Effect of Laser Strengthening on Electrochemical Corrosion of AA6082 Aluminum Alloy

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Abstract. In this study, the surface of 6082 aluminum alloy was machined by laser heat treatment, and the microstructure and properties of the affected zone of laser surface were discussed by scanning electron microscope (SEM). The experimental results show that the laser treatment has an obvious second phase fine grain strengthening effect on the surface of aluminum alloy. The local hardness of the surface laser action zone has been improved obviously. Combined with the polarization curve data and microscopic corrosion morphology, with the addition of laser, the corrosion resistance mechanism of aluminum alloy has been well optimized, and the number and continuity of pitting pits on the surface of aluminum alloy have been restrained. The intergranular corrosion and the maximum corrosion depth behavior decreased under the corrosion of Cl⁻. The comprehensive properties of aluminum alloy surface have been effectively optimized under the action of laser heat treatment. The effect of laser heat treatment on the corrosion resistance and the surface mechanical properties of AA6082 aluminum alloy was investigated.

1. Introduction

With the development of science and technology, aluminum alloy is widely used in various industries because of its high strength and good thermal conductivity [1-3]. Among them, Al-Mg-Si alloys are commonly used in automobile industry because of its excellent plasticity and corrosion resistance [4]. However, such aluminum alloy suffers local corrosion in aqueous solution containing chloride ions, which seriously reduces the service life of alloy components [5]. This requires that the alloy not only has good mechanical properties, but also has good corrosion resistance. Laser surface heat treatment is a kind of technology that can improve the surface properties of metal materials [6]. It can achieve the purpose of fine grain strengthening by laser remelting the extremely thin surface layer of materials. This method has a good effect on the performance strengthening of metal materials.

In recent years, this technique has been widely used in the study of material surface. Spierings et al. [7] reported the effect of laser heat treatment on the microstructure of Sc-Zr and Al-Mg aluminum alloys. The results show that the main reason for grain refinement is the oxide of Al or Mg produced during laser treatment. Su et al. [8] reported the effect of laser heat treatment on the mechanical properties of Al-Mg-Si aluminum alloy. As a result, the fine grains formed by recrystallization in the molten pool greatly improved the hardness of the alloy. However, the effect of laser heat treatment on the corrosion resistance of aluminum alloy is rarely studied.

Therefore, in this paper, the electrochemical corrosion characteristics of Al-Mg-Si alloy after laser strengthening were studied and revealed its corrosion mechanism in Cl⁻ environment. It is expect that provide a reliable theoretical basis and data support for the application of laser in the surface modification of aluminum alloy.
2. Experimental Materials and Methods

AA6082 aluminum alloy was used in this study. The chemical composition of the material is shown in Table 1. The heat treatment process of the sample is solution treatment (525°C × 45 min) and subsequent artificial aging treatment (170°C × 5 h), which is the peak aging (T6).

|   | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Ti  | Zn  | Ni  | Al  |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1.04 | 0.27 | 0.064 | 0.617 | 0.72 | 0.13 | 0.02 | 0.03 | 0.007 | Bal |

The 5020Nd:YAG solid-state laser made by TRUMPF company of Germany is used for laser heat treatment of alloy surface. In order to prevent the interference between laser beams, single laser scanning was used in the experiment, and the scanning interval was 10 mm. The laser power of 1000 W and scanning speed of 0.9 m/s were selected, and the defocusing amount was 5 mm, and the pure Ar shielding gas of 5 L/min was applied. The schematic diagram of laser scanning and sample preparation are shown in Figure 1.

The corrosion test was carried out on zennium electrochemical workstation. The conventional three electrode system was used. The working electrode was AA6082 aluminum alloy, the auxiliary electrode was platinum electrode, and the reference electrode was saturated calomel electrode. The corrosion medium is 1.5% NaCl solution, and the contact area with the sample is 1 cm². After the system is stable, the electrochemical corrosion test and polarization curve are collected. The scanning speed is 3 mV/s, and the open circuit potential range is -3V ~ 3V. After testing, the polarization curve was fitted by Tafel to obtain the electrochemical parameters such as corrosion potential (E_{corr}) and corrosion current density (I_{corr}). The microstructure and corrosion characteristics of laser zone were observed by scanning electron microscope and metallographic microscope. In order to explore the effect of laser strengthening on the microstructure and properties of AA6082 aluminum alloy, and to reveal the electrochemical corrosion mechanism, the micro corrosion morphology and corrosion depth before and after corrosion were compared and analyzed.
3. Results and Discussion

