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Tensile Strength and Electrical Conductivity of Carbon Nanotube Reinforced Aluminum Matrix Composites Fabricated by Powder Metallurgy Combined with Friction Stir Processing

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A route combining powder metallurgy and subsequent friction stir processing was utilized to fabricate carbon nanotube (CNT) reinforced Al (CNT/Al) and 6061Al (CNT/6061Al) composites. Microstructural observations indicated that CNTs were uniformly dispersed in the matrix in both CNT/Al and CNT/6061Al composites. Mg and Si elements tended to segregate at CNT–Al interfaces in the CNT/6061Al composite during artificial aging treatment. The tensile properties of both the Al and 6061Al were increased by CNT incorporation. The electrical conductivity of CNT/Al was decreased by CNT addition, while CNT/6061Al exhibited an increase in electrical conductivity due to the Mg and Si segregation.

KEY WORDS: Carbon nanotubes; Metal matrix composites; Mechanical properties; Electrical properties; Friction stir processing

1. Introduction

Carbon nanotubes (CNTs) have attracted many attentions due to their special atomic structure and fascinating mechanical properties (elastic modulus ∼1 TPa and strength ∼30 GPa[1–3]) as well as excellent thermal properties and good electrical properties[4,5]. Most previous research efforts on the CNT reinforced metal matrix (CNT/metal) composites have focused on the fabrication route and the mechanical properties of the composites for solving the problems of CNT clustering problems[6]. CNT clusters are easily induced as a result of their large aspect ratio and the strong Van der Waals force. The entangled and bundled CNTs would reduce either mechanical or physical properties of the CNT/metal composites[7].

Many fabrication methods, such as casting[8], spraying[9,10], and powder metallurgy (PM), have been tried to disperse CNTs into the metal matrix. In the past few years, many fabrication routes based on PM were commonly used to fabricate the CNT/metal composites because it is easier to incorporate the CNTs into the metal matrix by PM.

Among the routes based on the PM technique, high energy ball milling[11–14], molecular level mixing[15,16], friction stir processing (FSP)[17–22] and flaky powder metallurgy techniques[23,24] are the most promising methods that could well disperse the CNTs into the metal matrix. As a result, great increases in tensile properties were reported for the CNT/metal composites. Choi et al.[25] achieved a great strength increase in CNT/Al composites by means of high energy ball milling technique. Jiang et al.[26] obtained well dispersed CNTs in Al matrix in flaky powder metallurgy route, which increased the strength of the composites.

Compared with the above mentioned PM fabrication routes, the FSP incorporated little contamination during the composite fabrication and had the advantages to obtain the composites with higher tensile strength as well as better physical properties. In our previous investigations[17,19], CNTs were successfully dispersed into Al–Cu–Mg matrix by multi-pass FSP. During FSP, the rotating threaded pin results in severe plastic deformation and material mixing, thereby uniformly distributing the CNTs into the metal matrix.

Although great increases in the tensile properties have been achieved for the CNT/metal composites, the electrical properties of the CNT/metal composites have been rarely reported due to the poor wetting behavior or weak interfacial bonding between CNTs and metal matrix, and inhomogeneous distribution of

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CNTs in the composites. The observation by Feng et al.[27] for CNT/Ag composites showed an increase in the electrical resistivity compared with Ag matrix. Xu et al.[28] reported an increase in electrical resistivity by 66% in a 12.5 vol.% CNT/Al composite. It should be pointed out that CNT clustering or porosity problems were not completely solved in these composites. Therefore, electrical properties of these CNT/metal composites are highly questionable.

On the other hand, Uddin et al.[29] found that the electrical conductivity of bronze was increased by 0.1 wt% CNT incorporation. For the sintered CNT/bronze composite, many micro-pores were dispersed in the bronze matrix, and the CNTs could fill the micro-pores and connecting the bronze matrix. Thus the electrical conductivity of the composite could be increased. However, micro-pores could result in stress concentration and reduce the strength of the CNT/metal composites. As a result, the observed increase of electrical conductivity in the sintered CNT/bronze composite is not suitable for other CNT/metal composites.

In this study, the CNTs reinforced Al and 6061Al composites were successfully prepared by common powder metallurgy and subsequent multi-pass FSP. The CNT distribution, tensile properties and electrical conductivity of the composites were examined. The aims of this study are (a) to obtain composites with increased tensile strength and good electrical conductivity and (b) to explain the variation of tensile strength and electrical conductivity with the CNT incorporation.

