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RESEARCH PAPER

Microstructural Investigation of Laser-Welded Anodized 6061 Aluminum Alloy

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Abstract: *This study investigated the feasibility of laser welding on anodised aluminium alloy. Industry has a strong demand for welding anodised aluminium sheets. First, we varied the anodising time while keeping other anodising parameters constant. We performed the anodising process at three anodising times: 30, 45, and 60 min. We then selected the sample with the largest oxide layer thickness, obtained at the longer anodising time, for laser welding. We performed the welding process at a laser power of 1500 watts and a welding speed of 300 mm/s on anodised 6061-T6 aluminium alloy with an oxide layer thickness of 17 µm. The current investigation showed that a sound joint occurred between two anodised aluminium sheets. Although the anodised layer inhibits joining of aluminium sheets due to its high melting point, the results showed a homogeneous distribution of elements within the weld zone. Meanwhile, dendrite growth across the weldment indicates elemental concentration in the interdendritic regions.*

Keywords: *Aluminum alloy, Anodizing, Laser welding, Anodized layer, Dendrites.*

1. INTRODUCTION

Wrought Al alloys are classified into multiple series based on the main alloying element added to the Al lattice. The 6xxx series is one of the most utilized alloy groups in industry [1, 2]. Its main features are a high strength-to-weight ratio and the ability to be hardened through age-hardening heat treatment. This group is a suitable substitute for various steels in applications such as the marine and aerospace industries [3-5]. In addition, welding and permanent joint fabrication in this group are considered challenging and critical. This alloying group also has good weldability, formability, and machinability. Meanwhile, its corrosion resistance is relatively good [2, 6].

Anodizing is the electrochemical formation process of oxide coatings on the surface of aluminum alloys, which is carried out in an electrochemical cell in which the alloy is located as the anode [7]. The primary oxide surface is established O^{2-} and OH^{-} Anions migrate through the oxide film to react with Al^{3+} cations, resulting in further oxidation. A high electrical field around the anode is the main driving force behind this oxidation. The coating formed in the anodizing process increases the corrosion resistance, wear resistance, fatigue resistance, surface adhesion, heat absorption, and electrical insulation of the primary metal [8, 9].

Laser welding is a non-contact fusion welding process that melts and joins two similar or dissimilar materials using heat generated by an intense laser beam [10]. Utilizing this welding method for aluminum alloys is believed to offer several advantages, including a narrow heat-affected zone, a narrow fusion zone, and minimized thermal distortion. However, joining Al alloys by laser welding has proven challenging due to aluminium's physical properties [11, 12]. Matsuda et al. [13] investigated the effect of laser diameter on laser welding of AA6061 alloy. The results showed that reducing the diameter from 0.6 to 0.3 mm significantly reduced the energy required to achieve full penetration, improved process efficiency, and increased weld stability. Béguin et al. [14] investigated the laser welding behavior of heat-treatable aluminum alloys (AA6061, AA2024, and AA5083). They showed that weld quality strongly depends on chemical composition and input energy, and that selecting appropriate laser power and welding speed can result in complete penetration, reduced porosity and cracking, and improved mechanical properties. Batahgy et al. [15] have investigated the laser welding of 5000 and 6000 Al alloy groups. They reported that laser welding these alloys requires higher laser powers because aluminium's high surface reflectivity and thermal conductivity lead to evaporation of alloying elements. Furthermore, high equipment and operating costs [12] accurate beam and joint alignment [16], and the clamping and fitting of workpieces [17] are other challenges in laser welding aluminum alloys. Based on the hints above, improving laser beam absorption on the Al alloy surface would significantly reduce the minimum required energy and reduce the mentioned defects. Surface processing procedures, such as sandblasting and especially anodising, can help researchers achieve this goal. Rinker et al. [18] have investigated the mechanical and electrical properties of laser-welded anodized aluminum alloy. They indicated that increasing the thickness of the anodised layer before welding increases the likelihood of porosity and the deterioration of electrical conductivity. Meanwhile, there is a critical thickness value below which there is no sign of mechanical weakening.

