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The effect of laser surface melting on microstructure and corrosion behavior of friction stir welded aluminum alloy 2219

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ABSTRACT

This study aimed to explore the electrochemical properties and microstructure of friction stir welds to understand the correlation between their properties and processing. Friction stir welding is a promising solid-state joining process for high-strength aluminum alloys (AA). Although friction stir welding (FSW) eliminates the problems of fusion welding due to the fact that it is performed below T_m, it causes severe plastic deformation in the material. Some AA welded by FSW exhibit relatively poor corrosion resistance. In this research, the corrosion resistance of such welds was enhanced through laser surface melting. A friction stir weld of AA 2219 was laser melted. The melt depth and microstructure were observed using optical and scanning electron microscopy. The melt zone exhibited epitaxially grown columnar grains. The redistribution of elemental composition was analyzed using energy-dispersive spectroscopy. The anticorrosion properties of both laser-melted and original welds were studied in aqueous 3.5% NaCl solution using cyclic potentiodynamic polarization. The results indicated a noticeable increase in the pitting corrosion resistance after the laser treatment on the surface. The repassivation potential was nobler than the corrosion potential after the laser treatment, confirming that the resistance to pitting growth improved.

1. Introduction

High-strength aluminum alloys (HSAL), such as 2xxx series, are widely used in the aerospace and shipbuilding due to their excellent properties including high strength and low density. However, it is difficult for these alloys to be welded by conventional fusion methods. Since its invention in 1991 by the Welding Institute in England, friction stir welding (FSW) has emerged as a promising solid-state joining process with encouraging results and is being used to join HSAL alloys now (2xxx, 6xxx, 7xxx, and 8xxx series) [1–4]. FSW can cause minimal microstructural changes and improve mechanical properties of the weld compared with conventional joining techniques including tungsten inert gas and metal inert gas [5,6]. Although a number of publications have demonstrated that defect-free joints in these high-strength Al-alloys can be readily achieved by FSW [7–14], a few studies exist on the enhancement of the corrosion behavior of these joints.

Using a specially designed tool that rotates and plunges into the butting surfaces, FSW transforms the metal into a plastic state, creating a strong welded joint. The welding process transpires at a temperature below the melting temperature of the material [15], mitigating cracking problems associated with segregation during solidification of the weld metal [16]. Rigid clamping during FSW and specimen heating can affect residual stresses, reducing the anticorrosion property of weld joint and causing a negative impact on the structural integrity [17,18].

The rate of corrosion of aluminum alloys (AA) in chloride solutions is low according to studies and observation. However, pitting occurs, and pitting corrosion resistance of AA depends on their purity. The 1xxx series (purest alloy) is more resistant than other AAs. Al–Mg alloys display good resistance against a general localized corrosion. In contrast, Al–Cu alloys show a comparatively lower pitting resistance [19]. The pitting resistance may be further reduced after the friction stir welds of Al–Cu alloys. Pitting on AA generally takes place in an electrolyte with a pH of 4.5–8.5, which increases with temperature and electrolyte concentration. Alloying elements tend to either enhance or reduce the pitting resistance [19–22].

Laser surface melting (LSM) technology has drawn extensive attention with its unique performance in recent years. During the LSM process, no precipitation occurs, thus improving the corrosion resistance of the material. After LSM, the mechanical properties of the substrate do not decrease. The LSM technology has a high energy density and fast heating and cooling characteristics. Therefore, it can change the structure and composition of the surface

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layer, ultimately improving the corrosion resistance of materials. Some recent studies have focused on laser melting of AA, and a few have reported on the laser treatment of friction stir welds of AA.

This study examined the electrochemical properties and microstructure of such welds to understand the correlation between properties and processing.

2. Material and experimental procedures

2.1. Friction stir welding of AA 2219

The FSW process was carried out by the FSW-3LM-002 machine produced by China Friction Stir Welding Center. The base material used for this study was AA 2219. The 4-mm-thick sheets were cut into 300 × 100 mm^2 specimens prepared for FSW processing. The welding direction was aligned with the rolling direction of the material. Bead-on-plate friction stir welds were produced using an H13 steel tool consisting of a concave 16-mm-diameter shoulder and a 5-mm-diameter pin with the length of 3.75 mm. During the FSW, a constant tile angle of 2.5° was maintained.

