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Effect of heat treatment on microstructure and mechanical property of Al–10%Mg_2Si alloy

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ABSTRACT

After solution treatment at 520 °C for 6 h and subsequent aging at 200 °C for 6 h, eutectic Mg_2Si phase in Al–10%Mg_2Si alloy transforms from long rod to short fiber-like and spherical morphologies, and a great number of nano-sized β″ particles precipitate in the Al matrix. The fine eutectic Mg_2Si phase combined with nano-sized precipitates gives rise to enhanced hardness and high tensile strength of Al–10%Mg_2Si alloy (increasing from 186 MPa to 234.6 MPa).

1. Introduction

In recent years, materials design has shifted focus to pursue light weight, low cost, environmental friendliness. Magnesium silicide (Mg_2Si) exhibits high melting temperature (1085 °C), low density (1.99×10^3 kgm^{-3}), high hardness (4.5×10^9 Nm^{-2}), high elastic modulus (120 GPa) and low coefficient of thermal expansion (7.5×10^{-6} K^{-1}) [1,2]. The excellence combination of physical and mechanical properties of Mg_2Si makes it a suitable candidate as reinforcement to prepare Al–Mg_2Si alloys which are attractive candidate materials for automobile, aerospace and other applications [3–7].

In Al–Mg_2Si alloys, Mg_2Si phase exists in two forms: primary Mg_2Si and (Al + Mg_2Si) eutectic structure. The mechanical properties of Al–Mg_2Si alloys strongly depend upon the morphology, size and distribution of the primary and eutectic phases. Many advanced processing techniques have been adopted to artificially manipulate primary Mg_2Si particles transforming from enormous dendrite to fine polyhedron (octahedron or cube) in order to increase mechanical properties of alloys, such as rapid solidification processing [8,9], hot extrusion [10] and additions of refiners or modifiers [11–15].

Eutectic structure also affects the mechanical properties of Al–Mg_2Si alloys. Heat treatment exhibits good characteristics in homogenizing and refining eutectic microstructure and improving the properties of alloys, with low-cost and convenience to process [16–19]. So in the paper, the effect of heat treatment on microstructure and mechanical property of Al–10%Mg_2Si alloy was studied. It is favorable to realize the relationship between eutectic Mg_2Si and mechanical properties of Al–Mg_2Si alloys. Further, it may be of reference value for the manipulation of eutectic Mg_2Si phase in other metal matrix composites or alloys.

2. Experiment

Commercial pure Al (99.7%, all compositions quoted in this work are in wt.% unless otherwise stated), commercial pure crystalline Si (99.9%) and commercial pure Mg (99.8%) were used as starting materials to prepare Al–10%Mg_2Si alloy in a 25 kW medium frequency induction furnace. The alloy was remelted at 750 °C and held at this temperature. After being held 30 min, the melt was poured into a cast iron mold.

Samples of Al–10%Mg_2Si alloy for heat treatment were solution treated at 520 °C for 6 h, followed by quenching in cold water, and subsequently aged at 200 °C for 6 h (henceforth referred to as T6 heat treatment).

Metallographic specimens were cut at the same position of the tabulate samples and polished by a standard procedure. The

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microstructure of Al–10%Mg_2Si alloy was observed by scanning electron microscope (SEM, Hitachi S-4800). NaOH water solution (15%) was used as etchants of polishing samples to reveal three dimensional morphology of eutectic Mg_2Si. Thin foils for transmission electron microscopy (TEM) were prepared from 3 mm discs by using twin-jet electropolishing in a 30% nitric acid/70% methanol solution at −30 °C. TEM examinations were performed using a JEM-2100 microscope.

Hardness measurements were performed using a macro Vickers hardness tester with 2.5 kg load and a dwell time of 10 s. Each reported hardness value (Vickers hardness number, HVN) is the average of 10 individual measurements. Tensile testing was carried out at room temperature by a CSS-44100 tensile test machine, and the fracture surface was examined by SEM. The tensile strength and elongation were an average of at least 3 testing values.

3. Results and discussion

The microstructures of the Al–10%Mg_2Si alloy in the as-cast condition and after T6 heat treatment are shown in Fig. 1. It can be seen that two different solidified microstructures exist in the Al–10%Mg_2Si alloy. The primary α-Al is surrounded by Al–Mg_2Si binary eutectic structure (Fig. 1a and b). Interestingly, unlike the eutectic microstructure of as-cast Al–10%Mg_2Si alloy where large needle-like Mg_2Si particles (Fig. 1c) form in the Al matrix, the eutectic microstructure with very fine dot-like Mg_2Si particles has formed after T6 heat treatment, as shown in Fig. 1d. To investigate the change of the eutectic Mg_2Si particles with heat treatment, detailed three-dimensional image analysis was conducted on SEM obtained after Al matrix was deeply etched by NaOH water solution (15%) (Fig. 2). It can be seen that after T6 heat treatment, eutectic Mg_2Si transforms from long rod (needle in two-dimensional observation (Fig. 1c)) to short fiber or sphere (dot in two-dimensional observation (Fig. 1d), as shown in Fig. 2a and b.

