liquid interface), due to the cooling effect of the groove, the existence of large thermal gradient between the interface of BM and the molten pool, and small growth rate. In the subsequent solidification process, grains in the fine equiaxed crystal zone rapidly grew along to the preferred crystallographic directions. The proceeding would have the maximum growth speed toward the fusion center and subsequently grow into the columnar crystal structure (Figure 6(d)). This transition found near the FZ with coarser columnar grains had an abrupt change of grain size (Figure 6(d)), which maybe lead to a large gradient of mechanical properties.

The equiaxed dendritic grains in the WZ were formed (Figure 6(b)) due to the existence of dissociate dendrite arms and the mild cooling in the pool. The weld center

was dominated by the heat sources and the strong arc stirring effect on weld pool. Because the T-arc had an additional stirring effect on the pool, it could break up the coarsened dendrite structure and offered lots of nucleation sites. This structure would benefit the mechanical properties of the DWMW bead.

The wide of the HAZ was a direct function of the heat input and thermal conductivity of the BM (Figure 6(c)). A larger grain size was attributed to the recrystallization effect and was very critical in the welding of aluminum alloys, especially which were hardened by precipitation.

Welding efficiency analysis

At present, due to competitive industrial market, the welding efficiency has become a matter of great concern [29–48], and the welding speed is one of the important factors to represent the welding efficiency.

Figure 12 shows the welding speeds of different fusion welding methods for 1–7 mm aluminum alloy plates [1, 5, 8, 13, 29–46]. As presented above, the welding speeds of MIG and tungsten inert gas (TIG) welding, below 1000 mm/min, were lower than that of other welding methods. Nevertheless, the above two welding methods have many

Figure 7: Images of SEM and EDS analysis: (a) detail of WZ in a DWMW joint; (b) typical EDS analysis of the large precipitate and (c) typical EDS analysis of the small precipitate.

Figure 8: Hardness profile of the FZ and the HAZ of the DWMW joint.

advantages such as simple operation, cheap equipment and cost reduction [7, 11]. In addition, laser welding and hybrid laser-arc welding could achieve a higher range of welding speeds from 1000 to 6000 mm/min. On the one hand, due to their high-energy density, they have a higher welding efficiency than that of arc welding. On the other hand, the equipment and welding costs are far higher, and they are susceptible to the occurrence of welding defects [8].

The red marks represent the welding speed interval produced by DWMW in this study. Compared to the traditional single-wire MIG welding, because two wires simultaneously provided heat energy to the BM, DWMW could change the heat distribution, effectively avoid undercut, yield welding seams with high quality, and improve the welding speed (1100–1200 mm/min) [26, 49]. In addition, in contrast to the traditional MIG and laser-arc welding

Figure 9: Global view of butt joint fractured.

Figure 10: Nominal stress-strain curves of the DWMW joints.

[7, 50, 51] which had a tensile strength between 260 and 341 MPa, DWMW improved the welding efficiency without reducing the mechanical properties of the joints, thereby having a wide application prospect in the field of aluminum alloy welding.

Conclusions

In summary, 4 mm thick A7N01-T4 aluminum alloy plates were welded by DWMW at a high welding speed of 1200 mm/min. For the DWMW joint of A7N01 aluminum alloy, the WZ showed a dendritic structure of equiaxed grains, and in the FZ, the microstructure existed as a fine equiaxed crystal structure about 100 μm in thickness. In the WZ adjacent to the FZ, elongated columnar crystal structure distributed along to the interface, and coarse microstructure in the HAZ were found showing a typical rolling texture. The main precipitates in the WZ were assumed to be Fe-enriched phases, and Mg- and Zn-enriched phases. Tensile fracture generally occurred in the WZ adjacent to the FZ with a decrease in ductility, and it was consistent with the results of the microstructure analysis and

Figure 11: Fracture morphologies of a DWMW joint after tensile testing: (a) general view; (b) the ductile fracture appearance and (c) details of the ductile fracture surface.

Figure 12: Comparison of welding speeds for aluminum alloys of varying thicknesses using different fusion welding methods [1, 5, 8, 13, 29–46].

hardness profile. The mean ultimate tensile strength and elongation of specimens are 302 MPa and 4.5 %, respectively. DWMW improved the welding efficiency without reducing the mechanical properties of the joints, thereby having a good application prospect.

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