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Effect of filling materials on the microstructure and properties of hybrid laser welded Al-Mg-Si alloys joints

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ABSTRACT

A serious investigation was conducted to examine the influence of filling materials on the microstructure and properties of hybrid laser welded AA6061-T6 joints. The results of the tensile tests showed that the welded joint with ER4043 filling materials had higher tensile strength than that with ER5356 filling material. Based on the results obtained a strength model was built to predict and explain the enhancement of the yield strength of the hybrid laser welded AA6061-T6 joint with different welding wires. In contrast to the tensile strength, the ER4043 joint showed lower fatigue strength than that of the ER5356 joint due to extensive presence of micropores in fusion zone. Further, the corrosion experiment illustrated that the ER4043 joint had poorer resistance to the corrosive attack under 3.5% NaCl solution. A summary was made on the performance of both welded joints to shed new insights on selecting appropriate filling materials when welding AA6061-T6 by hybrid laser welding method.

1. Introduction

Metal thin sheets such as 6061 aluminium alloy sheets have found wide applications as structures of aircraft, high-speed train and automobile [1–3]. In the manufacturing process of such structures, welding is a primary choice due to its high efficiency and low cost. The commonly used welding process is fusion welding, such as metal inert gas (MIG) welding, tungsten inert gas (TIG) welding, and laser/hybrid laser welding. Among them, the hybrid laser welding is favourable, since it is featured with high welding speed, good bridging ability, and high penetration [4]. However, problems still exist in such advanced welding process due to its thermal cycles, which lead to shortcomings of coarse microstructure (precipitates and grain size), defects (cracks and pores), and loss of alloying elements (Mg and Zn) [5–8]. Consequently, most of its samples fracture in fusion zone (FZ) under tensile tests or fatigue tests [6–10], indicating that FZ is the softest part of the welded joint. It is impossible to eliminate the softening behaviour of the welded joint due to the process nature of the fusion welding. Nevertheless, the performance of welded joint can be improved by tailoring its microstructure.

One of the methods to resolve the problems above is to reduce the defects and evaporation of alloying elements by adjusting the welding process parameters [6, 11]. Inappropriate welding process would induce the defects of cracks, large pores, and alloying elements loss, which deteriorate the performance of the welded joint. Several authors [4, 7, 12, 13] suggested that adjusting the welding parameters, such as welding speed, the laser power/welding current, could make the welding process stable to achieve a sound welded joint. In addition to the welding parameters, the welding atmosphere, especially the humidity, could also influence the porosity and the properties of welded joint, as indicated by Gou et al. [14].

Another way to increase the mechanical properties or corrosion resistance of the welded joint is to use post weld heat treatment (PWHT). PWHT has been widely used to improve the properties of welds produced by TIG welding, friction stir welding, and MIG welding [15–17]. However, there are very few reports discussing on the effect of PWHT on the properties of hybrid laser welded Al alloys joint. Yan et al. [18] firstly applied PWHT to improve the corrosion properties of hybrid laser welded AA7N01 joint. The corrosion resistance of the welded joint could be improved through the PWHT, but the strength was deteriorated. Leo et al. [10] then investigated the role of PWHT on the microstructure and mechanical properties of AA5754 welds joined by hybrid laser welding, and reported that the microhardness and the mechanical properties of the heat-treated sample could be higher than the untreated one.

In the literature, few researchers tried to modify the alloying composition in the welded joint by altering the filling materials. Zhang et al. [9] studied the microstructure and mechanical properties of hybrid

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laser welded AA2219 alloys with filling materials of $AlMg_5$ and $AlCu_7$. It was found that the joint with $AlMg_5$ showed higher strength depending on two factors, considerable number of S-Al_2CuMg phases and their pinning effect on the dislocation motion. Wang et al. [19] investigated the effect of additional Ti and Sr on the microstructure and mechanical properties of AA4043 welding wire and the welded AA6082 joint with such wire. They claimed that the tensile strength of the welds with modified wire was significantly improved. It is generally accepted that Al-Si alloys are most suitable for welding Al-Mg-Si alloys because such filling material can maintain good fluidity during welding and thus reduce the sensitivity of cracking. Therefore, the welding of Al-Mg-Si alloys in most of the literatures was finished using Al-Si wire [12, 19–23]. However, the Al-Mg-Si alloys are sensitive to corrosion attack with higher Si content [24, 25], which means that the high-content-Si welds are also corroded easily and thus the in-service life is reduced under corrosive environment. Few literatures have reported the corrosion resistance for the welds, although the corrosion attack could result in brittle failure and cause catastrophe accidents during service. Actually, sound Al-Mg-Si welds with Al-Mg wire have been obtained without cracks [13, 26]. This suggests that the manufacturing process is not a problem for welding Al-Mg-Si alloys with either filling wire. But the question is what kind of wire should be used when hybrid laser welding Al-Mg-Si alloys? What kinds of criterial should be taken into consideration when selecting the filling materials? More importantly, how would the welded joint keep the in-service-life related properties unchanged or changed very slowly in a long term (such as fatigue strength and corrosion resistance)? To the best of our knowledge, no comparison has been made for these two kinds of welded joint with different filling materials.

