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CNT-reinforced aluminum composites: processing and mechanical properties

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Abstract

This work focus the development of aluminum silicon composites reinforced with carbon nanotubes.Several composites were obtained by a powder metallurgy route through hot pressing technique. The influence of different volume fraction of carbon nanotubes in metallurgical and mechanical properties of the composite was studied. Metallurgical evaluation was made by means of SEM/EDS for interface reaction between matrix and reinforcement and also reinforcement distribution in the matrix. Mechanical evaluation was made by tensile tests.

Keywords:aluminum composites; metal matrix composites; carbon nanotube.

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1. 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 [1]. The need to enhance the mechanical properties of aluminum alloys 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. In the last decade, 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 [2]. With outstanding mechanical properties, extraordinarily low thermal expansion, and high thermal conductivity, CNTs are an attractive reinforcing [3]. 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 [4]. Not surprisingly, carbon nanotubes have emerged as new reinforcements for a number of material systems including polymeric [5,6], metal [7-21] and ceramic matrices [22].The introduction of carbon nanotubes in metal matrices, mainly aluminum, begins to be common in many research works [7-14]. There are also other metals such as titanium [15], copper [16-20] and magnesium [21] 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 [2]. Thus, to achieve a uniform dispersion of carbon nanotubes in a metal matrix is quite difficult. The interfacial reaction

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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 [12].
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 [1,2,10,12,16,23-26]. Metal powders and carbon nanotubes are 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. 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.

2. Experimental procedure

Aluminum silicon (Al-Si) alloy supplied by Cymit with a powder size of <325 mesh (<44µm) and chemical composition listed on Table 1 was used.

Table 1. Chemical composition of Al-12Si alloy (wt.%)

Al	Si	Fe	Others
87.3	11.0	0.2	1.5

Nickel-coated MWCNTs with outer diameters of>50 nm, lengths of 0.5-2.0 µm, purity before coating >95 wt.% and ash content of <1.5 wt.% were used.Al-Si powder and different MWCNT additions (2, 4 and 6 wt.%) were then mechanically mixed in a quantity of 0.005 kg inside a closed stainless steel jar.
The mixture and steel milling balls with 10 mm diameter (BPR 10:1) were putted inside the jar. This jar was placed in a rotation machine, and the mixing was made with a constant rotation speed of 40 rpm during six 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 Fig. 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 35 MPa and maintained at this pressure level during a defined time stage at 550ºC for 10 minutes.

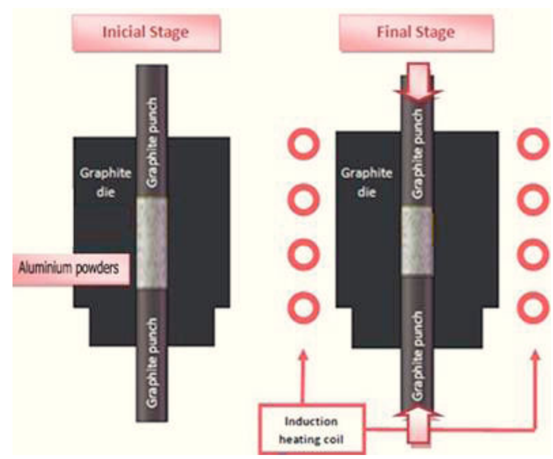


Fig. 1. Experimental apparatus of the hot-pressing controlled atmosphere sintering system.

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 properties of the composites, tensile tests were performed in a universal testing machine.

3. Results and discussion

Fig. 2 to 4 present the mechanical properties of aluminum 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 the top). Also aluminum specimens were produced for comparison with the composites. For each composition, six samples were tested.
In Fig. 2 and Fig. 3 it is clear that the composites containing 2 wt.% carbon nanotubes globally presents higher tensile and yield strengths as compared to the matrix material and also comparing with the samples with higher fractions of carbon nanotubes.

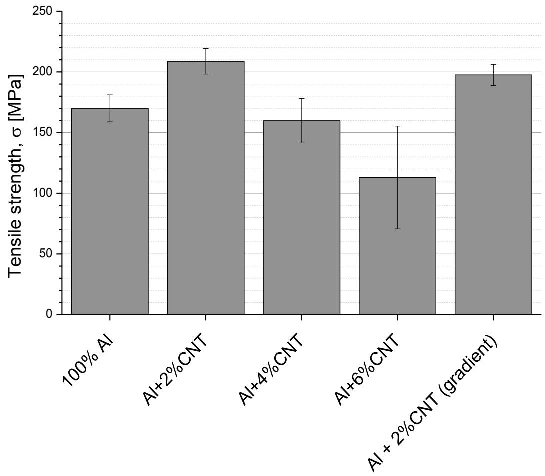


Fig. 2. Tensile strength of aluminum alloy; 2, 4 and 6 wt.% CNT composites and gradated composite.

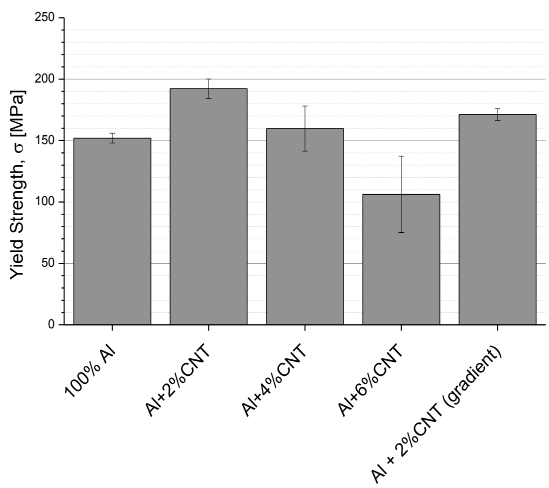


Fig. 3. Yield strength of aluminum alloy; 2, 4 and 6 wt.% CNT composites and gradated composite.

