ISSN 2229-5518

Development and Comparative Studies of Aluminum-Based Carbon Nano Tube Metal Matrix Composites using Powder Metallurgy and Stir Casting Technology

L. H. Manjunatha[1], Mohammed Yunus[2], Mohammad S. Alsoufi[2], P. Dinesh[3]

Abstract— Aluminum-based metal matrix composites (Al-MMC) are becoming popular because of their low density and high specific stiffness in the many fields of engineering applications such as automobiles, aerospace, electronic devices, etc., with the additional demand of very light material possessing excellent mechanical properties. Aluminium-based metal matrix composites with an ideal reinforcement as carbon nano tubes (CNT's) possesses an extremely high strength, modulus of elasticity and specific surface area to fulfill the requirements for the above applications. In this study, powder metallurgy and Stir casting routes have been employed for the Aluminium 6061 being matrix material and multi-wall CNT (MWCNT) in varying concentrations as the reinforcing agent. Mechanical properties such as compression, Tensile and Hardness tests were conducted on the Al-MWCNT composite specimens and compared with pure Aluminium samples to investigate the effects of varying concentrations of MWCNT in it subjected to T6 heat treatment and age hardening. Comparative results showed that the hardness and tensile strength of Al6061-MWCNT composite improved significantly while compression strength was decreased in case of stir casting technique subjected to heat treatment and age hardening compared to the powder metallurgy technique.

Index Terms— Aluminium Based MMC, Age Hardening, Carbon Nano Tube, Mechanical Properties, Powder Metallurgy, Stir Casting.

1 Introduction

Recently, a great deal of research in many areas is focusing on identifying reinforcement of engineering materials with better mechanical properties in order to satisfy various engineering applications. Moreover, of late CNT is found to be one such excellent reinforcing material which can improve the properties of Aluminium-based metal matrix composites (Al-MMC) significantly. Various engineering fields such as aerospace engineering, automotive, electronic equipment, medical equipment, space engineering and so on which need very light material possessing excellent mechanical properties. Al-MMC's with CNT reinforcement can successfully be used to satisfy the requirement of low weight with high strength [1]. There are two main types of CNTs can attain high structural perfection such as single walled carbon nano tube (SWCNT) consists of single seamless graphite sheets wrapped in cylindrical tubes and multi walled carbon nano tube (MWCNT) comprise an array of such nanotube that is concentrically nested like rings of a tree trunk [2], [3]. Graphite whiskers are produced by Bacon's productions used to study thermal and mechanical properties of CNTs to find Young's modulus and the yield strength [4]. Small structural variations due to the addition of CNT particles influenced the electrical properties of CNTs [5]. Even electronic as well as the structural properties of CNT measured by the electronic spin resonance spectroscopy shown improved [6] produced from a discharge between graphite electrodes [7]. MWCNT reinforced with aluminium matrix composites fabricated in cold uniaxial compaction followed by sintering and cold extrusion as the secondary process produced increased tensile yield and ultimate strength up to 90% with 2% wt. the addition of MWCNT [8], [9]. CNTs exhibited remarkable mechanical, electrical and thermal properties depending on their length, diameter chirality and orientations. In the case of mechanical properties almost 5 times the elastic modulus and approximately 100 times the tensile strength than those of high strength steels [10], [11]. The performance of nano-mechanics of CNTs and their composites with SWCNTs shown Young's modulus value of larger than tubes alone withstanding around 5 to 10% of axial strength before nanotube yielding [12]. CNT introduced a kind of low weight and a hollow core of nano-size reinforcement to increase immensely the aspect ratio for improving the properties make suitable for rapid demand in the growing field of aerospace, mechanical and civil systems [13], [14].

