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Grain boundary pre-precipitation and its contribution to enhancement of corrosion resistance of Al−Zn−Mg alloy

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Abstract: High temperature pre-precipitation (HTPP) took place in 7005 alloy at various temperatures after solution treatment and its influence on mechanical properties, corrosion behaviors and microstructure of the alloy was investigated using tensile test, intergranular corrosion (IGC) test, slow strain rate testing (SSRT), together with microstructural examinations. It is found that Vickers hardness of the aged alloy decreases gradually with decreasing the HTPP temperature, and almost a reverse trend of electrical conductivity is found compared to the hardness changes. Depending on the changes, two HTPP temperatures of 440 and 420 °C were chosen for comparative study. Results reveal that HTPP alloy tempers exhibit higher resistance to stress corrosion cracking (SCC) and IGC than none pre-precipitate one with an acceptable strength loss due to the substantial enhancement of distribution discontinuity of the coarse grain boundary precipitates (GBPs), and the coarsening and interspacing effect on GBPs becomes more obvious with decreasing the pre-precipitation temperature.

Key words: 7005 aluminum alloy; grain boundary pre-precipitation; stress corrosion cracking; intergranular corrosion; microstructure

1 Introduction

The heat treatable 7xxx series aluminum alloys have been extensively developed and used as advanced structural materials in military aircraft as well as commercial transportation industry due to a good combination of low density, high specific strength, satisfactory ductility and resistance to fatigue [1]. These alloys, unfortunately, are very vulnerable to stress corrosion cracking (SCC) in aqueous salt solution containing particularly the chlorine ions [2,3]. Besides, other forms of localized corrosion also occur under humid atmosphere and industrial waste gas, such as intergranular corrosion (IGC).

Up to the present, efforts have been made through heat treatments to overcome or reduce the SCC susceptibility of high strength 7xxx series aluminum alloys. It has been found that over-aged (T7x aging, with a strength loss of 10%−15% compared with that of T6 temper) or complicated retrogression and re-aged (RRA, without loss of strength) treatment can notably reduce the susceptibility of these alloys to SCC [2,3−5]. Nevertheless, correlations between grain boundary microstructures and SCC susceptibility for the over-aged alloys have not been fully established. The proposed mechanisms [6−8] to explain the beneficial effects of over-aging on SCC resistance are still controversial and none of these mechanisms can explain all the SCC experimental results. RRA treatment, an aging schedule which can optimize both strength and SCC resistance of these alloys, is inappropriate for large-section components owing to the request for a short retrogression time. Apart from aging, solution and quenching treatment is another important factor that has great effect on microstructure, and thus on localized corrosion behaviors. LIN et al [9] and OU et al [10] indicated that step-quenching and aging can modify the SCC resistance of 7050 alloy. CHEN et al [11] studied the effect of quenching rate on microstructure and SCC

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of 7085 alloy, and it was found that the improved SCC resistance is attributed to the relative high Cu content and large interspace of grain boundary precipitates (GBPs). HUANG et al [12,13] reported that high temperature pre-precipitation (HTPP) treatment not only keeps the high strength of 7A52 and 7055 alloy, but also enhances the resistance to IGC and SCC. In general, previous works showed that microstructure and microchemistry about localized corrosions including GBPs, matrix nearby and precipitate free zones (PFZ) can be controlled by heat treatments to improve the corrosion resistance [14−16].

7005 aluminum alloy has a long history, and it is still widely used in rail transit industry. However, little information is available in references about the effect of HTPP treatment on mechanical properties, localized corrosions and microstructure in mid-strength aluminum alloy. In this work, an attempt has been made to study the effect of HTPP treatment on mechanical properties, localized corrosion behaviors and microstructure of a mid-strength 7005 aluminum alloy, and the localized corrosion process and mechanism were also briefly analyzed.

