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Original

Carbon nanotube-reinforced aluminum composite produced by induction melting

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Abstract

Aluminum/carbon nanotube composite is a promising candidate material for aerospace applications owing to its high strength-to-weight ratio. Because of the low density of carbon nanotubes (CNTs), their dispersion is difficult in molten metal. We investigated induction melting, a fairly distinct approach to facilitate the dispersion of CNTs in molten aluminum. The nanocomposites were characterized using scanning electron microscopy, X-ray diffraction, transmission electron microscopy and mechanical testing. Refinement in crystallite size (∼320 nm) and increase in lattice strain (∼3.24×10^{-3}) were observed in the composites. A simultaneous increase in yield strength (∼77%), tensile strength (∼52%), ductility (∼44%) and hardness (∼45%) was observed. Induction melting appeared to be a potential method to fabricate aluminum–CNTs composites.

Keywords: Metal-matrix composites (MMCs); Induction melting; Crystallite size, Lattice strain; Mechanical properties; Fractography

1. Introduction

Liquid phase processing, or melt-cast, is an economical method to produce intricate shapes at the industrial scale. For metal matrix–carbon nanotube (MM–CNTs) nanocomposite fabrication, there are two major limitations: high melting temperature of matrix metal which may damage CNTs, and segregation of CNTs due to the surface tension forces of molten metal. In this regard, aluminum is a promising matrix material having low melting point and ease of subsequent processing; however, high surface tension forces of molten aluminum (i.e., 860 mN/m) remained a problem for the uniform dispersion of CNTs (Dujardin, Ebbesen, Hiura, & Tanigaki, 1994). To overcome segregation of CNTs in aluminum melt, some additional steps or processes (e.g., coating of CNTs and stirring) would be required. Liquid phase processes, nevertheless, suffer poor incorporation and distribution of the particles/reinforcements in the matrix. These problems become especially significant because of the extremely small size of CNTs, which causes acute agglomeration tendency and reduced wettability with the melt. To improve the dispersion and wettability of CNTs in molten aluminum, researchers have coated CNTs with different types of materials, e.g., Ni (Cho, Lim, Choe, & Lee, 2010), Cu (Chen, Wu, Lin, & Tan, 1999), Al (So et al., 2011), and SiC (So et al., 2013). The coated CNTs are then used as precursors for the incorporation in molten aluminum. In a similar work, Ko et al. (2013) first produced the powder precursor by mechanical milling of Al powder and CNTs. Then, nickel was electroplated on the milled powder, which increased its wetting with molten aluminum during the subsequent process. They have investigated 10 and 20 wt.% of multi wall carbon nanotubes (MWCNTs). The resultant cast aluminum–carbon nanotube (CNT/Al) nanocomposite exhibited good wetting of CNTs with matrix, although some segregation was also observed.

A further improvement in the dispersion of CNTs in the molten matrix occurred by the emergence of the mechanical stirring of the melt (Abbasipour, Niroumand, & Vaghefi, 2010; Li, Viereckl, Rottmair, & Singer, 2009; Zeng et al., 2010). Recently, Rashad, Awadallah, and Wifi (2013) used a novel approach, in which they first ball-milled aluminum powder and CNTs. Then, green billets of the milled powder were prepared and incorporated in molten aluminum during mechanical stirring. A good

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dispersion and interfacial bonding was achieved which resulted in increased mechanical strength (∼35%).

Abbasipour et al. (2010) fabricated CNT/Al nanocomposite of A356 cast aluminum alloy using compocasting technique, which is basically a stir casting method but it allows casting the composite in semi-molten state. They reduced the segregation of CNTs by first coating CNTs by electroless nickel plating and then injected the coated CNTs by the injector. Subsequently, it was cast in semi-liquidus forms. They reported increased hardness along with good nanotube dispersion in the matrix.

Similarly, Hamed et al. (Elshalakany, Osman, Khattab, Azzam, & Zaki, 2014) reported on the fabrication of CNT/Al nanocomposite by a combination of rheocasting and squeeze casting. They used a hypoeutectic aluminum–silicon alloy as matrix material. Their method caused de-bundling and dispersion of CNTs; additionally, they observed refinement of grain size and increased mechanical properties.

