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Effect of cooling aging on microstructure and mechanical properties of an Al–Zn–Mg–Cu alloy

Yan Liu *, Daming Jiang, Bingqing Li, Wenshu Yang, Jie Hu

Department of Material Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

In the present work, Al–Zn–Mg–Cu alloy was aged by non-isothermal cooling aging treatment (CAT). At high initial aging temperature (IAT), the hardness was decreased with the decreased cooling rate. However, when IAT was lower than 180 °C, the hardness was increased with the decreased cooling rate. Conductivity was increased with the decreased cooling rate regardless of IAT. The tensile strength, yield strength and conductivity of Al alloy after (200–100 °C, 80 °C/h) CAT were increased 2.9%, 8.1% and 8.3% than that after T6 treatment, respectively. With an increase of IAT and decrease of cooling rate, the fine GP zone and η′ phase were transformed to be larger η′ and η precipitates. Moreover, continuous η phase at grain boundary was also grown to be individual large precipitates. Cooling aging time was decreased about 90% than that for T6 treatment, indicating cooling aging could improve the mechanical properties, corrosion resistance and production efficiency with less energy consumption.

1. Introduction

Al–Zn–Mg–Cu alloys are widely utilized in aviation and aerospace industry due to their ultrahigh strength [1,2]. With the continuous development of aviation and aerospace industry, the demand of the properties of aluminum alloy was higher and higher [3]. Besides high strength [4], the high fracture toughness [5] and good corrosion resistance are also required [6]. A lot of heat treatment processes were explored to promote the comprehensive properties of aluminum alloy to meet the requirement of aviation and aerospace development [7–9]. It can be seen from the development of heat treatment that, aluminum alloys exhibit better and better comprehensive properties from T6 single-stage aging [10] to T7X two-stage aging [11,12] and further to RRA three-stage aging [13]. In RRA three-stage aged samples, due to precipitation behavior at different temperature, the size and distribution of precipitates in Al alloys are different than after T6 treatment. The precipitates at the grain boundary after RRA aging treatment are larger and separated from each other, which improves the corrosion behavior greatly [14]. This microstructure after RRA aging treatment could not be obtained after one-step traditional isothermal aging process. However, the duration of RRA treatment (more than 48 h) is much longer than that of T6 treatment (about 24 h), which leads to an increased cost.

In the past, non-isothermal process was only discussed in non-ideal quenching [15] and welding [16]. Due to different precipitation behavior occurred during non-isothermal process, the mechanical properties of Al alloys have been improved significantly [17]. However, the non-isothermal aging behavior in Al alloys was rarely reported. As the most convenient non-isothermal treatment, cooling aging could be considered as infinitely many-stage isothermal aging treatment. The precipitation behavior in different stages might be different. Therefore, the cooling aging may be utilized to promote comprehensive properties. Since the precipitation could be completed during cooling process, the duration of treatment might also be reduced.

In the present work, the cooling aging behavior of Al–8.35Zn–2.5Mg–2.25Cu ultra high strength alloy was investigated. Effects of cooling aging temperature and rate on the microstructure, mechanical and electronic properties were studied. The precipitation behavior of cooling aging process was also discussed.

2. Experimental details

Al–Zn–Mg–Cu alloy was prepared by semi-continuous casting, purchased from a Chinese novel aluminum company. Its composition was analyzed by chemical titration method, and the result was listed in Table 1. The alloy ingot was heat treated for homogenizing at 460 ± 10 °C for 36 h. The solution was performed in a salt bath furnace to avoid the oxidation of the alloy. After holding at 470 ± 5 °C for 2 h for solution, the alloy was quenched in water while the moving time was less than 10 s. In the meanwhile, the aging furnace was heated to the required temperature. After

* Corresponding author. Address: P.O. 3023, Science Park, No. 2 Yikuang Street, School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150080, China. Tel.: +86 451 86402373x4053; fax: +86 451 86412164.

E-mail addresses: liuyanjob@163.com, liuyan_hit@hit.edu.cn (Y. Liu).

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Table 1
The composition of Al–Zn–Mg–Cu alloy (wt.%).

Element	Si	Fe	Cu	Mg	Zn	Zr	Mn	Cr	Ni	Ti
Content	0.04	0.08	2.25	2.5	8.35	0.14	0.05	0.04	0.05	0.03

quenching treatment, the samples were then put into the aging furnace immediately and the cooling aging process was started. The schematic diagram of cooling aging process is shown in Fig. 1.

Hardness of the alloy was tested by HBS210-3000 Brinell hardness tester according to ASTM:E 10-12. Electrical conductivity was measured by FQR-7501 eddy-current device according to ASTM:E 1004-09. Tensile tests were carried out according to ASTM:E 8 M-13a to evaluate the mechanical properties of the samples. All tests have been performed with at least five samples to improve statistical significance of the results. Tensile properties were measured on Instron 5569 machine. Moreover, the morphology of the fractured tensile specimens was observed by S-4700 scanning electron microscope (SEM). The microstructure was further observed by FEI TENCNAI G2 F30 transmission electron microscope (TEM).

3. Results and discussion

3.1. Hardness and conductivity

Hardness and conductivity properties of Al alloys could reflect the mechanical strength and the corrosion resistance, respectively. Generally, high hardness implies high tensile properties while higher conductivity represents better corrosion resistance. The hardness and conductivity properties of Al alloy after different cooling aging treatment are shown in Fig. 2a and b, respectively.

