Powder Technology 284 (2015) 32–39

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Short communication

Uniformly dispersion of carbon nanotube in aluminum powders by wet shake-mixing approach

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ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form 26 May 2015
Accepted 13 June 2015
Available online 20 June 2015

Keywords:
Composite materials
Metal matrix composites
Raman spectra
Dispersion
Mixing

ABSTRACT

Since its discovery, carbon nanotube (CNT) was proposed as an ideal reinforcement material for metal matrix composite for its high strength, excellent electrical and thermal conductivity. CNT reinforced aluminum matrix composite has attracted most attention at the beginning of 21st century due to the need for advanced lightweight alloys for aerospace, automotive and defense industries. However, few researchers have successfully incorporated pristine and undamaged CNT into matrix to enhance the properties of the composite. Both traditional and novel powder metallurgical routes have been explored, nevertheless, challenges like the poor distribution of CNT in Al matrix, the agglomeration of CNTs and the damage of essential CNT tubular structure impeded the full translation of CNT potential into various matrix. To achieve a uniform dispersion of CNT without damaging the CNT structure, the authors have applied a novel wet shake-mixing method which combined the advantages of ultrasonication, turbular mixing and ball milling to fabricate an homogenous Al–0.5 wt.% multi-walled carbon nanotube (MWNT) composite. The original structure and morphology of MWNTs and aluminum powders were well preserved even after all the processing procedures in the as-produced powders. This is confirmed by scanning electron microscopy and X-ray diffraction analysis, particle size distribution and the Raman spectra of the as-produced composite powders.

1. Introduction

Composite materials consist of a bulk matrix material and one or more reinforcement phases, combining the desired properties of different constituents, which significantly break the performance limitation of traditional monolithic material systems and remarkably expand the horizon of signal transmission, biomedicine, aerospace and automobile industries [1]. For these industries, aluminum (Al) is the most widely applied metal due to its abundance, low price, good corrosion resistance and, more importantly, low density, which leads to a combination of good specific strength and light-weighted structure for increased fuel efficiency [2]. There is an increasing demand for Al-based systems with higher specific strength and specific modulus properties to cater for the development of modern aircrafts and vehicles that can be operated at higher speed, temperature and longer distance before maintenance [3]. Carbon nanotube (CNT), by its virtue of extraordinary mechanical properties, thermal stabilities and excellent electrical conductivity [3,4] was proposed as a promising reinforcement for aluminum matrix composite for both structural and functional applications. It is reported that multi-walled carbon nanotube (MWNT) possessed the highest specific strength (48,000 kN m/kg) of all materials, exhibiting five times Young's modulus (~1 TP) and up to one hundred times tensile strength (~150 GPa) than the best known steel of the same weight [5]. Also, the superb electrical conductivity [6] of carrying an electric current density of 4×10^9 A/cm^2, which is 1000 times greater than that of copper, makes CNT an ideal material for electrical and signal transmission. Moreover, the excellent chemical [7] and thermal stability (stable up to 2527 K in vacuum) of CNT contribute to its prospect application in extreme conditions.

Thus, a number of researchers [8–14] had tried to develop various methods of incorporating CNTs into Al matrix to increase specific strength, stiffness, thermal and electrical conductivities [15]. Liao and Tan [16] attempted low energy ball milling to disperse 0.5 wt.% CNT in Al matrix. After continuously milling the mixture for 4 h at a speed of 200 rpm (agate ball to powder weight ratio 5:1), micro CNT clusters can still be found among the Al powders. These CNT aggregates are resulted from the strong van der Waals force along the long and thin tube in which the length-to-diameter ratio of CNT is up to 1.32×10^8:1 [17]. Obviously, in order to achieve the full potential of reinforcements, CNTs need to be uniformly distributed in Al matrix. Otherwise, the existence of agglomerates will lead to lower density and more voids in the bulk materials and finally deteriorate the overall properties as the wetting angle between CNT and aluminum is very big that CNT agglomerates would impede the diffusion between aluminum particles and leave more pores in the bulk composite and thus decrease

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http://dx.doi.org/10.1016/j.powtec.2015.06.039
0032-5910/

the density. Liu and colleagues [18] utilized high energy ball milling to blend Al–0.5 wt.% CNT at a speed of 300 rpm (ball to powder weight ratio 8:1) for 8–12 h. They did not observe any CNT bundles in the matrix but the existing visible individual CNT was seriously shortened or damaged. It is clear that the seamless cylinder shape of CNT is vital for keeping its exceptional properties. No doubt that losing the structure means losing its strength and stability. Furthermore, the morphology of Al particle plays an important role in the dispersion of CNT and densification process. For example, the anchoring of CNT on to Al metal powder requires a particle morphology with a large surface area according to Jiang's research [19]. Whereas coarse and irregular shape particles have poor compaction and sintering ability which subsequently result in severe porosity, low density and weak bonding.

Apparently, it is critical to obtain a homogeneous mixture of CNT and Al with the structure of individual constituents intact before the production of bulk CNT reinforced Al composite for functional and structural applications [20]. Although high energy mechanical alloying is an effective way to disperse CNT in the metallic matrix, the damage of CNT after processing limits the overall properties of composite to a certain level. Hence, in the current work, a novel approach has been explored to fabricate an Al–0.5 wt.% MWNT composite that can preserve the CNT and Al particles in their original state, which is significantly beneficial to the subsequent powder compaction, consolidation and overall properties of the composite. Scanning electron microscopy (SEM), X-ray diffraction (XRD), particle size analysis and Raman spectroscopy were utilized to track the micro-structural evolution of CNT and Al constituents and validate the uniform distribution and structural retention of CNT in the as-produced composite.