This research demonstrates the feasibility of direct laser welding of anodised AA6061-T6 aluminium alloy without removing the anodised layer. Unlike previous studies, which generally removed the oxide coating before welding or examined only the effect of anodization on weld quality, this study produced a joint through a relatively thick anodised layer (17 µm) and analysed the resulting microstructure and elemental distribution.

2. EXPERIMENTAL PROCEDURES

First, three 6061-T6 aluminium alloy sheets (fabricated by AlumMetal Co.) were prepared at 6 mm thickness for anodising. Table 1 shows the chemical composition of the AA6061 alloy.

For this purpose, all specimen surfaces were abraded with 120- to 3000-grit abrasive papers and then mechanically polished before anodising—the abrasive solution of 5 wt.% alumina was used to obtain smooth surfaces. After preparing the specimens, the researchers anodised them. Table 2 shows the process specifications. Fig. 1 shows a schematic of the anodising equipment used in this research. In this process, all parameters were kept constant except the anodizing time. This study used anodising times of 30, 45, and 60 min.

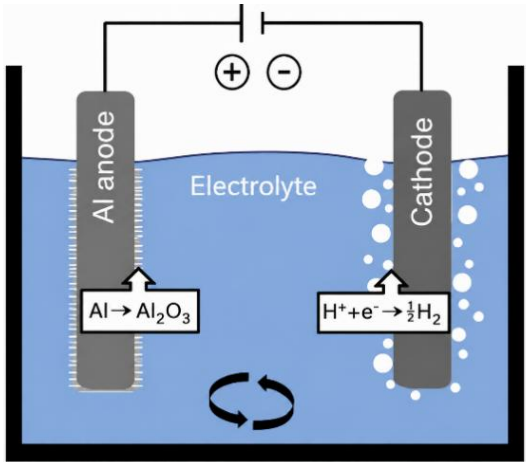

Fig. 1. The schematic of the Al anodizing process [19]

The laser welding experiments were carried out using a continuous-wave Nd: YAG laser (model DLD-2000W) with a wavelength of 1080 nm. The laser beam diameter at the workpiece surface was 0.6 mm. High-purity argon (99%) was used as the shielding gas at 15 L/min to minimise oxidation during welding. After welding, the specimen was wire-cut perpendicular to the joint to examine its weld quality. Afterwards, we polished and etched the section for scanning electron microscopy (SEM). In this research, we used a TESCAN-VEGA SEM. We determined the chemical composition of elements in the weld zone using planar and linear elemental analysis.

We determined the oxide layer thickness by optical microscopy (OM) after anodising. Indeed, the laser welding of aluminum alloys is very popular and well known to many scholars, and there are many publications in this field; however, no investigation has been reported to date regarding the laser welding of anodized aluminum alloys because the presence of an oxide layer plays an obstacle role between two aluminum sheets and no appropriate joining can be achieved, especially when the anodized layer thickness is high.

Table 1. The chemical composition of the Al 6061 alloy (wt.%)

Al	Mn	Mg	Cr	Cu	Fe	Si	Ti	Zn
Bal.	0.15	1.1	0.3	0.2	0.6	0.5	0.1	0.2

Table 2. The anodizing process conditions

Electrolyte solution	0.3 molar oxalic acid
Current density	$2\,\frac{A}{dm^2}$
Voltage	122 v
Temperature	0°C
Cathode material used	6061-T6 aluminum alloy

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3. RESULTS AND DISCUSSION

The aluminum sheets were anodized at anodizing times of 30, 45, and 60 min. The anodized samples were first characterized by an Optical Microscope to measure the anodized layer. Fig. 2 shows the OM images of samples anodized for 30, 45, and 60 minutes. The relationship between the anodizing layer thickness and the anodizing time is depicted in Fig. 3. As illustrated in Fig. 3, the thickness of the anodized layer increased with the increase in anodizing time. This is because anodization is a diffusion-based process, and the anodizing time influences the anodizing layer thickness. We repeated the anodised layer thickness measurement 3 times.