Powder metallurgy technique for manufacturing of CNTs reinforced MMCs with the help of a planetary ball mill to disperse and strengthening of MWCNT particles in an Al powder [15], [16]. Melt deposition method is good for producing magnesium nano-composites of CNTs [17] and provides a higher quality of dispersion of CNTs reinforced in Al-MMC help in obtaining the homogeneity and enhanced mechanical properties of these composites [18]. Other fabrication methods using Sol-Gel process and spark plasma sintering process for CNT reinforced Al-MMC produced a homogeneous distribution of

- *L. H. Manjunatha, Department of Mechanical Engineering, Reva Institute of Technology/RU, Bangalore, India.*
- *Mohammed Yunus, Mechanical Engineering Department, College of Engineering and Islamic Architecture, Umm Al-Qura University, Makkah, KSA. E-mail: yunus.mohammed@rediffmail.com*
- *Mohammad S. Alsoufi, Mechanical Engineering Department, College of Engineering and Islamic Architecture, Umm Al-Qura University, Makkah, KSA. E-mail: mssoufi@uqu.edu.sa*
- *P. Dinesh, Department of Mechanical Engineering, MSRIT, Bangalore, India.*

CNTs within alumina matrix by mixing with alumina solution and condensation into a gel [19], [20]. It produced light weight and high strength composites. Thermodynamic and kinetic analysis are useful to study interface in CNTs reinforced Al-silicon composites [21]. Efforts have been mostly focused on investigating CNT as reinforcements for Al and their contribution to the enhancement of the mechanical performance of the composites for increasing the tensile strength without compromising the elongation of a composite by a combination of spark plasma sintering followed by hot-extrusion processes [22], [23]. Friction stir process (FSP) is another fabrication method for dispersing MWCNTs uniformly [24] and varying their composition to obtain various properties of Al-MMC reinforced with CNT. The ultimate strength and micro-hardness value of Al-based MWCNT's composites gradually increased with a decrease in the elongation using FSP and surface shown fractures due to the increase of the MWCNT contents; hence the composite brittleness increased [25]. Using liquid metallurgy technique, Al7075-Al2O3 and Al6061-SiC composites prepared wherein 2 to 6% wt. of particulates were dispersed in the base matrix to bring out a class of low weight high-performance aluminium centric material systems for different aspects of mechanical and wear properties [26], [27]. A comparative study on the mechanical properties of Al6061/Albite and Al6061/graphite particulate composites consist of naturally occurring plagioclase feldspar ($NaAlSi_3O_8$) and graphite particulates varying from 0 to 4% wt. respectively helped in adopting different manufacturing techniques [28].

Based on the investigation gaps identified in the literature review, the present study focuses on CNT-reinforced MMCs that includes processing techniques, nano tube dispersion, interface, strengthening mechanisms and mechanical properties. Even as of now, the primary concern of researchers is in the areas of powder metallurgy and stir casting techniques to obtain the MMCs. Many researchers have studied varieties of reinforcements with an Al-based matrix to produce MMCs to achieve the certain required properties. The present study focuses on preparing Al-MMC with CNT reinforcements for various compositions and evaluating their mechanical properties. Powder metallurgy technique has emerged as a promising route for the fabrication of CNT reinforced MMCs. In the present work, Al6061 alloy as matrix and MWCNT as reinforcement by 0.0, 0.5, 1.0, 2.0 and 3.0 weight percentages have been fabricated by the powder metallurgy process. With the help of a hot extrusion set up, sintered billets were extruded and samples were prepared for various compositions in order to investigate for mechanical properties. Al6061 MMCs reinforced with CNTs are also fabricated by the stir casting technique. The specimens obtained through this stir casting method were subjected to T6 heat treatment and age hardening. Heat treatment has a significant impact on the hardness of the Al6061 matrix alloy and its composites. The present work attains significance in the context of the development of Al-MWCNT composite and its material characterization for applications in aerospace and automotive industries. Also, the study has established the stir casting technique as one of the possible new routes of obtaining the Al-MWCNT composite with encouraging results.