2. Experimental

2.1. Raw materials and composite fabrication

As-received CNTs (Fig. 1) with an outer diameter of 10–20 nm and a length of several microns (∼5 μm) were mixed with pure Al (99.8% purity) or 6061Al (Al–1.2 wt% Mg–0.6 wt% Si) powders, with an average diameter of 10 μm, in a bi-axis rotary mixer at 60 r/min for 8 h with a 1:1 ball to powder ratio. The volume fractions of CNTs in the mixed powders of CNT/Al and CNT/6061Al composites were both 1.5%. The as-mixed powders were cold-compacted in a cylinder die, degassed and then vacuum hot-pressed into cylindrical billets, with a diameter of 55 mm and a height of 50 mm, at 853 K for 1 h.

The as-pressed billets were then hot forged at 723 K into disc plates with a thickness of about 10 mm. Then the plates were subjected to 3-pass in-situ FSP at a tool rotation rate of 1200 rpm and a travel speed of 100 mm/min, using a tool with a concave shoulder of 20 mm in diameter, a threaded cylindrical pin of 6 mm in diameter and 4.2 mm in length. The CNT/6061Al composite was solution treated at 803 K for 1 h, water quenched and then artificially aged at 433 K for 12 h (T6 treatment). For comparison, unreinforced Al and 6061Al were also fabricated under the same conditions.

2.2. Characterization of the composites

The CNT distribution in the matrix under various fabrication conditions was examined by scanning electron microscopy (SEM, Quanta 600), field emission scanning electron microscopy (Leo Supra 35) and transmission electron microscopy (TEM, Tecnai G2 20). The CNT structure was observed by high resolution TEM (HRTEM), and the element distributions were detected by using an Energy Dispersive Spectrometer (EDS).

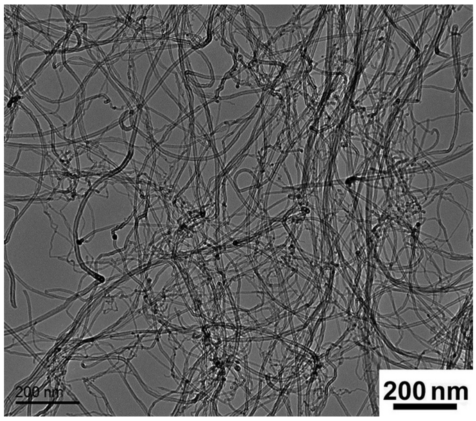

Fig. 1 Morphology of as-received CNTs.

Tensile specimens with a gauge length of 5 mm, a width of 1.5 mm and a thickness of 1 mm were machined from the FSP composites perpendicular to the FSP direction. Tensile tests were conducted at a strain rate of 1×10^{-3} s^{-1} at room temperature using an Instron 5848 microtester. The electrical conductivity of the composite and the matrix samples with a gauge diameter of 4 mm and a gauge length of 50 mm were tested by Voltmeter–ammeter Method.

3. Results and Discussion

3.1. CNT distribution in composites

Fig. 2 shows the CNT distributions in forged and FSP composites. Large CNT clusters with sizes of several micrometers were observed under SEM for either forged CNT/Al or CNT/6061Al composite (Fig. 2(a) and (c)). This is attributed to the fact that the low energy input of the simple mixing technique could not break the large CNT clusters. The clusters in the forged CNT/6061Al composite were much smaller than that in the forged CNT/Al composite, although they were fabricated in a similar mixing processing. This difference could be attributed to the appearance of a small amount of liquid in the CNT/6061Al composite during the stage of hot-pressing. The liquid made the interface bonding between clusters and matrix stronger, as a result the large clusters were more easily fractured into many smaller fragments during forging. After FSP, nearly no CNT clusters could be found under SEM (Fig. 2(b) and (d)), which demonstrated that the CNTs were dispersed into the matrix. The strong mechanical effect during FSP broke down the CNT clusters and dispersed the CNTs into the matrix.

Fig. 3 shows magnified images of CNTs in the forged and FSP CNT/6061Al composites. For the forged composite (Fig. 3(a)), the CNT clusters consisted of a large number of CNTs, and no matrix was observed to be immersed into the clusters. This mainly resulted from the large aspect ratio of the pores in CNT clusters and the poor wetting property between CNTs and Al. Brechet et al.[30] calculated the pressure that could immerse the matrix into pores in clusters, which indicated that larger pressure should be imposed for immersing the matrix alloy into the pores with larger aspect ratio in clusters. For the FSP composite (Fig. 3(b)), the CNTs were uniformly dispersed into the matrix. While some of the CNTs were singly dispersed, part of the CNTs was distributed in the matrix as fine CNT bundles consisting of