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Carbon Nano tube Reinforced Aluminium Matrix Nano-Composite: a Critical Review

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Abstract: This review is performed mainly to study and summarize the research scenario on carbon nanotube aluminium matrix nano-composite (CNT-AMC) prepared by powder metallurgy route for a wide variety of applications such as aerospace, automobile and sport equipment industries. Many research have been carried out in utilizing CNTs as reinforcement for nano-composite material development on aluminium matrix. The challenge is to distribute CNT uniformly in the matrix to enhance the mechanical and wear properties in the service life of the material. The result showed that powder metallurgy is the simpler and cheaper way of making aluminiumnano-composite with uniform dispersion of CNTs and improved mechanical, wear and frictional properties. This paper summarized the research on carbon nanotube aluminiumnano-composite prepared using powder metallurgy route and clearly stated the importance and benefits of CNT-Al nano-composite on other materials.

Key words: Powder metallurgy, carbon nanotube, aluminium matrix

INTRODUCTION

Nano-composite materials are multiphase materials obtained through the artificial combination of different materials in order to attain properties that the individual components by themselves cannot attain. If a relatively graphitic kind of carbon fiber is used, the thermal conductivity can also be enhanced significantly. The combination of low coefficient of thermal expansion (CTE) and high thermal conductivity makes them very attractive for electronic packaging applications (Fan *et al*. 2011 and Alan *et al*., 1999). Besides good thermal properties, their low density makes them particularly desirable for aerospace electronics and orbiting space structures. Compared to the metal alone, a carbon fiber metal-matrix nano-composite is characterized by a higher strength-to-density ratio (i.e., specific strength), a higher modulus-to-density ratio (i.e., specific modulus), better fatigue resistance, better high-temperature mechanical properties (a higher strength and a lower creep rate), a lower CTE, and better wear resistance. However, aluminiumis a suitable matrix material as it is cheaper and can be processed easily using powder metallurgy route which is also cost effective and captive route compared to other fabrication routes. Al matrix composites have wide prospects of application in aviation, spaceflight and automobile industries because of lower density (a requirement necessary for the weight reduction for many components thereby saving fuels and hence energy). Research in the field of carbon was revolutionized by the discovery of carbon nanotubes (CNTs) by Iijima (1991). Although CNTs might have been synthesised in Bacon(1960), it took the genius of Iijima to realise that they are tubes made by rolling a graphene sheet onto itself. A multiwalled carbon nanotube (MWCNT) is made up of many single walled carbon nanotubes (SWCNT) arranged in a concentric manner. Experiments and simulations showed that CNTs have extraordinary mechanical properties over carbon fibers, e.g. stiffness up to 1000 GPa, strength of the order of 100 GPa (Bakshi *et al*., 2010), and thermal conductivity of up to 6000 W mKBakshi *et al*., (2011). However, fabrication and characterization of CNT reinforced Al matrix nano-composite using cost effective and captive process are important in order to achieve high performance nanocomposite as the properties of this material highly depend on process parameters and variables. Therefore, in this paper, the fabrication of aluminiumnano composite using powder metallurgy route has been critically reviewed.

2. CNT-Al Nano-Composite:

Al is a soft silver colour, ductile and malleable metal that is abundant in the earth's crust. It is impossible to keep it in its pure form without chemical reactions; when exposed to air it directly forms an oxide layer on the surface which will act as a protective shield from further oxidation. It has a relatively low density compared to other metals which makes it one of the best choices for manufacturing components used in light weight applications. Al in its pure form is not applicable due to many factors of which the most important is the relatively low strength. That's why different Al based alloys and composites have been developed to enhance these factors while keeping most of the desired properties of the base metal (Al) present in the formed alloy or composite. Various types of Al matrix composites have been developed and extensively in use over the past decades in aerospace and automotive industries (Farahani 2010).