2 Materials and Experimental Procedure

The present study consists of the following steps: (1) fabrication of metal matrix composites by powder metallurgy technique, (2) fabrication of metal matrix composites by stir casting technique, (3) preparation of standard specimens and (4) heat treatment of specimens.

2.1 Fabrication of MMC using Powder Metallurgy Technique

Al6061 powder of 200 mesh size as a matrix and MWCNTs were used as reinforcement. Tables 1 and 2 show the properties of MWCNT and chemical composition of Al6061 powder by weight percentage, respectively. Table 3 shows the mechanical properties of reinforcement and matrix materials.

TABLE 1
Properties of MWCNT

Properties	Values
Purity	Carbon > 95% (trace metal basis)
OD × ID × L	10-30 nm × 2-6 nm × 15-30 µm
Total Impurities	Amorphous Carbon < 3%
Melting Point	3652-3697°C
Density	1~2 g/cm^3

TABLE 2
Mechanical properties of reinforcement and matrix materials

Material	Young's Modulus	Tensile Strength	Elongation at Break
MWCNT	0.2, 0.8, 0.95 TPa	11, 63, 150 GPa	15.4 %
Aluminium 6061	69-70 GPa	0.31 GPa	20 %

Powder metallurgy (PM) is a fabrication technique to produce the materials or components made from metal powders in a wide range of ways. The PM and sintering process in general consisting of three basic stages viz. powder blending, die compaction and sintering. Compaction and sintering are performed at room temperature and the elevated temperature process and atmospheric pressure under carefully controlled atmosphere respectively. To obtain particular characteristics or enhanced accuracy, arbitrary secondary processes such as coining or heat treatment. PM processes having an advantage of avoiding or reducing the requirement to adopt machining or metal removal processes, thereby drastically reduces yield losses in production and frequently results in lower costs. Powder metallurgy (PM) is a fabrication technique to produce the materials or components made from metal powders in a wide range of ways. The PM and sintering process in general consisting of three basic stages viz. powder blending, die compaction and sintering. Compaction and sintering are performed at room temperature and the elevated temperature process and atmospheric pressure under carefully controlled atmosphere respectively. To obtain particular characteristics or enhanced accuracy, arbitrary secondary processes such as

coining or heat treatment. PM processes having an advantage of avoiding or reducing the requirement to adopt machining or metal removal processes, thereby drastically reduces yield losses in production and frequently results in lower costs.

In the present study, the MWCNT powder was initially purified by mixing it with concentrated nitric acid, filtering it, washing it with deionized water and drying it at 120°C to remove any impurities such as graphitic particles, amorphous carbon or any other substance present in MWCNTs. 0.5, 1.0, 2.0 and 3.0 wt.% of CNTs weight percentage was mixed with Al6061 powder in ethanol solution. The mixing was carried out for the duration of 10 minutes at 200 rpm to obtain uniform mixing using the ball mill. The mixture of a required proportion of weight percentage of MWCNT and Al6061 was compacted in the die assembly using a hydraulic press at gradually applied a standard load of 200 kN. In the present study, the addition of MWCNT has been limited to 3 wt.% as beyond this value the specimen showed cracked surfaces rendering the sample unusable. Al powder of 20 grams was filled into a compacting steel die and pressed hydraulically at a pressure 180 kN with initial dimensions of 20 mm diameter and 40 mm length were compacted to a final size of 20 mm diameter 20 mm length. A low-cost sintering furnace was designed and fabricated for the current research work to impart strength and integrity. The compacted samples were sintered in the vacuum furnace at 600°C for 45 minutes followed by air-cooling in the nitrogen atmosphere. Samples were sintered in a tube furnace under the flowing nitrogen which passes over warm steel wool. Sintering of Aluminium is more efficient in nitrogen than argon since it induces weight gain, the formation of densification. Sintered billets were hot extruded by a hot extrusion process at 560°C to obtain a 25% reduction in diameter. Upon sintering, the metallic bonding between the powder particles is formed mainly by diffusion.

