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PROCESSING AND MECHANICAL EVALUATION OF ALUMINIUM COMPOSITES REINFORCED WITH CARBON NANOTUBES

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ABSTRACT

This work consists on the development of Aluminium Silicon Composites reinforced with carbon nanotubes.

The composites were obtained with powder metallurgy processes.

Was studied the influence of different volume fraction of carbon nanotubes in metallurgical and mechanical properties.

Metallurgical evaluation was made by means of SEM/EDS for interface reaction between matrix and reinforcement and reinforcement distribution in matrix.

Mechanical evaluation was made by tensile tests and fatigue tests.

The materials were processed through conventional Hot Pressing Powder Metallurgy techniques.

Keywords: Aluminum composites, metal matrix composites, carbon nanotubes.

Introduction

The discovery of carbon nanotubes (CNTs) opened new perspectives for the development of composite materials. CNTs have recently emerged as materials with exceptional properties exceeding those of any conventional material (Esawi et al., 2007). The need to enhance the mechanical properties of aluminum alloys has motivated the study of new materials and innovative processing routes. Aluminum-based metal matrix composites (MMCs) are of great interest because of their low density and high specific stiffness. These materials can be produced by dispersing oxides, carbides or nitrides into the metallic matrix. Recently, however, single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT) are raising a great interest in the scientific community as a new kind of reinforcement material for the production of novel MMCs because of their excellent mechanical properties (Pérez et al., 2008).

With outstanding mechanical properties, extraordinarily low thermal expansion, and high thermal conductivity, CNTs are an attractive reinforcing agent to components subjected to high temperatures like piston rings on motors (Tang et al., 2004). Theoretical calculations and experimental measurements of carbon nanotubes have also shown that these materials have excellent mechanical properties, such as elastic modulus as high as 1 TPa and strengths 10 to 100 times higher than the strongest steel at a fraction of the weight (Feng et al., 2005). Not surprisingly, carbon nanotubes have emerged as new reinforcements for a number of material systems including polymeric (Thostenson et al.,2001; Thostenson et al.,2005), metal [(Lim et al.,2005; George et al.,2005; Esawi et al.,2007; Deng et al.,2007; Zhong et al.,2003; Morsi et al.,2007; Kuzumaki et al.,2000; Carreno, 2006; Dong et al.,2001; Tu et al.,2001; Kim et al.,2006; Li et al.,2009; Carreno et al.,2003; Peigney et al.,2000) and ceramic matrices Darsono et al.,2008. The introduction of carbon nanotubes in the matrix metal, mainly aluminum, begins to be common in many research works (Lim et al.,2005; George et al.,2005; Esawi et al.,2007; Deng et al.,2007; Zhong et al.,2003; Morsi et al.,2007). There are also other metals such as titanium (Kuzumaki et al.,2000), copper (Carreno, 2006; Dong et al.,2001; Tu et al.,2001; Kim et al.,2006; Li et al.,2009) and magnesium (Carreno et al.,2003) where they are used.

One of the biggest problems in the field of carbon nanotube reinforced-metal matrix composites is the difficulty in disaggregate nanotubes due to their attractive van der Waals interactions (Pérez et al., 2008). Thus, to achieve a uniform dispersion of carbon nanotubes in a metal matrix is quite difficult; the interfacial reaction between carbon nanotubes and metal matrix may be rather serious resulting in the deterioration of composite properties, and a suitable fabrication technique is also very difficult. Further, as metal powder size is much larger than that of carbon nanotubes, it is difficult to achieve homogeneous distribution of carbon nanotubes in the composites (Deng et al.,2007).

