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Variation of microstructure and mechanical properties with nano-SiC_p levels in the nano-SiC_p/AlCuMnTi composites

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A B S T R A C T

Nano-sized SiC particles (SiC_{np} for short) reinforced Al-5Cu-0.5Mn-0.15Ti composites have been successfully fabricated by a process consisting of high energy ball milling, mechanical stirring and ultrasonic treatment for composite slurry and squeeze casting. The variation of microstructure and mechanical properties with SiC_{np} levels in $x$$SiC_{np}$/AlCuMnTi ($x = 0.5$, 1, 1.5, 2 wt%) composites is investigated for the first time. The SiC_{np} are uniformly distributed in the SiC_{np}/Al-5Cu composites made with the process. With the increase of SiC_{np} content from 0.5 to 2.0 wt%, the primary α-Al and Al_2Cu phases are refined significantly up to 1.5 wt% but then become coarser at 2.0 wt%. The optimal mechanical properties are obtained in 1.5 wt% SiC_{np}/AlCuMnTi composites, which exhibit 298 MPa in ultimate tensile strength (UTS), 178 MPa in yield strength (YS) and 12.9% in elongation. These properties are increased by 18.7%, 11.3% and 25.3%, respectively, compared with the AlCuMnTi matrix alloy. The enhancement of strength is attributed to four strengthening mechanisms, among which the $\Delta\sigma_{CTE}$ and $\Delta\sigma_{Orowan}$ are the most important contributors. It is noteworthy that with more SiC_{np} in the present composites, the strength increases while elongation increases as well.

1. Introduction

Aluminum matrix composites (AMCs) have recently attracted much attention due to their high specific strength, high elastic modulus and good wear resistance, etc. [1–4]. In general, AMCs are reinforced by various ceramic particles such as SiC, Al_2O_3 and TiC, among which SiC particle is regarded as a suitable reinforcement in aluminum matrix for its unique physical and mechanical properties [1–5]. Recent studies reveal that the nano-sized ceramic particle is more favorable than micron-sized ceramic particle and it is becoming a research hotspot in the metal matrix composites [6,7]. However, the SiC_{np} tend to agglomerate in the molten Al alloys due to their poor wettability, attractive Van Der Waals interactions and large surface-to-volume ratio [8], which can reduce the mechanical properties of composites. Therefore, it is essential to develop new preparation processes to improve the distribution of nano-sized reinforcements.

Up to now, AMCs have been fabricated using a variety of conventional fabrication methods including solid-state processing and liquid-state solidification processing, such as powder metallurgy and stir casting [8,9]. In molten-metal processes, ultrasonic treatment (UT) is a promising technology to prepare the SiC_{np} reinforced AMCs, for the ultrasonic vibration can give rise to great effects on the melt by the cavitation and acoustic streaming [10–12]. In order to facilitate more homogenous dispersion of SiC_{np} in the SiC_{np}/AlCuMnTi composites, other processes including high energy ball milling (HEBM) and squeeze casting are also needed. However, it has not been publically reported about the preparation of SiC_{np}/AlCuMnTi composites using the similar processes.

In general, SiC_{np} content also determines the mechanical properties of composites [8,13]. Wang et al. found that increasing SiC_{np} content in aluminum alloy led to an increase in UTS and YS of composites fabricated by semisolid stirring assisted with hot extrusion, but the elongation was decreased by 54.4% [8]. Yao et al. found that increasing the volume fraction of SiC_{np} in AA6063 alloy caused an increase in UTS and YS of composites fabricated by powder metallurgy, but the elongation to fracture decreased from 10.0% to 2.3% [13]. These researches indicated that more SiC_{np} led to higher UTS and YS, while lower elongation was obtained. Up to now, few researches have been carried out on the variation of microstructure and mechanical properties with SiC_{np} levels in SiC_{np}/AlCuMnTi composites fabricated by the similar processes.

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Therefore, it is significant to study the contributions of SiC_{np} content and various strengthening mechanisms to the increase of strength and elongation of SiC_{np}/AlCuMnTi composites.

In this study, the microstructure and mechanical properties of SiC_{np}/AlCuMnTi (Hereafter, Al-5Cu for short of the AlCuMnTi alloy) composites were investigated, which were successfully fabricated by a process consisting of HEBM, UT for composite slurry and squeeze casting. The SiC_{np} content various from 0.5 wt% to 2 wt% in order to evaluate the effects of it. Significantly, it is found that with more SiC_{np} in the present composites, the strength increases while elongation increases as well. Various strengthening mechanisms are discussed to analyze this behavior in detail.

2. Experimental procedure

2.1. Materials

The preparation process for (0.5, 1, 1.5, 2) wt.% SiC_{np}/Al-5Cu composites is as following developed by the authors. Firstly, pre-oxidation treatment was used for SiC_{np} at 850 °C for 2 h to form a SiO_2 coating layer about 3.6 nm in thickness, which would prevent the reaction between Al and SiC_{np}. The details of pre-oxidation treatment could be found in our previous study [14]. After pre-oxidation of SiC_{np}, the SiC_{np}/Al compound granules containing SiC_{np} were prepared by HEBM according to our previous work [10]. The mass fractions of SiC_{np} was 6 wt% in compound granules with the size of 1~2 μm, as shown in Fig. 1(a). Furthermore, the SiC_{np} were uniformly distributed in compound granules, which would be beneficial for the dispersion of SiC_{np} in the composites, as shown in Fig. 1(b).

