Advanced Powder Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

An investigation on the effect of sintering mode on various properties of copper-graphene metal matrix composite

C. Ayyappadas [a], A. Muthuchamy [a], A. Raja Annamalai [b,]*, Dinesh K. Agrawal [c]

[a] School of Mechanical Engineering, VIT University, Vellore 632 014, Tamil Nadu, India
[b] Centre for Innovative Manufacturing Research, VIT University, Vellore 632 014, Tamil Nadu, India
[c] Materials Research Institute, The Pennsylvania State University, University Park, PA 16802, USA

ARTICLE INFO

Article history:
Received 7 October 2016
Received in revised form 22 February 2017
Accepted 20 April 2017
Available online xxxx

Keywords:
Composites
Powder processing
Electrical properties
Mechanical properties
Microstructure
Optical microscopy

ABSTRACT

The present work investigates the effect of sintering mode and graphene addition on the microstructural, mechanical and electrical properties of copper–graphene metal matrix composites reinforced with varying amounts (0.9, 1.8, 2.7 and 3.6 vol%) of graphene particles fabricated through powder metallurgy route. Sintering was carried out at 900 °C in 95%N_2-5%H_2 (forming gas) atmosphere with a heating rate of 5°/min for conventional and 20 °C/min for microwave with a holding time of 60 min in both cases. All the composites were found to couple well with microwave field and had resulted in 63% reduction in the processing cycle time as compared to the conventional process. Micro-structural analysis revealed the homogeneous distribution of graphene in copper matrix. Copper-graphene composites exhibited excellent wear resistance due to higher hardness and excellent lubricating nature of graphene. It was observed that porosity has a significant effect on the electrical conductivity values.

1. Introduction

Copper metal powder has been widely used in engineering applications because of its high electrical and thermal conductivities combined with excellent corrosion resistance and ease of fabrication [1,2]. Pure copper has wide variety of applications such as electrical contacts in relays, magnetrons in microwaves, electromagnets, vacuum tubes, heat sinks, welding electrodes, semiconductors, microchips, piping systems, automobiles, etc. [3–5]. Copper is not considered as a good material for structural applications due to its poor mechanical properties especially at elevated temperature [6]. Therefore the researchers have been investigating the effect of different ways to improve its mechanical properties. The most effective method is making a Cu based composite by reinforcement addition of a suitable material [7]. Graphene is a 2-D allotrope of carbon and is considered as the strongest material ever tested with a tensile strength of 130 GPa, Young's modulus of 1 TPa and excellent lubricating properties in both dry and humid conditions [8–11]. It is considered an excellent reinforcement material because of its excellent mechanical strength, thermal conductivity (5300 W/mK), electrical conductivity, and large specific surface area (SSA- 500-1200 m^2/g) [12]. The dispersion of graphene in copper matrix is challenging due to the relatively high difference in densities of the matrix and reinforcement phase. The high interfacial contact area of graphene and the mis-match in thermal conductivities result in complex behavior of the resultant composite. An investigation to all these aspects is still in its infancy.

Researchers at the Korean Advanced Institute of Science and Technology recently reported that graphene reinforced composite materials exhibited up to 500 times tensile strength than the raw or monolithic material. Muhammad Rashad et al. investigated the effect of graphene on magnesium based metal matrix nano composites and reported uniform dispersion of multilayer graphene in the matrix that led to enhanced mechanical properties [13]. Varol et al. fabricated multilayer graphene copper nano composites by employing flake powder metallurgy and conventional sintering process. They reported that the composite resulted in reduced density, improved hardness and electrical conductivity due to non-homogeneous distribution of multilayer graphene in the copper matrix [14]. Zhang et al. studied the strengthening effect of graphene nano platelets and reduced graphene oxide in copper matrix through a modified molecular level mixing process and spark plasma sintering process [15]. Kim et al. fabricated Cu and Ni graphene nano layered composites with layer thickness of 70 nm and 100 nm for Cu-Gn and Ni-Gn nano composites respectively. The Cu-Gn and Ni-Gn nano composites exhibited strength of 1.5 and 4 GPa respectively. These values were the highest values

* Corresponding author.
E-mail address: raja.annamalai@vit.ac.in (A. Raja Annamalai).

http://dx.doi.org/10.1016/j.apt.2017.04.013

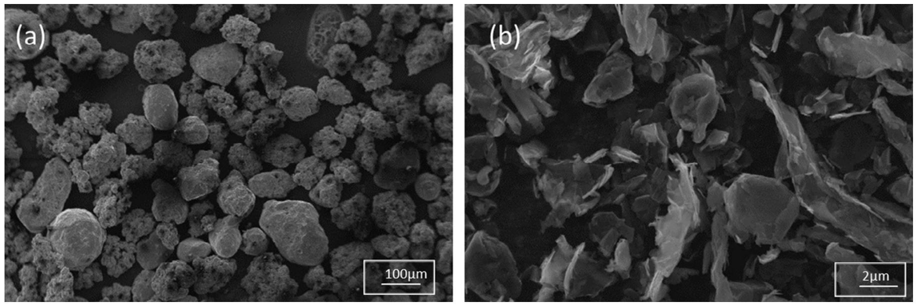

Fig. 1. Scanning electron micrographs of as received (a) copper powder and (b) graphene powder.

