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Microstructure and mechanical properties of high strength Al−Zn−Mg−Cu alloys used for oil drill pipes

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Abstract: Three Al−Zn−Mg−Cu alloys used for oil drill pipes (Alloy A: Al−6.9Zn−2.3Mg−1.7Cu−0.3Mn−0.17Cr; Alloy B: Al−8.0Zn−2.3Mg−2.6Cu−0.2Zr, Alloy C: Al−8.0Zn−2.3Mg−1.8Cu−0.18Zr) were studied by hardness tests, tensile tests and transmission electron microscopy (TEM). The results show that the ultimate tensile strength, yield strength and elongation for Alloys A, B and C are 736 MPa, 695.5 MPa and 7%; 711 MPa, 674 MPa and 12.5%; 740.5 MPa, 707.5 MPa and 13%, respectively after solid solution treatment ((450 °C, 2 h)+(470 °C, 1 h)) followed by aging at 120 °C for 12 h. The dominant strengthening phases in Alloy A are GPII zone and η' phase, the main precipitate in Alloy B is η' phase, and the main precipitates in Alloy C are GPI zone, GPII zone and η' phase, which are the reason for better comprehensive properties of Alloy C. The increase of zinc content leads to the improvement of the strength. The increase of copper content improves the elongation but slightly decreases the strength. Large second-phase particles formed by the increase in the manganese content induce a decrease in the elongation of alloys.

Key words: Al−Zn−Mg−Cu alloy; aging time; precipitate; microstructure; mechanical properties

1 Introduction

Drill pipes are a kind of the main tools in the drilling and oil industry [1]. Compared with conventional steel drill pipes, aluminum drill pipes have low density, high strength and good stress corrosion resistance; further, aluminum is non-magnetic. Therefore, aluminum alloys are now becoming ideal light structure materials for drilling [2].

The Al−Zn−Mg−Cu alloys have a strong aging strengthening effect through quenching and aging and have yield strength of up to 500 MPa at room temperature with higher impact toughness than other aluminum alloys [3]. High Zn and Mg contents reduce the ductility of the alloy and increase the brittleness. Low Cu content tends to decrease the embrittlement of the alloy and improve the plasticity, meanwhile, Cu atom can form *S* (Al_2CuMg) phase with Al atoms and Mg atoms to strengthen the alloy [4]. The addition of minor Cr, Mn, Zr and Ni elements in the alloy forms some intermetallics with Al atom, and the intermetallics are beneficial to improving the mechanical properties of the alloy. HE et al [5] and ZOU et al [6] reported that minor addition of Sc and Zr in Al−Zn−Mg−Cu alloys leads to forming $Al_3(Sc,Zr)$ particle which can greatly refine grains, inhibit recrystallization and improve the mechanical properties of the alloy.

High strength of Al−Zn−Mg−Cu alloys depends on their precipitation sequences. The usual sequences are as follows [7−10]:

Sequence 1: Supersaturated solid solution (SSS) → GP zone → η' phase ($MgZn_2$) → η phase ($MgZn_2$);

Sequence 2: Supersaturated solid solution (SSS) → GP zone → T' phase ($Al_2Zn_3Mg_3$) → T phase ($Al_2Zn_3Mg_3$).

These sequences are related to the aging temperature and Zn/Mg ratio [7,11,12]. GANG and CEREZO [12] found that when the Mg content is higher than the Zn content, the main precipitate in the alloy is the *T* phase. YANG et al [7] reported that an Al−7.60Zn−2.55Mg alloy with a characteristically high Mg/Zn mole ratio can be strengthened by the *T*-phase precipitates. Currently, however, the Zn content is higher

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than the Mg content in most Al−Zn−Mg−Cu alloys, the precipitation sequence is primarily the first sequence given above, and the GP zone, η' phase and η phase are still the main phases in Al−Zn−Mg−Cu alloys. ZANG et al [13] reported that a new Al−Zn−Mg−Cu alloy (Al−(7.5−8.7)Zn−(1.8−2.7)Mg−(1.4−2.1)Cu) aged at 120 °C for 24 h has superior mechanical properties compared with conventional ones, and the main phases in new alloy are GPI zone, GPII zone and η' phase. LI et al [14] studied the one-step aging behavior of Al−7.5Zn−1.7Mg−1.4Cu−0.12Zr alloy and found that small η' phase and GP zone distributed and dispersed in the matrix under the peak-aging condition. WANG et al [15] studied the one-step aging behavior of 7055 alloy and found that the GP zone and η' phase formed during aging significantly influenced the mechanical properties of the alloy. Recently, by the use of high-resolution transmission electron microscopy, some researchers [16,17] reported that GP−η_P zones or η-precursor existed in some Al−Zn−Mg−(Cu) alloys, these two intermediate phases play an indispensable role in phase transformation.

