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Enhanced mechanical properties in an Al–Cu–Mg–Ag alloy by duplex aging

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ABSTRACT

A type of duplex aging heat treatment was developed to improve the mechanical properties at room temperature and elevated temperatures in a pre-strained Al–Cu–Mg–Ag alloy. In contrast to the conventional T8 temper at 165 °C and 200 °C, the hardening response of the alloy to aging was increased by duplex aging treatment, the ultimate tensile strength and yield strength of duplex aging temper were improved by approximately 3–7%, which was attributed to the fact that the recovery of dislocations occurred and the precipitation of θ′ phase was restrained effectively at high aging temperature, and more Ω precipitates were formed during secondary aging.

1. Introduction

Al–Cu–Mg–Ag alloys are promising materials for aerospace applications due to their high strength and excellent thermal stability, as well as creep resistance [1–3]. These superior properties are attributed to the formation of a fine and uniform dispersion of hexagonal-shaped plate-like Ω precipitates on the $\{1\,1\,1\}_\alpha$ matrix planes, which is promoted by Ag addition to the alloy with high Cu/Mg ratios. There is competitive precipitation between θ′ and Ω precipitates in Al–Cu–Mg–Ag alloys, although the dominant phase is Ω phase. The precipitation sequences of the alloy can be represented as: SSS → GP zones → θ′′ → θ′ → θ and SSS → Mg cluster/Mg–Ag co-cluster → Ω → θ [4–6]. The thickening rate of Ω phase, however, was confirmed to be much smaller than that of θ′ phase even when exposed at elevated temperature up to 300 °C, showing a great thermal stability [7].

With the development of the aerospace industries, mechanical properties of aluminum alloys are required to be further improved to satisfy the applications [8]. New heat treatments can be developed to obtain the prescribed microstructures and properties in a wide range of age-hardenable aluminum alloys. The Al–Cu–Mg–Ag alloys show superior creep resistance in the underaged condition rather than in fully hardened T6 temper [9]. Recently, multiple-stage aging heat treatments (interrupted aging treatment or T6I6) have been developed to increase the strength and fracture toughness, which involves that the T6 treatment is interrupted by aging at a lower temperature (25–65 °C) before resuming the final aging at the temperature for the initial T6 treatment, or at another different elevated temperature [10–15]. These heat treatments were successfully applied to Al–Cu, Al–Cu–Mg–(Ag), Al–Mg–Si and Al–Zn–Mg–Cu alloys [10–15]. The increase of strength and fracture toughness is attributed to a secondary precipitation that occurs at a lower temperature, a finer and denser dispersion of strengthening phase is formed when T6 aging is resumed.

In commercial practice, a pre-straining processing is usually applied to straightening of products of wrought aluminum alloys in the as-quenched state. The presence of dislocations that generated in this process significantly influences the subsequent precipitation process and final mechanical response of the alloy. Based on a study by Ünlü et al. [16], the pre-straining process increases the mechanical properties in Al–5.0Cu–0.5Mg (wt%) alloy due to an increasing number density and a refinement of precipitates. However, Ringer et al. [17] revealed that dislocations introduced by cold-working prior to aging interfered with nucleation of the Ω phase and provided sites to facilitate heterogeneous nucleation of θ′ precipitates, the peak hardness values of Al–4Cu–0.3Mg–0.4Ag (wt%) alloy aged at 165 °C and 200 °C are reduced by 4.5% and 7.5%, respectively.

Although the T6I6 heat treatment in an Al–Cu–Mg–Ag alloy is reported [11], it cost too much time during the lower-temperature aging and there is no report so far about improvement of the mechanical properties of the alloy subjected to the pre-straining processing. In order to reduce the unfavorable effect of pre-straining on the mechanical properties and assist the precipitation of Ω phase in Al–Cu–Mg–Ag alloys, the present work aims to develop a type of duplex aging treatment, indicating that the first aging at 200 °C for 20 min was interrupted by aging at 165 °C.

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Table 1
Description of heat treatments for Al–Cu–Mg–Ag alloy.

Number	Heat treatment	Description and aging times		
1	T8/200	ST at 515 °C for 6 h + WQ + 2% pre-straining	Aging at 200 °C for up to 24 h	
2	T8/165		Aging at 165 °C for up to 100 h	
3	T8L6/165		Under aging at 200 °C for 20 min	Secondary aging at 165 °C for up to 100 h

2. Materials and methods

The chemical composition of the experimental material used in the present work was Al–4.94Cu–0.43Mg–1.04Ag–0.3Mn–0.15Zr (wt%). The ingot was homogenized after casting, and hot rolled to 2 mm thick strip at about 460 °C. All the samples were solution-treated (ST) at 515 °C for 6 h, water-quenched (WQ) and immediately stretched with 2%. Then the pre-strained specimens were aged at 165 °C and 200 °C (hereafter termed T8/165 and T8/200, respectively), or aged at 200 °C for 20 min followed by 165 °C for times up to 100 h. This new type of duplex aging heat treatment was termed T8L6/165. Details of these heat treatments are shown in Table 1.

