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The Mg_2Si phase evolution during thermomechanical processing of in-situ aluminum matrix macro-composite

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ABSTRACT

The microstructure and flow stress behavior of thermomechanically processed Al–Cu/Mg_2Si in-situ composite was studied emphasizing the evolution of primary and secondary reinforcement phases. Toward this end, the hot compression tests were conducted over the wide range of temperature (300–500 °C) and strain rate (0.001–0.1 s^{-1}). Both the temperature and strain rate are found to possess a significant effect on the microstructural characteristics where a considerable softening is identified specially at low temperature regime. Besides the occurrence of restoration processes (mainly particle stimulated nucleation) the dynamic evolution of the reinforcements is introduced as the main factors affecting the reported softening. In this regard, the mechanical fragmentation, thermal disintegration, micro-buckling, coalescence and spheroidization of the primary and secondary particles are quantitatively and qualitatively addressed through a comprehensive scanning electron microscopy studies.

1. Introduction

The size and volume fraction of the present reinforcements along with the nature of matrix–reinforcement interfaces have been recognized as the main factors affecting the characteristics of the metal matrix composites (MMCs) [1]. The optimum characteristics are obtained where the ceramic particles, relatively fine and thermally stable, are uniformly distributed within the metal matrix [2]. The recently efforts, which have been conducted made to meet such requirements, have resulted in developing in-situ metal matrix composites. In these composites the reinforcement forms as a result of chemical reactions basing on the nucleation and growth from the source matrix [3]. This would overcome any disadvantages of composite production through an external addition of ceramics reinforcement.

As is well established, magnesium silicide (Mg_2Si) exhibits low density, high melting temperature, high hardness, high elastic modulus and low coefficient of thermal expansion. Owing to the excellent combination of physical and mechanical properties, Mg_2Si has been widely used as a reinforcement phase to prepare aluminum-based metal matrix composites (AMMC) [4]. Pseudo-binary Al/Mg_2Si composites contain more than 13.9 wt% Mg_2Si thereby being an attractive ultra-light candidate for automobile and aerospace industries [5,6]. The primary Mg_2Si particles are firstly precipitated from the melt, and then they are surrounded by the co-solidified pseudo-eutectic lamellar structure of α_{Al} and Mg_2Si [7,8]. The main issue is the fact that the presence of coarse and unmodified state of primary Mg_2Si, the lamellar morphology of secondary Mg_2Si and also the defects associated with the casting structure would result in receiving unsuitable mechanical properties near the room temperature [9,10]. Accordingly, enormous studies have been conducted on eliminating these restrictions; nonetheless, all of these efforts can be categorized into two main groups. The first one deals with the researches which have employed long-time heat treatments [11]; and the second one is those which believe on the chemical modification through the addition of several elements such as Zirconium, Sodium, Manganese, Phosphorus, Bismuth and Strontium [12–18]. However, the former is accompanied with porosity increment and also environmental concerns, and the latter is time and energy consuming. As a promising alternative method, thermomechanical processing (TMP) can be considered to modify the microstructure of Al/Mg_2Si composites, the satisfying potential of which has been reported by some researchers to date [19–21]. It was found that the well-known TMP routes such as forward hot extrusion resulted in braking the pseudo-eutectic structure into the fine fragmented particles, slight decrease in primary Mg_2Si size and also removing the casting defects. However, it is worth noting that all of the sporadic researches linked to the use of TMP have been executed in a narrow range of temperature under a nearly constant strain

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rate. In addition there is no comprehensive report regarding the evolution of the primary and secondary phases including their fragmentation, coalescence, coarsening, and spheroidization. These would definitely change their morphology, size and distribution thus would affect the subsequent forming capability.

Taking all above-mentioned explanations into account, the present investigation is planned to uncover the high temperature deformation behavior of Al–Cu/Mg_2Si in-situ composite, with emphasizing the evolution of reinforcement particles. The knowledge of the detailed phenomena occurring under various thermomechanical treatment would be useful to control the industrial parameters and to reach the desired properties in the processed material.

