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Improving the strength and ductility of Al–Mg–Si–Cu alloys by a novel thermo-mechanical treatment

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ABSTRACT

A novel thermo-mechanical treatment, composed of under-aging, cold-rolling and re-aging, has been developed to improve the strength and ductility of Al–Mg–Si–Cu alloys pronouncedly. The thermo-mechanically treated 6061 Al sheets exhibit much higher ultimate tensile strength and yield strength (being 560 MPa and 542 MPa, respectively) than those of the conventional peak-aged sheets (being 365 MPa and 348 MPa, respectively), while maintaining rather good elongation to failure and uniform elongation (being 8.5% and 7%, respectively). The microstructure analyses show that the high strength is attributed to a combination of precipitation strengthening, dislocation strengthening, sub-structure strengthening and high Taylor factor value and the good ductility is attributed to both the recovery process and the re-precipitation of the GP zones. Furthermore, the contributions of different strengthening mechanisms are quantitatively estimated.

1. Introduction

Age-hardenable Al–Mg–Si–Cu alloys (6000 series) have found wide structural applications due to their light weight, good formability, corrosion resistance and weldability [1]. However, as compared to Al–Cu–Mg (2000 series) and Al–Zn–Mg–Cu (7000 series) Al alloys, the relatively low strength of the series Al alloys limits their further applications. Therefore, it is important to further enhance the mechanical properties of the alloys, such as strength and ductility.

In recent decades, many severe plastic deformation (SPD) techniques, such as equal channel angular pressing (ECAP), high pressure torsion (HPT), accumulative roll bonding (ARB) and rolling at cryogenic temperature (Cryorolling), have been carried out to increase the strength of Al alloys, while various strategies have been developed to enhance their ductility [2,3]. Nonetheless, these SPD methods have achieved limited practical applications until now due to operating difficulties, such as limited sample sizes, dangerous working conditions and complicated processing procedures. Therefore, it is of great importance to develop new treatments that can improve mechanical properties and are applicable for industrial use.

In the present study, a novel thermo-mechanical treatment is attempted to increase the tensile properties of the 6061 Al sheets, in which the main steps include under-aging (UA), heavy cold-rolling (CR) and re-aging (RA). The experimental results have shown that the strength of the 6061 Al sheets can be markedly increased while maintaining good elongation as compared with those of the alloys treated by other SPD methods [4–13]. Furthermore, the thermo-mechanical treatment is mostly appropriate for practical applications since the samples are treated by feasibly conventional cold-rolling and aging. The aim of the work is to clarify the microstructural evolution and mechanical behavior of the 6061 Al alloy during the treatment and to distinguish quantitatively the contribution of different strengthening mechanisms.

2. Experimental procedure

2.1. Materials

6061 Al alloy with the chemical compositions of 1.0 Mg, 0.72 Si, 0.2 Cu, 0.14 Fe, 0.13 Mn, 0.09 Cr, 0.01 Ti and balance Al (wt%) was supplied in the form of hot-rolled plates with an initial thickness of 4 mm.

2.2. Heat treatments

After solution treating (ST) at 550 °C for 1 h followed by water-quenching, the plates were firstly under-aged at 180 °C for 2 h, then cold-rolled at room temperate to 1 mm (75% reduction) and

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finally re-aged at 100 °C for 48 h. For comparison, two treatments were carried out after solution treatment. One was that the plates were directly peak-aged (PA) at 180 °C for 6 h (i.e. T6 temper) and the other was that the plates were firstly cold-rolled and then re-aged at 100 °C for 48 h without prior under-aging.

2.3. Mechanical testing

The tensile samples with a gage size of 35 mm × 8 mm were cut along the rolling direction of the sheets and tested on a WDT-30 machine at an initial strain rate of 5×10^{-4}/s.

2.4. Microstructural characterization

Microstructural observations were carried out on a TECNAI G^{2}20 transmission electron microscope (TEM) and a JEM 2100F high resolution transmission electron microscope (HRTEM) operating at 200 kV. Foil samples were prepared by the standard double-jet electropolishing method.

{111}, {200} and {220} incomplete pole figures (χ=0–80° and Φ=0–360°) were obtained with a texture goniometer mounted on the Bruker D8 Discover. Orientation distribution functions (ODFs) were calculated based on these three incomplete pole figures by the series expansion method proposed by Bunge [14]. The volume fractions of texture components were calculated by the decomposing method based on the particle swarm optimization algorithm [15]. Furthermore, the dislocation densities of the samples were estimated based on the measured lattice microstrains and crystal sizes, and the involved procedures have been described elsewhere in detail [16].

