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# Dispersoid Formation and Recrystallization Behavior in an Al-Mg-Si-Mn Alloy

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The nucleation and precipitation of Mn-containing dispersoids in an Al-Mg-Si-Mn alloy (6082) have been studied by optical microscopy, EPMA (electron probe microanalysis) and TEM (transmission electron microscopy). The influence of Mn-containing dispersoids on the recrystallization behavior was also investigated. The size and distribution of dispersoids were strongly affected by both the homogenization process and the alloying element distribution formed in the direct chill cast procedure. The Mn-containing dispersoids were observed to nucleate preferentially on the $\beta'$-$Mg_2Si$ phase and to be aligned along the <100> direction of the matrix. After cold deformation, the morphology of dispersoids greatly influences the recrystallization and grain growth behavior in the annealing process.

**KEY WORDS:** **Mn-containing dispersoids; Homogenization; Recrystallization; Grain refinement**

## 1. Introduction

Al-Mg-Si based alloys, also known as the 6000 series alloys, have attracted much industrial attention in recent years due to their superior mechanical properties, and have a wide range of applications in the aerospace, aircraft, automotive and construction industries. Methods to develop high performance Al-Mg-Si alloys are therefore very important. Alloy elements such as Mn, Cr, Cu, which have been long used as microalloying elements, are often added to Al-Mg-Si alloys to modify the microstructure and to improve the mechanical properties. For example, when Mn is added, intermetallic compounds (more commonly referred to as Mn-containing dispersoids) can be produced during homogenization heat treatments under appropriate heating rates. The $\beta$-$Mg_2Si$ phase and several associated metastable phases, such as $\beta'$ phase, are considered to be the nucleation sites for the Mn-containing dispersoids[1–3]. Lodgaard and Ryum[4] have investigated the formation of dispersoids containing Mn and/or Cr in Al-Mg-Si alloys. An intermediate phase having the hexagonal structure and rich in Mn and/or Cr, referred to as the "$u$-phase" was observed to nucleate on the $\beta'$ phase, and was considered to be the initial stage for formation of the Mn-containing dispersoids.

In the annealing process after cold deformation, the size and distribution of the dispersoids have a strong effect on the recovery, recrystallization and grain growth. For example, Troeger and Starke Jr[5] reported that in an Al-Mg-Si-Cu alloy a homogeneous distribution of micron-size precipitates was necessary for developing a fine and uniform grain structure.

The aim of the present work is to investigate the nucleation mechanism and precipitation behavior of Mn-containing dispersoids in Al-Mg-Si-Mn alloys, and to further investigate their influence on the recrystallization behavior.

## 2. Experimental

A direct chill-cast Al-Mg-Si-Mn (6082) alloy was

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**Table 1** Chemical composition of the prepared 6082 alloy (%, mass fraction)

| Al | Mg | Si | Mn | Cr | Fe | Ti |
|---|---|---|---|---|---|---|
| Bal. | 0.90 | 1.08 | 0.72 | 0.01 | 0.13 | 0.02 |

