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The Effect of Heat Treatment on Corrosion Resistance of 6061 Aluminum Alloy

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In this paper, the corrosion resistance in 3.5% NaCl solution of 6061 aluminum alloys after different heat treatment is investigated by slow strain rate equipment, polarization curves and impedance, combining scanning electron microscopy. The results showed that the results of three methods are consistent. The tensile fracture time of the alloy after solution treatment is longest, the one of alloy after dual-stage aging is shorter, and the one of alloy after single-stage aging is shortest; the passivation film of alloy after solution treatment is most stable, with the largest value of impedance, the passivation film of dual-stage aged and single-stage aged alloys are poorly stable, the impedance values are lower. Dual-stage aging makes the second phases coarser, cutting off continuous anodic dissolution channel and owing a smaller current density than single-stage aging alloys.

Keywords: 6061 aluminum alloy; heat treatment; slow strain rate; polarization curves; impedance

1. INTRODUCTION

The aluminum alloy of 6xxx series with moderately high strength is heat-treatable and good weldability, highly suitable in various structural, building, marine, machinery, and process-equipment applications[1,2]. Stress corrosion cracking (SCC) can cause the significant service failures of engineering materials in the aeronautical, nuclear, and petrochemical industries. 6061 aluminum alloy, as a representative of 6XXX-series aluminum alloy, is widely used as an aircraft structural material because of its high strength and low density. However, this alloy is susceptible to various forms of corrosion in chloride environments, such as SCC, pitting corrosion, intergranular corrosion, and exfoliation corrosion. Metal oxidation is well recognized as being associated with the reduction of hydrogen ions in aqueous acid solutions.

The corrosion resistance of 6061 aluminum alloy is closely related with heat treatment[3,4]. How to evaluate the corrosion resistance of materials heat treated is very important, which needs to take different methods into consideration from different aspects [5,6]. Related experiments used slow strain rate test (SSRT) to investigate the effect of Retrogression and Reaging treatment (RRA) on the stress corrosion resistance of 7075 aluminum[7,8]and the effect of step-solution on the corrosion resistance of 7075 aluminum alloy[9]. The literature[10] take advantage of SSRT and exfoliation corrosion test to investigate the effect of dual-aging on the corrosion resistance of aluminum alloy. Limited literatures used inter-granular corrosion test to research the effect of solution treatment and aging on inter-granular corrosion resistance of 6061 aluminum alloy [11,12].

According to the results of document retrieval, the investigation of corrosion resistance of 6061 aluminum alloy is limited to single SSRT and immersion test, however, the investigation of the effect of heat treatment on the corrosion resistance of 6061 aluminum alloy with the methods of combining with polarization, impedance analysis and SSRT is few. The experiment used SSRT, electrochemical workstation and SEM to investigate the corrosion resistance in 3.5% NaCl solution of 6061 aluminum alloy after different heat treatment, in order to provide comprehensive electrochemical analysis including polarization ,impedance and the results of SSRT.

2. EXPERIMENTAL

The material used in the experiment is 6061 aluminum alloy with chemical composition(wt%): Mg-0.9%, Cu-0.2%, Mn-0.15%, Zn-0.25%, Cr -0.1%, Ti-0.15%, Si-0.6%, Fe-0.7%, remaining Al.

The heat treatment test includes solution treatment and aging. Solution treatment: held for one hour at the temperature of 440℃, 470℃, 500℃, 530℃, 560℃ respectively, then water-cooled. Single-aging: held for 2h, 5h, 10h, 12h at 170℃, then air-cooled. Dual-aging: firstly held at 170℃ for 5h followed by air-cooling, then held respectively at 190℃, 210℃, 230℃, 250℃ for 2h.

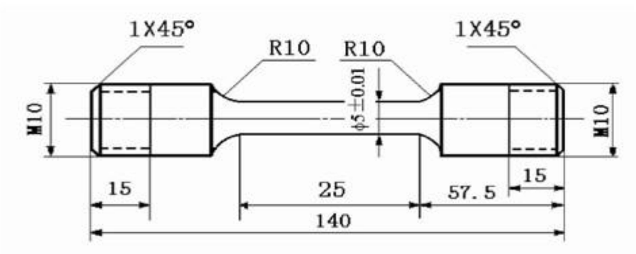

Figure 1. SSRT sample

Hardness testing: the MH-5 hardness tester with the load of 100N and loading time of 10 seconds. In SSRT, the medium solution is 3.5% NaCl solution. The size of sample is showed in figure one. The tensile speed is 0.00004mm/s. The fracture morphology is observed by SEM (JEOL-

JSM6480). The polarization curves and impedance spectroscopy is tested by Gamry Reference 600. SCE and Pt was used as reference electrode and counter electrode respectively. The scan rate for polarization is 0.1mV/s. And the test solution is 3.5% NaCl solution.

