Structure and Coarsening Behavior of the Strengthening Phase in RS Al-Fe-Mo-Si-Zr-Ti Alloys

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Abstract. The structure, space groups, lattice parameters and stoichiometric formula for the strengthening phase in Al-Fe-Mo-Si-Zr-Ti alloys were determined by X-ray diffraction, TEM, CBED and EDX. The coarsening behavior and mechanism of the strengthening phase were studied also using TEM and EDX. Results showed that the strengthening phase was identified to be BCC Al$_{12}$(Fe, Mo, Zr, Ti)$_3$Si ($Im3$, $a = 1.263$ nm) and the coarsening rates is the lowest in all the intermetallic phases of Al-Fe system, which is controlled by the diffusion of alloy element Zr in the matrix. Addition of Gd, Y make a volumetric coarsening rate one order of magnitude slower, at 477°C approaching to the coarsening rate Li$_2$ Al$_3$(Zr, V) phase.

Keywords: aluminum alloy, coarsening behavior, rapid solidification

Introduction

In the past two decades, significant interest has been directed to advance aluminum alloys produced by the powder metallurgy (P/M)-rapid solidification (RS) route. A specific target of P/M-RS processes was the development of high-temperature range 150 ~ 400°C [1]. Improvements in the processing conditions have made the alloy’s properties attractive, for example, tensile strengths of 450 to 600 MPa are achievable at room temperature, with an elongation to fracture and fracture toughness up to 17% and 25 MPa·m$^{3/2}$ respectively, while at 400°C the tensile strength retained may be as high as 250 MPa. Among the most successful development alloy system are Al-Fe-V-Si(8009, 8022) and Al-Fe-X(8019) produced by several different atomization techniques [2, 3]. These alloys could be utilized over a wide range of aircraft and space vehicle.

In order to fulfill the necessity and design requirements of the advanced aerospace vehicle and propulsion systems, in addition to the Al-Fe-V-Si and Al-Fe-Ce alloys, development of new Al alloy systems to be used above a temperature of 427°C(800 F) became an active field of research in the past five years [4]. According to experimental exploration by the present authors it is found that a new Al-Fe-Mo-Si-Zr-Ti alloy system with a new strengthening phase may hold good promise for this kind of application. In this paper, the strengthening phase and its coarsening behavior and mechanism of this alloy system are presented.

Experimental

The composition of the alloy powders produced by USGA technique are shown in Table 1. Powders of 40 µm or less were vacuum-degassed, hot-pressed and extruded at a 16:1 ratio into a 12.5 mm rod.

Foils for transmission electron microscopy (TEM) were prepared by the double-jet method using an electrolyte of 30% HNO$_3$ in methanol at 40 V and -30°C. The thin
Table 1. Alloy compositions.

<table>
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<tr>
<th></th>
<th>Fe</th>
<th>Mo</th>
<th>Si</th>
<th>Zr</th>
<th>Ti</th>
<th>Gd</th>
<th>Y</th>
<th>Al</th>
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<tr>
<td>1</td>
<td>8.0</td>
<td>1.6</td>
<td>1.5</td>
<td>1.0</td>
<td>0.2</td>
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<tr>
<td>2</td>
<td>8.0</td>
<td>1.6</td>
<td>1.5</td>
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<tr>
<td>3</td>
<td>8.0</td>
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foils were examined in Jeol 2000FX scanning TEM(STEM) equipped with a Link system 860 energy-dispersive X-ray analysis (EDX) spectrometer. Analysis by EDX were quantified using the Link systems RTS-2/FLS computer program.

To aid phase identification, X-ray analysis was conducted using a D/max-rB diffractometer with Cu Kα radiation.

Results and discussion

Identification of the strengthening phases in Alloy 1

The as-solidified microstructure of 5 ~ 74 μm powders was studied using OP, SEM, TEM and X-ray diffraction in detail [5]. Results shows that powders of 40 μm or less exhibit mixed microcellular and cellular microstructure.

X-ray diffraction studies was performed in as-extruded alloys. A typical X-ray diffraction pattern showing the variation of intensity(cps) as a function of 2θ is presented in Fig. 1 for the Alloy 1. It shows that hot-press and extrusion lead to precipitation of fine precipitate in α-Al matrix. All the precipitate reflections could be consistently indexed on the basis of a BCC lattice (h + k + l = 2n) with a = 1.262 nm, which closely matches the value of 1.256 nm for the BCC α-AlFeSi compound [6], and that of the precipitates reported in Al-Fe-V-Si alloys [2].

Figure 2a shows typical TEM images of the strengthening phase precipitates in Alloy 1 when aged at 427°C for 2 h. The microstructure consisted of a refined dispersion of precipitates. The size of the precipitates was about 50 nm. Further aging to 125 h produced no apparent change in the microstructure (Fig. 2b) and showed certain degree of particle coarsening.

Electron diffraction studies were carried out to confirm the X-ray results. Examples of diffraction patterns recorded from individual precipitates are shown in Fig. 3. These and all other patterns could be consistently indexed on the basis of a BCC lattice with a lattice parameter almost identical to that determined by X-ray diffraction. CBED pattern for the strengthening phase precipitate from [025] zones are shown in Fig. 4a, b. Both whole pattern symmetry and bright field symmetry are m, which gives the possible diffraction group as m, mlR and 2RmmR. For the BCC lattice and (uvw) zone axes, no m, mlR diffraction groups existed, therefore the diffraction group of the precipitates should be 2RmmR, and the point group corresponding to the diffraction group is m3 [7].

The possible space groups for this point group are Pm3, Pn3, Pa3, Fd3, Im3, and Ia3 [7]. Since the lattice is BCC, the choice of space groups is reduced to the last two, namely, Im3 or Ia3. For the latter space group, reflections of type 0kl for which k and l