The above-mentioned methods used different types of mechanical forces to disperse the nanotubes in the matrix, which though helped the dispersion but also induced certain level of degradation or defects in the nanotubes, which made them less contributing to the strengthening of the matrix. We are reporting on the fabrication of CNT/Al nanocomposite using induction melting. In the present work, the innate stirring action of induction melting was used to disperse CNTs in molten aluminum, hence reducing the degradation of the nanotubes during the dispersion process. Previously, Wilson, Barrera, and Bayazitoglu (2010) used the induction technique to melt the pre-mixed and mechanically-dispersed powders of CNTs and titanium. They have benefited rapid heating rate of induction technique to avoid thermal degradation of the nanotubes; otherwise, slow heating for the melting of titanium (melting point of titanium is 1677 °C) would cause thermal damage to the nanotubes. However, the technique has not been so far reported to disperse the nanotubes in the metal matrix during the fabrication of MM–CNT nanocomposites, to the best of our information.

1.1. Hypothesis and approach

In the previous discussion it has been mentioned that many researchers have tried various melt-cast routes to fabricate CNT/Al nanocomposites; nonetheless, their efforts have been mainly limited to mechanical stirring. In the present study, we have worked on the hypothesis of using induction melting to utilize the associated electromagnetic stirring action for the dispersion of nanotubes in molten aluminum. The rapid heating rate of induction heating will also help to avoid degradation of the nanotubes, which in turn increases the contribution of the nanotubes toward strengthening of the composite.

A major hindrance in using induction melting for aluminum is its reduced thermal efficiency due to high electrical and thermal conductivity of aluminum. In usual practice, graphite susceptors are used to increase thermal efficiency of the process; however, it limits the stirring action of the induction melting. Therefore, we designed a specific induction coil which, can render enough thermal efficiency along with stirring to melt aluminum and disperse CNTs.

Table 1
Results of the coil design analyses.

Geometrical analysis	
Height of molten metal	5.5 cm
Diameter of molten metal	3.0 cm
Volume of the molten melt	38.9 cm^3
Internal diameter of the induction coil	45.0 cm
Height of the inductor coil	6.0 cm
Thermal analysis	
Energy to melt aluminum	69,850 J
Energy to superheat molten aluminum	32,042 J
Energy to melt slag	144 J
Total heat energy required	102,036 J
Electromagnetic analysis	
Maximum magnetic flux density	0.00409 T
Current density through the coil	5.67 A mm^{-2}
Number of turns of the coil	4.47 turns

For the previously mentioned purpose, a coil was designed on the bases of the geometrical analysis, the thermal analysis and the electromagnetic analysis (Kennedy, 2013; Vaughan & Williamson, 1945). The results of these analyses for the present work are given in Table 1. Using these design parameters, the heating efficiency of the coil and stirring force in the melt were calculated according to the simulation work of Julio et al. (Walter & Ceglia, 2011) using finite element method magnetic software (FEMM 4.2). The coil design considerations, relevant simulation and efficiency factors are discussed in detail elsewhere (Mansoor & Shahid, 2014). Figure 1 represents the distribution of the magnetic fields in two types of induction melting approaches. In Figure 1a, magnetic field lines are plotted without any susceptor material, while in Figure 1b, a graphite susceptor is placed between the coil and the crucible. It could be seen that the presence of the susceptor has limited the magnetic field lines. The calculations showed that a heating efficiency >60% and stirring force <3 mN was achievable at the used parameters of the induction generator (i.e., frequency of 10 kHz and current of 100 A). Therefore, the designed coil was used for the subsequent experimental work.

2. Experimental

The multiwalled carbon nanotubes (MWCNTs) used for the present work were synthesized using chemical vapor deposition. The detailed synthesis of MWCNTs is discussed elsewhere (Mansoor & Shahid, 2014). The nanotubes had 10 nm outer diameter and 1.5 μm ca. length. High purity aluminum (AA1199) was used for the matrix material in wire (diameter: 4 mm) form. The aluminum wires were cut into 1 in. staples and treated with 10% solution of sodium hydroxide and washed to remove any kind of oil and excessive oxide layer on the surface. Subsequently, the washed aluminum was preheated for 30 min at 150 °C to eliminate any moisture entrapped on the surface.

The flux used for the melting purpose was a mixture of “recycling and remelting flux” and “cleaning flux” supplied by FOSECO under the trade names of COVERAL-912 and ALUFLUX-3, respectively. The purpose of using multi-flux was