When the initial aging temperature (IAT) was between 180 and 200 °C and the cooling rate was between 60 and 80 °C/h, the hardness of alloy after cooling aging treatment was close to or even higher than that after T6 treatment (Fig. 2a). It should be noted that the hardness of Al–Zn–Mg–Cu alloy was decreased with the decrease of cooling rate when IAT was above 180 °C. However, when the IAT was below 180 °C, the hardness of Al alloy was increased with the decrease of cooling rate.

In the present work, slower cooling rate and higher IAT implies longer aging duration. Therefore, when the IAT was higher than 180 °C, it could be considered that the hardness was decreased with the increase of aging time. It implies that the alloy was in peak-aging or over-aging status when the cooling rate was 80 °C/h. The aging time was prolonged with the increase of IAT and decrease of cooling rate. Therefore, the over-aged behavior was further intensified and decreased the hardness significantly. However, when the IAT was below 180 °C, the Al alloy was in under-aging status since the hardness of the Al alloy was increased with the aging time. It should be noted that the hardness of the Al alloy was decreased greatly when it was transformed from under- to peak-aging.

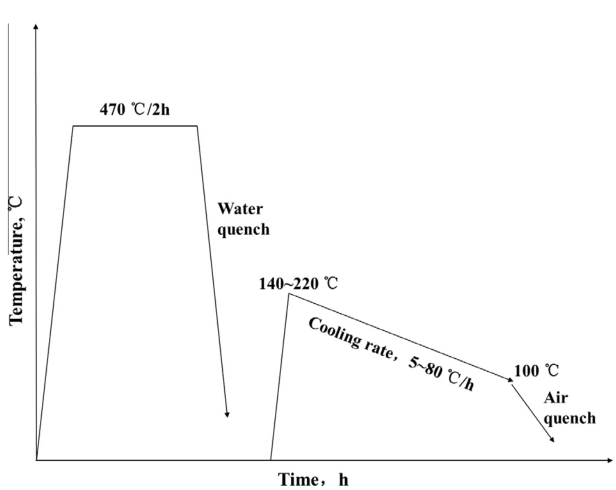

Fig. 1. Schematic of the cooling aging treatment.

The conductivity after cooling aging treatment was higher than that after T6 treatment (Fig. 2b). However, different to harness result, the conductivity of the Al alloy was increased with the decrease of cooling rate regardless of IAT. Moreover, IAT demonstrated more significant effect on the conductivity.

The effect of IAT on the hardness and conductivity of the alloy is shown in Fig. 3. With higher IAT (180–220 °C) and faster cooling rate (50–80 °C/h), the hardness was slightly increased with the IAT to 200 °C. Further increase of IAT up to 220 °C led to the sharp decrease of hardness. However, the conductivity property was increased with IAT, and increment was slightly changed at 200 °C. Therefore, 200 °C was found to be a critical temperature in the present work.

3.2. Tensile properties

Fig. 4 shows the tensile properties of the alloy under different cooling aging treatments. The trend of tensile and yield strength affected by the cooling aging treatment was similar to that of hardness. Table 2 shows properties comparison of Al alloy after T6 treatment and after four representative cooling treatments. The tensile strength, yield strength and conductivity of Al alloy cooling aged at IAT of 200 °C with cooling rate of 80 °C/h reached 670.5 MPa, 657.9 MPa, and 31.4%IACS, which increased 2.9%, 8.1% and 8.3% than that after T6 treatment, respectively. It should be noted that the time for cooling aging treatment was decreased about 90% than that for T6 treatment. Al alloy after T73 treatment usually shows higher conductivity (>38% IACS) while its tensile strength would decrease 10–15% than that after T6 treatment, which was about 550–580 MPa for the Al–Zn–Mg–Cu alloy used in the present work. In the current work, the conductivity of Al alloy cooling aged at IAT of 220 °C with cooling rate of 80 °C/h was about 38.9%IACS, which was close to that after T73 treatment. However, its tensile strength was about 632.6 MPa, which increased 9–14.9% than that after T73 treatment. Furthermore, the aging time spent in above treatment was less than 2 h, which was much shorter than that of T73 treatment (usually longer than 24 h). Therefore, it could be concluded that the cooling aging could improve the mechanical properties, corrosion resistance and production efficiency with less energy consumption.

Fracture morphology of Al alloy after different treatments was shown in Fig. 5. Although all characterized by the mixture of intergranular and transgranular, the fracture morphology and behavior of Al alloy was significant different after different treatments. A high proportion of intergranular and few shear zones could be found in Al alloy after T6 treatment (Fig. 5a), indicating its main fracture mechanism was intergranular. In Al alloy cooling aged at IAT of 180 °C with cooling rate of 80 °C/h, the proportion of intergranular was decreased while the amount of transgranular shear zones was increased (Fig. 5b) than in that after T6 treatment. However, in Al alloy cooling aged at IAT of 200 °C with cooling rate of 80 °C/h, very few intergranular were observed, and the fracture surface was mainly characterized by several fine dimples and large shear zones (Fig. 5c). Al alloy cooling aged at IAT of 220 °C with cooling rate of 20 °C/h was in over-aging status, and its fracture surface was composed by very large dimples while very few intergranular phenomenon was found. Therefore, the fracture of Al alloy was transformed from intergranular to transgranular mechanism.