Hardness measurement was performed on a HV-10B Vickers Hardness tester with a load of 3 kg. The hardness values reported here represent the average of at least ten measurements. Tensile testing was conducted on a SANS-CMJ5105 testing machine at room temperature (RT) and elevated temperatures (250 °C and 300 °C) with 2 mm/min loading speed. The values of strength and ductility were the mean values of three specimens. Differential scanning calorimeter (DSC) analysis was carried out on a NETZSCH SAT 449C calorimeter using high purity aluminum as a reference. Disc-like samples with a thickness of about 0.5 mm and diameter 5 mm were scanned at a heating rate of 10 °C/min in the temperature range from 20 °C to 400 °C. Specimens for transmission electron microscopy (TEM) were prepared by using twin-jet electrolytically polishing with a voltage of 10–15 V in a solution of 70% methanol and 30% nitric acid at −20 °C. The TEM observations were carried out on a TECNAI $G^2$20 transmission electron microscopy operated at 200 kV.

3. Results and discussion

Fig. 1 illustrates the hardness curves for Al–Cu–Mg–Ag alloy in the T8 and T8L6 conditions. The peak hardness of the T8 alloy decreased as the aging temperature was elevated from 165 to 200 °C, meanwhile the peak-aged time decreased from 20 h to 2 h. The hardness of the T8L6/165 temper significantly increased in compared with those of T8/165 and T8/200 tempers, whereas the peak-aged time for T8L6/165 and T8/165 tempers is almost the same. The peak hardness value of T8L6/165 temper is 162 HV, which exceeded the T8/165 and T8/200 peak-aged condition by 3% and 5%, respectively.

Table 2
Tensile properties of Al–Cu–Mg–Ag alloy in T8 and T8L6 peak-aged conditions tested at RT and elevated temperatures.

Temperature (°C)	Temper	UTS (MPa)	YS (MPa)	Elongation (%)
20	T8/200	492	461	9.3
	T8/165	495	460	10.7
	T8L6/165	508	476	10.7
250	T8/200	309	300	12.4
	T8/165	313	303	12.2
	T8L6/165	323	315	11.4
300	T8/200	212	209	13.2
	T8/165	203	199	12.8
	T8L6/165	217	213	12.4

The samples were all peak-aged treated for T8 and T8L6/165 tempers, and then tested at temperatures up to 300 °C. Table 2 provides a comparison of the tensile properties for the three tempers examined. It can be seen that T8L6/165 heat treatment produced improvements in the strength at RT and elevated temperatures, while the elongation was still at a high level. Comparing with the ultimate tensile strength (UTS) and yield strength (YS) of T8/165 temper, those of T8L6/165 temper were increased by 13 and 16 MPa at RT, respectively. Furthermore, an improvement of approximately 7% in the UTS and YS at 300 °C was achieved. It should be noted that the strength of T8/165 temper at RT and 250 °C was superior to that of T8/200 temper, whereas it was less at 300 °C. This was related to the type and number density of strengthening particles.

To demonstrate the effect of aging temperature on precipitation of Ω and θ′ precipitates in the Al–Cu–Mg–Ag alloy, DSC samples were prepared after hardness and tensile tests. Fig. 2 shows a typical DSC thermogram for the specimens of the Al–Cu–Mg–Ag alloy. According to literature [17–19], three peaks can be identified in

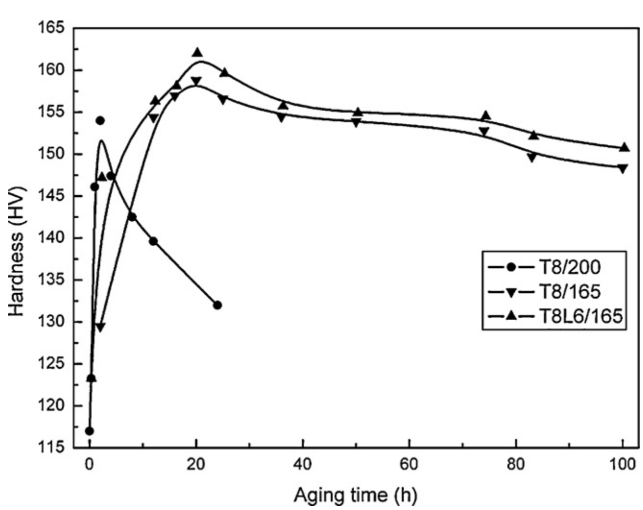

Fig. 1. Comparison of T8/165, T8/200 and T8L6/165 hardness curves.

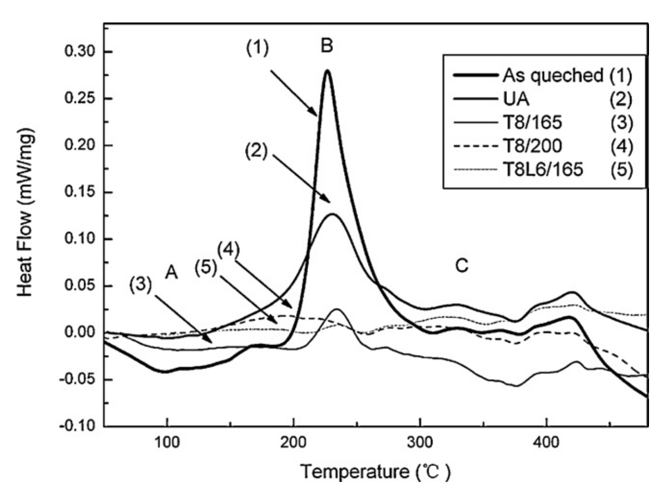

Fig. 2. DSC thermograms for Al–Cu–Mg–Ag alloy under different conditions.