3. RESULTS AND DISCUSION

3.1 Hardness test

The hardness curves of 6061 aluminum alloy after heat treatment is shown in Fig2. As shown in Fig 2, the hardness of sample after single -aging is hardest, that of sample after dual-aging is lower and that of sample after solution treatment is lowest.

As shown in Fig 2(1), increasing with the solution temperature, the hardness of samples firstly increased, then decreased and at 530℃, the hardness reached to pick. Related literature[13] showed, to some extent, the hardness reflect the strength. From Fig 2(2), the hardness of samples reach to pick at five hours. In Fig 2(3), conducting second aging of (190℃, 210℃, 230, ℃, 250℃)/2h on the basis of the aging of 170℃/5h makes the hardness decrease.

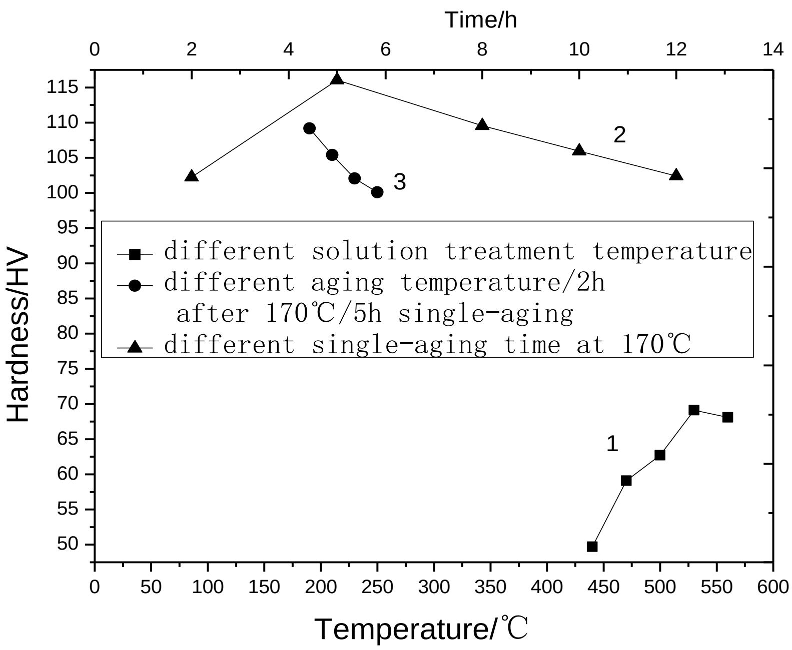

Figure 2. Graph of hardness about 6061 aluminum alloy after different heat treatment

3.2 SSRT

The table 1 shows date of SSRT of 6061aluminum alloy in 3.5% NaCl solution. The Fig 3 shows the stress-strain curves of 6061 aluminum after different heat treatment. The fig 4 shows fracture morphology of 6061 aluminum alloy after different heat treatment.

Table 1. The data of slow strain rate about 6061 aluminum alloy in 3.5% NaCl solution

	Tensile strength（MPa）	Fracture time（h）
170℃/5h+210℃/2h dual-stage aging	327	32.23
170℃/5h single-stage aging	333	30.65
530℃/1h solution treatment	238	62.65

As shown in table 2 and Fig 3, in 3.5% NaCl solution, the fracture time of 170℃/5h aged sample is shortest, showing worst corrosion resistance; the fracture time of 530℃ solution treated sample is longest, showing best corrosion resistance. The fracture time of 170℃/5h+210℃/2h dual-aged sample is a bit longer than the one of 170℃/5h aged sample, showing better corrosion resistance than the one of 170℃/5h aged sample.