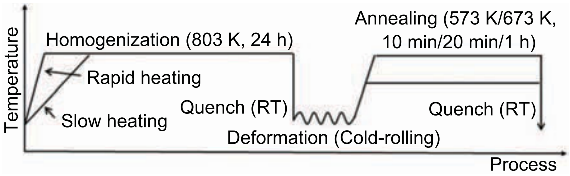


**Fig. 1** Heat treatment procedure

prepared in this work. The chemical composition of the alloy is listed in Table 1. The entire heat treatment procedure is shown in Fig. 1. In order to investigate the influence of the heat treatment on the precipitation behavior of Mn-containing dispersoids, two specimens were heated to 803 K with two different heating rates (rapid-heating, carried out in a salt bath, and slow-heating at 40 K/h), for an isothermal anneal of 24 h, then quenched in water at room temperature. Optical microscopy and electron probe microanalysis (EPMA) were conducted on the as-cast and homogenized specimens. For metallographic examination, the specimens were polished using diamond and colloidal silica suspensions, and then etched with a 0.5% hydrofluoric acid solution for 15 s. To investigate the nucleation mechanism of the Mn-containing dispersoids using transmission electron microscopy (TEM), another specimen was heated to 523 K using a medium-heating rate of 100 K/h for an isothermal anneal of 5 h, then quenched in water at room temperature. Thin foils for TEM observation were prepared using a Tenupol-5 twin-jet electropolisher with an electrolyte containing 20% nitric acid and 80% methanol. The thinning was performed at 20 V at 248 K. The TEM observations were conducted using a JEOL-3010 TEM. Cold-rolling was carried out on the two homogenized specimens to give a 60% thickness reduction. These samples were then isothermally annealed at either 573 or 673 K for 10 min, 20 min and 1 h. The as-rolled and annealed specimens were anodized for microstructural observation. Anodizing was carried out at 18 V for 3 min in the standard solution.

## 3. Results

Figure 2 shows the as-cast microstructure of the 6082 alloy. The darker phase is $Mg_2Si$ (indicated by A), while the lighter regions are Mn-containing particles (indicated by B) formed during solidification. The distributions of the main elements contained in the specimen are shown in Fig. 3. According to the maps, Mg, Si, Mn and Fe have a nonuniform distribution in the matrix. The large yellow areas along the grain boundaries indicate high concentrations, while dark areas in the center of the grains show low concentrations. The tendency for segregation of these elements at the grain boundary is very strong. In particular, Mn is markedly segregated, with a low concentration inside the grains and a high concentration along grain boundaries. Compared with these elements, Ti has rather uniform distribution, indicated by green and blue areas, representing similar concentrations.

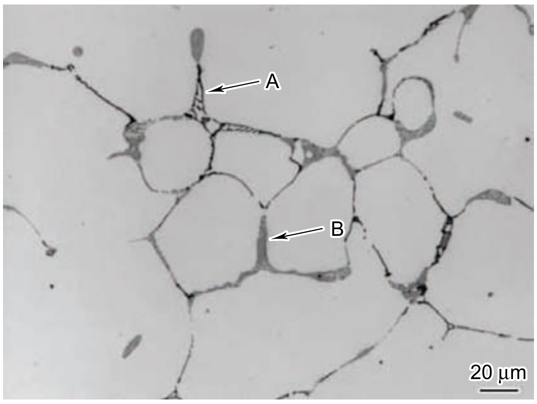


**Fig. 2** Optical micrograph for the as-cast 6082 alloy, showing crystallized intermetallic compounds as indicated by arrows A: $Mg_2Si$, and B: Mn-containing particle

Figure 4(a) and (b) show the influence of the different heating rates during homogenization on the size and distribution of Mn-containing dispersoids. The dispersoids have a nonuniform shape and heterogeneous distribution in the rapidly-heated specimen (Fig. 4(a)). Many of the dispersoids have a long needle shape with the length around 10 $\mu$m, while others are small with spherical shape with the radius less than 1 $\mu$m. Precipitate free zones (PFZs) are observed both near grain boundaries and in the central regions of grains. In the slowly-heated sample (Fig. 4(b)), the dispersoids are all small and spherical in shape with a uniform and homogeneous distribution, while the radius is less than 1 $\mu$m. The difference between two micrographs indicates that the heating rate strongly affects the size and distribution of Mn-containing dispersoids.

The reason for these differences can be traced back to the distribution of elements introduced during solidification (as shown in Fig. 3). During direct chill casting, the cooling rate is not fast, and this allows the alloying elements to segregate along the grain boundaries. The existence of Ti, which is a peritectic element with Al, also accelerates the segregation of eutectic elements. When a fast heating rate is used for the homogenization treatment, the $Mg_2Si$ phase is preferentially formed in the areas where Mg and Si are concentrated. On the contrary, if the heating rate