Microstructural Investigation of Laser-Welded Anodized 6061 Aluminum Alloy

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Abstract

In this study, the feasibility of laser welding on anodized aluminum alloy has been investigated. There are many demands in the industry for the welding of anodized aluminum sheets. Firstly, the anodizing process was performed by changing the anodizing time and keeping the other anodizing parameters constant. The anodizing process was performed at three different anodizing times of 30, 45, and 60 min. Then, the sample with the largest oxide layer thickness, which was obtained at the higher anodizing time, was chosen for the laser welding. The welding process was performed at a laser power of 1500 watts and a welding speed of 300 mm/s on an anodized 6061-T6 aluminum alloy with an oxide layer thickness of 17 μm. The current investigation depicted that a sound joint occurred between two anodized aluminum sheets. Although the anodized layer acts as an inhibitor for the joining of aluminum sheets due to its high melting point, the results showed a homogeneous distribution of the elements within the weld zone. In the meantime, the growth of dendrites across the weldment indicates elemental concentration in the interdendritic regions.

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

Introduction

For wrought Al alloys, there are 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

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features are high values of strength-to-weight ratio and the ability to be hardened via age-hardening heat treatment. This group is found to be a suitable substitution for various kinds of steels in applications such as the marine and aerial industries [3-5]. Besides, the weldability as well as the permanent joints of this group are found to be laborious and crucial. This alloying group also has good weldability, formability, and machinability. In the meantime, 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, the 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 source and main force that causes this oxidation to occur. 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 consisting of melting and joining two similar or dissimilar materials using the 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, it is irrefutable that joining Al alloys by laser welding proved to be challenging due to the physical properties of aluminum [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 the weld quality

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strongly depends on the chemical composition and the amount of input energy, and that appropriate selection of 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 the laser welding of these alloys requires higher laser powers due to the high surface reflection of aluminum and its high thermal conductivity, which leads to the 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 mentioned above, promoting the laser beam absorption of the Al alloy surface would significantly reduce the minimum required energy, leading to the deterioration of the mentioned defects. The surface processing procedures, like sandblasting and especially anodizing, can help researchers fulfill this goal. Rinker et al. [18] have investigated the mechanical and electrical properties of laser-welded anodized aluminum alloy. They indicated that an increase in the thickness of the anodized layer before the welding increases the probability of porosity inducement as well as the deterioration of electrical conductivity. Meanwhile, there is a critical thickness value below which there is no sign of mechanical weakening.

This research lies in demonstrating the feasibility of direct laser welding of anodized AA6061-T6 aluminum alloy without removing the anodized layer before welding. Unlike previous studies, which generally removed the oxide coating before welding or investigated only the effect of anodization on weld quality, the present study produced a joint through a relatively thick anodized layer (17 μm) and analyzed the resulting microstructure and elemental distribution.

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Materials and Methods

First, three 6061-T6 aluminum alloy sheets (fabricated by AlumMetal Co.) were prepared with a thickness of 6 mm for the anodizing process. The chemical composition of the AA6061 alloy is depicted in Table 1.

Table 1. The chemical composition of 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

For this purpose, all surfaces of specimens were abraded with 120 to 3000-grit abrasive papers and then mechanically polished before anodizing. The abrasive solution of 5 wt.% alumina was used to obtain smooth surfaces. After preparing the specimens, the anodizing process was performed. The specifications of the process are illustrated in Table 2. Fig. 1 depicts a schematic of the utilized anodizing equipment in this research. In this process, all parameters were kept constant except the anodizing time. The anodizing times of 30, 45, and 60 min were applied for this study.

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 ℃
Cathode material used	6061-T6 aluminum alloy

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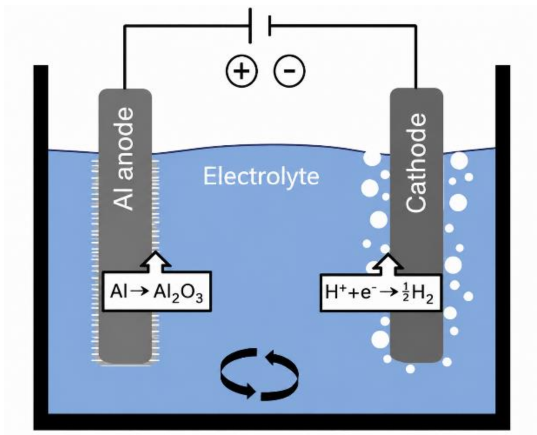

Fig. 1. The schematic of the Al anodizing process [19].