For Al–Mg_2Si pseudobinary system, the maximum solubility of Mg_2Si in Al is 1.91 wt.% [20]. During the solution treatment process, the concave pit has large curvature (marked as A in Fig. 2a). Therefore, the Mg and Si atoms will dissolve in the Al matrix and diffuse from this position to flat interface with lower atom concentration [17], leading to the fragmentation of long rod-like eutectic Mg_2Si. With the prolonging time of solution treatment, eutectic Mg_2Si phase continuously dissolves, diffuses and spherizes to reduce the surface energy, resulting in the formation of Mg_2Si particles with short fiber-like and spherical morphologies (marked as B and C in Fig. 2b). Most of the Mg_2Si particles in cast Al–10% Mg_2Si alloy are more than 20 μm in length (Fig. 2a). After T6 heat treatment, the size of most Mg_2Si particles has reduced to less than 5 μm, and even 1 μm (Fig. 2b).

Moreover, it is found that a number of nano-sized β″ particles are embedded in the Al matrix after T6 heat treatment, and the particles have only a diameter of less than 20 nm, as shown in Fig. 3. In Al–Mg–Si wrought alloys, the dissolution precipitation sequence of β (Mg_2Si) phase during aging has been well accepted as supersaturation solution → GP zone (Mg/Si clusters) → β″ → β' → β [21,22]. For Al–10%Mg_2Si alloy, after solution treatment, Mg and Si elements exceed equilibrium concentration in the supersaturated solid solution of Al matrix. During the subsequently artificial aging process, Mg and Si composite clusters continuously grow and transform into nano-sized metastable β″ particles. The detail of precipitation kinetics and behavior of the metastable (β″ and β′) and stable (β) phases in Al–Mg_2Si cast alloy remains to be researched and determined.

The variation of the mechanical properties of the Al–10%Mg_2Si alloy under the states of as-cast and T6 heat treatment is presented in Table 1. Due to the refining eutectic structure and the precipitation of nano-sized particles in Al matrix, the alloy exhibits an enhanced hardening response. The hardness of primary α-Al and eutectic structure increases to 76.4 and 92.2HVN, respectively (corresponding 69.1 and 78.5 HVN in cast alloy). Further T6 heat treatment leads to a significant improvement in ultimate tensile strength (UTS) and elongation. The ultimate tensile strength increases to 234.6 MPa, 26% higher than that of cast alloy (186.0 MPa), and elongation increases from 0.875% to 1.233%.

Fig. 4 shows the fracture surface of the Al–10%Mg_2Si alloy

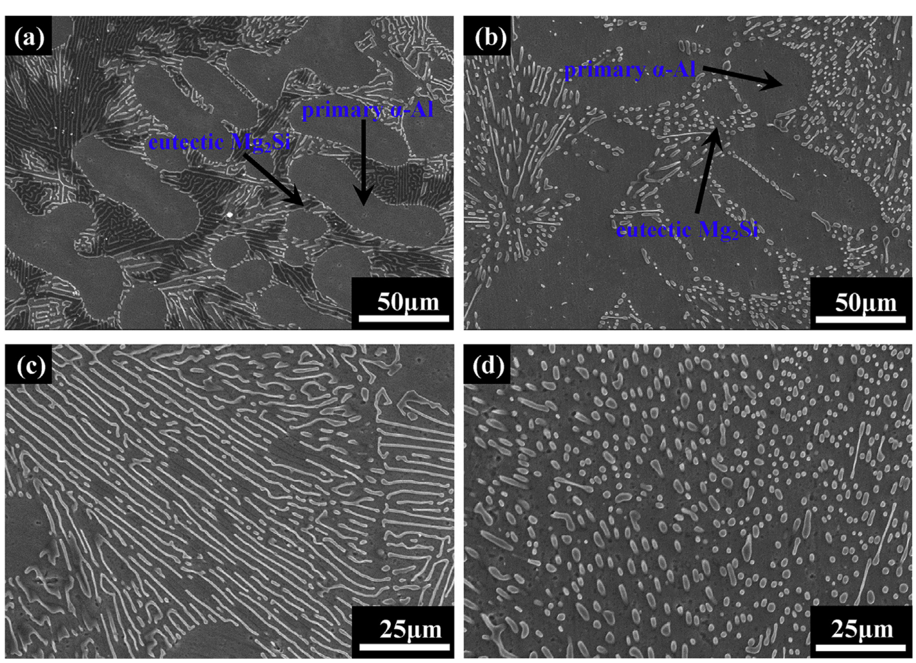

Fig. 1. Microstructures of Al–10% Mg_2Si alloy: (a) in as-cast condition; (b) after T6 heat treatment; (c) enlarged morphology of eutectic Mg_2Si in (a); (d) enlarged morphology of eutectic Mg_2Si in (b).