3.1. Microstructure Analysis

The macro morphology of the surface and cross section of the aluminum alloy sample after laser heat treatment is shown in Figure 2. The dark area in Figure 2 (a) is the laser action zone with a width of about 7 mm, and the surface is smooth without melting. The light color part is the matrix area. The crescent shaped area in Figure 2 (b) is the laser action area, and the average depth of the influence layer is 0.52 mm. This distribution pattern conforms to the law of laser energy distribution, that is, the laser beam energy is Gaussian distribution, the central energy is large, and the influence layer is deeper. Figure 3 is the comparison of metallographic structure of aluminum alloy before and after laser heat treatment. Figure 3 (a) shows the metallographic structure of aluminum alloy matrix. It can be observed that there are many second phase particles with different shapes in aluminum alloy matrix, which are distributed irregularly. Figure 3 (b) shows the microstructure of the alloy after laser heat treatment. It is obvious that the number and distribution of the second phase particles in the aluminum matrix have changed significantly. The main reason for the microstructure difference is that the solid solubility of the aluminum alloy increases after laser irradiation, resulting in a large amount of intermetallic compounds in the alloy, which can greatly improve the mechanical properties of the material [9], that is, the second phase strengthening.

![Figure 2](image1.png)

**Figure 2.** Surface and cross section morphology of AA6082 aluminum alloy after laser treatment. (a) surface morphology, (b) cross section morphology

![Figure 3](image2.png)

**Figure 3.** Metallographic microstructure of AA6082 aluminum alloy surface. (a) alloy matrix, (b) laser heat treatment

![Figure 4](image3.png)

**Figure 4.** Metallographic structure of AA6082 aluminum alloy after 0.5% HF corrosion. (a) alloy matrix, (b) laser heat treatment

The corrosion metallographic morphology of aluminum alloy cross section is shown in Figure 4. In order to observe the microstructure change of laser heat treatment more clearly, 0.5% HF was used to corrode the sample. It can be seen from Figure 4(a) that the forging streamline inside the aluminum
alloy under peak aging is curvilinear around each initial crystalline α-Al matrix, and the intermetallic particles are basically disorderly distributed on the forging streamline. As shown in Figure 4(b), after laser treatment, the forging streamline of alloy sample disappears, and it is difficult to observe large second phase particles, which indicated that the microstructure of aluminum alloy has changed greatly after laser treatment, and the second phase particles are refined and dispersed on the grain and grain boundaries. The α-Al in the alloy matrix is refined into uniform equiaxed grains, and some intermetallic particles such as Mg in Mg$_2$Si are selectively evaporated when heated, resulting in the enrichment of Si with high melting point [10], which increases the possibility of non spontaneous nucleation, that is, the nucleation rate increases. This further promotes the refinement of the organization. In other words, the grain refinement degree is proportional to the number of crystal nuclei, and the second phase particles will preferentially precipitate at the grain boundary.

3.2. Microhardness Analysis

Figure 5 shows the structure distribution of laser affected zone and the selection direction of hardness test. The hardness test was carried out on the same parallel line with the same force application interval. Figure 6 is the gradient diagram of hardness curve. It can be seen from the Figure 6(a) that the microhardness of laser affected zone is the highest after laser strengthening treatment, and it tends to decrease gradually towards the matrix. The hardness of laser affected zone can reach 100 HV, 36% - 43% higher than that of base metal. The hardness distribution of the cross section is the highest in the laser surface layer and decreases rapidly with the increase of the depth. According to the hardness gradient trend in both horizontal and vertical directions and microstructure metallographic photos, it is concluded that the second phase strengthening and solution strengthening effects brought by laser processing greatly refine the microstructure of laser affected zone and finally present higher microhardness. With the weakening of laser effect, the grain refinement degree of horizontal and longitudinal transition zone gradually decreases, thus showing a small micro hardness value.

