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In-situ carbon nanotube-covered silicon carbide particle reinforced aluminum matrix composites fabricated by powder metallurgy

Shisheng Li, Yishi Su, Qiubao Ouyang *, Di Zhang

State Key Laboratory of Metal Matrix Composites, Shanghai Jiao Tong University, Shanghai 200240, PR China

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ABSTRACT

In order to achieve a uniform distribution of carbon nanotube (CNT) reinforcement in aluminum (Al) matrix, novel nano/micro-sized hybrid reinforcements with CNT growing on the surface of SiC particle (SiCp) was synthesized by a chemical vapor deposition method. Subsequently, the hybrid reinforcement (defined as SiCp(CNT)) was mixed in the pure Al matrix by merely blending powder, as a result, CNT was well-dispersed in the matrix with the help of micro-sized SiCp as a "vehicle". With the novel reinforcement, SiCp(CNT)/Al composite exhibited both improved elastic modulus of 93 GPa (35% higher than that of Al matrix) and tensile strength of 202 MPa (74% higher than that of Al matrix), mainly because CNT was dispersed uniformly and achieved intimate interfaces with Al matrix with the help of well dispersed SiCp.

1. Introduction

Owing to their higher specific modulus and specific strength, conventional metal matrix composites (MMCs) reinforced with micro-sized particles have been widely used in aerospace, ground transportation, and military industry [1]. However, micro-sized particles are prone to crack during mechanical loading, leading to premature failure and low ductility of the composites [2]. Recently, many researchers have tried to decrease the size of particles from micrometer to nanometer level for the simultaneous enhancement of the strength and ductility of MMCs [3–7]. Among the nano-sized reinforcements, carbon nanotube has become an attractive enhancing material owing to its low density, excellent mechanical, thermal and electrical properties in the past decades [8]. However, due to the strong intrinsic van der Waals forces, CNT tends to hold together and entangle with each other, which make it difficult to uniformly disperse in metal matrix. Therefore, a lot of research work has been carried out to overcome these obstacles [9]. Several methods, such as high energy ball milling [10], molecular level mixing [11] and nanoscale dispersion [12], have shown promising results to achieve uniform dispersion of CNT. But all of these techniques have evinced varying degree of success with some limitations (such as structure and integrity of CNT be damaged). It is well know that most CNT for commercial composite applications are obtained by chemical vapor deposition (CVD), which can produce CNT at low cost and large scale. Consequently, a few research groups [13–15] have developed a strategy based on the direct synthesis of CNT on aluminum (Al) particles by in situ CVD. Though this process exhibits obvious advantages of CNT dispersion and interfacial bonding strength, it requires Al particles to immerse into NaOH aqueous solution, which hydrolyzes Al and then adversely affects the property of composites. On the other hand, some researches [12,16,17] found that it may be much easier to disperse CNT with the help of SiCp as a mixing medium "vehicle". Meanwhile, through in-situ grafting of CNT on the surface of micrometric substrates, the obtained nano/micro hybrid structures have been reported to possess certain advantages in achieving more controllable CNT dispersion in the polymer matrix composites [18–20]. However, no systematic work has been reported on the subject of implementing a nano/micro hybrid structures in MMCs yet.

The present work reports a novel CNT-covered micro-sized SiCp hybrid reinforced Al matrix composites fabricated by conventional powder metallurgy (PM). In-situ CVD is utilized for combining nano-sized CNT with micro-sized SiCp to form the nano/micro-sized hybrid reinforcements-SiCp(CNT), in which the CNT is uniformly dispersed and strongly bonded with the SiCp. As a result, the new composite from the hybrid reinforcements may have the following advantages: first, the CNT can be much more homogeneously dispersed in the Al matrix by conventional PM with the help of micro-sized SiCp as a "vehicles"; second, both CNT and SiCp have excellent mechanical properties, and their hybrid reinforcement can play a superior enhancing effect for the fabricated SiCp(CNT)/Al hybrid composites.