2. Materials and methods

The experimental material was an Al–Cu/Mg_2Si in situ metal matrix composite, the chemical composition of which is shown in Table 1.The initial microstructure of the alloy (Fig. 1a) consists of the coarse polygonal-shape primary Mg_2Si particles (defined as $[Mg_2Si]_P$) surrounded by pseudo-eutectic lamellar structure of secondary Mg_2Si/α_{Al} (defined as $[Mg_2Si]_S$). In addition, the presence of θ phases ($CuAl_2$) can be recognized specifically at the cell boundaries, which form during the final steps of solidification due to the copper addition [22]. Also, the electron backscattered diffraction (EBSD) image of as-received material is shown in Fig. 1b. The cylindrical compression testing specimens were machined from as-cast experimental material in the sizes of $\phi 8$ mm × $H12$ mm according to ASTM E209 standard [23]. The isothermal hot compression tests were carried out on Gotech-AI7000 universal testing machine equipped with electrical resistance furnace. In order to specify the proper range of hot working conditions, the specimens were first compressed down to the logarithmic strain of 0.6 at temperatures in the range of 100–500 °C under the strain rate of 0.01 s^{-1}. Considering the results of preliminary tests, the experiments were then conducted at temperatures of 300, 400, 450 and 500 °C under the strain rates of 0.1, 0.01 and 0.001 s^{-1}. To follow the predetermined TMP cycle, the specimens were first heated up to the deformation temperature and held isothermally for 7 min prior to straining to allow the temperature to equalize throughout the specimens. A very thin mica plate was used in order to reduce the friction and prevent the adhesion of the specimen to the anvils. The specimens were water-quenched from the test temperature right after straining in order to preserve the final microstructure. The deformed specimens were sectioned parallel to the compression axis and the cut surfaces were grinded, polished and etched by HF 1% solution. The scanning electron microscope (back-scattered contrast) equipped with a proper image analyzer was employed to examine the microstructure. The EBSD analysis was conducted with a JEOL 7001F-JSM FE-SEM equipped with AZtecHKL EBSD system from Oxford Instruments. An accelerating voltage of 20 kV was applied for EBSD runs.

Moreover, the circular diameter parameter related to the primary Mg_2Si particles are calculated according a valid procedure [24]. Also, the shape factor parameter was calculated according to the following equation. F is the shape factor value which will be unity if the morphology of particle is circular completely and more than one in case of deviating from a circular shape.

$$F = \frac{1}{n} \sum_{k-1}^{n} \frac{P^2}{4\pi A}$$

where P is the perimeter and A is the mean value of area fraction related to the primary Mg_2Si.

Table 1
The chemical composition (in wt%) of the experimental Al–Cu/Mg_2Si metal matrix composite.

Al	Mg	Si	Cu	Fe	Mn	Ni	Zn
Balance	9.42	5.53	4.95	0.09	0.02	0.01	0.01

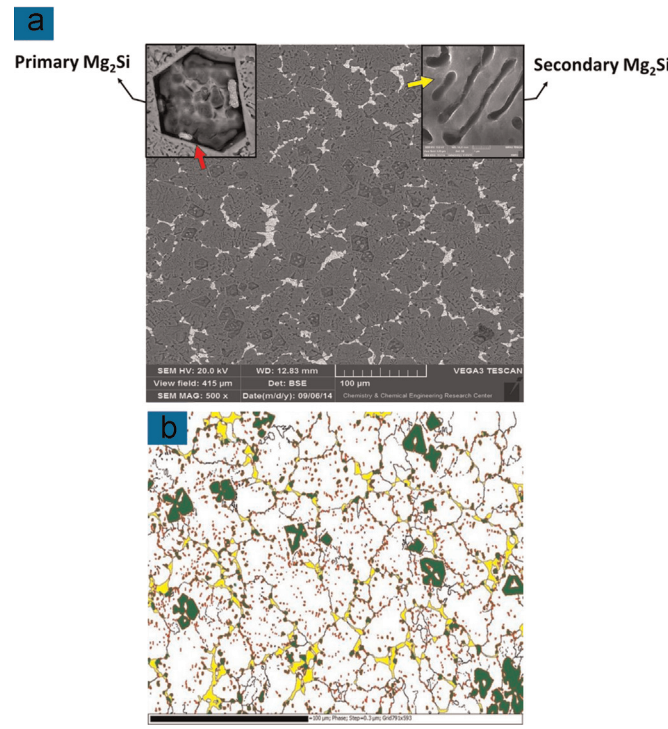

Fig. 1. (a) Scanning electron microscopy and (b) electron backscattered diffraction image of as-received material.

3. Results and discussion

3.1. The primary Mg_2Si evolution

3.1.1. Mechanical fragmentation

The mechanical fragmentation of the primary Mg_2Si phase is identified as one of the main microstructural features at low temperature regime and high strain rates. This can be well traced in the microstructure of the specimen deformed at 300 °C (Fig. 2a). It is speculated that the provided thermal energy is insufficient to cause the annihilation of the dislocation pile-ups around the sharp points of the particles. In fact, the different plastic behavior of the particles and matrix and the necessity of the material to preserve its continuity end to form the geometrically necessary dislocation at the vicinity of particle/matrix interface [24]. In spite of the brittle reinforcement particles, the ductile aluminum matrix is capable to accommodate the applied strain and meets the lower amount of prevention. In addition, the different thermal expansion coefficient of the phases may also leads to the particle/matrix incompatibility. These would results in creation of an area around the $[Mg_2Si]_P$ with a localized amount of strain (due to dislocation accumulation) called Particle Affected Zone (PAZ) [25]. Definitely, the primary coarse $[Mg_2Si]_P$, with relatively large mean circular diameter (~15 μm) and non-deformable nature, would be capable of being influenced through the strain distribution in its neighborhood. The intensified stress around the non-modified point of the particles due to the localized strain, may cause debonding the particle/matrix interface [26]. The latter is less common for the present in-situ metal matrix