![Figure 5. Schematic diagram of laser action on aluminum alloy cross section](image)

![Figure 6. Hardness distribution of AA6082 aluminum alloy. (a) laser treatment of surface, (b) laser processing cross section direction](image)

Based on the above hardness gradient observation, it is concluded that the microstructure refinement of the molten pool produced by laser treatment leads to the increase of hardness. Meanwhile, the process of strengthening grain refinement of the second phase is accompanied by the
dislocation strengthening effect caused by the shrinkage and solidification of the molten pool, which further improves the microhardness of the aluminum alloy [11].

3.3. Corrosion Resistance Analysis
The polarization curves of the samples before and after laser treatment are compared and analyzed in Figure 7. It is obvious that in neutral NaCl solution, the polarization trend of aluminum alloy is the same, and obvious passivation range appears, which indicates that laser heat treatment changes the mechanical properties of aluminum alloy, but does not change its corrosion mechanism. However, after laser treatment, the corrosion current density of the samples decreased greatly from 40 μA/cm² to 16 μA/cm², which indicated that the corrosion resistance of the aluminum alloy samples was improved and the corrosion rate was reduced.

Figure 7. Comparison of surface polarization curves of AA6082 aluminum alloy after laser treatment

Figure 8 shows the SEM morphology of aluminum alloy sample surface corroded by Cl⁻. The left of the dotted line is the aluminum alloy matrix area, and the right of the dotted line is the laser scanning area. Under the same experimental conditions, serious corrosion occurred on the surface of the alloy matrix, and large volume and continuous corrosion pits were formed on the surface. However, the surface of laser heat treatment area is relatively complete, and there are pitting pits in some areas, and the pitting pits are discontinuous distribution. The SEM results show that laser heat treatment enhances the corrosion resistance of aluminum alloy, which is consistent with the polarization curve.

Figure 8. SEM morphology of AA6082 aluminum alloy after surface corrosion

Figure 9 shows the corrosion morphology of aluminum alloy cross-section, in which Figure 9 (a) is the SEM photo of matrix corrosion, while Figure 9 (b) is corrosion morphology after laser heat treatment. The alloy matrix presents typical intergranular corrosion in neutral NaCl solution, and the intergranular corrosion continues to expand into the matrix, which is consistent with previous studies. In contrast, the corrosion morphology of the sample after laser treatment is "particle", similar to the denudation of small grains, and some small pits are mainly distributed in the equiaxial grain boundaries. The main reason is that the microstructure of aluminum alloy is changed under the action of laser, and the intermetallic compounds in the alloy precipitate at the grain boundary, resulting in the formation of multiple groups of corrosion micro couple at the grain boundary. When corrosion occurs, it is preferentially carried out around the second phase, i.e. at the grain boundary. Furthermore, there
are less corrosion cracks on the cross section of the sample after laser treatment, and it is not easy to form continuous intergranular corrosion channel, which can hinder the corrosion of corrosive solution to a certain extent. In contrast, the subsurface layer of the alloy matrix is almost completely occupied by the corrosion net, and there is a large cavity in the matrix, and the bonding strength between grains is low, which results in the failure of the subsurface layer of aluminum matrix. Through the measurement of the maximum corrosion depth of the section, it is found that the maximum corrosion depth of the aluminum alloy section decreases from 180 μm to 130 μm after laser heat treatment. It can be seen that laser heat treatment effectively hindered the expansion of corrosion, reduced the corrosion rate and prolonged the service life of the alloy, which is consistent with the polarization curve test results.

![Figure 9. Corrosion morphology of AA6082 aluminum alloy cross section. (a) matrix, (b) laser heat treatment](image)

4. Conclusions
According to the observation and analysis of the microstructure and properties of AA6082 aluminum alloy, the conclusions are as follows:

(1) The surface grains of aluminum alloy are refined obviously by laser treatment, and the grains are transformed into uniform fine equiaxed grains under the action of laser.

(2) The hardness in the center of the laser affected zone is 36% - 42% higher than that of the base metal, and with the decrease of laser refining effect, the hardness value decreases from the laser affected area to the substrate in a Gaussian distribution.

(3) After laser heat treatment, the continuity of etch pits is reduced, the corrosion current density is decreased in macroscopic view, and the maximum corrosion depth is decreased in microscopic view, and the corrosion resistance is increased.

(4) After laser treatment, the second phase remelting occurs on the surface of aluminum alloy and precipitates preferentially at the grain boundary, which changes the mode of intergranular corrosion, inhibits the propagation of corrosion cracks and reduces the corrosion rate.

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6. References
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