To solve this problem many techniques are appearing. Mechanical alloying is the technique most used in powder metallurgy. The most referred to in literature is the ball milling technique (Esawi et al., 2007; Pérez et al., 2008; George et al.,2005; Deng et al.,2007; Carreno-Morelli, 2006; Darsono et al.,2008; Tao et al.,2004; Esawia et al.,2009; Deng et al.,2007). Metal powders and carbon nanotubes were placed in stainless steel jars containing stainless steel balls. Normally the jars were filled with argon to avoid the oxidation of metal powders and then agitated using a mechanical system with a certain rotation velocity. However, one of the most promising techniques consists of ultrasonically blending metal powders with CNTs in an organic solvent (e.g. alcohol), followed by solvent evaporation, ball milling and sintering or hot consolidation of the powdered mixture. Another issue to take into account is the reactivity between matrix and reinforcement. Undesirable reactions with formation of fragile phases must be avoided. In this study carbon nanotubes were functionalized with nickel in order to avoid reactivity with the Al-Si matrix. This work will provide results concerning different methods of preparing the powder mixtures and their influences on mechanical properties. Interface behavior with the new materials is also discussed.

EXPERIMENTAL PROCEDURE

An eutectic Al-Si alloy (Table 1), with powder size under 44 μm, was used. Nickel coated MWCNTs, with outer diameters of about 50 nm and lengths between 0.5 and 2.0 μm were used. The MWCNT's had a purity level, before coating, higher then 95 % and an ash content lower than 1.5 % (all in wt%)(supplier information).

Table 1 – Chemical composition (supplier data) of the Al-Si alloy (in wt%).

Al	Si	Fe	Other
87.3	11.0	0.20	1.5

Al-Si powder and different MWCNT additions (2, 4, 6 and 10 wt%) were then mechanically mixed inside a close stainless steel jar. Inside the jar was put the mixture and the steel milling balls (balls with 10 mm diameter). The initial ball-to-powder weight ratio was (BPR) = 10:1. The jar were filled with argon and then placed in a rotation machine and the mixing was made with a constant rotation speed of 40 rpm during 6 days (low-energy ball milling).

The obtained mixture was divided and placed inside graphite molds with 3.4 mm height and 44 mm length. CNT-reinforced Al-Si samples were then sintered by means of a pressure-assisted sintering process in vacuum at 10^{-2} mBar using a high frequency induction furnace, shown in Figure 1, according to the following procedure. The mold was placed inside the chamber where the sample was compressed at 1.30 MPa, and then heated up to 550ºC using a heating rate of 25ºC/min . When the temperature reached 500ºC , the pressure on the sample was raised to 6.55 MPa and maintained at this pressure level during a defined time stage at 550ºC for 10 minutes.

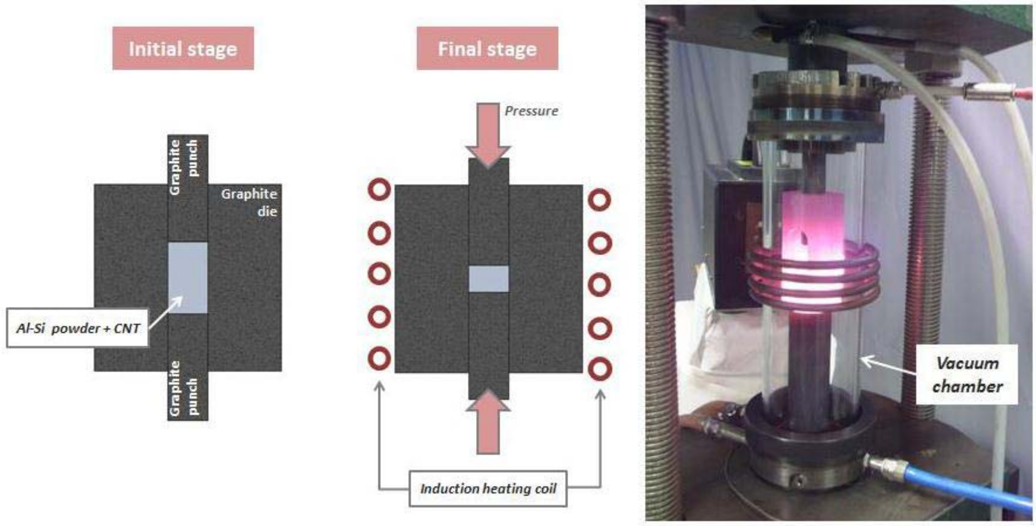


Figure 1 - Experimental apparatus of the hot-pressing controlled atmosphere sintering system

