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Effect of Si addition on the microstructure and mechanical properties of Al–Cu–Mg alloy

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ABSTRACT

The effect of Si additions on microstructure and mechanical properties of Al–4Cu–1.3Mg (wt%) alloy was investigated by microhardness measurements, TEM and HRTEM observations, mechanical properties test. The results indicate that the cubic σ-$Al_5Cu_6Mg_2$ phases precipitate from matrix of the Al–4Cu–1.3Mg–0.3Si and Al–4Cu–1.3Mg–0.6Si alloys. The presence of σ-$Al_5Cu_6Mg_2$ phases improved the tensile strengths of the alloys efficiently at elevated temperatures. The Al–4Cu–1.3Mg–0.9Si alloy following T6 peak ageing temper contained S′-Al_2CuMg and β′-Mg_2Si precipitates but slightly inhibited σ-$Al_5Cu_6Mg_2$. The absence of σ precipitates leads to a loss of the tensile strengths of the alloy at elevated temperature.

1. Introduction

Alloys of the Al–Cu–Mg system form an important part of the 2000 series alloys and are widely used in the aircraft manufacturing industry, where the high hardness and strength of appropriately processed components contribute to the high degree of damage tolerance displayed in service. Phase formation in Al–Cu–Mg alloy is sensitive to the total solute content of the alloy and particularly to the Cu/Mg ratio [1,2]. Ternary Al–Cu–Mg alloys having Cu:Mg weight ratios of 2–4 lie in the $\alpha + S$ phase field of the Al–Cu–Mg phase diagram [3,4]. Here, S represents the equilibrium phase Al_2CuMg. The Al–Cu–Mg alloys like the 2024, 2219 or 2618 series are currently used for applications where good specific strength and heat resistant capability up to 150 °C [5]. One of the candidate materials for the construction of fuselage of the second generation of civil supersonic aircraft is based on Al–Cu–Mg alloys. It was used for skin of the hight-speed civil transport plane where they would be exposed to temperatures near 170 °C for 120,000 h [6]. In this case, S′-Al_2CuMg phase coarsening significantly at temperatures greater than 150 causes loss of mechanical properties. To enhance the elevated temperature performance of an aluminum alloy, the precipitating phases must be thermodynamically stable and resist coarsening at the temperature of interest [7]. Moreover, it has been shown that addition of small amount of Si greatly affect the age hardening characteristics of Al–Cu–Mg alloys [8]. Microalloying of an Al–Cu–Mg alloy with Si alone accelerates and enhances the age-hardening response via the stabilization of GPB zones [9]. The addition of Si to Al–Cu–Mg alloys facilitates the formation of a new precipitate phase called σ-Al5Cu6Mg2. The σ phase has a cubic crystal structure with a lattice parameter of 0.831 nm. The σ precipitate has been shown to retain its morphological stability at relatively high temperatures (e.g.265 °C).

The objective of this study was to investigate the effect of Si addition on the microstructure and mechanical properties of Al–4Cu–1.3Mg (wt%) alloy. In particular, we will summarize the available experimental data in order to explain the precipitation in Al–Cu–Mg–Si alloys.

2. Experimental procedures

Systematic additions of 0.3, 0.6, and 0.9 wt pct Si were made a base alloy composition of Al–4Cu–1.3Mg (wt pct) (Table 1). The alloys were melted by induction heating, and then cast into iron molds to produce billets of 300 mm in length and 210 mm in diameter. The billets were homogenized at 490 °C for 24 h, and subsequently at 520 °C for 12 h, followed by air cooling to room temperature. The billets were then scalped to 190 mm diameter and extruded at 420 °C into plates of 100 × 25 mm in cross-section (extrusion ratio 12.6:1). The plates were solution treated at 500 °C for 3 h followed by immediate quenching into cold water, and finally aged for different periods of time at 190 °C.

The room and elevated temperature tensile tests were conducted with an Instron tensile testing machine at an initial strain rate of 0.5 s^{-1}. The elevated temperature tensile tests were conducted at 573 K at the same initial strain rate. In the tests at high temperatures, the specimens were held at the temperature for about 15 min before loading. A Wilson-wolpert microhardness Tester (Model 430SVA)

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Table 1
The chemical compositions of the present alloys (wt.%).

