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The intergranular corrosion susceptibility of 2024 Al alloy during re–ageing after solution treating and cold–rolling

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ABSTRACT

The intergranular corrosion (IGC) susceptibility of 2024 Al alloy during re–ageing after solution treating and cold–rolling was investigated by accelerated corrosion testing, open circuit potential testing, transmission electron microscopy and scanning electron microscopy. The absence of IGC in both the peak–re–aged and over–re–aged samples is related to the dislocation pile–ups which prevent the supersaturated solutes from diffusing into the grain boundaries and precipitating the continuous S–Al_2CuMg phase. The aggregated pitting corrosion in the over–re–aged samples arises from the S–phase precipitates on the dislocation cell walls which accelerate the anodic dissolution of the cell interiors.

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1. Introduction

Precipitation hardening is accepted usually as the most important strengthening mechanism for age–hardenable Al alloys. For example, 2024 Al alloy (Al–Cu–Mg) derives its high strength mainly by the matrix precipitation of S–Al_2CuMg phase or its precursors of solute cluster, Guinier–Preston–Bagaryatsky (GPB) zones, S″ and S′ phase as a result of natural or artificial ageing [1]. However, due to the solute segregation during the heat treatments of solution treating, quenching and ageing, precipitation heterogeneity is often observed in the vicinity of grain boundaries in age–hardenable Al alloys, which is characterized by the grain boundary precipitates and solute–depleted precipitate free zones (PFZs) adjacent to the grain boundaries [2]. Resultantly, the electrochemical microcouples can be formed between the grain boundary precipitates and PFZs, or between the matrix and PFZs because of their difference in the chemical composition and further corrosion potential. Furthermore, the age–hardenable Al alloys become susceptible to IGC via the anodic dissolution of the electrochemical microcouples in the aqueous solutions containing chloride if these electrochemical microcouples are distributed continuously along the grain boundaries [3–6]. In practice, IGC can be the potential sites for initiation of cracks and may result in catastrophic failure of alloy structures. Therefore, it is of theoretical and technological importance to reduce and even eliminate the IGC susceptibility of age–hardenable Al alloys.

On the other hand, some severe plastic deformation methods, such as equal channel angular pressing (ECAP) [7], high pressure torsion [8], accumulative rolling bonding [9] and so on, have received wide attention recently in order to increase mechanical properties (e.g. strength) of Al alloys further. Because of strong effectiveness in preparing ultrafine grained structures, these severe plastic deformation methods can increase mechanical properties of the Al alloys greatly. However, since the volume fractions of grain boundaries in the Al alloys can be increased remarkably as a result of grain ultra refinement by the severe plastic deformation methods, the IGC susceptibility of the alloys may be influenced correspondingly. Jilani et al. [10] indicated that the IGC susceptibility in coarse grained pure Al was eliminated by ECAP and only pitting corrosion was observed. Such phenomenon was attributed to the destruction of the preexisting grain boundaries during ECAP. Similarly, Brunner et al. [11] reported that the elimination of the IGC

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susceptibility in the 2024–T351 Al alloy was attributed to the rearrangement of grain boundaries and redistribution of Cu element as a result of ECAP. However, it is noted that the severe plastic deformation methods have rather difficulty in industrial applications due to their own disadvantages, such as limited sample sizes and complicated processing routes [12].

Recently, we proposed a conventional thermomechanical treatment composed of solution treating, cold rolling and re–ageing at relatively lower temperatures, which can increase the strength of 2024 Al alloy remarkably accompanied by an acceptable ductility [13]. For example, after solution treating at 495 °C for 1 h, cold–rolling at room temperature with a thickness reduction of 83% and re–ageing to peak strength at 100 °C for 72 h, the ultimate tensile strength, yield strength and elongation to failure of the 2024 Al alloy were 755 MPa, 711 MPa and 7.3%, respectively. By contrast, the ultimate tensile strength, yield strength and elongation to failure of the conventionally peak–aged sample at 190 °C for 8 h were 528 MPa, 426 MPa and 13%, respectively. Another remarkable advantage of the thermomechanical treatment is its feasible industrial applications in comparison with those severe plastic deformation methods, because the involved operations of the thermomechanical treatment are based on the existing industrial processing conditions.

In the present study, the IGC susceptibility of 2024 Al alloy during the thermomechanical treatment above was evaluated by immersing the samples in an acidified sodium chloride solution (30 g NaCl and 0.01 L concentrated hydrochloric acid (1190 g/L, thereafter) per liter of distilled water) for 24 h, aiming to verify whether both high strength and IGC resistance can be achieved simultaneously for the alloy via the thermomechanical treatment. Furthermore, the microstructural evolution was characterized by transmission electron microscopy (TEM) and then used to clarify the IGC susceptibility of the alloy in combination with scanning electron microscopy (SEM) and open circuit potential (OCP) testing to understand the corrosion behavior of 2024 Al alloy at the different processing stages of the thermomechanical treatment.