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. Also, high-purity argon (99%) was employed as the shielding gas at a flow rate of 15 L/min to minimize oxidation during welding.

After welding, the specimen was wire-cut perpendicular to the joint to examine its weld quality. Afterward, the section was polished and then etched to be studied by scanning electron microscopy (SEM). In this research, the TESCAN-VEGA model of SEM was used. The chemical composition of elements in the weld zone was determined by using planar and linear elemental analysis.

The oxide layer thickness values were determined by an optical microscope (OM) after anodizing. 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 till now 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.

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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 relation 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. The measurement of the anodized layer thickness was repeated 3 times.

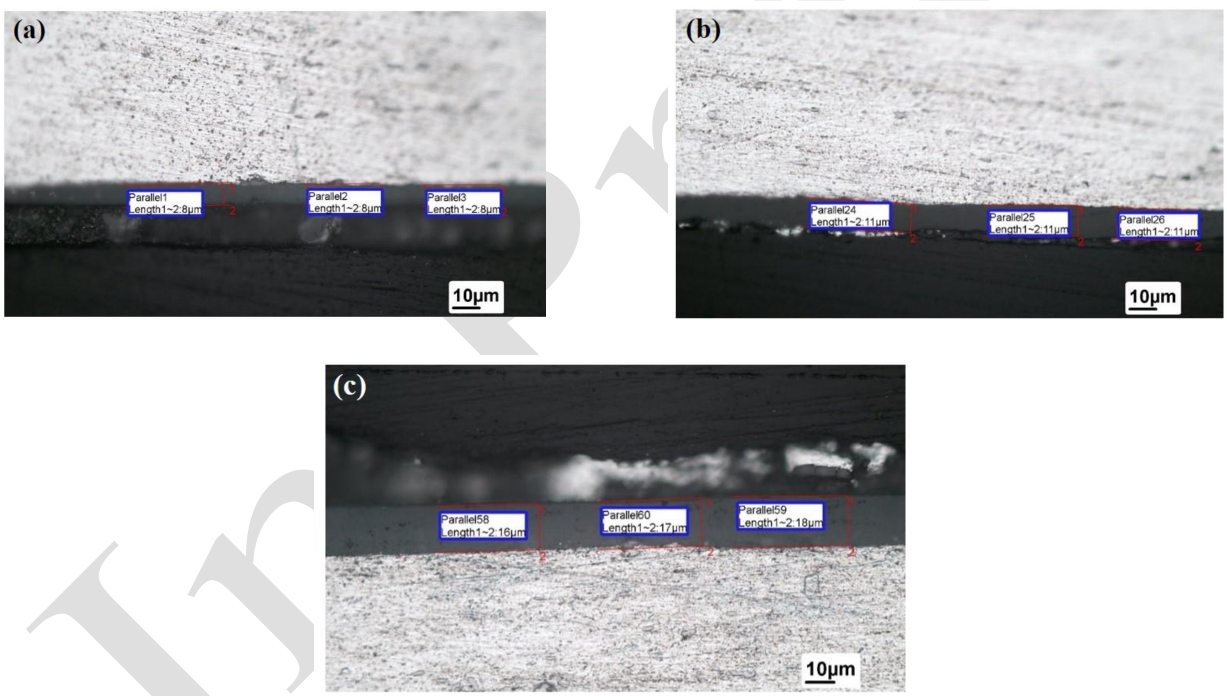

Fig. 2. OM images of the cross sections of samples anodized at the anodizing times of (a) 30, (b) 45, and (c) 60 minutes.

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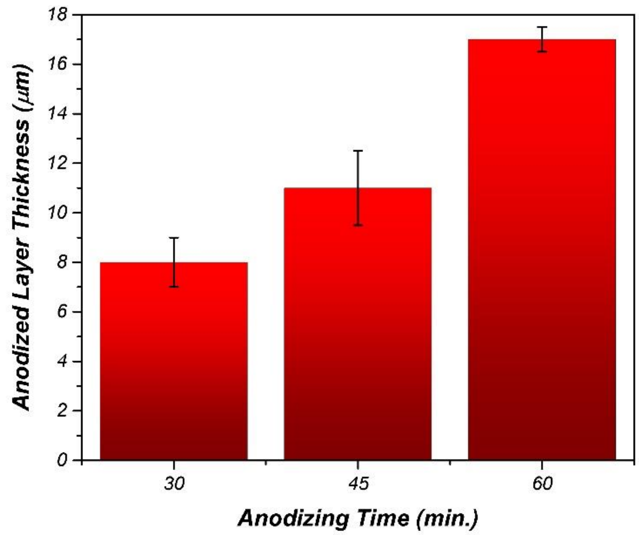

Fig. 3. The relation between the anodized layer thickness and the anodizing time

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, 6061-T6 anodized aluminum alloy with the thickest anodized layer was chosen to investigate the weldability of anodized aluminum alloy by laser. Therefore, the sample with a 17 μm anodized layer was selected for the butt laser welding. This selection indicates that the laser welding can be generalized to other samples with a lower anodized layer thickness if a good weld is established between two samples with the highest layer thickness.