The oxide layers deposited on the surface of Al sheets during the anodizing process act as an inhibitor between the two Al sheets to be welded. However, we chose 6061-T6 anodised aluminium alloy with the thickest anodised layer to investigate the weldability of anodised aluminium alloy by laser. Therefore, we selected a sample with a 17 µm anodised layer for butt laser welding. This selection indicates that laser welding can be generalised to samples with lower anodised layer thickness if a good weld is established between two samples with the highest layer thickness.

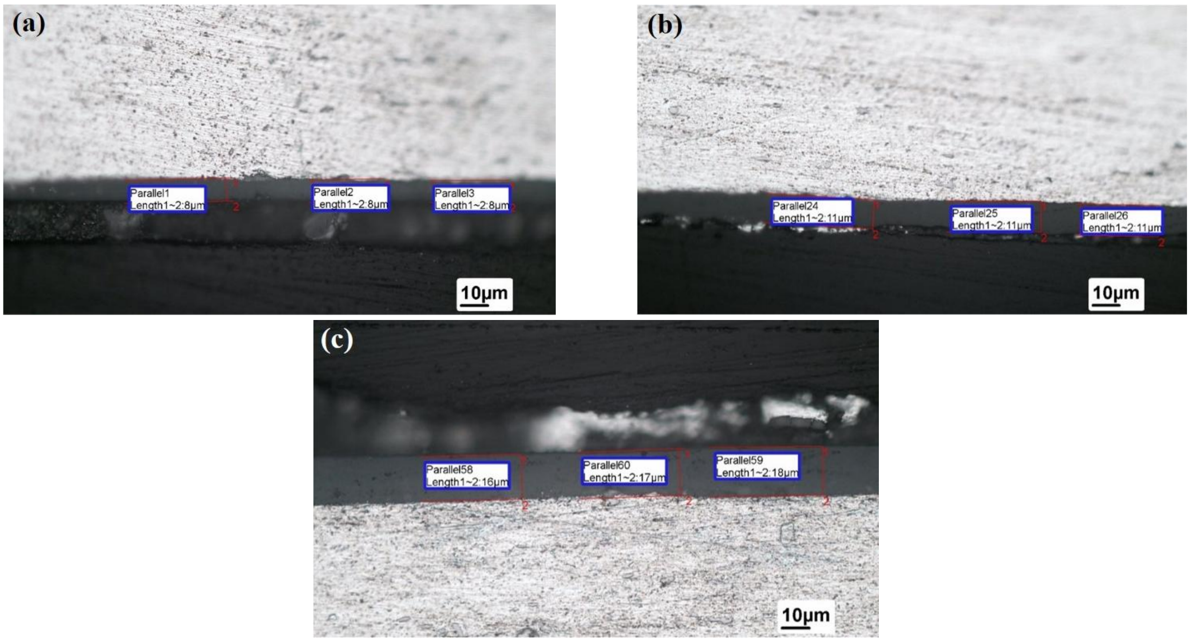

Fig. 2. OM images of the cross sections of samples anodized at the anodizing times of a) 30, b) 45, and c) 60 minutes

