Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

Microwave and spark plasma sintering of carbon nanotube and graphene reinforced aluminum matrix composite

Ehsan Ghasali [a,*], *Parvaneh Sangpour* [a], *Alireza Jam* [a], *Hosein Rajaei* [a], *Kamyar Shirvanimoghaddam* [b,*], *Touradj Ebadzadeh* [a]

[a] *Ceramic Department, Materials and Energy Research Center, Alborz, Iran*
[b] *Carbon Nexus, Institute for Frontier Materials, Deakin University, Vic 3216, Australia*

ARTICLE INFO

Article history:
Received 2 December 2017
Accepted 12 February 2018
Available online

Keywords:
Carbon nanotube
Graphene
Microwave
Spark plasma sintering

ABSTRACT

Graphene and carbon nanotube due to their outstanding mechanical performance were used as reinforcement in aluminum (Al) based composite through spark plasma sintering (SPS), microwave (MW) and conventional techniques. The initial compositions of Al-1 wt% CNT, Al-1 wt% GNP and Al-1 wt% CNT–1 wt% GNP were mixed by a high energy ultrasonic device and mixer mill to achieve homogenous dispersion. The SPS, MW and conventional processes were conducted at almost 450, 600 and 700 °C, respectively. The maximum relative density (99.7 ± 0.2% of theoretical density) and bending strength (337 ± 11 MPa) obtained by SPS, while maximum microhardness of 221 ± 11 Vickers achieved by microwave for Al-1 wt % CNT–1 wt% GNP hybrid composite. X-ray diffraction (XRD) examinations identified Al as the only dominant phase accompanied by very low intensity peaks of Al_4C_3. Field emission scanning electron microscopy (FESEM) micrographs demonstrated uniform distribution of GNP as well as CNT reinforcement in spark plasma sintered samples.

1. Introduction

Aluminum matrix composites especially novel AMCs with using nanoscale reinforcement have been developed in many research works as new generation of these light composites in the past decade [1–3]. One of the challenging issues during fabrication of these composites is considered as uniform distribution or avoiding the agglomeration of reinforcement particles in the matrix. The agglomeration was found to increase with decrease in particle size of reinforcement particles [4,5]. Besides, there are lots of parameters that affect the uniform distribution of reinforcement particles such as difference between matrix and reinforcement density, mixing conditions, amount of reinforcement, etc. [6–8]. But, it seems that the original problem in using nano-scaled particles usually appears to be the agglomeration phenomenon [9,10]. The agglomeration of reinforcement leads to weakening of

* *Corresponding authors.*
E-mail addresses: Ehsan_ghasali@yahoo.com (E. Ghasali), kshirvan@deakin.edu.au (K. Shirvanimoghaddam).
https://doi.org/10.1016/j.acme.2018.02.006
1644-9665/

mechanical properties of products with a high volume fraction of porosity between particles [11,12].

CNTs and GNPs have been regarded as the most interesting fillers in metal matrix composite owing to their superior performance in past decade [13–16]. The high surface area nano-carbon materials lead to form clusters during composite processing. The optimization of mixing conditions is necessary to find solutions for reducing the clusters by using nano-carbon materials as a reinforcement and also proper sintering process is needed to avoid the reaction of reinforcement materials with metal matrix especially aluminum [17]. There have been several reports focusing on the formation of interfacial Al_4C_3 carbide by reaction between aluminum and nano-carbon materials during composite processing. The reaction equation of $4Al + 3C \rightarrow Al_4C_3$, is thermodynamically favorable with below zero Gibbs free energy by both casting and powder metallurgy processing routes. The improper effect of Al_4C_3 on mechanical properties of AMCs products, causing structural damage of carbon nanomaterials have been reported [18–20]. On the other hand, it is proposed that the positive effect of Al_4C_3 interfacial product on final mechanical properties of prepared composites is due to improved C/Al interfacial bonding [21–23]. From the above discussion, it can be concluded that the amount of produced interfacial phase effectively changes the final mechanical behaviors [24].