2. Experimental

2.1. Materials and processing

2024 Al alloy with the chemical composition of 4.3 Cu, 1.4 Mg, 0.76 Mn, 0.23 Si, 0.19 Fe, 0.01 Cr and balance Al (wt.%) was used in the form of hot rolled plates with a thickness of 6 mm. The as–received plates were solution treated at 495 °C for 1 h and then quenched in water at room temperature. Afterwards, the as–quenched (AQ) plates were cold–rolled (CR) at room temperature to 1 mm thickness with a reduction of 83%. These CR sheets were classed into two parts: one part of the sheets were re–aged (RA) for various times at 100 °C, 120 °C and 140 °C, respectively, aiming to understand the corrosion behavior of 2024 Al alloy in the different hardening conditions. The other part of the sheets were solution treated again at 495 °C for 1 h and quenched in room temperature water, and then aged at 190 °C for 8 h and 120 h, respectively, which represented the conventionally peak–aged (PA) and over–aged (OA) conditions of the 2024 Al alloy, to compare the corrosion behavior of the RA samples with the conventionally aged samples. The ageing treatments were carried out in an air–blasting drying oven with a temperature accuracy of ±2 °C

2.2. Electrochemical/corrosion testing

The IGC susceptibility of 2024 Al alloy at the different thermomechanical processing stages was evaluated in the mixed solution of 30 g NaCl and 0.01 L concentrated hydrochloric acid (1190 g/L) per liter of distilled water. For each processing condition of the alloy, one sample with a size of 50 mm length × 30 mm width × 1 mm thickness was machined from the sheets and the orientations were illustrated in Fig. 1. The IGC testing procedures of the samples included degreasing in acetone, etching in NaOH solution (50 g/L) at 60 °C for 3 min and immersing in the mixed solution of 30 g NaCl and 0.01 L concentrated hydrochloric acid per liter of distilled water for 24 h. After the immersion, the corroded samples were cut along the transverse direction (the dash line in Fig. 1) of the sheets with an interval of 10 mm. Then, the eight cross–sections (S–T planes) were obtained for each processing condition of the alloy. Afterwards, these cross–sectional samples were mechanically ground with increased grades (400, 800, 1000 and 1500 grit) fine SiC papers with water. Finally, the corrosion behavior of the alloy in each processing condition was evaluated by observing all the eight ground cross–sections on a XJG–05 optical microscopy and at the same time the measured deepest corrosion depth was taken as its maximum corrosion depth.

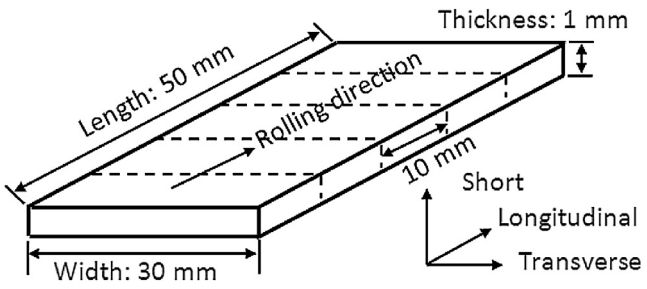

Fig. 1. Sizes and orienations of the IGC testing sample.

To reveal the corrosion initiation behavior of 2024 Al alloy in the different processing conditions, the samples with a size of 10 mm length × 10 mm width × 1 mm thickness were cut and sealed with paraffin. Then, their rolling surfaces (L–T planes) were ground with different SiC papers (400, 800, 1000 and 1500 grit) and polished with 1 μm alumina paste on the cloth polishing pads using ethyl alcohol as the lubricant. The polished rolling surfaces were immered in the mixed solution of 30 g NaCl and 0.01 L concentrated hydrochloric acid per liter of distilled water for 30 min. After cleaning in distilled water, the corrosion morphologies of the rolling surfaces were observed using a Zessi SUPRA55 (VP) field emission scanning electron microscopy (FESEM).

To characterize the electrochemical corrosion tendency of 2024 Al alloy in the different processing conditions, the OCP tests were also carried out using a CHI 660C Electrochemical Workstation. Similarly, the rolling surfaces (L–T planes) of the samples with a size of 10 mm length × 10 mm width were ground progressively using 400, 800, 1000, 1500 and 2000 grit SiC papers under ethyl alcohol. The ground surfaces were exposed to the solution of 35 g/L NaCl. The OCP values were tested for 30 min after 30 min of immersion. During the OCP test, the alloy was used as the working electrode and a saturated calomel electrode (SCE) were used as the reference electrode.

2.3. Microanalysis

To characterize the microstructural evolution of 2024 Al alloy at the different processing stages of the thermomechanical treatment, TEM observations were carried out on a Tecnai G2 F20 S–TWIN machine at an operating voltage of 200 kV. TEM foil samples were prepared by the standard two–jet electropolishing method in the solution of 30% nitric acid and 70% methanol (vol.%) at −30 °C with an applied voltage of 20 V.

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