Mechanical properties of CNT-reinforced aluminum composites depend largely on CNT content in the composite and also on dispersion in the matrix[2].
Based on mechanical properties it is possible that the maximum dispersion is achieved with 2 wt.% CNTs, once when the CNT content increases CNTs start functioning as a defect due to their clustering.
Fig. 4 shows that the dispersion of carbon nanotubes has not been well achieved. As a fact, the presence of agglomerates of carbon nanotubes is a major problem regarding 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 [1,2]. This study is in agreement with other studies which confirm that the amount of carbon nanotubes may substantially affect mechanical properties [2,10,12,27]. Regarding mechanical properties, and due to the fact that there were still CNT agglomerates, it is possible to further improve them by optimizing the mixing process.
In fact it was found that some CNT agglomeration occurred in samples with 2 wt.% CNTs (Figure 4). With higher CNT contents the number of agglomerates increases, which is confirmed below in Figure 5. Figure 5 shows the polished surfaces of samples containing different CNT contents. 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 CNT agglomerates that were isolated and enhanced by image processing. Doing a qualitative analysis of these images, it can be seen that CNT clustering is increasing as the weight percent of CNT increases, contributing to a deterioration of mechanical properties, as seen in Figures 2 and 3.

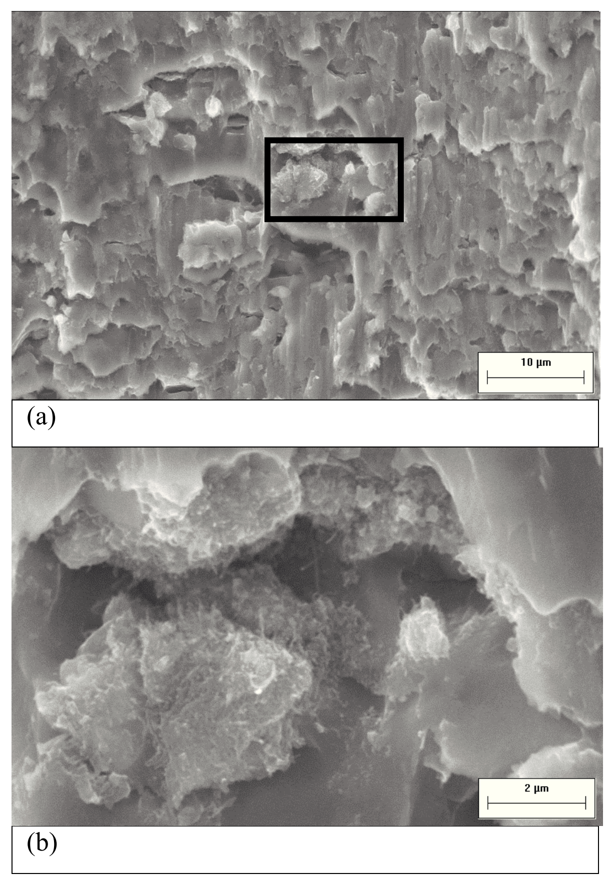
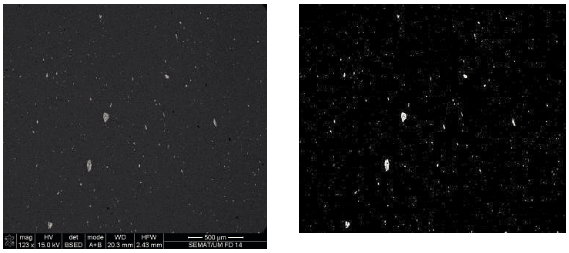
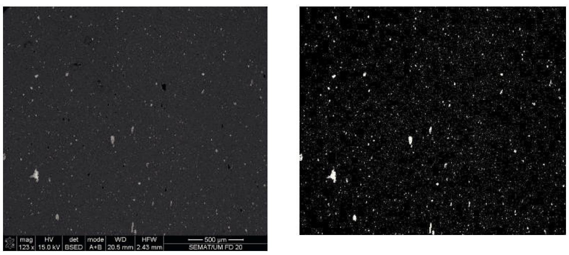


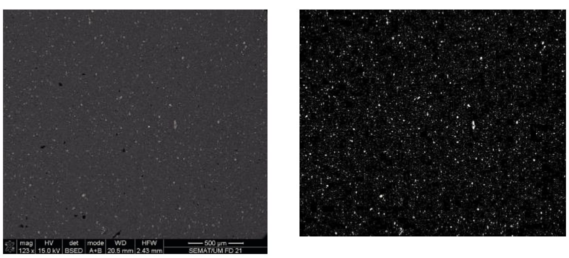
Fig. 4. (a) SEM micrograph of the composite obtained using low-energy ball milling for 2 wt.% CNTs and (b) higher magnification of local region shown in (a).



(a) - 2 wt.% CNT



(b) - 4 wt.% CNT



(c) 6 wt.% CNT

Fig. 5. SEM micrographs of 2, 4 and 6 wt.% CNT composites; left side - image from SEM; rightside-image enhancedtoisolate CNTs.

4. Conclusions

The mechanical properties of the produced CNT-reinforced aluminum composites depend largely on the CNT dispersion in the aluminum alloy matrix. Although an increase in mechanical proprieties was achieved (2 wt.% CNT), the tested mixing processes still produces CNT agglomerates. This way it is possible to conclude that further improvements in mechanical properties are possible once good carbon nanotubes dispersion is assured. Higher CNT content (4 and 6 wt.%) lead to a decline in tensile strength, consequence of CNT clustering.

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