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 is related to the final stage of dendrite growth, where solidification is finished, and then the concentration of some elements, and then the formation of the brittle intermetallic compounds or oxides. The susceptibility of laser-welded aluminum and its alloys to such defects has already been confirmed in Norman et al.'s research [20]. However, the joining was successful, although the welding of anodized samples seems to be much more difficult. The justification for the observed crack is shown in Fig. 4.

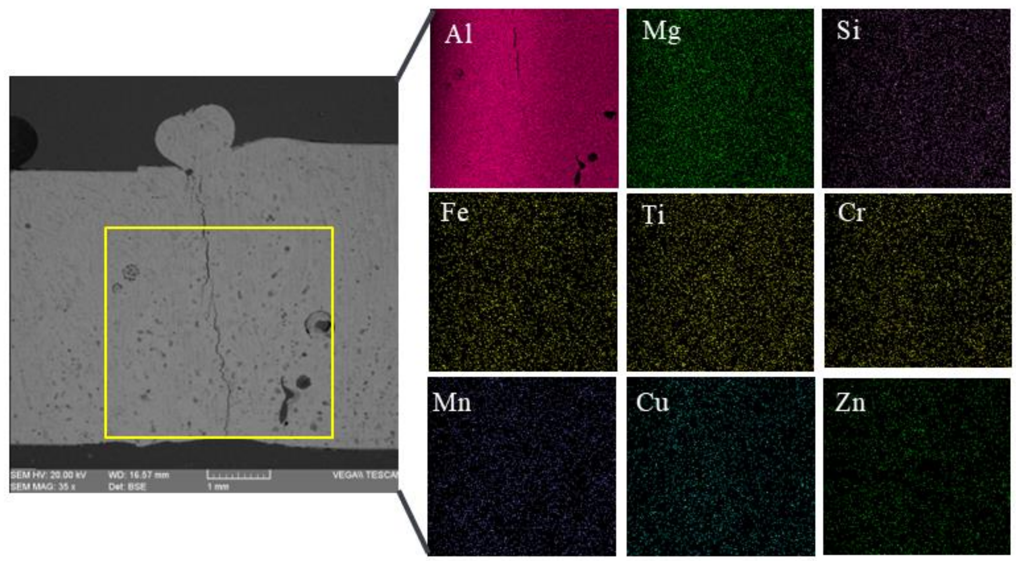

Fig. 4. The SEM cross-section of the weldment of the sample with a 17 μm oxide layer containing the line and surface EDS scanning regions.

Fig. 5 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 the solidification is non-equilibrium in the weld pool. This means that the distribution of the elements occurred roughly homogeneously, and the sound joining happened between two sheets. 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 has a noticeable fluctuation along the scanned region. The reason for this observation is the dendritic structure of the alloy 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. 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 that solidifies. This means that the highest element concentration occurred at the center of the weldment, as depicted in Fig. 5(b). For instance, the major elements that have higher concentration in the middle are zinc, copper, silicon, and iron, while the concentration of aluminium is decreased in this region, as illustrated in Fig. 5(a). Many of these metallic elements can create intermetallic compounds (IMCs) in this region. Since most of the IMCs are recognized as brittle compounds, the middle of the weldment can crack due to the thermal stresses caused by the rapid cooling after the welding.