2.2 Fabrication of MMC using Stir Casting Technique

Stir casting is one of the most economical techniques of processing Al-MMCs. Reinforced Al6061-CNT composites were manufactured by using a stir casting technique with Al6061 alloy as a matrix and MWCNTs as reinforcement. The various proportions of CNTs 0.0, 0.5, 1.0, 2.0 and 3.0 volumes are mixed with Al alloy to make castings. The use of MWCNT was limited to 3 to 4 wt.% by weight. Al6061 alloy is melted in the furnace to a temperature of 800°C to 850°C and then MWCNTs in the powdered form (10 nm - 30 nm) poured slowly. Simultaneously, a stirrer is made to rotate at an optimum speed of 450 rpm for about 5-10 minutes such that the melt is degassed by the supply of nitrogen gas. Later, the molten metal is poured into the finger metal mold. The mold is coated with chalk powder to prevent sticking of the molten metal into its surface. The cast samples prepared are subjected to heat treatment as well as hot extrusion.

2.3 Preparation of Standard Specimens

In the present study, MMC has been developed by powder metallurgy and stir casting methods. The samples for material characterization to study mechanical properties were prepared as per ASTM standards such as hardness test, tensile test and compression test samples as per ASTM B-925, ASTM E-8-95A and ASTM-E9-95 standards respectively. Table 4 shows the heat treatment steps for stir cast specimens.

TABLE 4
Heat treatment steps for stir cast specimens

Test Type	Heat treatment/mechanical working of test specimen
Hardness	T6 heat treatment with further quenching in air, boiling water and ice respectively. Specimens were age hardened at 175°C for durations of 0.0, 2.0, 4.0, 6.0, 8.0 and 10.0 hours, respectively.
Compression	

2.4 Heat Treatment of Specimens

All stir cast as cast Al6061-MWCNT specimens for hardness, the compressive strength was subjected to a T6 artificial aging treatment. Al6061 alloy and the composites were solutionized at 555°C for 8 hours and quenched in three different media such as air, boiling water, ice and later age hardened. Age hardening consisted of maintaining a constant temperature of 175°C in the furnace and keeping the specimens in this for aging. The aging times were 0.0, 2.0, 4.0, 6.0, 8.0 and 10.0 hours.

3 Results and Discussions

Results of hardness, tensile and compressive strengths for the specimens of Al-MWCNT composites (using multi-wall type synthesized nano tubes) obtained by both powder metallurgy and stir casting techniques were compared and presented in the subsequent sections.

3.1 Heat Treatment of Specimens

Fig. 1(a) illustrates the variation of Brinell Hardness Number (BHN) of Al-MWCNT (0.5% weight of MWCNT) developed by two production methods compared to the base alloy Al6061. The increase in hardness behaviour of Al-MWCNT composites was due to the greater hardness of dispersed particles of MWCNT. There was no appreciable variation in the hardness value of a green condition which justifies sintering of specimens by powder metallurgy. However, there was a substantial variation in the hardness of samples prepared by stir casting with heat treatment due to uniform distribution of MWCNT hardened particles and less porosity. Hardness values also increased with a nominal value in the case of the as cast and extrusion process of stir casting method compared to the matrix alloy due to less porosity, grain refinement and uniform distribution of MWCNT particles.

Fig. 1(b) shows the variation of BHN of specimens by different quenching methods for Al-MWCNT having a weight 0.5% of MWCNT. As compared to the base alloy, the % increase in hardness for Al-MWCNT composite is a nominal change whereas quenching methods have improved hardness behaviour due to the refining and uniform distribution of dispersed particles in the stir casting matrix material. This increase in hardness properties could be due to the higher hardness of dispersed particles in powder metallurgy and stir casting specimens. As compared to the base alloy the % increase in hardness found varying only in the case of heat-treated stir casting composites.