Afterward the samples were allowed to cool inside the mold under vacuum until room temperature. The obtained samples had average dimensions of 3.4 x 44 x 4.3 mm^3. In order to study the mechanical and wear proprieties of the composites, tensile stress and wear tests were performed. The tensile stress tests were made in a universal tensile stress machine. The wear tests were conducted using a load of 10 N , and the chosen track was obtained from cast iron, the same material used in cylinder sleeving of a combustion engine. The sample tests had the same curvature as the piston ring.

RESULTS AND DISCUSSION

Figure 2 to Figure 4 present the mechanical properties of aluminium composite samples containing 2, 4 and 6 wt% of carbon nanotubes and a sample with a composition gradation along the section (linear variation from 2% at the bottom to 0% in the middle with posterior linear variation up to 2% on top). For each composition, six samples were utilized.

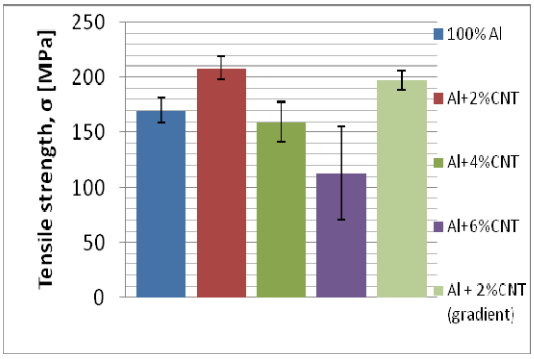


Figure 2 – Tensile strength of the composites containing different amounts of carbon nanotubes.

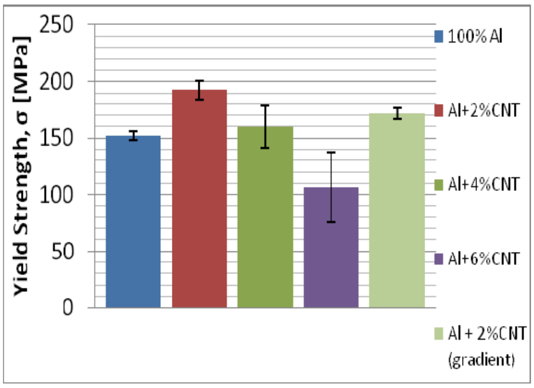


Figure 3 - Yield strength of the composites containing different amounts of carbon nanotubes.

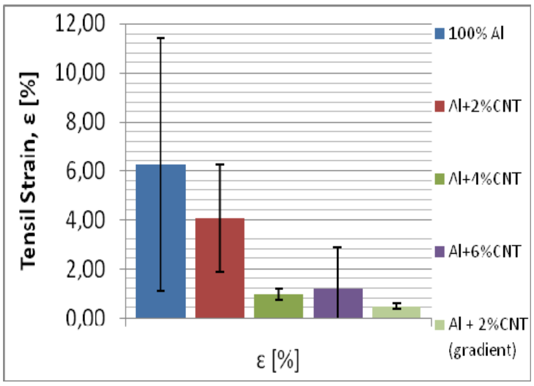
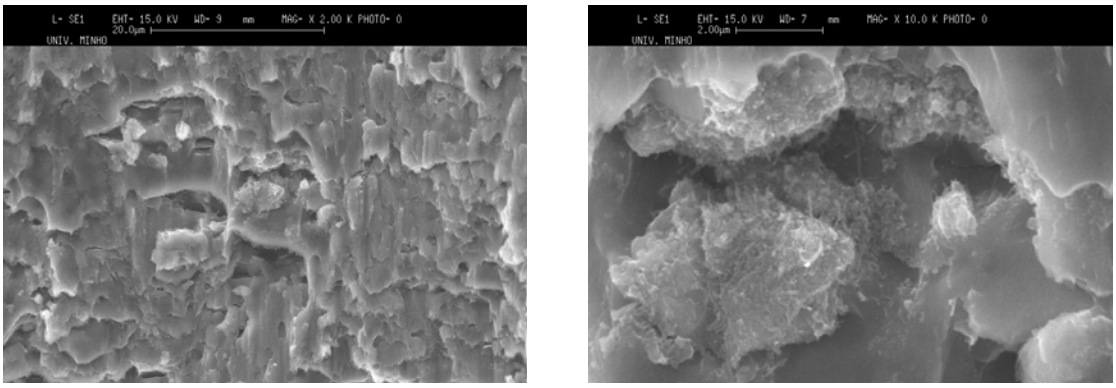


