Progress in Materials Science 90 (2017) 276–324

Contents lists available at ScienceDirect

Progress in Materials Science

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

Physicomechanical properties of spark plasma sintered carbon nanotube-reinforced metal matrix nanocomposites

Abolfazl Azarniya [a,*], Amir Azarniya [a], Saeed Sovizi [a], Hamid Reza Madaah Hosseini [a,*], Temel Varol [b], Akira Kawasaki [c], Seeram Ramakrishna [d]

[a] Materials Science and Engineering Department, Sharif University of Technology, P.O. Box 11155-9466, Azadi Avenue, Tehran, Iran
[b] Department of Metallurgical and Materials Engineering, Engineering Faculty, Karadeniz Technical University, Trabzon, Turkey
[c] Department of Materials Processing, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan
[d] Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore

ARTICLE INFO

Article history:
Received 16 January 2017
Received in revised form 30 June 2017
Accepted 24 July 2017
Available online 25 July 2017

Keywords:
Spark plasma sintering
Carbon nanotube
Composite
Phase transformation

ABSTRACT

The technological and industrial needs for development of fully dense nanocomposites have led to significant advances in spark plasma sintering (SPS) technique and its enhanced forms. This technique has opened up a new prospect over carbon nanotube (CNT)-metal matrix nanocomposites (MMNCs) with superior physical or mechanical characteristics. To date, a large number of authentic papers have been published over this ongoing field, but have not been comprehensively reviewed. The pertinent research works cover some significant aspects of CNT-MMNCs requiring a concise review on (i) the potential phase transformations of pure CNTs and microstructure evolution; (ii) the novel approaches for uniform dispersion of CNTs inside the metallic matrices including Cu, Al, Ag, Ni, Ti, Mg, and Fe; and (iii) recent improvements in mechanical, thermal, electrical, biological, and tribological properties of CNT-MMNCs. The present review paper strives to scrutinize the aforementioned topics and provide a broad overview of the unsolved challenges and suggested solutions for them.

Contents

* Corresponding authors.
E-mail addresses: Azarniya_abolfazl@mehr.sharif.edu (A. Azarniya), azarniya_amir@mehr.sharif.edu (A. Azarniya), s.soveyzi@gmail.com (S. Sovizi), madaah@sharif.edu (H.R.M. Hosseini), tvarol@ktu.edu.tr (T. Varol), kawasaki@material.tohoku.ac.jp (A. Kawasaki), seeram@nus.edu.sg (S. Ramakrishna).

http://dx.doi.org/10.1016/j.pmatsci.2017.07.007
0079-6425/

1. Introduction

The ever increasing use of advanced materials within a wide range of the industrial applications places emphasis on a wide research into developing fully dense materials of superior physical or mechanical properties [1]. Nanoparticle-reinforced nanocomposites are believed to exhibit great promise as engineered materials and serve as alternatives to new ones. Nowadays, there exists a variety of advanced nanocomposites fulfilling the feasible needs, but they all bear some common features: (i) They are fabricated by the combination of some nanomaterials intermingling on a nanometer scale; (ii) The additives enhance some physical or mechanical characteristics of the original material if engineered; and (iii) Achieving a broad range of properties is possible due to their dependency on the microstructure and reinforcements size [1–3]. The physicomechanical properties of nanoparticle-reinforced MMNCs are far superior to those of micron and submicron particle-reinforced ones with a similar weight percentage or volume fraction of particles. Many efforts have been made to deeply understand the behavior of smallest building blocks of the nanocomposites. From a simple mechanical point of view, the matrix transfers the applied load to the nanoscale reinforcement via shear and strives to enhance load bearing capacity of the original material [4]. Additionally, there are some nanocomposites exhibiting well-organized levels of hierarchical structure from macroscopic to microscopic length scale. This new generation of nanocomposites gives further impetus to improvement of desired properties and the processing control [4,5].

The overall aim behind the fabrication of MMNCs is to develop a new generation of stiff, tough, super-strong, and lightweight structural materials as well as modification or manipulation of some specific characteristics such as electrical or optical properties in some cases [6,7]. However, some serious challenges to these materials still remain to restrict the properties of these nanocomposites:

(i) to obtain uniform dispersion of nano-reinforcements (bearing a high aspect ratio) and sterling interfacial coherency with no damage to them [8,9].
(ii) low ductility arose from particulate cracking and void formation into the aggregates, and more importantly, significant difference between thermal expansion coefficients of stiff reinforcements and soft matrix; and
(iii) the agglomeration of reinforcements and potential interfacial chemical reactions between the additive and matrix depending on the processing conditions [10].

The aforementioned restrictions limit the effective load-bearing capacity and resultant mechanical properties of the nanocomposites and do not allow the engineers to utilize each arbitrary hard material as reinforcement. To overcome these limitations, a high interfacial strength is required to hinder interfacial cracking and enhance the practical efficiency of particles loading [10–12].

Depending on applicability and functionality, a variety of ceramic reinforcements are used for strengthening MMNCs [13]. Among the most conventional materials used as matrix, Al [10,14,15], Cu [3,16], Co [17], Fe [18,19], Mo [20], Ni [21] and Ti [22–24] are the most important. According to the good electrical and thermal conductivities, Cu matrix has been preferred in the electrical and tribological applications. On the other hand, Al is used in aerospace and automotive industries due to its relatively low density and good workability. Furthermore, some stiff materials including CNTs, Al_2O_3, SiC, TiB_2, TiC, Fe_3O_4 and ZrO_2 are widely utilized as suitable reinforcements in metal matrices in an effort to increase the material's resistance against bearing the applied load [25–27]. The reasons why these materials are selected as reinforcing agents are their distinguished characteristics such as low density, excellent strength, high stiffness, generally good resistance to chemical agents and an appropriate degree of brittleness and hardness [10,28–31]. Among all reinforcements under development, much progress has been achieved in CNTs with the aim to enhance the hardness or mechanical properties of metallic systems. As well, CNT-based nanocomposites have been recently developed in an effort to fabricate advanced materials with enhanced conductivity, electroactivity, and electromagnetic interference shielding [32–34]. Such features originate from the intrinsic nature of CNTs.

Numerous empirical studies have been conducted to estimate the mechanical properties of CNTs, but the obtained results are somewhat contradictory. Further investigations verify that such contradiction is ascribed to the type of experimental method used, i.e. 'direct' or 'indirect' measurements [35]. Whereas direct measurements are referred to as all techniques determining the mechanical properties of individual CNTs, indirect measurements are related to the techniques in which the mechanical properties of CNTs are estimated based on the mechanical properties of CNT-containing metal matrix