The chemical compositions of the Al-5Cu alloys used as matrix alloy were 5 wt% Cu, 0.5 wt% Mn, 0.15 wt% Ti, 0.3 wt% Mg, 0.15 wt% Fe, and balance Al. The raw materials including pure Al, pure Mg, pure Cu, Al-5%Ti-B master alloy and Al-10%Mn master alloy were melted in a graphite crucible at 750 °C. Then the molten metal was degassed with pure argon gas for 10 min. After that, the SiC_{np}/Al compound granules were added to melts with mechanical stirring at 120 rmp for 10 min, which was beneficial to accelerate the melting of SiC_{np}/Al compound granules and promote the dispersion of SiC_{np} in melt. The whole process was protected by argon gas. The SiC_{np} content in the composites was controlled to 0, 0.5, 1, 1.5, and 2 wt%, respectively.

Then, the melt was treated by UT to assist the homogenous dispersion of SiC_{np}. The details of UT system could be found in our previous study [10]. The ultrasonic horn preheated for 5 min at 720 °C was inserted into the melt below surface at 10–15 mm, and the UT time was set at 5 min. The whole process of UT was protected by argon gas. Finally, the composite ingots with diameter of 30 mm and height of 100 mm were fabricated by squeeze casting. The squeeze pressure was set at 50 MPa.

2.2. Characterization

Specimens for metallographic observation were cut from the top of casting ingots. The microstructure characterization was performed by using a XRD-7000S X-ray diffraction (XRD), a DMM-480C optical microscopy (OM), a JSM-7600F scanning electron microscopy (SEM) equipped with an energy dispersive spectrometer (EDS) and a Tecnai G2-F30 telecom electron micrograph (TEM). The grain size of the primary α-Al phase was calculated by using a self-developed software system (Solidvf 3.0) with Heyn's linear intercept method [10]. Then the room temperature tensile properties were measured by a SHIMADZU AG-IC machine under a constant rate of 1 mm/min. The average UTS, YS and elongation values were obtained from three samples for each specified condition. The size of sample was shown in Fig. 2.

3. Results and discussion

3.1. XRD analysis of SiC_{np}/Al-5Cu composites

The XRD patterns of $x$$SiC_{np}$/Al-5Cu ($x$ = 0.5, 1, 1.5, 2 wt%) composites are shown in Fig. 3, which exhibits the peaks for SiC_{np}, α-Al and Al_2Cu phase. It indicates that the SiC_{np} have been successfully introduced into the melt by the novel process of UT combined with HEBM and squeeze casting. No peak for Al_4C_3 can be found, which suggests that the pre-oxidation can efficiently prevent the reaction between SiC_{np} and Al-melt. In addition, the intensity of SiC_{np} peak is very low because of the low content (2 wt% for maximum).

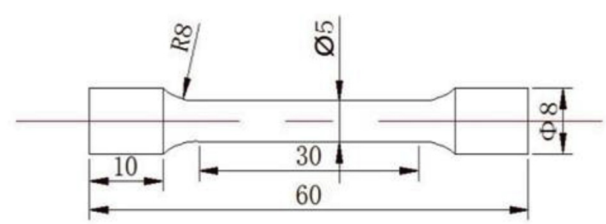

Fig. 2. The draft of the tensile test sample.

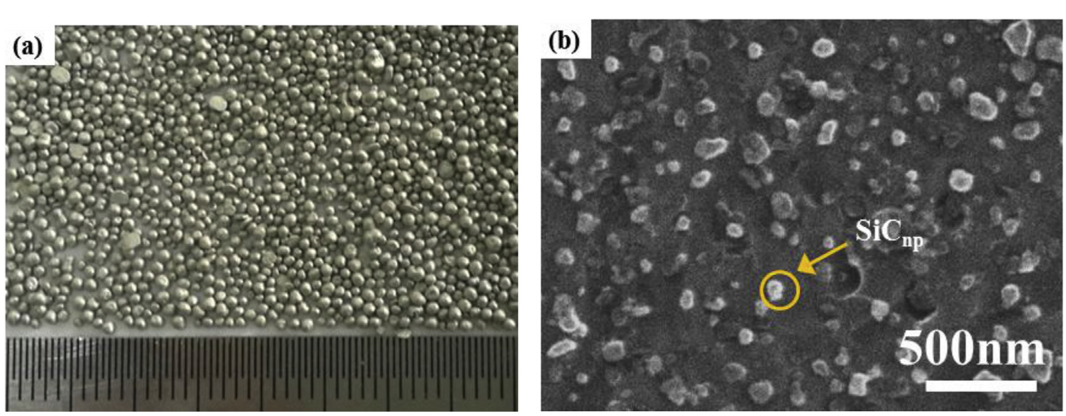

Fig. 1. Composite granules after HEBM: (a) morphology, (b) SiC_{np} distribution in compound granules.