3. Results

3.1. Tensile properties

Fig. 1 shows the tensile engineering stress–strain curves of the UA, PA, UA+CR, UA+CR+RA and ST+CR+RA samples. As compared to the UA samples, the ultimate tensile strength (UTS) and yield strength (YS) of the UA+CR samples increase remarkably from 354 MPa to 520 MPa and from 327 MPa to 517 MPa, respectively, but the elongation to failure (E_f) and uniform elongation (E_u) decrease from 18.2% to 4.5% and from 12% to 1%, respectively, which is a common phenomenon appearing in work-hardening metals. The low E_u value verifies the weak strain hardening capability of the UA+CR samples. When the UA+CR samples are re-aged at 100 °C for 48 h, the UTS and YS values of the UA+CR+RA samples further increase to 560 MPa and 542 MPa, respectively, and more significantly, the E_f and E_u also increase to 8.5% and 7%, respectively. By comparison, when the plates are conventionally peak-aged at 180 °C for 6 h, the UTS, YS, E_f and E_u values of the PA samples are 365 MPa, 348 MPa, 13.6% and 10%, respectively. Obviously, the thermo-mechanical treatment can increase the strength of the 6061 Al sheets while still maintaining good ductility. As compared to the ST+CR+RA samples, in which the UTS, YS, E_f and E_u values are 521 MPa, 494 MPa, 8.8% and 6.5%, respectively, the higher strength of the UA+CR+RA samples implies that the UA treatment plays an important role in further enhancing the strength. Furthermore, the UA+CR+RA sheets also exhibit higher strength than those of the 6061 Al alloys processed by the other SPD methods as shown in Table 1; however, it is should be noted that the presented UA+CR+RA treatment has superiority in achieving industrial applications since only conventional cold-rolling deformation and aging treatment are involved.

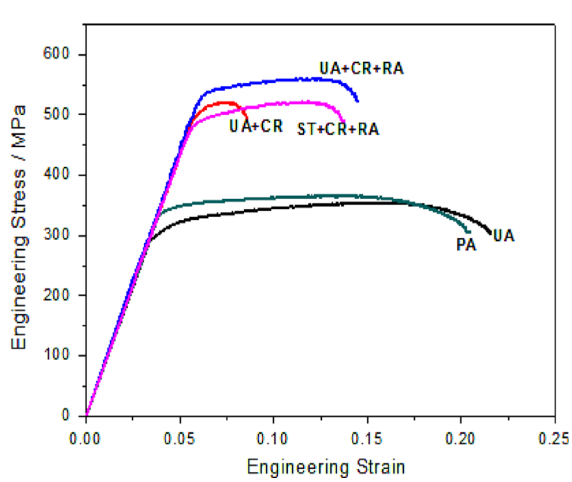

Fig. 1. Typical tensile engineering stress–strain curves of the 6061 Al alloy subjected to different treatments.

Table 1
The tensile properties of 6061 Al alloy after different thermo-mechanical treatments.

Treatments	UTS/MPa	YS/MPa	E_f/%	Ref.
UA+CR+RA	560	542	8.5	This study
CR+WR+PA	406	380	10	[4]
MA+PA	385	–	11	[5]
ECAP+PA	450	425	–	[6]
CR(RT)+PA	430	400	11	[7]
CR+PA	362	304	10.6	[8]
CR+SA+PA	360	304	10	[9]
ARB+PA	450	-	7	[10]
HRDSR+PA	489	455	7.4	[11]
ECAP+PA	463	427	17	[12]
TWVR+PA	491	480	–	[13]

3.2. TEM observation

Fig. 2 shows the TEM microstructures of the UA, UA+CR, UA+CR+RA and PA samples. After under-aging at 180 °C for 2 h, a number of spherical GP zones (or pre-β″) precipitate in the UA samples (Fig. 2a) [17]. Fig. 2b shows a high density of dislocations (about 4.4×10^{14} m^{-2}) and dislocation cells (about 0.3 μm in diameter) present in the UA+CR samples due to the heavy CR reduction in thickness of 75%. Further TEM and HRTEM observations verify that no precipitates are observed in the UA+CR samples (Fig. 2c), which implies that the GP zones that precipitated in the UA samples redissolve in the matrix due to the dislocation shearing effect during the CR deforamtion. After re-aging at 100 °C for 48 h, no recrystallized grains are observed in the UA+CR+RA samples, but the fact that their dislocation density slightly decreases to 4.1×10^{14} m^{-2} means that a slight recovery process indeed occurs during RA (Fig. 2d). On the other hand, a high number density of GP zones re-precipitates in the matrix (Fig. 2e). By comparison, when the samples are directly peak-aged at 180 °C for 6 h, the precipitates mainly consist of needle-like β″ along with a small amount of lath-like Q′ (Fig. 2f) [18].

3.3. Texture development

Fig. 3 shows the ODFs of the UA samples (Fig. 3a) and UA+CR+RA samples (Fig. 3b). Obviously, the texture components in the UA samples consist mainly of the recrystallization textures of Cube {001} ⟨110⟩ and Goss {011} ⟨100⟩ along with a small amount of rolling texture of Cu {112} ⟨111⟩ and Brass {011} ⟨211⟩. The calculated volume fractions of the textures of Cu, Brass, Goss and Cube are 16.8%, 18.7%, 18.5% and 46.0%, respectively. After the CR deformation, the components of the rolling textures increase in the UA+CR