Novel aluminum-carbon nanotubes composites for structural applications

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ABSTRACT

The development of aluminum-carbon nanotubes (Al-CNT) composites has seen a surge in interest following promising results reported by various groups. The latest enhancements achieved by the research group: an increase in tensile strength and Young's modulus of 69% and 23% respectively for Al-CNT composites with 5 wt. % MWCNT were accompanied by a reduction in ductility expected to limit the applications of these novel composites. This is currently being addressed through the use of (1) dual matrix approach in which the CNTs are embedded in a first matrix of aluminum powders which are consequently embedded in a second matrix of aluminum; (2) functionally-graded (FG) approach in which a gradual change in the composition of the CNT-reinforced regions is tailored so as to produce a design-efficient material with an ultra hard surface that gradually leads to a soft core. The two approaches aim at enhancing the formability of the material for wider industrial applications.

Keywords:
Aluminum-carbon nanotubes composites, mechanical properties, dual matrix, functionally graded composites

1 INTRODUCTION

Recently, the development of Al-CNT composites has seen a surge in interest following promising results reported by various groups. Their high thermal resistance, superior mechanical properties and light weight make them ideal candidates for structural applications in the aerospace, automotive and energy industries.

One of the main obstacles facing producing Al-CNT composites has been the difficulty in dispersing CNTs within the aluminum matrix. This has been overcome by the research group through the use of high energy ball milling and powder metallurgy techniques. In addition to dispersing the CNTs, ball milling refines the matrix structure and thus contributes to the strengthening achieved. Although ball milling can impart some structural damage to the CNTs, it has been shown that they play a significant role in matrix strengthening provided their tubular structure is retained. This allows the use of cheaper MWCNTs with structural defects in producing more economically-competitive composites [1-4].

Considerable enhancements in mechanical performance have been reported and reflect the efficiency of the technique in producing composites with relatively higher CNT content than other reports in the literature. The observed mechanical advantage combined with the outstanding wear resistance of the composites (reported by the group in another study [5]), confirm the potential of this novel material in light weight structural applications.

Similar to other composites, the strength enhancement is usually accompanied by a reduction in ductility which can have serious implications on the formability of the material into various shapes.

Two approaches currently being investigated to enhance ductility are (1) dual matrix approach and (2) a functionally graded approach. Both are currently under investigation and the preliminary results are reported in this paper. A dual matrix composite in which the reinforcement is first embedded in an inner matrix which is then embedded in an outer softer matrix can provide a tradeoff between strength and ductility. Functionally-graded (FG) materials are an emerging class of advanced materials which have recently attracted the attention of researchers. They are "design-efficient" materials in which, for example, a composition gradient can be implemented so that the surface of a mechanical component is much harder and more wear resistant than its core which remains soft. In FG materials sharp interfaces which often are sites for initial cracks are replaced by gradient interfaces and accordingly a smooth transition from one material to the next. There is only one report in the literature in which the FG approach is used for Al-CNT composites [6].

2 EXPERIMENTAL

2.1 Single and Dual matrix composites

200-mesh Aluminum powder of 99.7% purity (Aluminum Powder Company Ltd.) was mixed with Elicarb® multi-wall carbon nanotubes (MWCNTs) (THOMAS SWAN Corporation) having an average diameter of around 30 nm and lengths extending to tens of microns. The high energy ball milling technique was used to produce either single matrix or dual matrix composites using the procedure in Figure 1. In addition to pure aluminum, Al-CNT powder composites were obtained by dispersing 1, 2, and 5 wt % CNTs within the aluminum powders using a Retsch® PM400 planetary ball mill operated at a milling speed of 400 rpm, ball to powder weight ratio of 5:1 for 1 hour. This was followed by cold compaction and then hot extrusion using an extrusion ratio of 4:1. Bulk composite specimens were machined to standard dimensions according to ASTM E8-08 standard tension testing procedure for metallic materials using an electrically-derived 50 KN INSTRON® universal testing machine. An MTS® XP-type nanoindenter was used to carry out all nanoindentation tests using the constant-stiffness method with a 3-sided Berkovich diamond indenter and a drift correction of 0.05 nm/sec. An array of 6x6 100µm inter-spaced indentations was made. Microstructural analysis of CNT-Al powders and fracture surface investigations of failed tensile test specimens were carried out using a LEO® Supra55 field emission scanning electron microscope.

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Figure 1: Experimental Procedure for preparing single and dual matrix Al-CNT powders

2.2 Functionally-graded composites

The powder metallurgy route was also employed to produce functionally graded Al-CNT composites using similar ball milling conditions to the single and dual matrix composites powders. The samples produced were layered with either 3 or 5 layers, as shown in Figure 2. The middle layers in both configurations were pure unmilled aluminum.

Relative density of the produced FG composites was measured using Archimedes principle. Micro Hardness was measured using MitutoyoVHN 810 micro indenter at HV 0.5 and 15 seconds dwell time. FG layers were characterized using LEO SEM to investigate the interfaces between the different layers. Nano-indentation test was conducted to investigate the hardness of each layer. A 50 tons MTS Universal testing machine was employed for compression tests on composite compacts having a height to diameter ratio of 1.5.