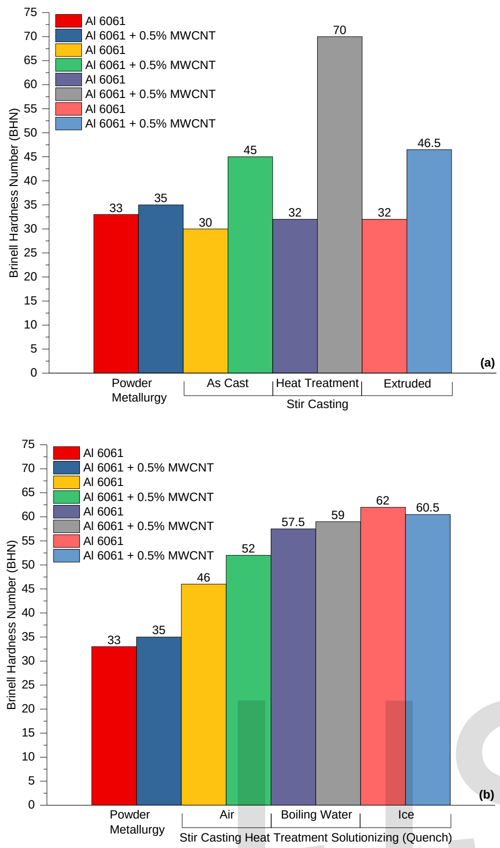

Fig. 1. BHN *vs.* (a) powder metallurgy and stir casting specimen and (b) powder metallurgy and stir casting heat treatment specimen

The effect of age hardening using different quenching methods (air, boiling water, ice) and aging time (zero, two, four hours) on the hardness value of varying compositions of wt.% of MWCNT and base alloy produced by two different production techniques was compared. In the boiling water quench method, maximum hardness is obtained at 0.5 wt.% of MWCNT. For higher wt.% of MWCNT particles longer aging times are preferred to obtain higher hardness strength. In the air quenching method, at 2 hours and 4 hours of aging time, high hardness is obtained for 0.5% and 2.0% wt. of MWCNT particles respectively due to the attainment of saturation level. In the sintered billets manufactured by powder metallurgy, hardness increases with wt.% of MWCNT particles without heat treatment. Therefore, hardness is affected by the age hardening in stir cast techniques as shown in Fig. 2(a), 2(b) and 2(c).

3.2 Tensile Strength Analysis

The percentage increase in the ultimate tensile strength was found to be more predominant in the specimens obtained by the stir casting technique for Al-MWCNT samples with various concentrations of MWCNTs (0.5, 1.0, 2.0 and 3.0 wt.%) produced by two different techniques which are depicted in Fig. 3.