Reinforcing aluminium with minimum percentage of carbon nanotubes (CNT) using powder metallurgy processing route for the development of lighter weight nano-composite will improve the homogeneity, reduce

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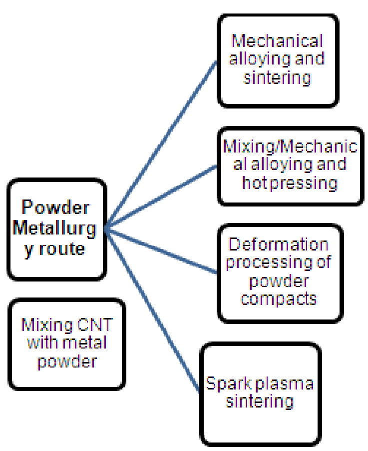
the susceptibility to oxidation, enhance the strength and stiffness, wear resistance, stable friction co-efficient, density and coefficient of thermal expansion. Therefore, this will attract the lightweight industries, such as aerospace, automotive and other industries to use nano-composite material for tribological applications. Research has been done by Cho *et al*. (2011) using copper as a matrix and CNT as reinforcement and achieved increased mechanical properties of the composite material compared to matrix material. Liao *et al*. (2011) conducted a study on the CNT dispersion in Al powder by different mixing techniques, i.e. (i) high energy ball milling, (ii) low energy ball milling and (iii) a polyester binder-assisted (PBA) approach. Zare *et al*. (2012) achieved uniform distribution of CNTs without agglomeration in aluminium powder using ultrasonic and ball mill attrition. The main features of CNT-Al composites are: lower density, high heat dissipation properties, stable friction coefficient, dimensional stability and better wear resistance the surrounding components in the brake system. These properties can fulfill of many structural and tribological components and hence can be considered for automotive and aerospace applications.

3. Processing routes:

3.1 Powder Metallurgy Route:

Powder metallurgy (PM) is considered to be the most common and cheaper production route for composite fabrication and characterized by good dimensional and geometrical precision as well as good mechanical properties. Using PM process, several properties of nano-composite can be improved such as hardness, wear resistance, mechanical durability, thermal durability, and thermal conductivity with decreased density of the material. With this improvement in nano-composite properties, the material exhibited better quality and can be used in many applications whereby demand of quality and less cost material are high especially in automotive and aerospace applications. Powder metallurgy route can be sub divided in to four different methods depending on type of pressure and heat. Fig.1 shows subdivisions of PM route which can be employed for CNT-Al fabrication purposes.

The basic overall process steps consist of mixing of CNTs with aluminium powder by grinding or mechanical alloying, followed by compaction consolidation and sintering, cold isostatic pressing, hot isostatic pressing, or spark plasma sintering. Fig. 2 shows the deposition of CNTs on to aluminium powder by pressure and heat process.



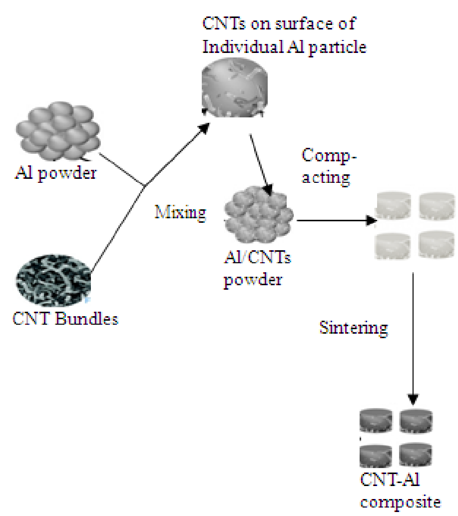


Fig. 1: Sub divisions of powder metallurgy routeFig. 2 PM route for Carbon nanotube aluminiumnano-composite.

Fig. 2 shows the deposition of CNT on individual particle of aluminum, through the process of mixing the two powders by powder metallurgy route. Uniform dispersion of CNT on the aluminium particle was observed and the expected property of the material composite was increase mechanical property, increase harness, increase wear resistance and decrease density. Esawi *et al*. (2008) used a powder rolling technique to fabricate carbon nanotube-reinforced aluminium strips. The CNT-Al mixtures are blended in a mixer-shaker at a rotary speed of 46rpm, and under argon gas in a planetary mill at a rotary speed of 300rpm, prior to rolling. Morsi and Esawi (2007) investigated the effect of milling time and carbon nanotube content on the evolution of aluminium carbon nanotube composite using mechanical alloying and mixing.Salimi *et al*. (2011) conducted a work similar to powder rolling to fabricate an aluminium carbon nanotube metal matrix composite by a modified accumulative roll bonding.

