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# Microstructure characteristics of thick aluminum alloy plate joints welded by fiber laser

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ABSTRACT

It's difficult to weld high strength thick plate since the groove is huge when using traditional arc welding, and the weld tends to be softened and large deformation could occur after multi-layer welding. All of these can affect the industrial application of high strength thick plate wielding. In this case, developing advanced welding technology and welding material is necessary to optimize the microstructure and performance of the welds. Fiber laser has many advantages such as good monochrome and high quality laser beam. In order to decrease the heat damage to the base metal from the welding heat source, low heat input is employed for welding thick plate. Fiber laser is applied in the welding of 20 mm thick Al–Zn–Mg–Cu alloy with super narrow gap filler wire. The microstructure comparison of Al–Mg–Mn alloy and Al–Mg–Mn–Zr–Er alloy welded joints reveals that a huge amount of fine equiaxed grains is formed in the weld zone of Zr and Er micro-alloying Al–Mg–Mn alloy welding wire and a great number of precipitation strengthening phases are precipitated in the weld zone after the heat treatment of welded joints in the entirety.

## 1. Introduction

The welding of thick metallic plates usually involves wide-angle groove, multilayer, multipass, large amount of metal filling and tremendous residual stress. The narrow gap welding method for welding thick metal plates can-not only reduce the transverse section of the groove drastically and cut down the amount of weld metal deposition significantly, but also realize efficient welding with small weld heat input [1–3]. The commonly used narrow gap welding technologies include narrow gap submerged arc welding (SAW), narrow gap argon tungsten-arc welding, narrow gap electroslag welding and narrow gap laser welding. Nonetheless, super narrow gap fiber laser welding with filler wire is rarely reported. It applies linear heat input smaller than commonly adopted narrow gap welding, which can be minimized to 0.5 kj/mm. Fiber laser boasts the advantages of high quality light beam, perfect monochromaticity, short wave length and favorable technological adaptability [4,5]. Combining the edges of fiber laser and super narrow gap, it can reduce the heat losses upon the welding structure remarkably by welding heat source. As a result, an appropriate selection of welding materials can enhance the overall mechanical properties of welded joints.

Aluminum alloy is the priority material for aircraft and spacecraft, which is extensively applied in the aerospace industry [6]. For example, 180 t thick aluminum plates are used in each airbus. However, in practical application, the aluminum alloy thicker than or equal to 20 mm accounts for 50%. The purpose of the present work aims at adopting small power fiber laser for effective welding of 20 mm thick Al–Zn–Mg–Cu alloy, with single "I" pass groove whose horizontal width is 2.5 mm.

Micro-alloying functions as a pivotal method to boost the properties of aluminum alloy. Studies indicate that the additions of trace rare earth elements into the aluminum alloy can remarkably refine the grains [7], and could purify the composition of alloy so as to improve the mechanical properties at last. The addition of Sc into the aluminum alloy can ostentatiously boost the strength of alloy while the low cost element Er shares similar functions with Sc in the aluminum alloy [8]. In order to compare the influence of different welding materials upon the microstructure of joints welded by super narrow gap fiber laser, the present study selects 5183 alloy and 5E06 as the welding wire.

## 2. Experimental procedures

YLS-4000 YB-doped fiber laser with a wave-length of 1070 nm and maximum rate output power of 4000 W produced by IPG Photonics is applied in the experiment. During the welding, the laser head vertically deviates from the direction of the work piece by 10° to prevent reflective laser from damaging the focus lens. The motor execution system adopts two-dimensional welding machines. The experimental materials are 7A52 high strength aluminum alloy with a dimension of 160 mm × 80 mm × 20 mm. Filler wires with different chemical

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**Table 1**
Chemical composition of 7A52, 5183 and 5E06 (wt.%).

| Alloy | Zn | Mg | Cu | Mn | Cr | Ti | Zr | Er | Fe | Si | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7A52 | 4.2 | 2.1 | 0.08 | 0.30 | 0.16 | 0.08 | 0.14 | – | ≤0.30 | ≤0.25 | Bal. |
| 5183 | – | 4.7 | – | 0.8 | – | 0.1 | – | – | – | – | Bal. |
| 5E06 | – | 4.9 | – | 0.7 | – | – | 0.1 | 0.3 | – | – | Bal. |

compositions are used including 5183 welding wire and 5E06 welding wire. The diameter of both welding wires is 1.6 mm. The chemical compositions of the parent metal and the welding wires are listed in Table 1. Backing welding is used to penetrate the truncated edge and the entire welding process is completed in the manner of laser feeding from the bottom up. 50%He + 50%Ar gas is selected as the protective gas for welding. Mechanical polishing and electrolytic polishing are applied for specimens. An ISM-7001F scanning electron microscope (SEM), JEOL-2100 transmission electron microscopy (TEM) and FEI-F20 high resolution TEM are utilized to observe the microstructural morphology and precipitated phases in the weld zones. Corresponding supporting EDAX energy disperse spectroscopy is adopted for semi-quantitative analysis of the chemical composition. Three parallel samples are prepared for each processing state. The test value in each state is determined by the average value of the measurements. Hardness test is carried out 100 gf load for 10 s, with an HVS-1000 digital microhardness tester. Each test is conducted on both sides at an interval of 1 mm from the center of the transverse section of the weld. The value of hardness tested is the average of the three measurements. Thermal treatment is applied to the welded joints of 5E06 alloy after welding. In this process, samples are treated at 470 °C for 3 h in a nitrate oven and afterwards at 120 °C for 12 h artificial aging treatment in the thermostatic drier box.