In this work, two kinds of welded joints were produced by means of hybrid laser welding with two filling materials, ER5356 and ER4043. The microstructure of both joints was then characterized by optical microscope, scanning electron microscope (SEM), electron backscattered diffraction (EBSD), and energy dispersive spectrometer (EDS). The mechanical properties and hardness of the obtained joints were further examined and compared. The in-service-life related properties, such as fatigue strength and corrosion resistance, were studied as well to get the liability of the welded joint. The difference between these two kinds of joints was finally discussed. The aim of this paper is to provide useful guiding information for selecting appropriate filling materials when welding AA6061 using hybrid laser welding process.

2. Experimental Methods

2.1. Materials

The base metal (BM) used in this study was AA 6061-T6 with a dimension of 250 mm × 250 mm × 4 mm. The filler materials were ER5356 and ER4043, whose diameter was 1.6 mm. The former was Al-Mg alloys while the latter was Al-Si alloys. The chemical composition of BM and filler materials is listed in Table 1. Hereafter, we denote the welded joint with ER5356 and ER4043 filling materials as the ER5356 joint and the ER4043 joint, respectively.

2.2. Hybrid Laser Welding

The AA6061-T6 plates were joined by a hybrid laser welding system. Details of the systems can be found in Ref. [8]. To obtain a sound welded joint, considerable number of welding parameters (e.g., laser power, arc current, arc voltage, and welding speed) were applied to avoid welding defects or losing alloying elements due to excessive heat input. The optimized parameters for the welding process with two different filling materials are listed in Table 2. After welding, the welded plates were examined using X-ray Inspection System to see if any defects (e.g., porosity, cracks) were included in the weldments. As shown in Fig. 1, no macro pores and cracks exist in the joint, and the weld appearance is of high quality without undercut.

Table 2
Parameters for hybrid laser welding AA6061-T6 with different filling materials.

Filling material	Arc current (A)	Arc voltage (V)	Laser power (KW)	Welding speed (m/min)
ER5356	148	24.4	2.3	1.2
ER4043	173	21.1	2.2	1.2

2.3. Sample Preparation and Characterization

Cross section of the joint was mounted in resin block. Then standard metallurgy grinding, and polishing method was applied to prepare the mounted sample. Generally, the sample was firstly grinded using SiC paper of grade 400#, 800#, and 1200# consecutively. Then the sample was polished using 6 μm and 3 μm diamond paste to get mirror surface. Finally, the sample was polished using 0.02 μm colloidal silica solution for at least 40 min to remove all scratches and deformed layers. At least two samples were prepared for each kind of joint. One sample was for etching to reveal the microstructure, the other one was for electron back scatter diffraction (EBSD) test.

The etching experiment was done using Keller's solution. Then light microscope was used to see the microstructure in the welded joint. The microstructure of the sample was also examined under Zeiss Ultraplus Field Emission Scanning Electron Microscope (FESEM). The chemical composition of the matrix and the precipitates was measured using energy dispersive spectroscopy (EDS). Electron backscatter diffraction (EBSD) test was performed to obtain the grain size and orientation distribution in FZ. The EBSD test was carried out with the parameters of 20 KV acceleration voltages, 4 nA beam current, and 24.5 mm working distance. The step size of the test was 3 μm to maintain the data accuracy and efficiency. The EBSD data was processed with commercial HKL software.

2.4. Mechanical and Fatigue Test

After welding, the material in HAZ could recover some strength due to the natural ageing, but this effect is significant in the first month (more accurately first 14 days) and decreases considerably in the following ageing time [27, 28]. Thus, the welded joint was intended to be naturally aged for one month before performing any mechanical test to minimise the ageing effect on the strength of the welded joint. All samples for the mechanical test were taken from the welded joint in the direction perpendicular to the welding direction. Standard dog-bone samples for tensile tests were made using electron discharge machining (EDM) method with the dimension similar to that in Ref. [26]. The tensile test was conducted at room temperature with the displacement

Table 1
Chemical composition of the base metal and filler materials (wt%).

	Mg	Si	Cr	Mn	Fe	Cu	Zn	Ti	Al
AA6061-T6	0.8–1.2	0.4–0.8	0.04–0.35	0.15	0.7	0.15–0.4	0.25	0.15	Balanced
ER4043	0.05	4.5–6.0	–	0.05	0.8	0.3	0.1	0.2	Balanced
ER5356	4.8	0.1	0.1	0.15	0.4	0.1	0.1	0.13	Balanced