3.2 Conventional Compaction and Sintering:

This method is widely used to fabricate CNT/MMC composite. Esawi *et al*. (2008), used a powder rolling technique to fabricate carbon nanotube-reinforced aluminium strips. The CNT-Al mixtures are blended in a mixer-shaker at a rotary speed of 46rpm, and under argon gas in a planetary mill at a rotary speed of 300rpm, prior to rolling. However, the dispersion of the nanotubes was found to be better under the higher energy planetary action. The strength of the rolled strips is evaluated for various wt% of CNT nano-composite samples. The 0.5 wt% CNT-Al composite strips exhibited enhanced mechanical properties. The CNT- reinforced aluminium strips can have numerous attractive applications in the aerospace, automotive and electronics industries. Liao *et al*. (2011), conducted a study on the CNT dispersion in Al powder by different mixing techniques, i.e. (i) high energy ball milling, (ii) low energy ball milling and (iii) a polyester binder-assisted (PBA) approach. The study revealed that using the high energy ball-milled CNTs were well dispersed, though not sufficiently distributed within the Al powder because of the gravity separation (density difference). These high energy ball milled CNTs were disintegrated due to residual stresses in the CNTs. The polyester binder-assisted CNTs were coated on the surface of Al powder. The greatest advantage of PBA method lied in the maintenance of the CNTs structure and morphology in its original form. As a comparison, the low energy ball-milled shows moderate damage. The results of mechanical properties revealed that the powder mixing was successful. Small addition of CNTs (0.5 wt.%) could enhanced the strength and hardness of the composite compared with the pure aluminium matrix.

Liao *et al*. (2011), fabricated CNT-Al composite by PM technique, and the evolution of CNTs within the matrix was characterized using SEM and TEM machines. The result showed that, the separation of CNTs was affected by both the powder mixing operation and the secondary processing. Secondary processing with a large enough deformation could homogeneously redistribute the reinforcements. However, the amount of defects increased in the CNTs after mixing and sintering due to the physical compression force; whilst the graphitic structures were not damaged during the secondary processing, due to the protection of the soft matrix. However, CNTs were subjected to substantial compression stress not only in powder mixing but also sintering, due to constraint from the consolidation and shrinkage from thermal mismatch. Jin-long et. al.(2007), fabricated aluminum matrix composites reinforced with carbon nanotube by a powder metallurgy method. The hardness of the composites increases with increasing CNTs content, but then decreases for more than 2.0% which means that 2.0% CNTs showed the highest value of hardness. They also found that within the range of CNTs content from 1.0% to 2.0%, the CNTs can decreased both friction coefficient and wear rate of the composites, especially composite containing 2.0% CNTs exhibited lower friction coefficient and wear rate. It was also observed that, the main wear mechanism was the delamination wear on the worn surface for 2.0% CNTs. Sridhar *et al*. (2009), successfully manufactured aluminium matrix composites reinforced with 0.5, 1.0, and 2.0 wt% of multi walled carbon nanotubes (MWCNTs) using cold compaction followed by sintering and cold extrusion techniques to near net shape. The sintering temperature was controlled to prevent the formation of interrmetallic compounds such as aluminium carbide. Enhenced mechanical properties of Al-MWCNT composites was achieved and indicating that the used manufacturing route is a viable cost-effective process route. However, they ignored the on the wear and creep properties of these composite and also to explore strengthening mechanisms. Zare *et al*.(2012), achieved uniform distribution of CNTs without agglomeration in aluminium powder using ultrasonic and ball mill attrition. Morsi and Esawi (2007) investigated the effect of milling time and carbon nanotube content on the evolution of aluminium carbon nanotube composite using mechanical alloying and mixing. The result presented that mechanical alloying is a promising technique for dispersing CNT in aluminium and controlling CNT-Al powder morphology and size. They also found that the use of process control agent such as methanol or ethanol is beneficial in allowing reasonable particle sizes for low CNT content material to be attained with mechanical alloying. The fig.2 shows the compacted and uncompacted powder. Todd *et al*., (1994), a typhical tool and die for compaction process is shown in fig. 2 which shows better understanding on the process and steps involved in powder compaction.