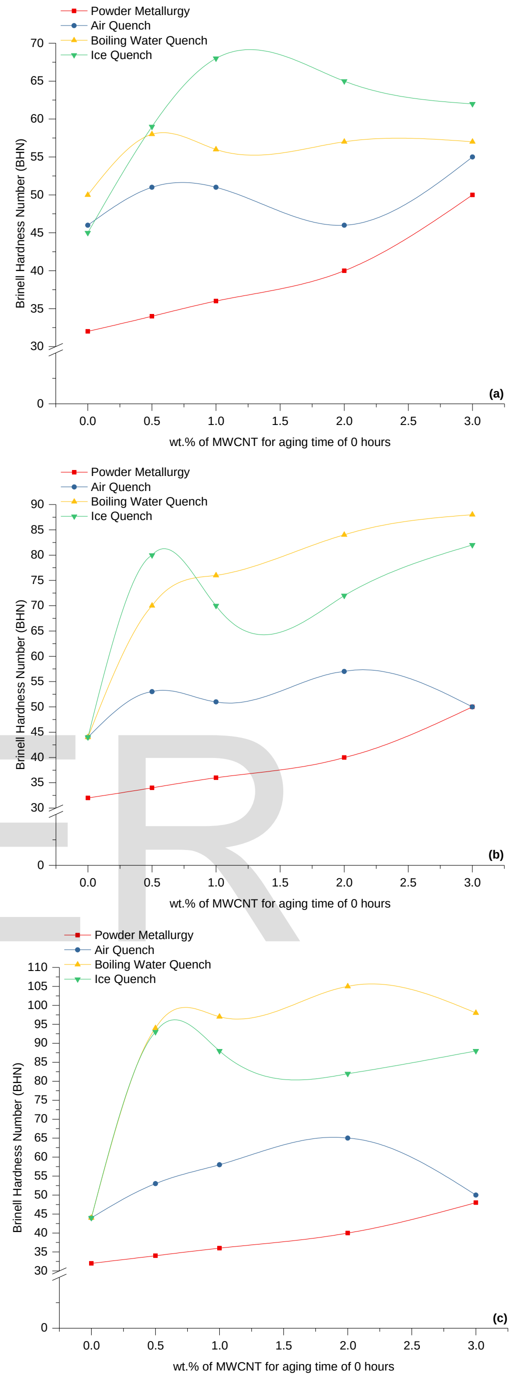

Fig. 2. BHN *vs.* wt.% of MWCNT for aging time of (a) 0 hours, (b) 2 hours and (c) 4 hours

Comparative studies show that ultimate tensile strength values increase as compared with the matrix alloy for both cases by addition of MWCNT particles. This is due to their presence, uniform distribution, and cohesive strength between the hard particles of MWCNT. Stir casting techniques are preferred for higher tensile strength achievement between 1 to 3 wt. % of MWCNT because these particles can act as obstacles to the movement of dislocation and provide protection to the softer matrix in the matrix alloy. Thus, it limits deformation and resists the penetration and cutting of slides on the surface of the composites. Ultimate tensile strength of all the composites was significantly greater than the base alloy characterized by the hard nature of the MWCNT particles.

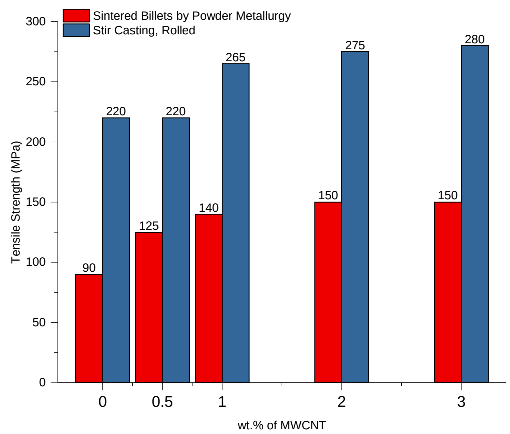

Fig. 3. Tensile strength *vs.* wt.% of MWCNT

3.3 Compression Strength Analysis

The effect of percentage weight of MWCNT dispersed particles on the compression characteristics of aluminium-based MMC for different quenching methods under ageing time from zero up to eight hours are shown in Fig. 4(a), 4(b) and 4(c). The compression strength is a very important mechanical property in withstanding high weight, large deformation with high stiffness because of the requirement for light material in the field of automobiles, aerospace engineering and so on. Compression strength of sintered billets has not shown much variation despite a varying percentage of MWCNT particles. In the stir cast method, there is an increase in the compression strength of the heated and quenched specimen compared to the base alloy matrix at 3% of wt. of MWCNTs. The increase in reinforcement of MWCNT particles decreases the compression strength of the composites at applied loads except in the case of the ice quenching method where for zero hour of aging time, 0.5 and 3.0 of wt.% of MWCNT and maximum compressive strength found at 2 hours of aging time for all composition of MWCNT compared to the base alloy matrix. As compared to the base alloy the % decrease in compression strength for Al-MWCNT composite changed due to its hollow structure and high aspect ratio of MWCNT and these tend to undergo buckling when placed under compression, see Fig. 4(d).