2 Experimental

Hot extruded 7005 alloy plate with a thickness of 8.0 mm was used for this study. Nominal chemical composition of which is shown as follows: 4.15 Zn, 1.27 Mg, 0.017 Cu, 0.15 Fe, 0.14 Si, 0.29 Mn, 0.20 Cr, 0.10 Zr, 0.035 Ti, 0.01 V (mass fraction, %) and balance Al. A two-staged solution treatment was carried out, i.e., all the specimens were held at 450 °C for 30 min and ramped up to 470 °C for 30 min again and then ramped down to a temperature of 460, 440, 420, 400, 380, 370 and 360 °C respectively for another 30 min before quenching in water at room temperature followed by T6 artificial aging at 120 °C for 42 h. During the pre-precipitation process, temperature dropped at a controlled cooling rate of 1 °C/min from 470 °C to 460, 440, 420, 400, 380, 370 and 360 °C, respectively. Specimen hardness and conductivity measurements were used to monitor value changes during pre-precipitation process and the values reported here represented an average of at least 5 individual measurements. Accelerated IGC tests were performed according to the test standard of GB/T 7998—2005 [17], and the maximum depth of attack was measured and defined as the IGC susceptibility.

Slow strain rate tests (SSRT) were carried out at an initial strain rate of 1.0×10^{-6} s^{-1} in dry air and in aqueous 3.5% NaCl solution (mass fraction) on a slow strain rate tensile machine (LETRY WDML−1) at room temperature. The gauge portion of the SSRT specimen, made from the longitudinal direction of the alloy plate, having dimensions of 25 mm × 5 mm with a thickness of 3.0 mm was metallographically abraded and polished to produce scratch-free smooth surface. Failed specimen surfaces after SSRT were observed using a scanning electron microscopy (Sirion200) operated at 15 kV.

The relative ductility loss, $I_{SCC}(\delta)$, is defined as the SCC susceptibility [18],

$$I_{scc}(\delta)=\left(1-\frac{\delta_{sol.}}{\delta_{air}}\right)\times 100\% \quad (1)$$

where $\delta_{sol.}$ and δ_{air} are the elongations of the specimens in test solution and in dry air, respectively.

All samples for TEM observations were taken from sections perpendicular to the extruding direction and electropolished in a solution of 30% HNO_3 in CH_3OH at about −25 °C and 16 V. The thin foils were examined by a transmission electron microscope (Tecnai G^2 20ST) operated at 200 kV.

Electrochemical measurement was carried out using a three-electrode cell, furnished with a saturated calomel reference electrode (SCE) and a platinum sheet counter electrode. The studied alloy with an exposed square surface of 1 cm^2 acted as the working electrode. Potentiodynamic polarization tests were carried out at the applied potential, ranging from −0.2 to 0.2 V (vs OCP) in aqueous 3.5% NaCl solution with a scan rate of 1.0 mV/s. Cview program was used for data fitting of polarization curves.

The polarization resistance, R_p, was calculated according to the following equation [19]:

$$\frac{1}{R_p}=2.303J_{corr}\left(\frac{1}{b_a}+\frac{1}{|b_c|}\right) \quad (2)$$

where b_a, b_c and J_{corr} refer to the anodic Tafel slope, cathodic Tafel slope and corrosion current density, respectively.

3 Results

3.1 Hardness, conductivity and tensile properties

The initial as-extruded alloy was subjected to a two-staged solution treatment, i.e., held at 450 °C and 470 °C for 30 min respectively and then ramped down to a temperature of 460, 440, 420, 400, 380, 370 and 360 °C respectively for another 30 min before quenching in water at room temperature followed by an artificial aging at 120 °C for 42 h. Effect of various HTPP temperatures on Vickers hardness and conductivity of the aged specimen is shown in Fig. 1. Generally, the aged specimen hardness decreases gradually with the decrease of HTPP temperature. No obvious changes were monitored in hardness of the aged specimen after solution (pre-precipitation) treatment when the pre-precipitation temperature is close to the solution