Figure 4 - Tensile strain of the composites containing different amounts of carbon nanotubes.

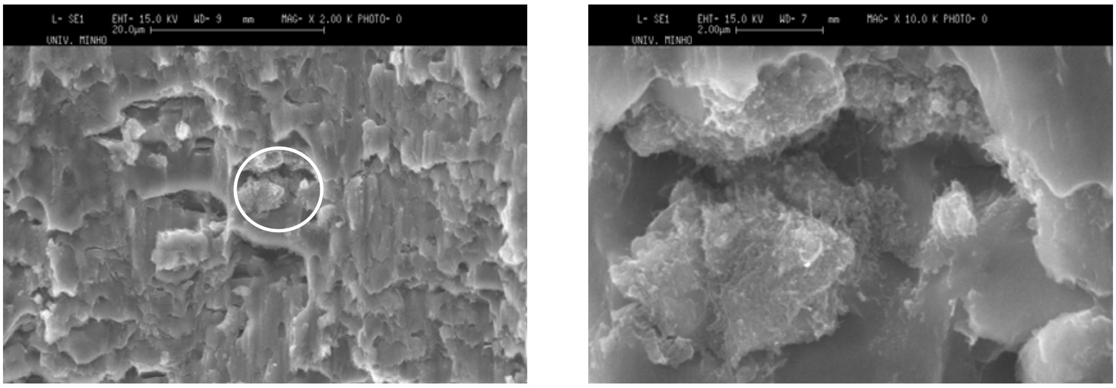
In Figure 2 and Figure 3 it is clear that the composites containing 2 wt% carbon nanotubes globally have higher tensile and yield strengths as compared to the matrix material and the samples with higher fractions of carbon nanotubes. The maximum mechanical properties are achieved with 2 wt% carbon nanotubes. Figure 4 shows a substantial decrease in tensile strain with the increase of the carbon nanotubes fraction leading to an embrittlement of the composite.

The mechanical properties of aluminum composites reinforced with carbon nanotubes depend on several factors such as level of carbon nanotubes, dispersion in the aluminum matrix and the reactivity between the nanotubes and the metal matrix (Pérez et al., 2008). So it is possible that the maximum dispersion rate is achieved with 2 wt% CNTs. When the amount of nanotubes increases it is possible that they start functioning as a defect due to cluster formations. In fact it was found that some agglomeration of the carbon nanotubes occurred in samples with 2% wt CNTs (see Figure 5). Therefore, with a quantity higher than 2 wt% it is probable that the number of agglomerates is higher, which is confirmed below in Figure 6.