Fig. 3: Compacted and uncompacted powder (Todd et. al)

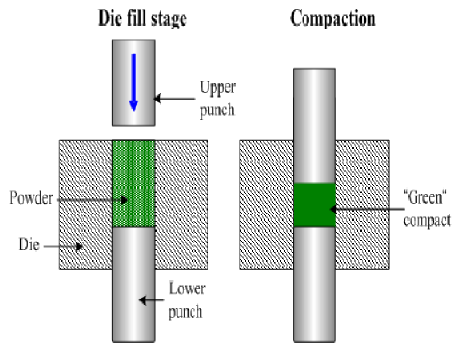


Fig. 4: Compaction process (German R.M)

Fig. 3 and 4 illustrates compaction process and the end product (green compact/green body) after powder compaction at a suitable pressure depending on the type of powder material.

3.3 Hot Press Consolidation Process:

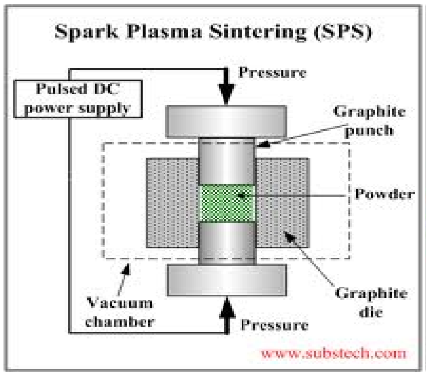
Hot pressing is a high-pressure, low-strain-rate powder metallurgy process for forming a powder or powder compact at a temperature high enough to induce sintering and creep processes.This is achieved by the simultaneous application of heat and pressure. Some researchers have used hot pressing consolidation of powder mixture instead of sintering, however, it shows advanced result during the fabrication of Al-CNT composites due to the clustering of CNTs (Zulfia *et al* 1999).

Haghighi *et al*. (2011), make a comparison between two methods for consolidation of aluminium metal matrix composite, such as equal channel angular pressing (ECAP) and hot extrusion. It is found that three passes of ECAP in a tube at 200 ^{O}C is capable of consolidating the composite to 99.3% of its theoretical density whereas after hot extrusion of the composite the density reached to 98.5% of its theoretical density. Moreover extrusion needs higher temperature and pressure in comparison to the ECAP method. The nano-composite after three passes of ECAP shows better wear resistance compared to hot extruded composite.

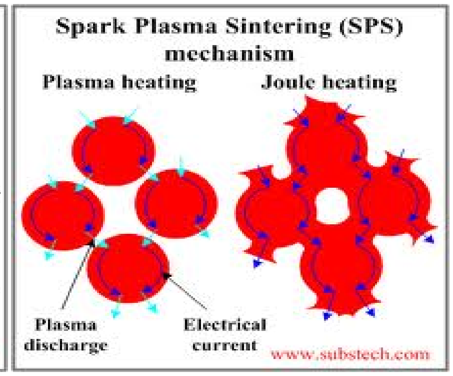
3.4 Spark Plasma Sintering:

Sintering is a process of heating a green body at a temperature of about two third of the melting temperature of the material used to make the green body.It is based on atomic diffusion. Diffusion occurs in any material above absolute zero, but it occurs much faster at higher temperatures. In most sintering processes, the powdered material is held in a mold and then heated to a temperature below the melting point. The atoms in the powder particles diffuse across the boundaries of the particles, fusing the particles together and creating one solid piece. Because the sintering temperature does not have to reach the melting point of the material, sintering is often chosen as the shaping process for materials with extremely high melting-points such as tungsten and molybdenum.

The main characteristic of Spark plasma sintering is that the pulsed DC current directly passes through the graphite die, as well as the powder compact, in case of conductive samples. Therefore, the heat is generated internally, in contrast to the conventional hot pressing, where the heat is provided by external heating elements. The fig. 4 shows the spark plasma sintering process along with mechanism involved in the process. The general speed of the process ensures that it has the potential of densifying powders with nanosize or nanostructure while avoiding coarsening which accompanies standard densification routes. Liao *et al*. (2010), prepared aluminium carbon nanotube composite using spark plasma sintering (SPS) followed by hot extrusion to near full density shape. The MWCNT treated with sodium dodecyl sulphate (SDS) surfactant and roller milling of the aluminium powder has effectiveness in dispersing the MWCNTs for low weight fraction and is not effective at higher weight fractions. The MWCNT are aligned along the extrusion direction and predominantly located at the grain boundaries and the mechanical properties of the Al-0.5 wt% MWCNTs due to the agglomeration of MWCNTs and insufficient interfacial bonding.



