Microstructure and strength of a novel heat-resistant aluminum alloy strengthened by T-$Al_6Mg_{11}Zn_{11}$ phase at elevated temperatures

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ABSTRACT

We designed an aluminum (Al)-based alloy with the α-Al (fcc) matrix strengthened by the T-$Al_6Mg_{11}Zn_{11}$ (cubic) intermetallic phase using a large two-phase region of α and T phases in the Al–Mg–Zn ternary system. Thermodynamic analysis assessed a composition of Al–5Mg–3.5Zn (at%) with the α-Al phase reinforced with high fractions (approximately 10%) of T phase. We observed that the T phase preferentially precipitated at grain boundaries in the α-Al matrix, increasing the area fraction of the T phase at grain boundaries during aging. The granular precipitates of the T phase were dispersed rather homogenously in the α-Al matrix with a particular orientation relationship of $(1-11)_\alpha // (1-21)_T$ and $[011]_\alpha // [111]_T$ at temperatures above 300 °C. After aging at 200 °C, numerous fine precipitates with a mean size of ~20 nm in the grain interior were observed, which were likely the metastable phase associated with the T phase. The present alloy (pre-aged at 200 °C for 1 h) exhibited a high yield strength of approximately 260 MPa at 200 °C, much higher than those of the conventional Al alloys at elevated temperatures corresponding to service temperatures for compressor impellers in turbochargers.

1. Introduction

Wrought aluminum alloys with relatively high specific strength are widely used for radial compressor impellers in vehicle turbochargers [1,2]. The turbocharger converts waste energy from the exhaust into compressed air, which is then pushed into the engine, increasing the overall efficiency of the combustion process [1]. The compression ratio for conventional diesel engines (currently around 5:1 [2]) is limited by the yield strength of the wrought Al alloys used in the engines and related to its fatigue resistance at elevated temperatures. One of the common wrought Al alloys used for radial compressors is the 2618 alloy. The strength of this alloy significantly decreases at temperatures above 200 °C [3]. This strength reduction is thought to be due to the low instability of the metastable intermetallic phases precipitated in the α-Al (face-centered cubic, fcc) matrix at aging temperatures below 200 °C. At elevated temperatures, the metastable precipitates can transform into stable S-Al_2CuMg [4], resulting in coarsening of the precipitates in the α-Al matrix. In addition, the limited volume fraction of the S phase in the 2618 alloy contributes slightly to strengthening the material at high temperature. The poor high-temperature strength limits the service temperature of compressor impellers for turbochargers. Thus, further improvements in the combustion efficiency require higher process temperatures of the Al alloys applied for the radial

compressor impellers.

The development of Ni-based superalloys has resulted in a steady increase in operating temperatures of jet engines, improving performance and efficiency [5]. Ni-based superalloy components in jet engines can reach temperatures approaching 1150 °C [6], which is approximately 0.8 T_m (T_m: melting temperature of the alloys). A key requirement for achieving superior strength at elevated temperatures is the formation of a multi-phase microstructure consisting of high volume fractions of stable intermetallic phases in strengthened materials. For Ni-based superalloys, the γ-Ni (fcc) phase acts as a matrix that binds the γ'-Ni_3M phase ($L1_2$ structure) for strengthening. The γ' phase is in equilibrium with the γ-Ni matrix in high volume fractions at the required service temperatures [5]. Therefore, introducing thermodynamically stable intermetallic phases in the metal-matrix effectively improves high-temperature strength. This method for controlling a multi-phase microstructure could be applied to Al alloys and potentially improve their high-temperature properties for use in compressor impellers. This approach was recently applied to cast Al alloys using eutectic reactions during solidification [7–10], whereas there are few reports of strengthening by precipitates of stable intermetallic phase with high volume fractions in the α-Al (fcc) matrix of wrought Al alloys via heat treatments.