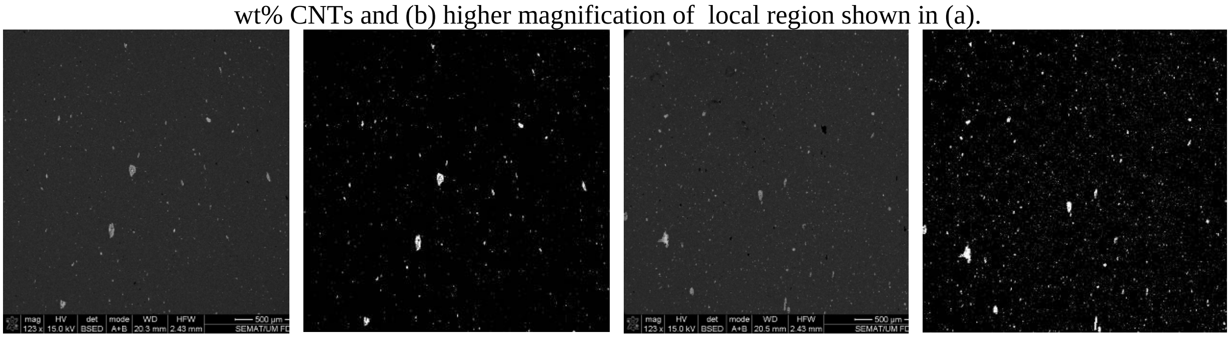
a) b)

Figure 5 shows that the dispersion of carbon nanotubes has not been well achieved. As a fact the presence of clusterings of carbon nanotubes is a major problem in regard to mechanical performance. This phenomenon is difficult to overcome because of the large difference between the size of carbon nanotubes and the metal powders and due to their attractive van der Waals interactions (Esawi et al., 2007; Pérez et al., 2008. This study is in agreement with other studies which confirm that the amount of carbon nanotubes may substantially affect mechanical properties (Pérez et al., 2008; George et al.,2005; Deng et al.,2007; Kuzumaki et al.,1998). Regarding mechanical properties, and due to the fact that there were still nanotube agglomerates, it is possible to further improve them by refining the mixing process.

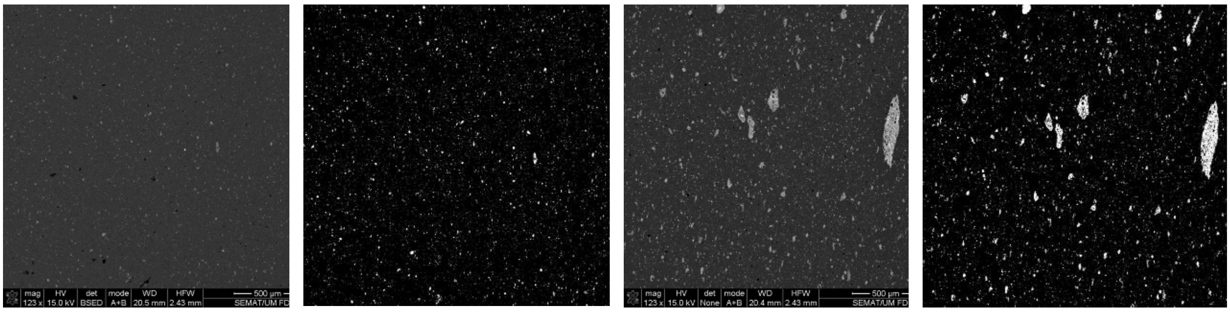


a) b)

Figure 5 – (a) SEM micrograph of the composite obtained by the mixing process with 2.0 wt% CNTs and (b) higher magnification of local region shown in (a).



(a) - 2.0 wt.% CNTs (b) - 4.0 wt.% CNTs



(c) 6.0 wt.% CNTs (d) 10.0 wt.% CNTs

Figure 6 - SEM micrographs of the composites with different amounts of CNTs; left side - image from SEM; right side - image enhanced to isolate CNTs.

Figure 6 illustrates the polished surfaces of samples containing different amounts of CNTs. The images on the right side were derived from the images on the left which were obtained by SEM/EDS (x-ray maps). The white areas on the right images are agglomerates of CNTs that were isolated and enhanced by image processing. Doing a qualitative analysis of images represented in Figure 6, it can be seen that CNT agglomerations are increasing as the weight percent of CNTs increases, which contributes to a deterioration of mechanical properties as seen in Figures 2 and 3. The results of the samples with 10 wt% CNT are not shown in Figures 2 and 3 because the dispersion was too high.