(a)Shematic diagram of SPS process



(b) Mechanism involved in SPS

Fig. 5: Spark plasma sintering process (German R.M)

3.5 Powder Rolling:

This process consists of a powder feed system, which continuously replenishes a reservoir above the metal roll. Initially the raw materials are ball-milled with dispersants, organic binders and plasticizers to achieve proper particle size distribution slurry rheology. The slurry is then spray dried to form a flowable powder that can be fabricated in to a tape when roll compacted. Powder rolling does not require large capital investment. A metal strip can be clad on one or both the side by using it as a carrier of the selected powder through the rolls. A large percentage of any scrap material reclaimed in powder from can be reused. Salimi *et al*.(2011), conducted a work similar to powder rolling to fabricated an aluminium carbon nanotube metal matrix composite by a modified accumulative roll bonding. CNT was sprayed on the surface of two aluminium strip and the sandwich was passed through the roller, and the process was effective in producing a composite microstructure with multiwalled CNTs embedded in an ultra fine-grainedaluminium matrix. The CNTs with diameters >30nm and more than 30 walls readily endured four consecutive roll-bonding operations, and their multiwalled structure was preserved in the final composite.

Table I: Critical review analysis of CNT-Al nano-composite

Investigators name	Characteristic study	Findings
Amal *et al.*, (2007)	To produce CNT-Al strip using a powder and rolling technique.	The dispersion of the nanotubes is shown to be better under the higher energy ball milling planetary action.
Esawi *et al.* (2009)	Fabrication and properties of dispersed carbon nanotube aluminium composites	Tensile strength enhanced ~21% for a 2wt% CNT reinforced aluminium processed by cold compaction and hot extrusion compared to hot isostatic press, however, annealing at 500°C for 10hrs did not affect the nanostructure of the matrix
Liao *et al* (2010)	Preparation of MWCNT-Al composite using plasma sintering followed by hot extrusion	The mechanical properties of 0.5w%MWCNT-Al composite enhanced noticeably at room temperature compared to 5wt%CNT.
Salimi *et al.*, (2011)	To investigate the microstructure of the composite.	The MWCNT were embedded in to the Al matrix while maintaining there structucture. Measurement of of the micro and nano structure revealed that asreceived CNTs had a bimodal diameter size distribution.
Esawi *et al.*, (2011)	To investigate the effect of CNT morphology and diameter in the dispersion of CNTs in the matrix	CNTs morphology plays an important role which affect the dispersion of CNT in the matrix.
Liao *et al.*, (2011)	Mixing of carbon nanotubes and aluminium powder for powder metallurgy use, using high energy ball mill	CNTs dispersed with high energy ball milling within the aluminium powder and the results of the mechanical properties revealed that the mixing was successful with the small addition of CNTs as observed using SEM and TEM machines.
Singhal *et al.*, (2012)	To grow the carbon nanotubes on Al powder and fabricate CNT-Al nano-composite with the produced powder	Carbon nanotubes of uniform size and cylindrical morphology was synthesized with the diameter of 50-100nm. The concentration of CNTs grown on Al powder was approximately 6 wt% and dispersed well in Al powder

A critical review analysis of CNT-Al nano-composite material is shown in Table I. The table summarizes the investigated work done on CNT-Al fabrication using powder metallurgy route. It presents the authors aim of the research and findings.

4. Concluding Remarks:

In this paper, recent achievements in some important areas of CNT-Al nano-composite fabrication are introduced. In the area of fabrication of CNT-Al nano-composite, PM is the most cost effective and captive process. Therefore, this PM process route with appropriate processing technique factors can help to develop a new nano-composite material without sacrificing any functional properties and hence, the lightweight industries, such as aerospace, automotive, sports and other industries will be attracted to use this material for many structural and tribological applications.

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