Recently, hybrid composites with using higher than two types of reinforcement have been developed in different aspects of AMCs investigations. These studies revealed that hybrid composite can usually offer better properties than individual reinforcement due to the presence of two kinds of materials with different properties [25–27]. Lots of articles have been performed individually on Al-CNT [28] and Al-GNP [29] composites, while, a few research works can be found on the hybrid Al-CNT-GNP composites. For example, Zan Li et al. [30] investigated the synergetic strengthening effect of GNP-CNT hybrid structure on aluminum matrix composites. They used composite flake assembly process to produce a hybrid composite with higher mechanical properties compared to Al matrix reinforced by CNT and GNP separately.

It is worth mentioning that besides of reinforcement types and mixing conditions, the sintering process in powder metallurgy routs changes the performance of final composite significantly. Spark plasma and microwave sintering techniques with unique advantages could offer special effects on the final properties of product which were investigated by researchers [31–33].

To the best of authors' knowledge, there have been conducted limited works with the focus on using CNT and GNP for enhancing final mechanical and structural performance of AMCs prepared by MW and SPS techniques. A simple mixing condition is suggested to obtain homogeneous dispersion of carbon nanomaterials. Finally, the effect of heating method on the reaction behavior of reinforcements and final products has been studied.

2. Material and methods

MWCNTs (US Research nanomaterials Inc, >95%, OD: 5–15 nm), GNP (XG Scinces, Grade C, average thickness of approximately 2 nanometers, particle diameter of less than 2 μm, average surface areas: 750 m^2/g) and aluminum powder (MERCK-1056, average particle size of 45 μm, 99% purity) were used as starting materials. Three different mixture of Al-1 wt% CNT, Al-1 wt% GNP and Al-1 wt% CNT–1 wt% GNP were ball milled (Spex mixer mill-8000D model) in Ethanol media. At the first stage, CNT and GNP were mixed with Ethanol. Then, Sodium dodecylbenzene sulfonate (SDS) was added to mixture and a high energy ultrasonic was used to enhance dispersion of carbon nanomaterials in ethanol media [34,35]. The next stage was the addition of aluminum powder and alumina balls in a shaker mill for the preparation of above

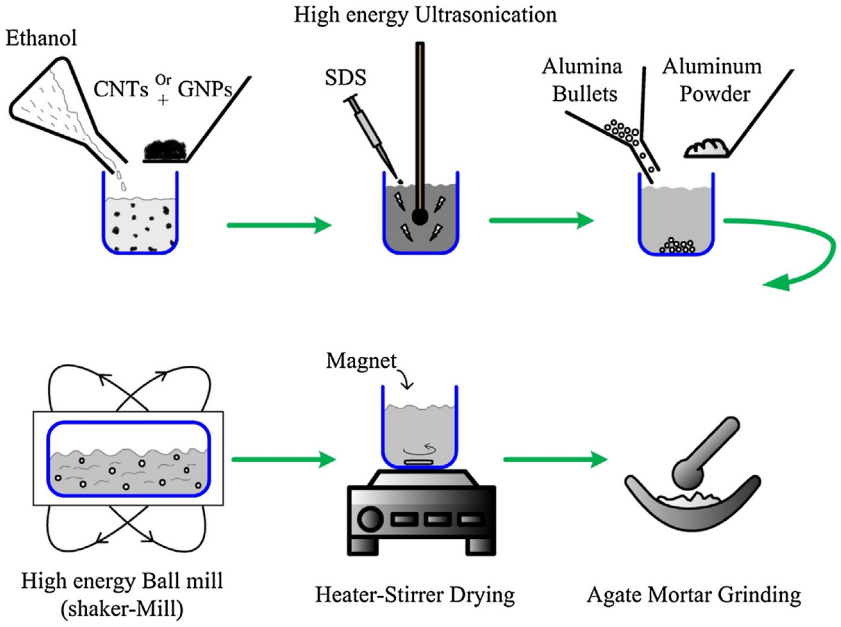

Fig. 1 – Schematic of CNT and GNP mixing process with aluminum powder.