The fatigue analysis reveals, like the wear tests, that it is possible to increase material properties with the addition of CNTs. Tests with 2% nanotubes were conducted because this content appeared to maximize mechanical properties. Figure 67 shows the fatigue results obtained as SN curves. It should be noted that samples contained a pre-notch, so propagation life, not initiation life, is measured.

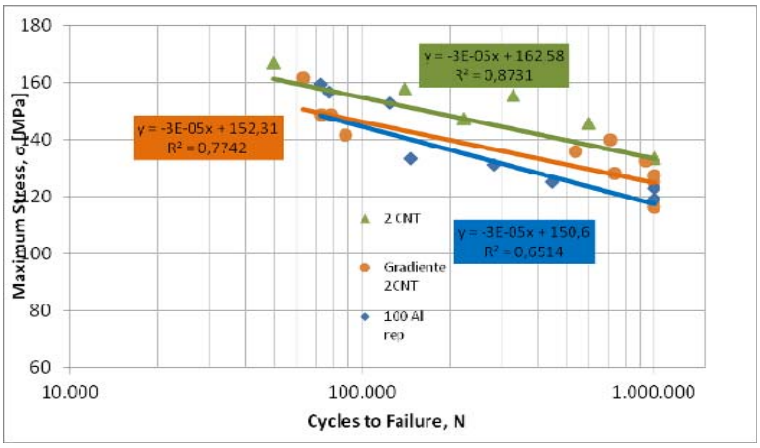


Figure 7 - SN curves for aluminum and aluminum composites with nano-tubes, with and without gradient.

CONCLUSIONS

The mechanical properties of the aluminum composites depend largely on the CNT dispersion level in the aluminum alloy matrix. Although having an increase in most mechanical proprieties, the tested mixing processes still produce carbon nanotubes agglomerates. Thus, it is possible to further improve mechanical properties. For this purpose it is essential to develop a process that guaranties good carbon nanotubes dispersion. Samples with a 2 wt% carbon nanotubes fraction overall showed better mechanical properties. Samples with a 10 wt% carbon nanotubes fraction had too many agglomerations to be useful material and the 4 wt% samples have properties that are between 2 wt% and 6 wt% samples properties.

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REFERENCES

Esawi A, Morsi K. Dispersion of carbon nanotubes (CNTs) in aluminum powder. Composites, Part A, 2007, vol. 38, pp. 646–650

Pérez-Bustamante R, Estrada-Guel I, Antúnez-Flores W, Miki-Yoshida M,. Ferreira PJ, Martínez-Sánchez R. Novel Al-matrix nanocomposites reinforced with multi-walled carbon nanotubes. Journal of Alloys and Compounds, 2008, vol. 450, pp. 323–326

Tang Y, Cong H, Zhong R, Cheng HM. Thermal expansion of a composite of single-walled carbon nanotubes and nanocrystalline aluminum. Carbon, 2004, vol. 42, pp. 3260–3262

Feng Y, Yuan HL, Zhang M. Fabrication and properties of silver-matrix composites reinforced by carbon nanotubes. Materials Characterization, 2005, vol. 55, pp. 211 – 218

Thostenson ET, Li C, Chou TW. Nanocomposites in context. Composites Science and Technology, 2005, vol. 65, pp. 491–516

Thostenson ET, Ren Z,. Chou TW. Advances in the science and technology of carbon nanotubes and their composites: a review. Composites Science and Technology, 2001, vol. 61, pp.1899–1912

Xu CL, Wei BQ, Ma RZ, Liang J, Ma XK, Wu DH. Fabrication of aluminum–carbon nanotube composites and their electrical properties. Carbon, 1999, vol. 37, pp. 855–888.

Tang Y, Cong H, Zhong R, Cheng HM. Thermal expansion of a composite of single-walled carbon nanotubes and nanocrystalline aluminum. Carbon, 2004, vol. 42, pp. 3251–3272.