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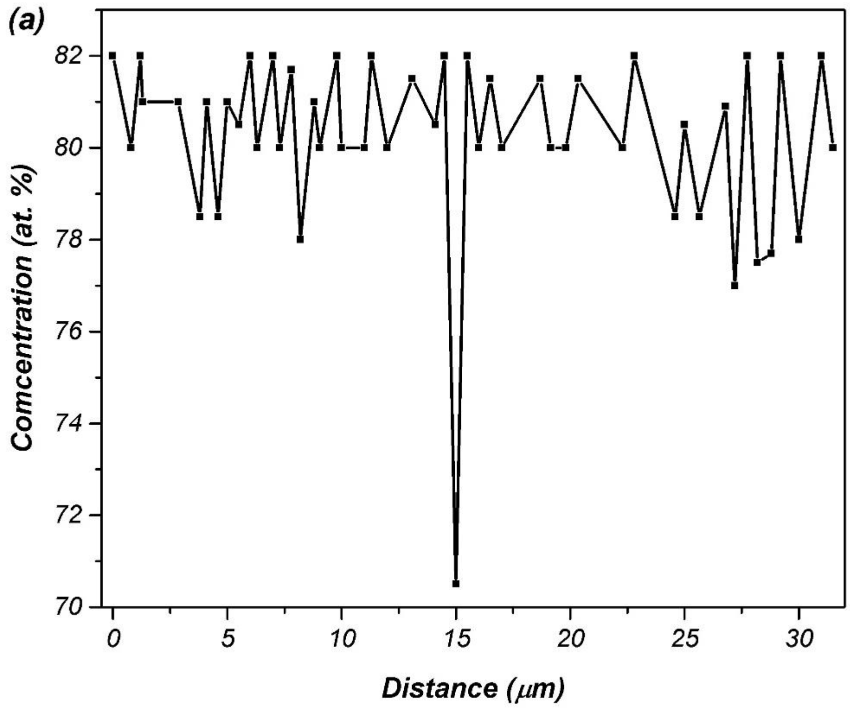

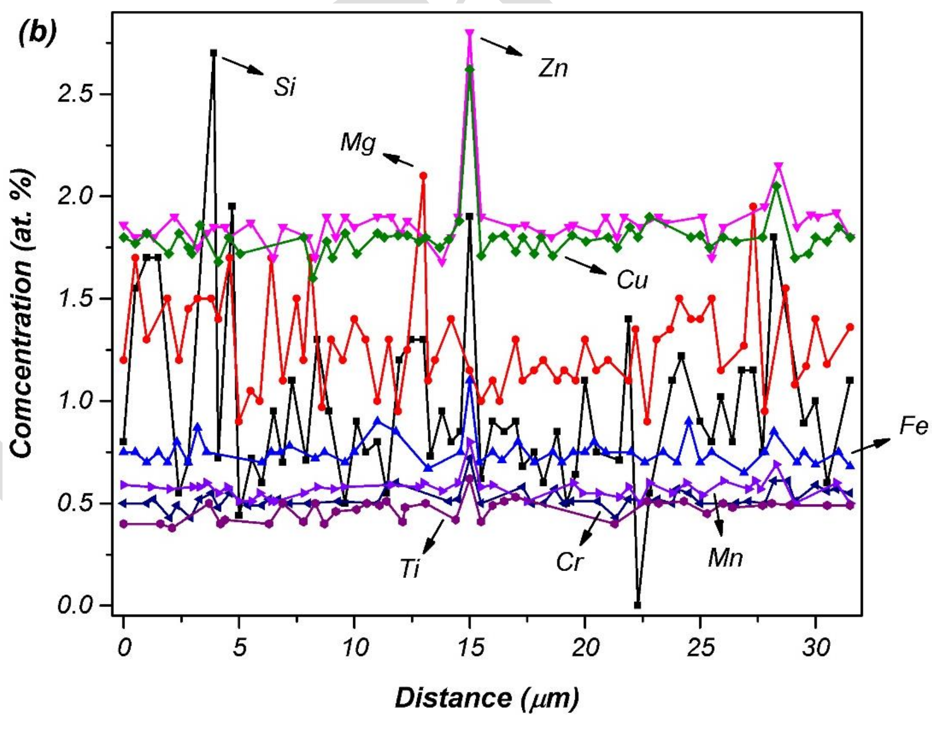

Fig. 5. Results of SEM line scan for (a) aluminum and (b) the rest of the elements along the weld section.

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The present results demonstrate that the laser welding of anodized AA6061-T6 is feasible; however, the presence of the anodized layer introduces additional metallurgical challenges. Although fusion between the sheets was achieved, a 4.26 mm crack was observed in the weld zone, indicating that successful fusion did not necessarily result in a defect-free joint. This behavior can be attributed to the rapid solidification of the laser welding, during which alloying elements such as Cu, Si, Fe, and Zn are rejected from the growing dendrites and progressively enriched in the interdendritic regions. Since the weld center is the last region to solidify, it consequently 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 are consistent with previously reported challenges associated with 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.

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 the homogeneous distribution of the elements within the weldment. In the meantime, the growth of dendrites across the weldment indicates elemental concentration in the interdendritic regions.

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