Table 1
Powder characteristics of the as received powders.

Characteristics	Copper	Graphene
Apparent density (g/cc)	4.5	0.015
Tap density (g/cm)	5.3	0.12
Flow rate in secs, 50 g	30	Non flowing
Particle size (μm)		
D_{10}	13.82	3.90
D_{50}	30.53	8.84
D_{90}	62.02	17.77
Theoretical density, g/cm^3	8.96	2.2
Surface area, m^2/g	0.246	0.842
Shape	Spherical	Flaky
Purity	>99.5%	99.99%

reported for any MMCs ever fabricated [9]. Literature presented here mainly depicts the improvement in properties of the composites as compared to the monolithic material as a result of graphene addition. The major strengthening mechanisms in Cu-Gn composites are also identified.

Copper graphene composites in general exhibit superior electrical and thermal conductivity with low coefficient of thermal expansion (CTE), good lubricating properties and improved mechanical properties [16–18]. Copper-graphene composites find application in bearing materials, heat spreaders, electro-friction materials and a variety of applications which require low thermal expansion coefficient, high electrical and thermal conductivity with higher hardness values [19]. The challenge to develop graphene based metal matrix composites is to address the agglomeration tendency and poor wettability of graphene and metal matrix [20]. Microwave heating is a rapid sintering technique for the consolidation of various materials. The major advantage of microwave sintering over conventional sintering is that it provides rapid heating resulting into much finer microstructure [21,22]. Material get heated up as a result of the coupling reaction between samples and the electromagnetic wave. In addition to this, the grain boundary diffusion is promoted by the decrease in the activation energy for sintering [23,24]. Microstructural homogeneity is preserved even though the heating rates are high. Though sintering process are many, microwave sintering is projected as environment friendly and energy efficient technique [24–30]. Zheng et al. reported that microwave sintering could result in enhanced densification, smaller grain size due to faster heating rate and lower sintering temperature [31]. Limited numbers of researches are reported on metal based composite materials processed by powder metallurgy route [32–35]. Manoj Gupta et al. synthesized aluminium based composites by employing microwave sintering. It was reported that the process parameters used in powder metallurgy route coupled with microwave sintering which was suitable in producing hybrid composite materials with improved microstructure, good distribution of reinforcement and mechanical characteristics [36]. Adrian Goldstein et al. conducted microwave sintering on ceramic mixtures. Results showed a dense composite with high hardness [27]. Flora Molinari et al. synthesised M type hexaferrite in a single mode microwave cavity and reported that the precursors couple well with microwave mode without any susceptor. The magnetic properties of samples heated in microwave cavity for 30 min were similar to those exhibited by conventionally sintered samples for a time period of 12 h [37]. Yoon et al. made comparisons between microwave and conventional pressure-less sintering. Relative density of microwave sintered samples crossed 99% and phase transformation rate achieved was 100% at a temperature of 1600 °C whereas for conventional pressure less sintering such high density and phase transformation rate could not be achieved even at sintering temperature of 1850 °C [38]. Xu et al. studied the characteristics of microwave melting of copper powder. Changes in microstructure and densification were analyzed. Results showed that copper powder could be quickly heated to melting. Microwave heating efficiency and the heating rate were found to be higher with the decrease in particle size and increase in microwave power. Heating rate had a linear relationship with the reciprocal of the particle size. Microstructure and density indicates that the densification process accelerates when the temperature is above 900 °C. At lower temperature the migration of the matter for copper particles is mainly internal diffusion [28]. Xu studied the effect of kinds and contents of additives on mechanical properties, phase transformation and microstructure behavior of Si_3N_4 ceramic materials processed by microwave sintering [39].

Literature points out that addition of even a small amount of graphene to the monolithic material can improve the properties to a considerable extent [40,41]. In this work composites of copper

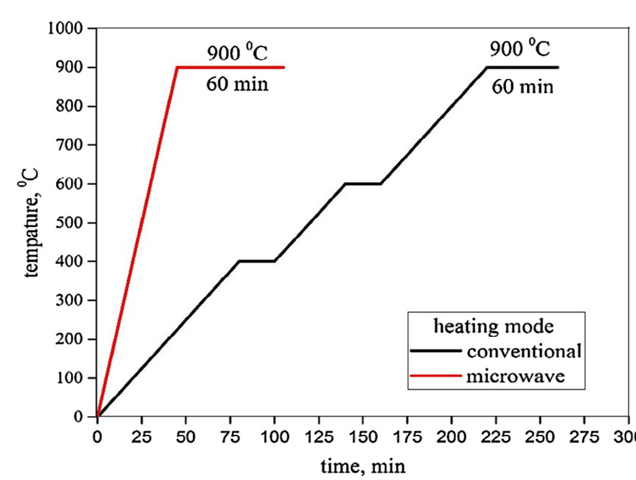

Fig. 2. Comparison of the temperature profile for conventional and microwave sintering modes.

Please cite this article in press as: C. Ayyappadas et al., An investigation on the effect of sintering mode on various properties of copper-graphene metal matrix composite, Advanced Powder Technology (2017), http://dx.doi.org/10.1016/j.apt.2017.04.013