Fig. 1 shows the appearance of friction stir welded joint of AA 2219. It can be seen that sound weld without obvious defects was obtained when rotation speed was 1000 rpm and travel speed was 100 mm/min. The joints were cross-sectioned perpendicular to the welding direction for microstructure analyses. The cross-sections of the metallographic specimens were observed by optical microscopy after etching with Keller's reagent (1 mL of HF + 1.5 mL of HCl + 2.5 mL of HNO_3 + 95 mL of distilled water).

2.2. LSM of friction stir weld of AA 2219

The YLS-6000 fiber laser, which has a maximum output power of 6 KW and high stability, was used in the LSM process. The laser system consisted of a laser generator, water cooling systems, conducting path and focus systems, welding head, automatic programming software, and CNC numerical control system. The laser beam was focused on the surface of the specimen, using a 310-mm focal length objective lens. The continuous-wave mode was employed using the laser power of 1000, 1200, and 1500 W with a scanning speed of 1000 mm/min. AA 2219 after laser melting of the surface is shown in Fig. 2.

2.3. Microstructure

Laser surface–melted friction stir weld specimens were characterized in the microstructure using the VHX-900 depth of field digital microscopes. Scanning electron microscopy (SEM) was used to analyze the microstructure; while energy-dispersive spectroscopy (EDS) analyzed the chemical composition and redistribution of elements in the laser-melted and unmelted zones.

Fig. 1. As-processed friction stir weld of AA 2219.

2.4. Immersion test

The immersion test was performed in a 3.5% NaCl solution at 25 °C open to the atmosphere under quiescent conditions to understand how corrosion impacted the properties of laser-melted and unmelted regions of a friction stir weld of AA 2219. At the end of the immersion test, which lasted for 24 h, the sample was cleaned using an ultrasonic cleaner in distilled water to remove loosely bound corrosion products. The cleaned sample was immediately observed under VHX-900 Super-Depth-of-Field Digital Microscope and SEM for evaluation.

2.5. Electrochemical characterization

The effects of laser treatment on corrosion property of the friction stir weld were studied in naturally aerated aqueous 3.5% NaCl solution at 25 °C under normal atmospheric conditions. Both laser surface–melted and native friction stir welds were tested for corrosion property using the electrochemical technique. The specimens were cut into a rectangular shape. Then, the epoxy resin was used to pack samples, and a top surface of approximately 1 cm^2 was exposed.

The electrochemical test was done on CS double-cell electrochemical workstation. A 1-cm^2 foil was used as the auxiliary electrode, and the saturated calomel electrode was used as the reference electrode in measuring anodic polarization curves. Electrochemical testing settings ranged from open circuit potential of positive and negative 0.2 V, scan speed 1 mV/s. Polarization measurements began just after the open circuit voltage stability.

3. Results and discussion

3.1. Macrostructure of friction stir welded joint

The cross-section of the specimen was ground and polished using the standard metallographic procedure to identify and locate different areas of the friction stir weld of AA 2219. A cross-section of the friction stir welded joint is shown in Fig. 3. The metallographic section shows a classic weld nugget region and significant signs, commonly represented as "onion rings." The structure in the nugget was fine and equiaxed with grain sizes significantly smaller than the parent material grain. The nugget zone under the action of the metal pins underwent plastic deformation, and frictional heat increased the temperature of the material. The grain was crushed and generated a lot of nonspontaneous crystallization. Recrystallization occurred, and grains became fine and uniform, which were called equiaxed grains.

3.2. Microstructure of welded joint

Fig. 4 shows the optical micrographs of laser-melted friction stir weld of AA 2219 treated with 1000, 1200, and 1500 W power at a scanning speed of 150 mm/min. A set of laser parameters were tested to exclude unreasonable adverseness and achieve the optimal ones to further explore laser melting effects on the FSW welds of AA. The solubility of hydrogen in molten AA was larger than that of other parameters with the power of 1500 W laser melting. The hydrogen in the weld escaped with long cooling time. Fig. 5 shows the optical micrograph of the laser surface–melted friction stir weld treated with different parameters, showing the depth, width, overlapping region, and intersection angle of the melt tracks. As shown in Fig. 6, the width of single-pass melt track, depth of

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