

Simultaneously enhancing the tensile properties and intergranular corrosion resistance of Al–Mg–Si–Cu alloys by a thermo-mechanical treatment

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ABSTRACT

A novel thermo-mechanical treatment consisting of conventional pre-aging, cold-rolling and re-aging was developed to enhance the tensile properties and intergranular corrosion resistance of Al–Mg–Si–Cu alloys simultaneously. The thermo-mechanically treated 6061 Al sheets exhibit higher ultimate tensile strength and yield strength (being 466 MPa and 451 MPa) than those of the conventionally peak-aged alloys (being 365 MPa and 347 MPa), and meanwhile have no intergranular corrosion susceptibility and good elongation of 8.1%. Based on the microstructure evolution during the thermo-mechanical treatment, the factors that enhance the tensile properties and intergranular corrosion resistance of the treated sheets are discussed in detail.

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1. Introduction

Owing to the combination of light weight, high strength, good formability and weldability, the Al–Mg–Si–Cu alloys (6000 series) have found wide structural applications [1–3]. Compared to the Al–Mg–Si ternary alloys, the Al–Mg–Si–Cu quaternary alloys exhibit increased strength, but reduced intergranular corrosion (IGC) resistance due to the addition of Cu, especially when treated in the peak-aged (PA) state (T6 temper) [4–9]. The high IGC susceptibility of the peak-aged Al–Mg–Si–Cu alloys limits their industrial applications in some corrosive conditions. In order to enhance the corrosion resistance of the Al–Mg–Si–Cu alloys, over-aging (OA) treatments are often carried out, which usually in turn decrease their strength by about 5–20% as compared to those of the T6-treated alloys. For instance, Dif et al. [10] reported that the ultimate tensile strength (UTS) of the 6056-T6 and 6056-T78 (T78, a two-stage OA treatment) alloys was 397 MPa and 360 MPa, respectively. Zhang et al. [11] investigated the effect of two-stage aging treatment on the mechanical properties of the 6156 alloy. They found that the UTS of the 6156-T6 alloy was 374 MPa, whereas after the T78 treatment the UTS decreased to

350 MPa. Furthermore, Lin et al. [12] reported that the UTS of the 6156-T6 alloy was 425 MPa, and the UTS of the 6156-T78 alloy decreased to 358 MPa. Therefore, it is of great industrial importance to remove the IGC susceptibility of the Al–Mg–Si–Cu alloys without reducing their strength as compared with the conventionally peak-aged alloys.

Al–Mg–Si–Cu alloys belong to age-hardenable Al alloys, whose strength derives mainly from the matrix precipitation during aging treatments [13], whereas their IGC susceptibility correlates closely with the heterogeneous precipitation at the grain boundary regions. Owing to the solute segregation during solution treating, quenching and aging treatments [14], the typical grain boundary region microstructures consist of precipitation free zones (PFZs), grain boundary precipitates (GBPs) and the neighboring matrix. These microstructures sometimes lead to the formation of the electro-chemical micro-couplings distributed continuously along grain boundaries. Finally, the anodic dissolution of the continuous micro-couplings in corrosive mediums results in the IGC susceptibility of age-hardenable aluminum alloys [15–21]. The IGC susceptibility can be eliminated by OA treatments [10,20]. However, OA treatments also lead to excessive coarsening of the matrix precipitates, which decreases the strength of the alloys inevitably. Therefore, in order to remove the IGC susceptibility of the Al–Mg–Si–Cu alloys, meanwhile and to maintain or even increase their strength as compared to those

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in the T6 condition, one of the effective ways is introducing additional strengthening mechanisms except for precipitation strengthening, such as dislocation strengthening or grain boundary strengthening. Then, appropriate OA treatments are carried out further to inhibit the IGC susceptibility of the alloys. Since the strength of the alloys is increased greatly by introducing additional strengthening mechanisms, and although the OA treatments decrease the strength inevitably, it still probably results in larger strength than that of the conventional T6-treated alloys.

In the present study a novel thermo-mechanical treatment was developed to enhance the tensile properties and IGC resistance of the 6061 Al alloy simultaneously. The processing steps included: (i) pre-aging at 180 °C for different times to produce different precipitation characteristics, (ii) cold-rolling (CR) with large thickness reductions at room temperature to increase the strength of the alloy and (iii) re-aging (RA) at 180 °C for 6 h to achieve good tensile properties and IGC resistance simultaneously. The aim of this study is to clarify the evolution of microstructures, tensile properties and IGC susceptibility of the 6061 Al alloy during the thermo-mechanical treatment.

2. Experimental procedure

2.1. Materials and thermo-mechanical treatment

The experiments were performed on hot-rolled 6061 Al sheets of 4 mm thickness, whose chemical composition is 1.0 Mg, 0.72 Si, 0.2 Cu, 0.14 Fe, 0.13 Mn, 0.09 Cr, 0.01 Ti and balance of Al (wt%). After solution treatment at 550 °C for 1 h and water quenching (WQ), these sheets were pre-aged at 180 °C for 2 h, 6 h and 48 h, respectively, which represented the under-aged (UA), PA and OA conditions, respectively, according to the hardening response of the 6000 series Al alloys aged at 180 °C [22]. To simplify the description, the WQ, UA, PA and OA conditions were designated as the pre-treated (PT) state. Afterwards, these PT sheets were further cold-rolled at room temperature to 1 mm thickness with the total reduction of 75% in thickness. Finally, all the CR samples were re-aged at 180 °C for 6 h.