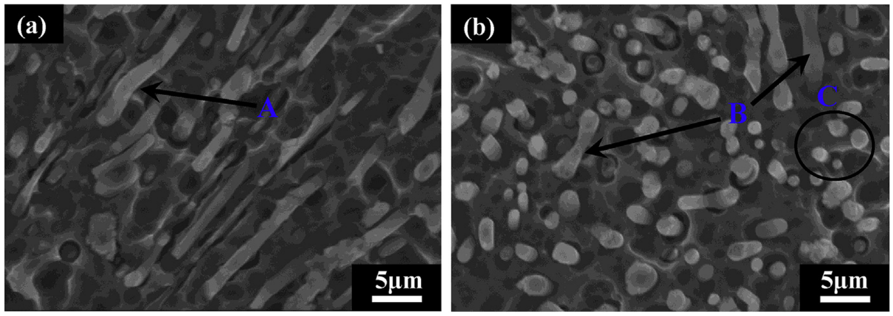

Fig. 2. Detailed three-dimensional images of eutectic Mg_2Si in in as-cast condition (a) and after T6 heat treatment (b).

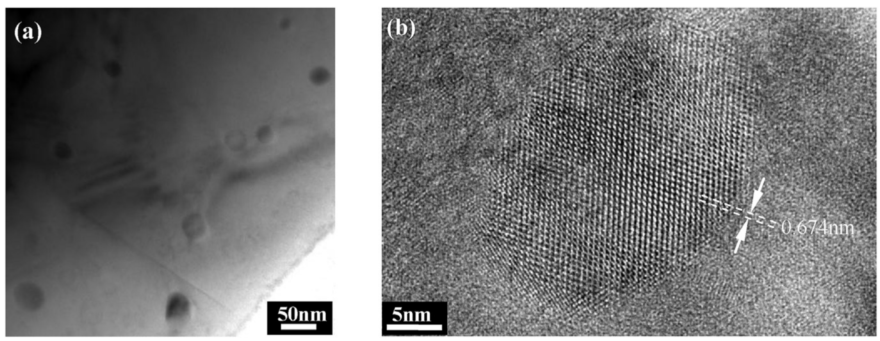

Fig. 3. (a) TEM micrograph of Al–10%Mg_2Si alloy after T6 heat treatment; (b) HRTEM image of an β″ particle.

Table 1
Mechanical properties of the Al–10%Mg_2Si alloy.

Sample	Hardness (HVN)		UTS (MPa)	Elongation (%)
	α-Al	Eutectic structure		
as cast	69.1	78.5	186.0	0.875
T6 heat treatment	76.4	92.2	234.6	1.233

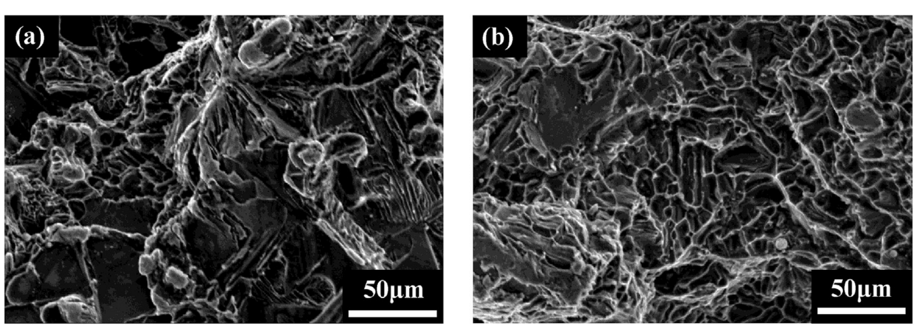

Fig. 4. SEM images of fracture surface of Al–10%Mg_2Si in as-cast condition (a) and after T6 heat treatment (b).

before and after T6 heat treatment. A typical brittle failure with regular cleavage planes can be seen in the as-cast Al–10%Mg_2Si (Fig. 4a). After T6 heat treatment, a large number of dimples are observed across the fracture surface (Fig. 4b), which is indicative of a highly ductile fracture. In tensile loading, localized shearing can easily initiate cracks and promote crack propagation, triggering a fast fracture with a nominal plastic strain of only a few percent [23]. The fine fiber-like and spherical Mg_2Si particles can ease the localized shearing and hence suppress the crack initiation and propagation. Therefore, there is enhanced tensile ductility in the Al–10%Mg_2Si with T6 heat treatment, compared with cast alloy.

4. Conclusion

After solution treatment at 520 °C for 6 h and subsequent aging at 200 °C for 6 h, long rod-like eutectic Mg_2Si in Al–10%Mg_2Si alloy transforms to short fiber-like and spherical morphologies, due to the fragmentation and spheroidization of eutectic Mg_2Si. Meanwhile, a great number of nano-sized β″ particles with a diameter below 20 nm precipitate in the Al matrix. The refining eutectic structure and precipitation of nano-sized particles lead to the alloy exhibiting an enhanced hardening response and a significant improvement in ultimate tensile strength (234.6 MPa, 26% higher than that of cast alloy).

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