In this study, we focused on two commonly used metals (Mg and Zn)

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as alloying elements and fabricated a wrought Al-based alloy strengthened by the T-$Al_6Mg_{11}Zn_{11}$ (cubic) intermetallic phase [11] in the Al–Mg–Zn ternary system. The alloy composition was designed based on thermodynamic equilibrium calculations [12–14] using a previously reported thermodynamic database [15]. The microstructures of the solution-treated and subsequently aged alloy samples were investigated. The yield strengths of the designed alloy at various temperatures were also measured. These results were used to discuss the possibility of our proposed alloy for their application as high-temperature materials.

2. Thermodynamic equilibrium calculations

In order to achieve high volume fractions of precipitates in Al-based alloys, high solubility of alloy elements in the α-Al matrix is required at elevated temperatures (corresponding to the solution-treatment temperature). The α-Al phase has limited solubilities less than 2 at% in most of Al-X (X: alloy elements) binary systems [16], whereas Al–Mg and Al–Zn binary phase diagrams indicate high solubilities of approximately 18.5 at% and 67 at% in the α-Al phase, respectively. The Al–Mg–Zn ternary phase diagram [15] presents a ternary intermetallic compound of T-$Al_6Mg_{11}Zn_{11}$ phase in equilibrium with the α-Al phase. These insights open an opportunity to design an Al-based alloy strengthened by thermodynamically stable T-$Al_6Mg_{11}Zn_{11}$ phase with high volume fractions in the Al–Mg–Zn ternary system. In the present study, to assess the two-phase region between α-Al (fcc) and intermetallic phases in the Al–Mg–Zn ternary system, thermodynamic equilibrium calculations were performed using the CALPHAD method [12–14] based on a previously reported thermodynamic database [15]. Fig. 1 shows the calculated isothermal section of the Al–Mg–Zn ternary system at 450 °C. The calculated isothermal section represents the α-Al phase in equilibrium with T-$Al_6Mg_{11}Zn_{11}$ over a wide compositional range (Fig. 1(b)), indicating the possibility of strengthening the α-Al matrix using this intermetallic compound in the Al–Mg–Zn ternary system. The crystal structure of T-$Al_6Mg_{11}Zn_{11}$ is shown in Fig. 1(c). The vertical sections were calculated along a tie-line between the α and T phases (as shown in Fig. 1(a)), where the results are presented in Fig. 2(a). It is noteworthy that a relatively large α-Al single-phase region was observed at high temperatures (above 450 °C) in the Al-rich portion of the Al–Mg–Zn ternary system. The vertical section indicates a two-phase region of α and T phases at low temperatures (below 400 °C). The α single-phase region and the α/T two-phase region would be available during solution-treatment to form the single α-phase, and

subsequent aging would form the T phase in the α-matrix. The thermodynamic calculations determined an alloy composition of Al–5Mg–3.5Zn (at%) with an α-Al matrix strengthened by high volume fractions of T-phase precipitates (all compositions are given in atomic percent unless specified otherwise). The calculated equilibrium mole fractions of the constituent phases in the Al–5Mg–3.5Zn alloy as a function of temperature are presented in Fig. 2(b). The calculations resulted in an α-Al single-phase region at temperatures in the range of around 460–500 °C. Below the temperature range for the α-Al single-phase, the formation of both the T and α-Al phases was predicted. The equilibrium volume fraction of the T phase at 200 °C (the target service temperature for radial compressor impellers) was ~ 10%, equivalent to that of the γ′ phase in conventional Ni-based wrought alloys [5]. These results show that applying solution-treatment and subsequent aging may produce an α-Al matrix strengthened by a thermodynamically stable T phase with a fraction up to 10%.