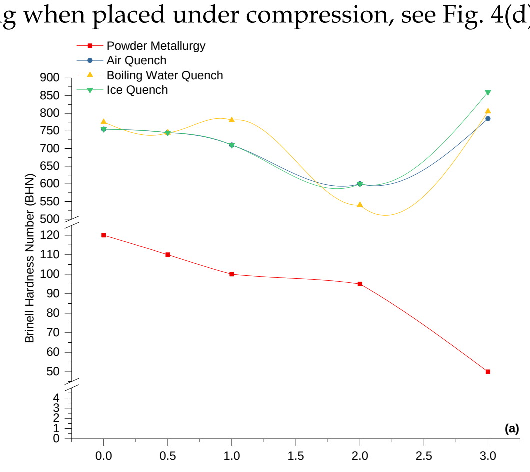

Fig. 4. Compression strength *vs.* wt.% of MWCNT under the conditions of (a) heat treat solutionizing, (b) air quench, (c) boiling water quench and (d) ice quench

4 CONCLUSIONS

The present study has highlighted the need for developing Al-MWCNT metal matrix composites with heat treatment and age hardening to explore the possibility of using different fabrication techniques in enhancing the mechanical characteristics. The MMCs have been prepared successfully using powder metallurgy and stir casting methods. Hardness test, tensile strength and compressive strength of various compositions of wt.% of MWCNTs under different heat treatment and age hardening have been obtained and compared with the mechanical properties of base alloy matrix.

Comparative studies of mechanical properties revealed a decrease in compressive strength due to the hollow structure, high aspect ratio of MWCNT and the tendency to undergo buckling with good improvement in the hardness and tensile strength of the specimens prepared by the stir casting method under different quenching and age hardening conditions. The percentage increase and decrease of the strength were found to be more predominant in the specimens obtained by the stir casting technique due to less porous and fine grains in the microstructure compared to the powder metallurgy technique. Novel processing techniques are to be applied to enhance the mechanical properties especially the compression strength to improve the particle distribution and elimination of porosity.

REFERENCES

[1] Anilkumar, H.C., H.S. Hebbar, and K.S. Ravishankar, Mechanical properties of fly ash reinforced aluminium alloy (Al6061) composites. Intl. Jl. of Mech. & Materials Engg. 6(1): p. 41-45 (2011).

[2] Baughman, R.H., A.A. Zakhidov, and W.A. de Heer, Carbon Nanotubes--the Route Toward Applications. Science, 297(5582): p. 787 (2002).

[3] Mdogangun. sustainable nano. [cited 2016 08/11]; Available from: http://sustainable-nano.com/2014/03/04/turning-plastic-bags-into-carbon-nanotubes/ (2014).

[4] Ruoff, R.S. and D.C. Lorents, Mechanical and thermal properties of carbon nanotubes. Carbon, 33(7): p. 925-930 (1995).

[5] Ebbesen, T.W., et al., Electrical conductivity of individual carbon nanotubes. Nature, 382(6586): p. 54-56 (1996).

[6] Tanaka, K., et al., Electronic properties of carbon nanotube. Chemical Physics Letters, 1994. 223(1): p. 65-68 (1994).

[7] Zhang, Z. and C.M. Lieber, Nanotube structure and electronic properties probed by scanning tunneling microscopy. Applied Physics Letters, 62(22): p. 2792-2794 (1993).

[8] Wong, E.W., P.E. Sheehan, and C.M. Lieber, Nanobeam Mechanics: Elasticity, Strength, and Toughness of Nanorods and Nanotubes. Science, 277(5334): p. 1971 (1997).

[9] Sridhar, I. and K.R. Narayanan, Processing and characterization of MWCNT reinforced aluminum matrix composites. Journal of Materials Science, 44(7): p. 1750-1756 (2009).