* Corresponding author.
E-mail address: oyqb@sjtu.edu.cn (Q. Ouyang).

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2. Experimental

2.1. Synthesis of SiCp(CNT) hybrid reinforcements

Ni $(NO_3)_2 \cdot 6H_2O$ and SiCp (5.5 μm) were mixed in distilled water with a weight ratio of Ni/Al=5:95. NaOH solution was added to the mixture dropwise under magnetic stirring to obtain binary colloid ($Ni(OH)_2$/SiCp). The colloid was filtered, dried and finally calcined in air at 350 °C for 4 h to form fine NiO-covered SiCp. Then, the as-obtained particles were reduced by H_2 at 400 °C for 2 h to form catalyst particle Ni-covered SiCp (defined as SiCp (Ni)) in a horizontal quartz tube reactor. Subsequently, CNT was synthesized at 700 °C by introducing a mixture of CH_4/H_2/Ar into the reactor. Finally, the system was cooled down to room temperature (RT) under Ar, and SiCp(CNT) hybrid reinforcements were obtained. The content of CNT was calculated as follows:

$$CNT(wt\%) = (A-B)/A \times 100\% \quad (1)$$

A is the weight of the as-synthesized hybrid reinforcements obtained by CVD and *B* is the weight of the SiCp(Ni) catalyst. According to Eq. (1), a CNT yield of 6 wt% was obtained in the SiCp (CNT) hybrid reinforcements with the reaction time of 30 min at 700 °C.

2.2. Fabrication of SiCp(CNT)/Al hybrid composites

At first, The SiCp(CNT) hybrid reinforcements (synthesized time of 30 min at 700 °C) with pure Al particles(10 μm) were mixed by blending in a jar mill at 200 rpm for 1 h with zirconia balls. The weight ratio of SiCp(CNT) and Al was adjusted to 17:83 to acquire SiCp(CNT)/Al composite powder with the contents of 1 wt% CNT and 16 wt% SiCp. Subsequently, the obtained composite powders were consolidated in a steel mold with 38 mm in diameter and vacuum hot pressed at 580 °C for 0.5 h under a pressure of 400 MPa. Finally, SiCp(CNT)/Al composites were obtained through extrusion with an extrusion ratio of 22:1 at temperature of 400 °C. For comparison purpose, the ex-situ CNT (1 wt%) and SiCp (14 wt%) reinforced Al matrix composite (defined as SiCp/CNT/Al hereafter) and Al bulk material were also prepared under the same processing condition.

2.3. Characterization

Three tensile specimens with 5 mm in diameter and 25 mm in length were machined from each material, and the tensile specimens were parallel to extrusion direction. Tensile tests were carried out on a Shimadzu Autograph AG-I (100 KN) at a constant strain rate of $3 \times 10^{-4}\ s^{-1}$ at RT. The Young's modulus was determined from the tensile stress–strain relations. The microstructure of the Al and the as-fabricated composites was characterized by Field Emission Scanning Electron Microscopy (FE-SEM, LEO Supra 55) and High-Resolution Transmission Electron Microscopy (HRTEM, JEOL 2010F). The phase in the composite was analyzed by X-ray diffraction (XRD, Rigaku and CN2301) with a Cu Ka radiation source. The density of the extruded composites was measured by Archimedes method in which deionized water was used as the immersion medium.