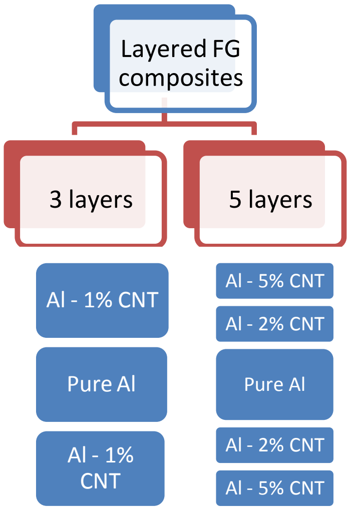

Figure 2: Configuration of FG Al-CNT composites

3 RESULTS

3.1 Single and dual matrix composites

Figures 3 and 4 present the tensile strength and the Young's modulus values obtained for the various single matrix composites. Enhancements of 69% in tensile strength and 23% in Young's modulus are observed. What is also noticeable is the increasing trend in properties with increase in CNT content up to 5wt% CNT which reflects the efficiency of the technique in dispersing higher CNT contents than most other reports in the literature. Similar enhancements were observed for hardness (not shown).

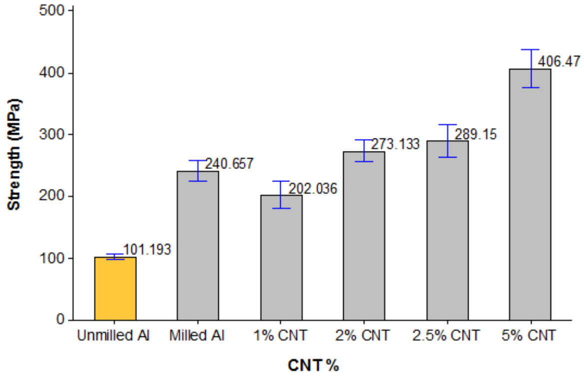

Figure 3: Tensile strength of Al-CNT composites

Table 1 presents a comparison between the properties of the single and dual matrix composites of the same composition. The results confirm that the dual matrix approach can produce composites with enhanced ductility with only a slight reduction in strength.

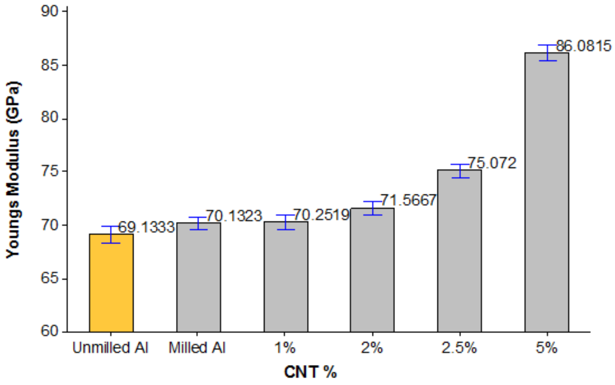

Figure 4: Young’s Modulus of Al-CNT composites

3.2 FG composites

Table 2 presents the results of the properties of the FG composites of the 3 layer and 5 layer configurations. The microhardness of the various layers as well as the hardness of the interfacial layers are presented together with the overall compressive strength of the composites. A noticeable increase in hardness with CNT content is observed. The overall compressive strength of the 5 layer sample is higher than the 3 layer one and is attributed to the higher overall CNT content. Figure 5 shows a 5 layer compact after the compression test where it is clear that the central pure aluminum layer has bulged out whereas the top and bottom CNT reinforced layers have cracked.

Figure 5: Failure of a 5-layer sample

Figure 6 presents an SEM image of the interface between a pure and a 2 wt% CNT layer and shows that the reinforced layer is very brittle due to the presence of the CNTs.

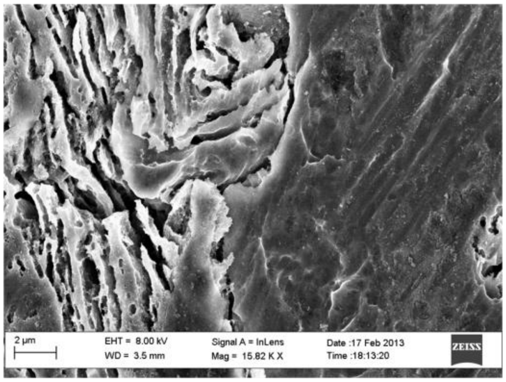

Figure 6: SEM of the interface between 2% and 0% layer

3.3 Further experiments

Further experiments are underway to introduce improvements to the procedure in order to reach a better compromise between the strength and ductility. Varying the proportion of soft to hard constituents in the dual matrix composites is being investigated. Tailoring the interface in FG composites by devising novel processing techniques that can allow a more gradual transition between the two dissimilar phases is also under further investigation. Finally, FG composites with gradient layers in the form of concentric cylinders are currently being produced.

4 CONCLUSION

Both dual matrix and functionally graded Al-CNT composites have been successfully fabricated by the powder metallurgy route. Up to 5 wt% CNTs were uniformly dispersed in the aluminum matrix. Enhancements in the ductility of the dual matrix composites were observed. Gradient layers in FG composites with different amounts of CNTs showed different microstructures and hardness. The layers also showed good adhesion with no interfacial cracks.

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	Tensile Strength (MPa)		Tensile Strain (%)	
Composition	**Dual**	**Single (2h)**	**Dual**	**Single (2h)**
1wt.%	298.3	328.7	11.16	10.08
2.5wt.%	348.3	372.1	7.14	5.69

Table 1: Tensile strengths and strain properties of single and dual matrix composites

Sample	Density gm/cm^3	Microhardness HV		Compressive strength (MPa)
3 layer composite	**2.611**	**Al-1%CNT**	112.23	**140.8**
		Pure Al	47.32	
		Interface between AL and 1% layers	74.40	
5 layer composite	**2.612**	**Al-5%CNT**	189.15	**171.6**
		Al-2%CNT	145.62	
		Pure Al	50.73	
		Interface between 0% and 2% layers	100.34	
		Interface between 5% and 2% layers	142.61	

Table 2: Properties of FG composites