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Parametric optimization of dry sliding wear loss of copper−MWCNT composites

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Abstract: The wear behavior of multi-walled carbon nano-tubes (MWCNTs) reinforced copper metal matrix composites (MMCs) processed through powder metallurgy (PM) route was focused on and further investigated for varying MWCNT quantity via experimental, statistical and artificial neural network (ANN) techniques. Microhardness increases with increment in MWCNT quantity. Wear loss against varying load and sliding distance was analyzed as per L16 orthogonal array using a pin-on-disc tribometer. Process parameter optimization by Taguchi's method revealed that wear loss was affected to a greater extent by the introduction of MWCNT; this wear resistant property of newer composite was further analyzed and confirmed through analysis of variance (ANOVA). MWCNT content (76.48%) is the most influencing factor on wear loss followed by applied load (12.18%) and sliding distance (9.91%). ANN model simulations for varying hidden nodes were tried out and the model yielding lower MAE value with 3-7-1 network topology is identified to be reliable. ANN model predictions with *R* value of 99.5% which highly correlated with the outcomes of ANOVA were successfully employed to investigate individual parameter's effect on wear loss of Cu−MWCNT MMCs.

Key words: copper; multi-walled carbon nano-tube (MWCNT); powder metallurgy; wear; Taguchi method; analysis of variance (ANOVA); artificial neural network

1 Introduction

Metal matrix composites (MMCs), well known for higher values of hardness, strength, specific modulus and thermal stability when compared with their monolithic metals or alloys, have defined a new era in the field of transportation, electronics, aerospace, nuclear and defense industries [1]. In the recent past, wear resistance of these newly developed MMCs has been a major focus of study owing to the fact that wear loss decreases with considerable increase in particle size and volume fraction of the hard ceramic particle reinforcements [2].

Copper (Cu), well known for its thermal, electric and certain mechanical and corrosion resistant properties, has embarked a wide range of application in the field of automotives, marine and electronics packaging. Cu-based alloys known for their thermal conductivity have also positioned themselves in heat sinks as structural material; even then strength being a main concern at elevated temperatures, researchers has been under forced voluntarily to opt for dispersion strengthening thereby achieving high strength under normal conditions [3]. Cu matrix along with dispersions such as silicon carbide and diamond has undergone a wide range of research for thermal and tribological management. Cu-based composites reinforced with SiC showed a poor thermal conductivity while diamond reinforced MMC excited only low machinability [4].

Powder metallurgy (a commonly used process to produce MMCs) processed materials have enough potential for usage in many applications in lieu of attaining certain admirable properties over any other competing methods [5]. Reinforcing nano- and micro-particles on the matrix material such as Al, Mg and Cu improves wear resistance, damping property and mechanical strength. Cu-based bulk metallic glass composites reinforced by titanium carbide exposed an improvement in yield and fracture strength besides delivering 25% improvement in ductility and hardness [6]. Ti-reinforced Cu-based composite material developed by powder metallurgy process has experienced appropriate thermal conductivity and coefficient of thermal expansion of 5.4 W/(m·K) [7]. The homogenous distribution of reinforcements into the metal matrix was supposed to be an important problem

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faced while processing was easily carried out by mechanical alloying. Mechanical alloying of matrix and reinforcement particles has to be carried out for a longer time in order to achieve a uniform, dense mixture of these materials [8]. Mechanical alloying of particles defines that the powders undergo cold welding, fracturing and re-welding continuously within the high energy ball mill so as to attain an alloy or composite of particles with less particle spacing in lieu of the prevailed temperature [9]. Cu-based composite materials produced through powder metallurgy have proved to offer excellent heat conductivity, anti-wear properties and hence broadly used in aircraft, trains, and ship braking systems. Particulate reinforced copper metal matrix composite (Cu-MMC) has established application in electronics field, as a wear and heat resistant material, and for brush, torch nozzle material too [10−14].

In general, carbon nano-tubes (CNTs) have been considered by worldwide researchers as an ideal reinforcement material to improve the performance of many base materials. Because of its exceptional smaller diameter as well as high elastic modulus, tensile strength, and high chemical stability, CNT is exposed as an attractive reinforcement material for lightweight and high-strength metallic matrix composite development. In spite of its applicability in the field of nano science, its superior stiffness and strength at low density had made it to evolve as an ultimate fiber in the development of advanced composite materials [15]. Even though, CNT tends to agglomerate because of van der Waals force which is considered to be the main hitch in employing CNT as reinforcements, it has been used with many metals and ceramics for diverse applications [16]. The researchers carried out many studies regarding thermal, electrical and strengthening mechanisms of CNT in Cu-MMCs; however, the tribological properties of CNT-dispersed Cu-MMCs were scarcely explored.

Taguchi's method, a powerful technique in design of experiments helps to optimize at ease the control factors efficiently by means of systematic approach and likewise for analyzing the effect of various control factors over performance characteristics. Spear headed for the said technocrats, many studies have been carried out in optimizing the wear rate of composites employing Taguchi method. No matter what signifies, analysis of variance (ANOVA), a statistical method working on least square approach was carried out on experimental values and end results soon after Taguchi technique so as to investigate the significance of each parameter upon its performance characteristics [17,18]. Artificial neural network (ANN) evolved from the human brain is now at major focus for wear property modeling. In this technique, both control factors and performance parameters were provided to ANN model comprising of input, hidden and output layers with various nodes. Based on the inputs and outputs, ANN develops a relationship creating a model possessing ability to predict the performance parameter for the given inputs [19,20]. This model can again be used for finding the exact control factors that confers better performance. Studies have stated that these models can even be developed from small data sets to solve problems at a faster pace equal to any other approaches of similitude [21].

The main aim of this study is to prepare and characterize the Cu-based MMCs reinforced with various volume traces of multi-walled carbon nano-tubes (MWCNTs) through powder metallurgy technique. Besides evaluating density, SEM microstructure and hardness, wear performance of the developed composite specimens were statistically studied in detail using Taguchi and ANOVA techniques. The attained results were then trained using neural network tool box in order to develop a potential ANN model to predict the wear loss of Cu-MWCNT MMCs.

2 Experimental

2.1 Materials

Copper, the primary material with 99% purity commonly known as electrolytic copper, was purchased as such. The copper matrix material with powder mean size of 35−40 μm was considered for this study. MWCNTs with mean size of 20−40 nm were employed as reinforcement in this research for the want of dispersion strengthening. Details of the powders utilized in this study for powder compaction process are provided in Table 1.

Table 1 Properties of powders

Powder	Mean size/μm	Purity/%	Density/(g·cm^{-3})
Cu	35−40	99	8.96
MWCNTs	20−40	99.5	0.37

2.2 Composite preparation and testing

Powder metallurgy process was considered for developing Cu-MMCs reinforced with multi-walled CNTs synthesized through chemical vapour deposition technique. Primarily, the powders (as-received conditions) were weighed in agreement to different compositions as pure copper, copper with 1%, 2% and 3% MWCNTs (volume fraction). The weighed proportion was then blended utilizing a planetary ball mill for total 6 h with an intermission of 30 min for every 1 h to improve the dispersion of MWCNT into the matrix. SEM images of 0, 1%, and 3% MWCNT (volume fraction) were taken after blending of powders and are shown in Fig. 1. These images bring in a clear view for the dispersion of