Lim DS, You DH,. Choi HJ, Lim SH, Jang H. Effect of CNT distribution on tribological behavior of alumina–CNT composites. Wear, 2005, vol. 259, pp. 539–544

George R., Kashyap KT, Rahul R, Yamdagni S. Strengthening in carbon nanotube/aluminium (CNT/Al) composites. Scripta Materialia, 2005, vol. 53, pp. 1159–1163

Esawi A, Morsi K. Dispersion of carbon nanotubes (CNTs) in aluminum powder. Composites: Part A, 2007, vol. 38 , pp. 646–650

Deng CF, Wang DZ, Zhang XX, Li AB. Processing and properties of carbon nanotubes reinforced aluminum composites. Materials Science and Engineering A, 2007, vol. 444, pp. 138–145

Zhong R, Cong H, Hou P. Fabrication of nano-Al based composites reinforced by single-walled carbon nanotubes. Carbon, 2003, vol. 41, pp. 848-851

Morsi K, Esawi A. Effect of mechanical alloying time and carbon nanotubo (CNT) content on the evolution of aluminum (Al)–CNT composite powders. J Mater Sci, 2007, vol. 42, pp. 4954–4959

Kuzumaki T, Ujiie O, Ichinose H, Ito K. Mechanical characteristics and preparation of carbon nanotube fiber-reinforced Ti composite. Adv. Eng. Mater. 2000, vol. 2, pp. 416–418.

Carreno-Morelli E. Carbon Nanotubes: Metal Matrix Composites'', Dekker Encyclopedia of Nanoscience and Nanotechnology. Taylor & Francis, 2006, pp. 1-9

Dong SR, Tu JP, Zhang XB. An investigation of the sliding wear behavior of Cu-matrix composite reinforced by carbon nanotubes. Mater. Sci. Eng. A, 2001, vol. 313, pp. 83–87

Tu JP, Yang YZ, Wang LY, Ma XC, Zhang XB. Tribological properties of carbon-nanotube-reinforced copper composites. Tribology Letters, 2001, vol. 10, no. 4, pp. 225-228

Kim KT, Cha SI, Hong SH. Microstructures and tensile behavior of carbon nanotube reinforced Cu matrix nanocomposites. Materials Science and Engineering A, 2006, vol. 430, pp. 27–33

Li H, Misra A, Zhu Y, Horita Z, Koch CC, Holesinger TG. Processing and characterization of nanostructured Cu-carbon nanotube composites. Materials Science and Engineering A, 2009

Carreno-Morelli E, Yang J, Schaller R, Bonjour C. Tiny tubes boost for metal matrix composites", Metal Powder Rep., 2004, vol. 7, pp. 40–43, reprinted from Proceedings of European Conference on Powder Metallurgy 2003, Valencia, Spain, Oct. 20–22, 2003; European Powder Metallurgy Association: Shrewsbury, UK, 2003, vol. 2, pp. 59–62

Peigney A, Laurent C, Flahaut E, Rousset A. Carbon nanotubes in novel ceramic matrix nanocomposites. Ceramics International, 2000, vol. 26, pp. 677-683

Darsono N, Yoon DH, Kim J. Milling and dispersion of multi-walled carbon nanotubes in Texanol. Applied Surface Science, 2008, vol. 254, pp. 3412–3419

Tao Z, Geng H, Yuc K, Yang Z, Wang Y. Effects of high-energy ball milling on the morphology and the field emission property of multi-walled carbon nanotubes. Materials Letters, 2004, vol. 58, pp. 3410– 3413

Esawia AMK, Morsi K, Sayeda A, Abdel Gawad A, Borah P. Fabrication and properties of dispersed carbon nanotube–aluminum composites. Materials Science and Engineering A, 2009, vol. 508, pp.167–173

Deng C, Zhang XX, Wang D, Lin Q, Li A. Preparation and characterization of carbon nanotubes/aluminum matrix composites. Materials Letters, 2007, vol.61, pp. 1725–1728

Kuzumaki T, Miyazawa K, Ichinose H. Processing of carbon nanotube reinforced aluminum composite. Mater. Res., 1998, vol. 13, pp. 2445–2449