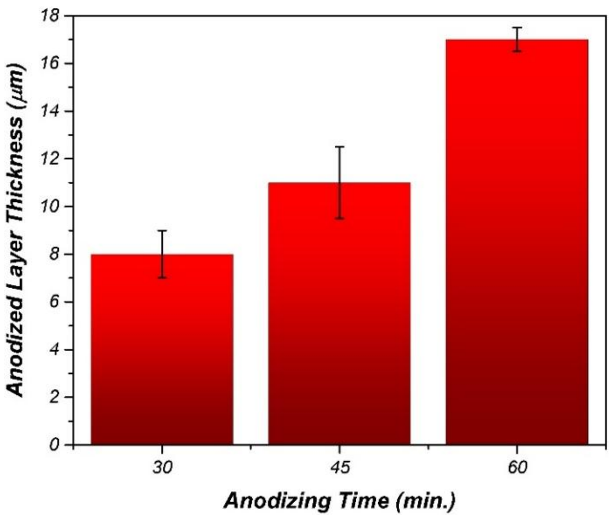

Fig. 3. The relation between the anodized layer thickness and the anodizing time

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The SEM image of the weldment of the anodized sample containing 17 μm of anodized layer is depicted in Fig. 4. As shown in Fig. 4, a crack of 4.26 mm length has been created in the weld section. This relates to the final stage of dendrite growth, where solidification ends, followed by the concentration of some elements and the formation of brittle intermetallic compounds or oxides. Norman et al. [20] have already confirmed the susceptibility of laser-welded aluminium and its alloys to such defects. However, the joining was successful, although welding anodised samples seems much more difficult. Fig. 4 justifies the observed crack. Fig. 5 illustrates the EDS map analysis of the different elements from the yellow square. This figure indicates that the weld zone's chemical composition is relatively homogeneous, although solidification in the weld pool is non-equilibrium. This means the elements were distributed roughly homogeneously, and the two sheets joined soundly.

Figs. 5(a) and 5(b) depict the concentrations of aluminium and other elements, respectively, along the yellow line of Fig. 5 from Point A to Point B. The concentration fluctuates noticeably along the scanned region. This observation is due to the alloy's dendritic structure in the weldment.The distribution coefficient (K_0) of elements, which is equivalent to $\frac{C_s}{C_l}$, is believed to be smaller than 1 in this alloy system. C_s is the concentration of alloying elements behind the solid/liquid interface, while C_l is the concentration of alloying elements in front of the solid/liquid interface. Therefore, the concentration of alloying elements behind the solid/liquid interface is always lower than the concentration of alloying elements in front of the solid/liquid interface.

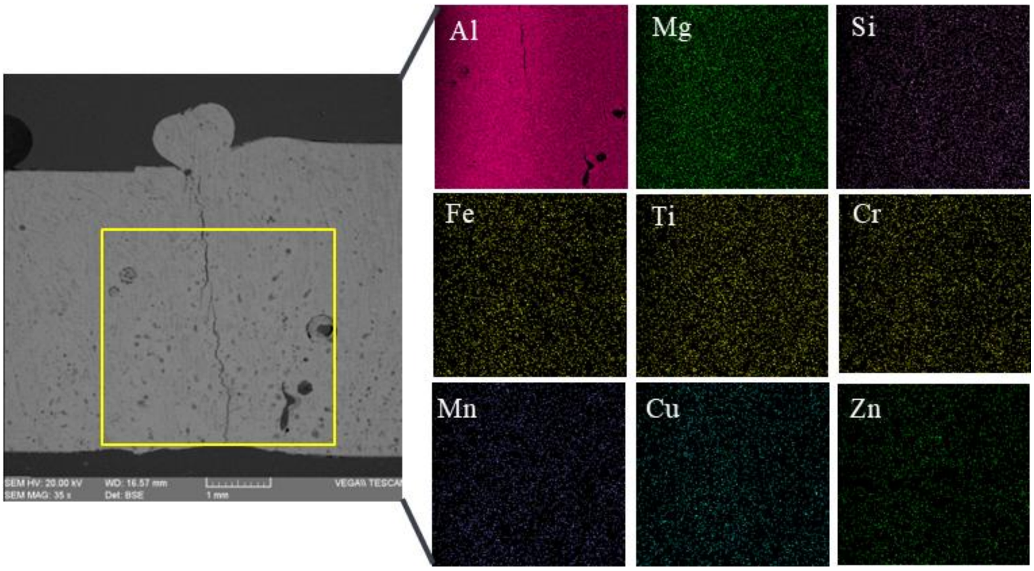

Fig. 4. The SEM cross-section of the weldment of the sample with a 17 μm oxide layer containing the line and surface EDS scanning regions