Alloy	Cu	Mg	Si	Al
A0	4.0	1.3	–	Balance
A1	4.0	1.3	0.3	Balance
A2	4.0	1.3	0.6	Balance
A3	4.0	1.3	0.9	Balance

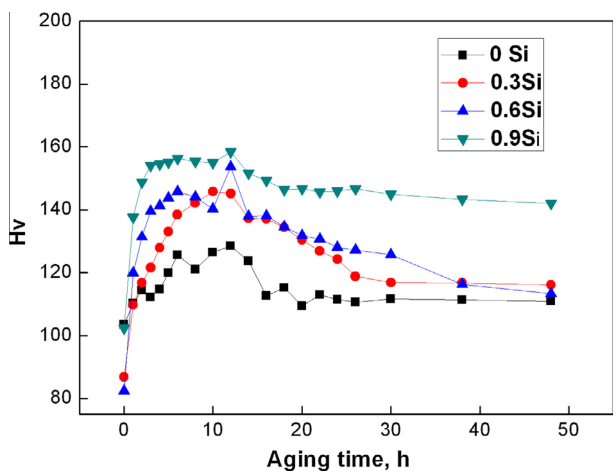

Fig. 1. The microhardness of the four alloys as a function of ageing time at 190 °C, ■: Si free alloy. ●: 0.3Si containing alloy. ▲: 0.6 Si containing alloy. ▼: 0.9Si containing alloy.

was used for hardness measurements with a load 50 g applied for 10 s and five measurements were taken for each condition. TEM samples were prepared in the conventional manner and examined using a JEM-2010FX microscope. The discs were electro-polished using a voltage of 15 V in a solution of 25% nitric acid in methanol at approximately −15 °C.

3. Results and discussion

3.1. Hardness

Samples of the Si-free and Si-containing alloys were solution heat treated at 500 °C for 3 h followed by water quenching. These samples were then aged for various times at 190 °C. Fig. 1 provides the hardness of the four alloys as a function of ageing time at 190 °C. In this case, all alloys exhibited two stages of hardening. As shown in Fig. 1, the first stage of hardening may occur very rapidly and it is completed within 2 h. The second stage of hardening involved a relatively steady rise to peak hardness followed by overageing. However, with increasing of Si content, the hardness of the present alloys was increased. Also noteworthy is the values of the peak hardness for Si-containing alloys were greater than for Si-free alloy, although the time-to-peak aging remained the same (12 h).

3.2. Microstructure

Representative TEM micrographs and corresponding $[1\,0\,0]_{\alpha}$ selected area diffraction patters for Al–4Cu–1.3Mg alloy aged 12, 24 h at 190 °C are presented in Fig. 2. Fig. 2(a) shows the typical high resolution image of one of the precipitates of the alloy aged 12 h at 190 °C, it can be seen that the precipitate has a lath shape. A detailed analysis of the FFT image (Fig. 2(b)) indicates that the lath-shaped precipitate is in agreement with S′-Al_2CuMg phase,

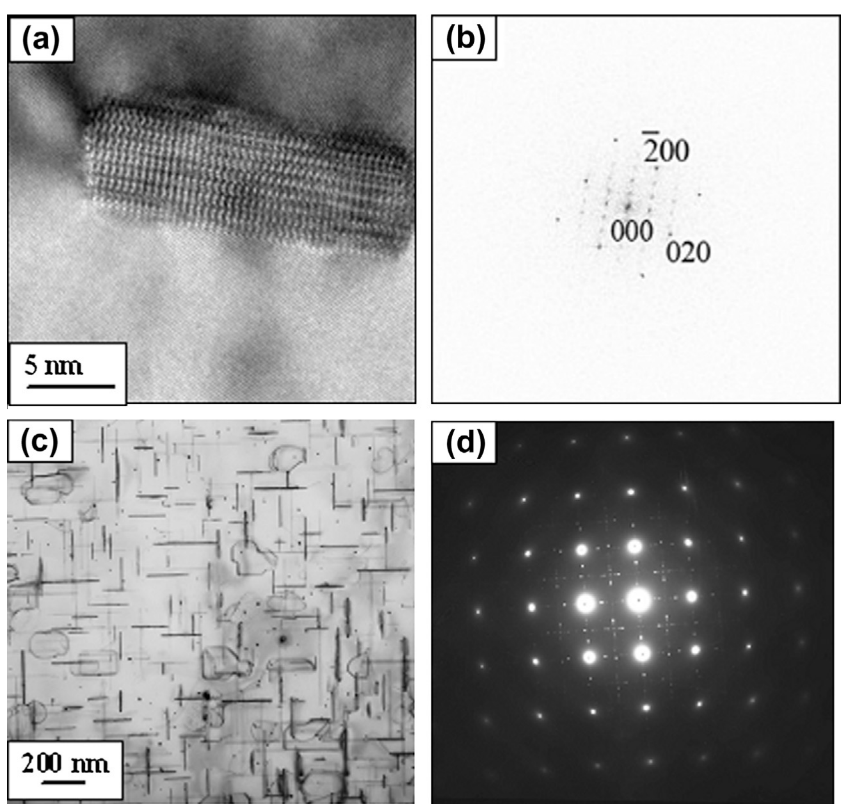

Fig. 2. TEM micrographs and corresponding SAD patters recorded near the $[001]_{\alpha}$ orientation from Al–4Cu–1.3Mg alloy, (a) peak-aged condition (190 °C, 12 h): HRTEM image of a typical lath-shaped precipitate, (b) the corresponding FFT diffractogram; (c) overaged condition (190 °C, 24 h): BF TEM micrograph, (d) the corresponding SEAD pattern shown in (c).