## 3. Results and discussion

Fig. 1 indicates the macroscopic morphology of the transverse section of welded joints. The groove is 3 mm in width and the upper and bottom widths of weld are consistently less than 4 mm. It can be seen that perfect fusion forms between the side walls of groove and the passes without defects such as holes, inclusion or cracks. The difficulties of narrow gap welding lie in the fusion of side walls. Defocused spots of the same size of groove gap are selected during welding, which can develop perfect fusion of side walls. The laser reflection composed of fusion curve and side walls becomes the primary reason for the fusion of side walls.

In order to compare the differences of welded joints of diverse welding materials in morphology, backscattered-electron diffraction (EBSD) is utilized to observe the morphology of grains near the fusion line of the welded joints. Fig. 2(a) and (b) present the morphology features of grains near the fusion line filled with 5183 welding wire and 5E06 welding wire, respectively. It is discovered that epitaxial solidification appears near the fusion line of weld filled with 5183 welding wire and coarse columnar crystals grow in the weld center [9]. The columnar crystals generate from the parent metal zone at the weld boundary. In contrast, fine equiaxed grains with small size and tiny width in random distribution occur in the fusion zone of 5E06 welding wire, indicating no epitaxial solidification occurs at the parent metal. Nucleation may take place on the grains of the matrix where the lattice in the liquid metal does not have to overcome any energy barrier, resulting in the so-called epitaxial solidification. Nevertheless, when the composition of weld metal is different from that of the matrix metal, or heterogeneous grains exist in the fusion bath, the mode of crystallization may be destroyed and these equiaxed fine grains hinder the growth of epitaxial crystals. Since homogeneous nucleation can hardly happen in weld solidification, the nucleation of equiaxed grains sources from heterogeneous nucleation and the degree of supercooling of the composition existing in the leading edge of the solid–liquid phases [10,11].

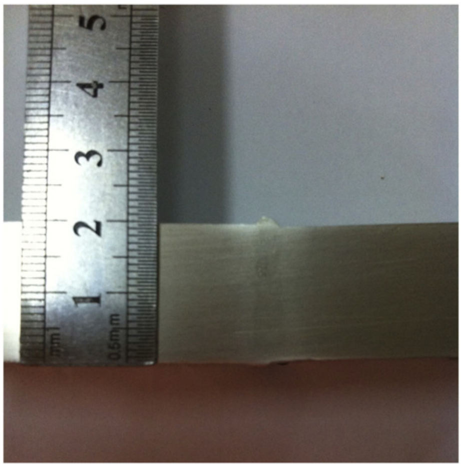

**Fig. 1.** Macroscopic schematic diagram of welded joints.

EBSD is used to observe the morphology of grains in the bond zone of welded joints with diverse passes. Compared with other areas, the microstructures in these zones go through twice heat cycle where the microstructural changes become more sophisticated and the tapping points become weak links. These zones can better reflect the mechanical properties of the entire welded joint. Fig. 2(c) and (d) respectively exhibit the morphology of grains in interlayer structures of weld zones of 5183 and 5E06 welding wires. Fig. 2(c) illustrates the existence of obvious interfacial transition zone between the passes and the coexistence of the coarse grain zone and the fine grain zone. The reason is that the previous layer will go through re-fusion and heat treatment when the latter layer is welded. Under the effects of high heat laser, the more distinctively the grains grow close to the fusion line, the more refined the grains are between the weld passes. It results from the fairly small super narrow gap fusion bath and the high degree of supercooling of laser welding. The thermogenesis of the following layer upon the previous layer is equivalent to short-term heat treatment. Twice re-crystallization both during the heating and the cooling generates notable grain refinement. Therefore, this zone boasts higher overall mechanical properties. Fig. 2(c) displays the columnar grains of an average size of 168 μm. The crystal in the re-fusion zone grows in a changed direction because of the directions of temperature gradient and grain growth shift with heat dissipation of multilayer weld fusion bath. Fig. 2(d) demonstrates the equiaxed grains. It is compared that the grains in the weld zone of Al–Mg–Mn alloy welding wire after Zr and Er micro-alloying are evidently refined, the grain size sharply shrinks to 36 μm and the grain morphology transforms from columnar crystal to equiaxed crystal. The weld and the casting share similar solidification processes, usually from the surface to the center and featuring controlled directional solidification. As the solidification zone gradually sways away from the fusion bath surface, the temperature gradient of the leading edge of the solid–liquid interface diminishes little by little, the solidification velocity gradually drops, the solute content increasingly rises and the constitutional supercooling zone significantly expands. As a result, the crystalline form turns from dendrite to equiaxed grain [12]. When the size and the amount of free crystal formed in the liquid phase in front of the solidification interface reach a certain value, the columnar crystal will be blocked in growth and morph into equiaxed crystal. Liquid-phase flow plays a decisive role in the formation of free crystal in front of the solidification interface. The cooling speed of fusion bath during laser welding is exceedingly high, which will further augment constitutional supercooling and refine the weld metal grains. The degree of supercooling is the crucial factor deciding the formation of equiaxed crystal [13,14]. Another reason for grain refinement is the effect of metamorphic element Zr and rare element Er. Gutierez [15] discovered that $Al_3Zr$ and $Al_3(Li, Zr)$ originally in disperse distribution near the boundary of the fusion bath remain and the atoms in the liquid metal can be ranked in the crystal morphology