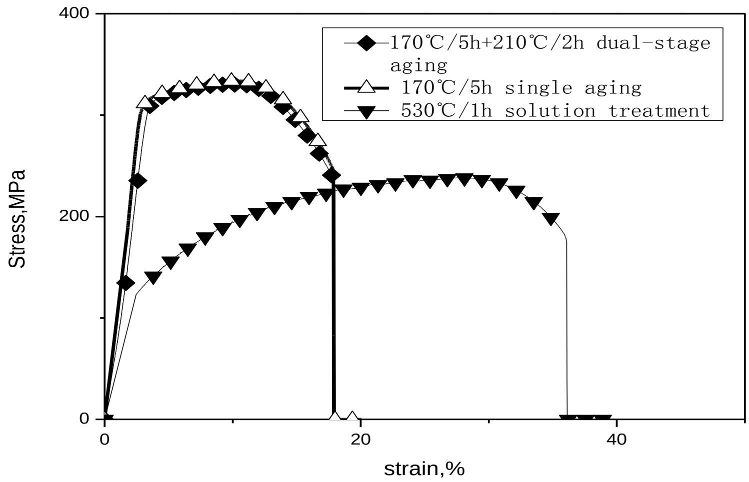

Figure 3. Stress-strain curves of 6061 aluminum after different heat treatment

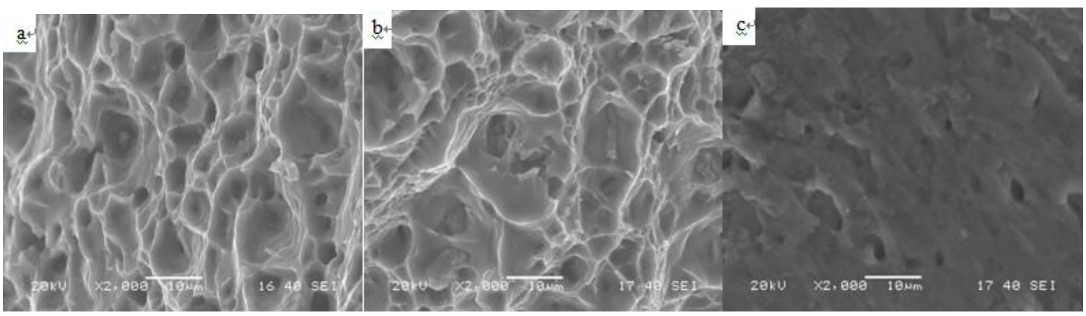

Figure 4. Fracture morphology of 6061 aluminum alloy after different heat treatment：（a）T6（b）170℃/5h+210℃/2h dual-stage aging（c）170℃/5h single-stage aging（d）530℃/1h solution treatment

Observed in Fig 4, fracture morphology exists corrosion pits of the 170℃/5h+210℃/2h dual-aged sample and 170℃/5h aged sample, which resulted from corroding. From Fig 4(c), the corrosion pits of 530℃ solution treated sample is fewer than other two, showing better corrosion resistance.

3.3 Polarization curves and impedance

Table 3 shows tafel fitting results of 6061 aluminum alloy after different heat treatment in 3.5% NaCl solution. Fig 5 shows polarization curves of 6061 aluminum alloy after different heat treatment in 3.5% NaCl solution. Fig 6 shows impedance of 6061 aluminum alloy after different heat treatment in 3.5% NaCl solution.

Table 3. Tafel fitting results

Heat treatment	I_{corr} , (A/cm^2)	E_{corr} (V)
530℃/1h solution treatment	1.512E-6	-1.2586
170℃/5h single-stage aging	6.1876E-7	-1.0242
170℃/5h+210℃/2h dual-stage aging	2.6594E-7	-0.97973

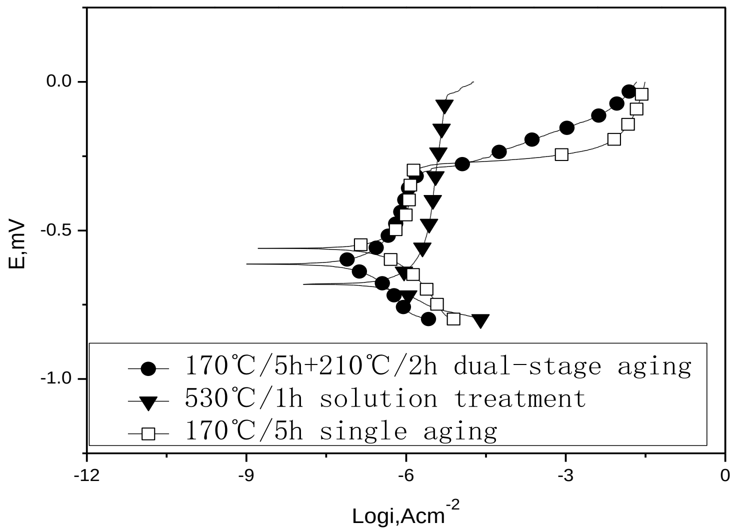

Figure 5. Polarization curves of 6061 aluminum alloy after different heat treatment in 3.5% NaCl solution

As shown in Fig 5, in 3.5% NaCl solution, 530℃ solution treated sample has a widest passivation, however, passivation of single-aged and dual-aged sample is narrower. Improving electric potential further, the passivation of single-aged and dual-aged sample is damaged, with shape increasing of corrosion current, which exhibits worse corrosion resistance. However, the corrosion current of solution treated sample increases slowly, exhibiting better corrosion resistance. From table 3, the corrosion current value of dual-aged sample is lower than that of single-aged sample, which shows that dual-aged sample owns a better corrosion resistance than single-aged sample.