3. Results and discussion

As shown in the Fig. 1a, the shape of SiCp is angular and faceted with ridges on its surface, which are favorable to the retention of catalyst particles at the inter-ridge spacing. The distribution of Ni

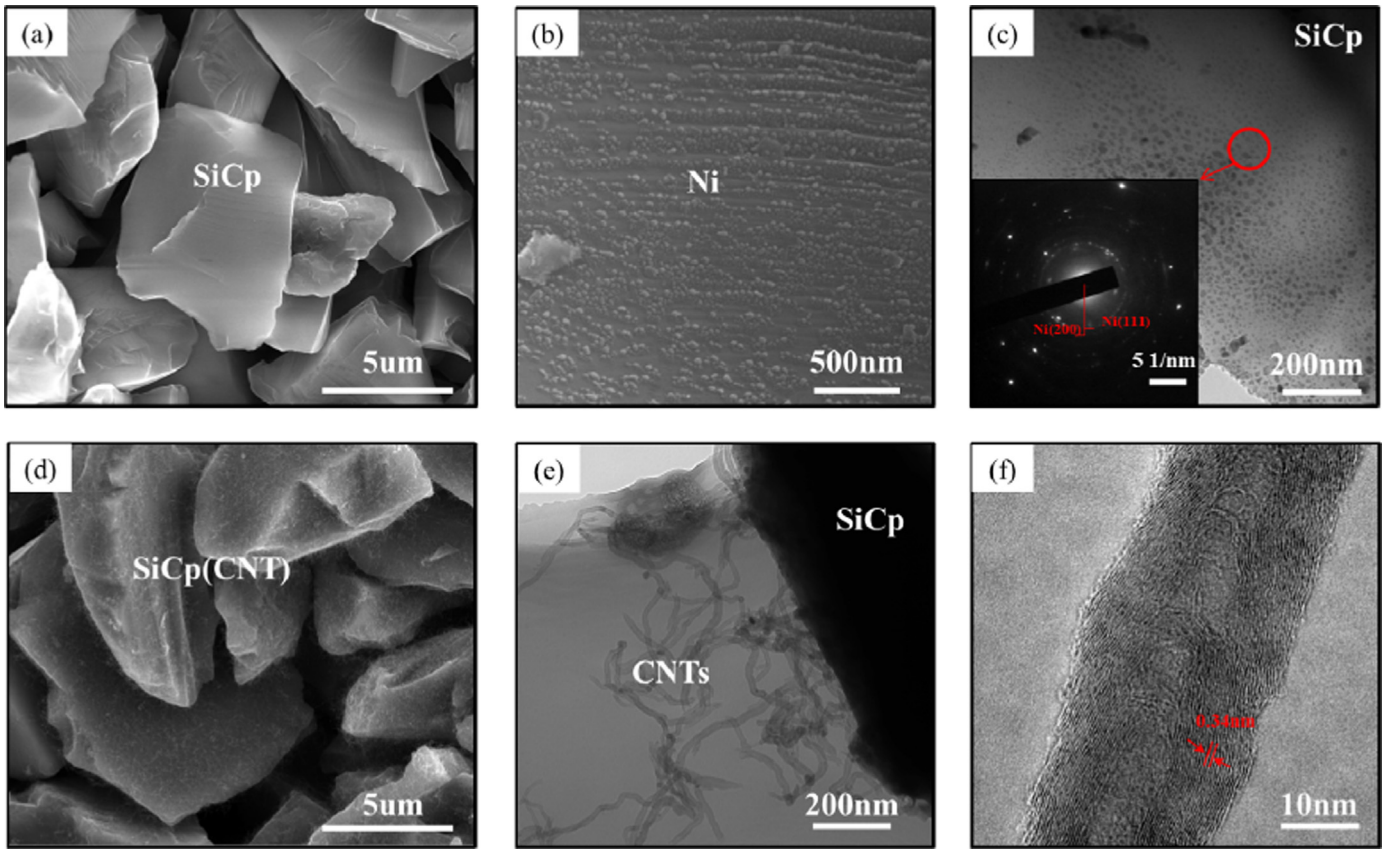

Fig. 1. (a) SEM image of raw SiCp; (b) SEM morphology of Ni catalytic particles; (c) TEM image of SiCp(Ni) particle. The inset shows selection electron diffraction of Ni catalytic particle; (d) SEM image of SiCp(CNT) composite particles; (e) TEM image of SiCp(CNT) composite powders; (f) HRTEM image of a typical CNT.