In order to optimize the mechanical properties of aluminum drill pipes, it is necessary to investigate the effect of microstructure evolution and alloying element on mechanical properties during aging. The object of the present work is to reveal the strengthening mechanism and relationship between the microstructure and mechanical properties of the alloys by investigating the effects of aging treatment.

2 Experimental

The compositions of the three alloys studied are listed in Table 1. The ingots were prepared using an induction furnace. The as-cast alloys were subjected to two-step homogenization treatment ((395 °C, 12 h) + (460 °C, 32 h)). After homogenization treatment, rods of the alloys were extruded using a 300 t extrusion machine. The as-extruded samples were solid solution-treated ((450 °C, 2 h) + (470 °C, 1 h)), and then water-quenched to room temperature. After quenching, the samples were immediately aged at 120 °C for 4, 12, 24, 36 and 48 h, respectively. The Vickers hardness testing was performed on an HV−10B hardness tester with a load of 2 kg and each hardness value was obtained by averaging five measurements. The tensile tests were performed at room temperature using a DDL100 testing machine and three measurements were made to obtain the average value. The alloys were also observed using a Tecnai G2 F20 transmission electron microscope (TEM). Slices for TEM samples were cut from the aged tensile samples, and subsequently ground to less than 100 μm and punched into 3 mm discs. The thin foils were obtained by electrothinning at 20 V. The electrolyte was a mixture of 75% methanol and 25% nitric acid, and thinning was performed at −25 °C.

Table 1 Compositions of studied alloys

Alloy	Mass fraction/%									
	Cu	Mg	Zn	Mn	Fe	Ni	Cr	Ti	Zr	Al
A	1.7	2.3	6.9	0.3	0.3	0.1	0.17	0	0	Bal.
B	2.6	2.3	8.0	0.05	0	0	0.04	0	0.2	Bal.
C	1.8	2.3	8.0	0.05	0	0	0.04	0.02	0.18	Bal.

3 Results

3.1 Mechanical properties

The Vickers hardness and tensile properties of Alloys A, B and C during aging at 120 °C for different time are shown in Fig. 1, Table 2 and Fig. 2. Alloys A, B and C are clearly strengthened by aging. At the early stage of aging, the hardness of the three alloys increases rapidly and approaches the first peak value after aging for 4 h. Subsequently, the hardness of Alloy C maintains at a high level for a long time. For Alloys A and B, the hardness reaches the second peak value after aging for 24 h and 36 h, respectively. The strengths of the three alloys exhibit the same change tendency as the hardness shown in Fig. 1. The strengths of Alloys A and B attain maximum and then decrease slightly at the later stage of aging. However, the strength of Alloy C remains stable during a long aging process. When aged at 120 °C for 12 h, three alloys have the best overall mechanical properties. Table 2 shows the mechanical properties of three alloys aged at 120 °C for 12 h.

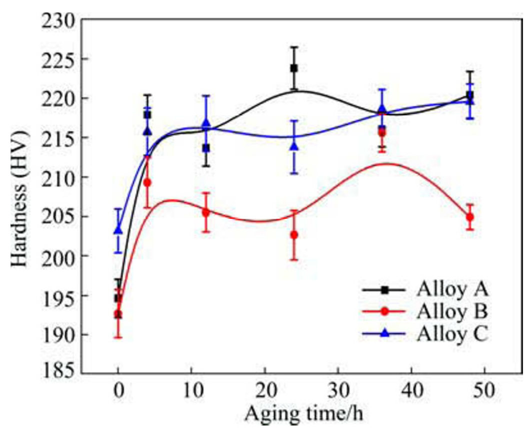

Fig. 1 Effect of aging time on hardness of Alloys A, B and C

Table 2 Mechanical properties of Alloy A, B and C aged at 120 °C for 12 h

Alloy	σ_b/MPa	$\sigma_{0.2}$/MPa	δ/%
A	736	695.5	7
B	711	674	12.5
C	740.5	707.5	13