3. Experimental procedures

The nominal composition of the studied alloys was Al–5Mg–3.5Zn (at%). The alloy was melted and hold at approximately 720 °C for 0.5 h in an alumina tube using an induction melting furnace in an Ar atmosphere and then cooled to solidify the alloy by turning off the power to the furnace. This process resulted in rod-shaped alloy ingots. Small ingots (~ 30 g) with a diameter of approximately 20 mm were used for microstructural observations. Large ingots were prepared for tensile tests, where the alloy specimens were prepared by induction melting (hold at approximately 700 °C for 0.5 h) and cast into rods with a diameter of approximately 67 mm. The chemical compositions of the center of these ingots were analyzed using inductively coupled plasma atomic emission spectrometry (ICP-AES). These results are summarized in Table 1. Small deviations in the alloy composition from the nominal would vary the fraction of the T phase from the calculated value (Fig. 2(b)). Phase fractions within 0.5% of were predicted by the thermodynamic calculations. These ingots were then solution-treated at 450–500 °C for various periods from 1 to 48 h. In order to examine the precipitation kinetics of the T phase in the α-Al matrix, the solution-treated samples were aged at various temperatures from 200 to 450 °C for times from 0.17 h (10 min) to 3600 h.

The surfaces of these samples were mechanically ground and then polished with colloidal silica. The microstructures were examined using scanning electron microscopy (SEM: JEOL JSM-6610A) at 30 kV. Thin samples for transmission electron microscopy (TEM) observations were
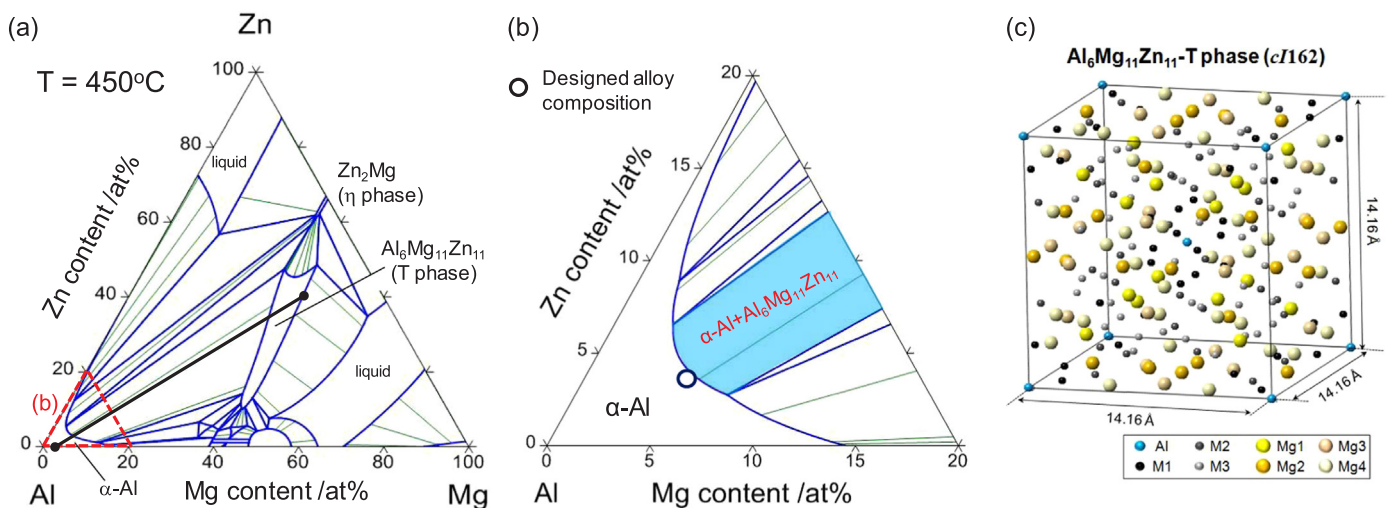

Fig. 1. (a) Isothermal section at 450 °C of the Al-Mg-Zn ternary system calculated and (b) the designed alloy composition plotted on the Al-rich portion of the isothermal section and (c) crystal structure of T-$Al_6Mg_{11}Zn_{11}$ (cubic) phase. Green lines present the tie-lines in (a,b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).