2.2. Characterization

For tensile property measurement, tensile samples with a gauge length of 35 mm and 8 mm in width were cut along the rolling direction of the sheets. Tensile properties were tested on a WDT-30 machine at an initial strain rate of $5 \times 10^{-4} \text{ s}^{-1}$ and the values of the tensile properties were obtained on three parallel samples for averaging.

The IGC susceptibility of the samples was measured according to the Chinese Standard GB/T 7998-2005. The testing procedures included degreasing by acetone, alkaline etching and immersing in a mixed solution of 30 g/L NaCl and 1% concentrated HCl at 35 °C for 24 h. The corrosion behavior of the samples was evaluated by observing the cross-sectional morphologies on an XJG-05 optical microscope.

Microstructure morphologies were observed by a Tecnai G²20 transmission electron microscope (TEM) and JEM 2100F high-resolution transmission electron microscope (HRTEM). Foil samples were prepared by mechanically grinding to about 100 μm thickness and then two-jet electro-polishing at about -25°C and 12 V in a mixture solution of 67% methanol and 33% nitric acid (vol%).

3. Results

3.1. Tensile properties

The tensile properties of PT, CR and RA samples are shown in Fig. 1. Fig.1(a) shows that the WQ samples have low tensile strength and high ductility, whose UTS, yield strength (YS) and elongation (EI) are 218 MPa, 129 MPa and 26.4%, respectively. After under-aging at 180 °C for 2 h, the UTS and YS of the UA samples increase quickly to 354 MPa and 327 MPa, respectively, but the EI decreases to 18.2%. When peak-aging at 180 °C for 6 h, the UTS, YS and EI of the PA samples are 365 MPa, 347 MPa and 13.6%,

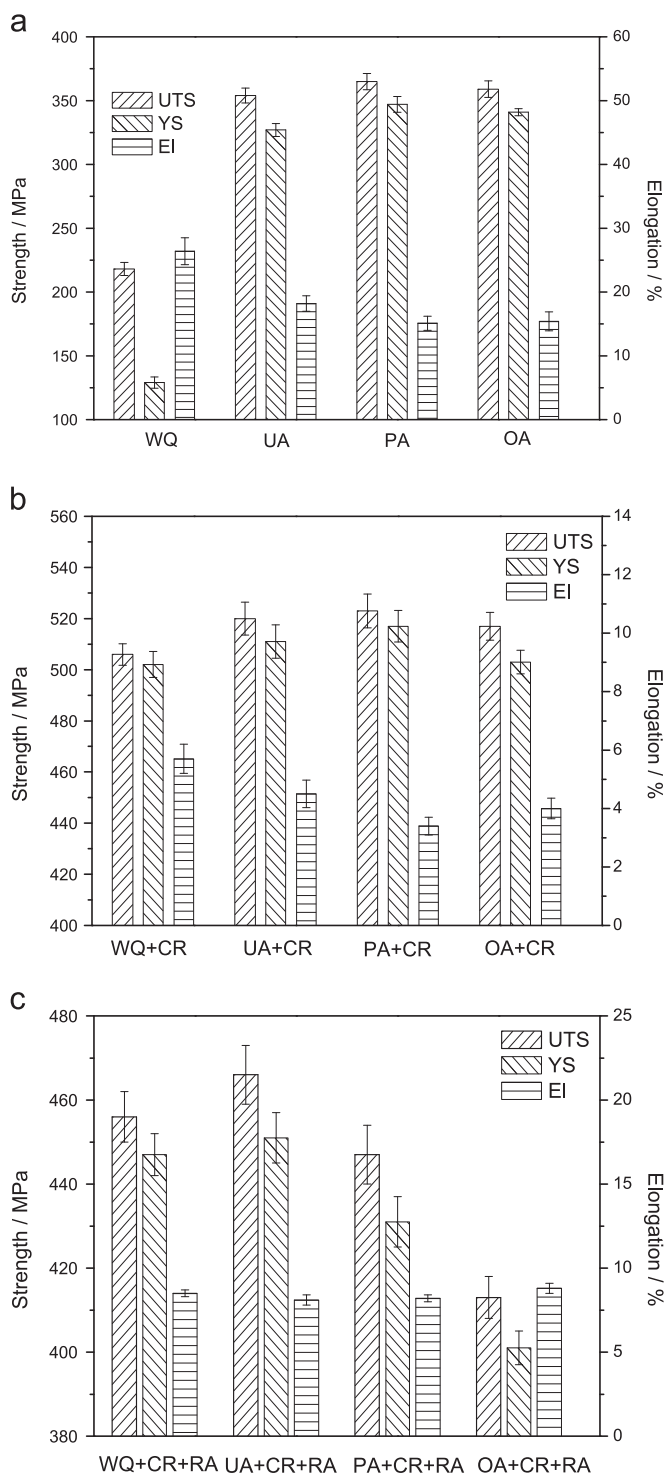


Fig. 1. The tensile properties of the 6061 alloy after different treatments of (a) PT, (b) CR and (c) RA.

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