According to the principle of electrochemical impedance[14], the radius of curves can react the value of impedance. As shown in fig 6, the impedance value of solution treated sample is greatest, the one of dual-aged sample is lower and that of single-aged sample is lowest.

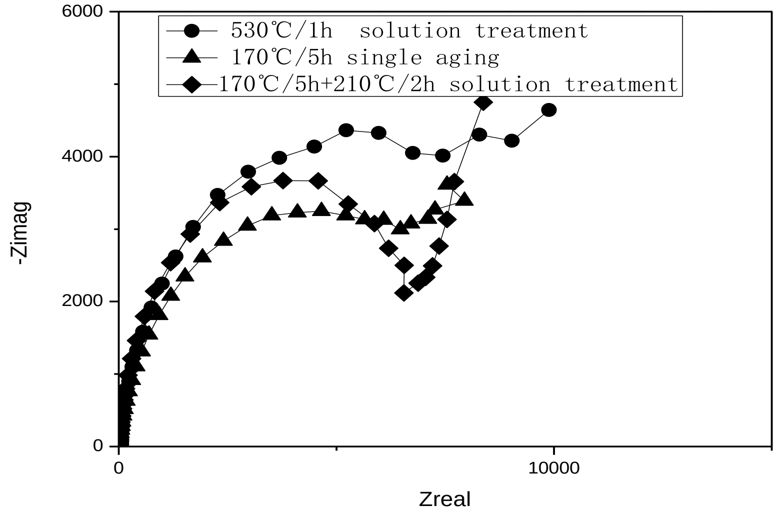

Figure 6. EIS of 6061 aluminum alloy after different heat treatment in 3.5% NaCl solution

3.4 Discussion

Solution treatment is important to the second phase resulted from aging and the properties of materials[15]. Related researches show that with increasing the solution temperature, more Mg and Si solute atoms dissolved into α-Al matrix, resulting in severe distortion of the lattice of matrix, making hardness increase.

When 6061 aluminum alloy is aged, distribution of the second phase has a big effect on the properties of alloys. The inter-granular precipitation sequence isα-supersaturated solid solution, coherent GP zones, coherent β′′ phase, semi-coherent β′ phase, incoherent equilibrium β phase; the grain boundary precipitation sequence isα-supersaturated solid solution, incoherent equilibrium β phase[16,17]. Related researches [11] show that Si will cluster in the Al matrix in early aging, formatting segregation area (S.A). With prolonging aging time, S.A. becomes larger, but remains coherent relationship with the matrix, which hinder the movement of dislocations, improving hardness. Prolonging aging time further, S.A. makes into β′ phase and β phase, leading to the decline of hardness. Conducting second aging in higher temperature, the S.A. will reflow into the matrix, making the sum of strengthening phase decrease and hardness decrease[18]. In the experiment, the relationship between hardness and different heat treatment is consistent with the above literatures, which explains the precipitates in grain boundary and grain interior in the experiment.

The precipitates in grain boundary is related with heat treatment, their size and distribution has a significant effect on the corrosion resistance of materials[19]. To solution treated samples, solute atoms almost dissolve into the matrix, making little electrochemical differences, which hinders micro-cell corrosion formatting, showing better corrosion resistance than aged samples. However, in aging, because of the precipitates in grain boundary, leading to electrochemical differences in part, which reduces corrosion resistance. To the 170℃/5h single-aged sample, its grain boundaries have higher interfacial energy, making solute atoms segregate near grain boundaries, followed by the format of continuous anodic dissolution channel that will dissolve firstly. This will lead to inter-granular corrosion, showing bad corrosion resistance[5,20]. For 170℃/5h+210℃/2h dual-aged samples, higher temperature makes precipitates in grain boundary coarse and spherical, which cuts down continuous anodic dissolution channel, reducing the corrosion tendency, so the corrosion resistance of dual-aged samples is better than single-aged samples.

4. CONCLUSION

1. Compared with the solution treatment, 6061aluminum alloys obtain higher hardness through aging, however, it reduces the corrosion resistance of materials.

2. Conducting second aging at a higher temperature on the basis of single-stage aging will decrease the hardness of the alloys, but improve the corrosion resistance of the alloys.

3. Combining with SSRT, the method of polarization curves and impedance analysis to evaluate the corrosion resistance could make the results more accurate and more perfect.

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