2. Experimental

2.1. Materials

An argon gas atomized, spherical shape aluminum powder, with a size range of up to 10 μm produced by the Aluminum Powder Company Ltd, Alpoco was selected as the matrix constituent in order to increase the surface area to attach more MWNT in the aluminum matrix. Multi-walled carbon nanotube (MWNT), 140 ± 30 nm in diameter and 7 ± 2 μm in length synthesized by chemical vapor deposition (CVD) method, was purchased from Materials and Electrochemical Research Corporation (M.E.R. Corporation) as the reinforcements in the composite.

2.2. Material processing

It is critical to employ an appropriate mixing technique to obtain homogeneous dispersion of reinforcements in the composite. In the current work, the authors combined ultra-sonication, magnetic stirring and shake-mixing to manufacture an Al–0.5 wt.% MWNT composite, in which MWNTs are evenly distributed in the aluminum matrix. The detailed fabrication procedures are depicted in Fig. 1. Firstly, 0.5 g of MWNT was added into 150 mL of ethanol in a 1 L glass beaker, which was then put into an ultrasonic bath (James Products Limited, model: Sonic 4500). The solution was sonicated for 4 h by a Colour Direct ultrasonic machine (model: CD-M06 031) to separate pristine CNT bundles into individual tubes by high frequency agitation (power: 180 W, frequency: 42,000 Hz). Meanwhile, 0.5 g of polyvinyl butyral (PVB) was dissolved in 150 mL of ethanol and then 99.5 g of Al powders was added into the as-produced transparent PVB-ethanol slurry. After magnetic stirred the Al–PVB–ethanol mixture for 2 h at a speed of 400 rpm, ideally the surface of Al particles was evenly covered by a thin layer of PVB molecules, which reduced the surface tension of Al and help to absorb MWNT on Al particles [22].

Afterwards, the as-prepared 150 mL PVB coated Al–ethanol suspension was poured into the 150 mL MWNT–ethanol solution for further magnetic stirring for another 4 h at a speed of 500 rpm to homogenously disperse MWNTs in the Al matrix. In case of any MWNTs agglomerating together in the stirring process, the as-produced Al–0.5 wt.% MWNT slurry mixture together with 15 of stainless steel ball bearings (diameter: 10 mm, ball to powder ratio: 3:5) was transferred into a plastic bottle. A TURBULA Shake-Mixer (Model: T2F) was used to mix this mixture for 10 min at a speed of 101 rpm. As the shake-mixing is more powerful than simple magnetic stirring but less violent than high energy ball milling, it promotes the uniformity of the composite mixture while keeping the MWNT and Al particles in the original state. Eventually, the as-blended slurry mixture was dried at 140 °C for 12 h and shake-mixed for another 10 min to break down the powder lumps into uniform composite powders. Subsequently, the MWNT/Al composite powders were compacted into cylinders at 475 MPa and were sintered at 630 °C for 1 h in argon atmosphere.

2.3. Material characterization

A Philips XL-30 and a JEOL 7000 field emission scanning electron microscope (FESEM) were employed to track the size, shape and morphology of Al and MWNT during the processing as well as the distribution of MWNT in Al composite. X-ray diffractometer (Inel EQUINOX 3000) and Raman spectroscopy (Renishaw inVia confocal Raman microscope) were employed to characterize the crystal structure and bonding nature of the constituents respectively. The particle size distribution of MWNT reinforced Al matrix was assessed HELOS/KR-VIBRI/L particle size analyzer.

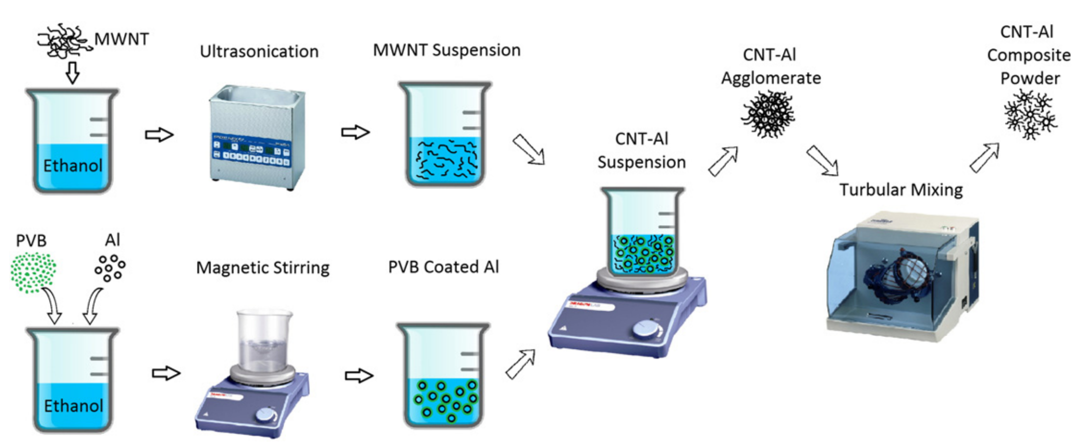

Fig. 1. Schematic illustration of the processing procedures for MWNT/Al composites.