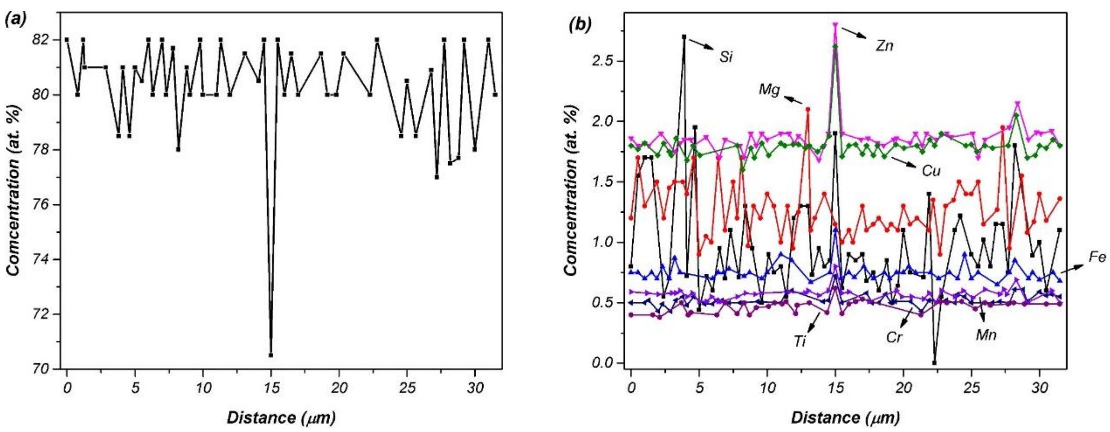

Fig. 5. Results of SEM line scan for a) aluminum and b) the rest of the elements along the weld section

The higher elemental concentration in front of the interface increases the concentration at the interdendritic regions compared with the dendrite core. This caused an enhancement in the elemental concentration at the grain boundaries and also decreased the concentration inside the dendrites, as depicted in Fig. 5. However, there is a huge fluctuation in the middle of the joint. The center of the joint is the last region to solidify. This means the highest element concentration occurred at the center of the weldment, as shown in Fig. 5(b). For instance, the major elements with higher concentrations in the middle are zinc, copper, silicon, and iron, while aluminium concentration decreases in this region, as illustrated in Fig. 5(a). Many of these metallic elements can create intermetallic compounds (IMCs) in this region. Since most IMCs are brittle, the middle of the weldment can crack due to thermal stresses caused by rapid cooling after welding.

The results show that laser welding of anodised AA6061-T6 is feasible; however, the anodised layer introduces additional metallurgical challenges. Although the sheets fused, a 4.26 mm crack was observed in the weld zone, indicating that successful fusion did not necessarily produce a defect-free joint. This behaviour can be attributed to rapid solidification during laser welding, during which alloying elements such as Cu, Si, Fe, and Zn are rejected from the growing dendrites and progressively enrich the interdendritic regions. Because the weld centre is the last region to solidify, it exhibits a higher concentration of these elements, as confirmed by the EDS line-scan results. This local chemical segregation can promote the formation of secondary or intermetallic phases and weaken the interdendritic regions. Simultaneously, thermal contraction during the final stage of solidification generates tensile stresses, thereby increasing the susceptibility to solidification cracking. These findings align with previously reported challenges in laser welding of aluminum alloys [15, 18, 19] and indicate that anodized layer thickness should be considered in process optimization, in addition to laser power and welding speed. From an industrial perspective, welding without prior removal of the anodized coating could eliminate an additional surface-preparation step, provided that the process parameters are optimized to minimize the segregation and solidification cracking.

4. CONCLUSIONS

The following conclusions can be obtained from this study:

1- The influence of the anodizing time on the anodized layer thickness was investigated.

2- The possibility of laser welding of anodized T6-6061 aluminum alloy containing the maximum anodized layer thickness was successfully examined.

3- The results inferred a homogeneous distribution of the elements within the weldment. Meanwhile, dendrite growth across the weldment indicates elemental concentration in the interdendritic regions.

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