[10] Laha, T., et al., Synthesis and characterization of plasma spray formed carbon nanotube reinforced aluminum composite. Materials Sci. and Engineering: A, 381(1–2): p. 249-258 (2004).

[11] Rutkowska, A., et al., Visualisation of electrochemical processes at optically transparent carbon nanotube ultramicroelectrodes, Physical Chemistry Chemical Physics, 13(12): p. 5223-5226 (2011).

[12] Srivastava, D., C. Wei, and K. Cho, Nanomechanics of carbon nanotubes and composites. Applied Mechanics Reviews, 56(2): p. 215-230 (2003).

[13] Deng, C., et al., Preparation and characterization of carbon nanotubes/aluminum matrix composites. Materials Letters, 61(8–9): p. 1725-1728 (2007).

[14] Deng, C.F., et al., Damping characteristics of carbon nanotube reinforced aluminum composite. Materials Letters, 61(14–15): p. 3229-3231(2007).

[15] Esawi, A.M.K., et al., Fabrication and properties of dispersed carbon nanotube–aluminum composites. Materials Science and Engineering: A, 508(1–2): p. 167-173 (2009).

[16] George, R., et al., Strengthening in carbon nanotube/aluminium (CNT/Al) composites. Script Material, 53(10): p. 1159-1163 (2005).

[17] Goh, C.S., et al., Simultaneous enhancement in strength and ductility by reinforcing magnesium with carbon nanotubes. Materials Science and Engineering: A, 423(1–2): p. 153-156 (2006).

[18] Liao, J. and M.-J. Tan, Mixing of carbon nanotubes (CNTs) and aluminum powder for powder metallurgy use. Powder Technology, 208(1): p. 42-48(2011).

[19] Mo, C.B., et al., Fabrication of carbon nanotube reinforced alumina matrix nanocomposite by sol–gel process. Materials Science and Engineering: A, 395(1–2): p. 124-128 (2005).

[20] Li, Q., et al., Improved processing of carbon nanotube/magnesium alloy composites. Composites Sci. and Tech., 69(7–8): p. 1193-1199 (2009).

[21] Bakshi, S.R., et al., Interface in carbon nanotube reinforced aluminum silicon composites: Thermodynamic analysis and experimental verification. Journal of Alloys and Compounds, 481(1–2): p. 207-213 (2009).

[22] Esawi, A.M.K., et al., Effect of carbon nanotube content on the mechanical properties of CNT-reinforced aluminium composites. Composites Science and Tech., 70(16): p. 2237-2241 (2010).

[23] Kwon, H., et al., Investigation of carbon nanotube reinforced aluminum matrix composite materials. Composites Science and Technology, 70(3): p. 546-550 (2010).

[24] Liu, Q., et al., Microstructure and mechanical property of multi-walled carbon nanotubes reinforced aluminum matrix composites fabricated by friction stir processing. Materials & Design, 45: p. 343-348 (2013).

[25] Kumar, G., C. Rao, and N. Selvaraj, Mechanical and Tribological Behavior of Particulate Reinforced Aluminum Metal Matrix Composites - a review. Journal of Minerals and Materials Characterization and Engineering, 10(1): p. 59-91 (2011).

[26] Surappa, M.K., Aluminium matrix composites: Challenges and opportunities. Sadhana, 28(1): p. 319-334 (2003).

[27] Kumar, G., et al., Studies on Al6061-SiC and Al7075-Al2O3 Metal Matrix Composites. Journal of Minerals and Materials Characterization and Engineering, 9(1): p. 43-55 (2010).

[28] Ramesh, A., et al., Comparison of the Mechanical Properties of AL6061/Albite and AL6061/ Graphite MMCs. Jl. of Minerals and Materials Characterization & Engg., 8(2): p. 93-106 (2009).

[29] Nien, Y.-H., The Application of Carbon Nanotube to Bone Cement, in Carbon Nanotubes - Polymer Nanocomposites, S. Yellampalli, Editor. (2011).