A State of the Art Review of Dispersion and Inspection Techniques for Carbon Nanotubes (CNTs) into Matrix Composites

Hussein Zein^{1,2,*} and Yaser A. Al-Shataif¹

¹Mechanical Engineering Department, College of Engineering, Qassim University, Buraidah 51452, Saudi Arabia

²Mechanical Design and Production Department, Faculty of Engineering, Cairo University, Giza 12613, Egypt

This review is provided with a detailed overview of common reinforcement and inspection techniques for producing reinforced composite materials. This study focuses on the state of the art for how used carbon nanotubes (CNTs) as a reinforced material to obtain micro-composite and nano-composite materials. On the other hand, up to now, the major problem is to get a uniform dispersion of the CNTs in the wanted reinforced composite material. So, this review paper emphasizes on several techniques which are utilized for improving the dispersion of CNTs in a metallic powder, such as copper (Cu), aluminum (Al), and magnesium (Mg) as matrix composites. Furthermore, this review presents two different experimental techniques (destructive testing and non-destructive testing) with the purpose of detection of CNTs dispersion in the reinforced composite material. As a result, this review is a helpful tool for all scientists for deciding which technique is more suitable for their research composite materials. [doi:10.2320/matertrans.MT-M2019221]

(Received August 7, 2019; Accepted October 15, 2019; Published December 25, 2019)

Keywords: carbon nanotubes, dispersion, reinforcement techniques, destructive testing, non-destructive testing

1. Introduction

A large number of research efforts were placed into the development of nanotube-based polymer composites¹⁻⁶⁾ with some efforts into the development of ceramic⁷⁻⁹⁾ and metal¹⁰⁻²⁴⁾ composites with CNT reinforcements. Interest into the development of metal CNTs reinforced composites has, however, grown considerably and in particular the carbon nanotube/matrix composites. A number of studies have reported that the use of CNTs reinforcements enhanced the mechanical properties of metal matrices composites.²⁵⁻³⁰⁾ The importance of composite materials reinforced by CNTs and graphene nano-plates (GNPs) comes from using it in many applications due to its high strength properties and lightweight.

1.1 Copper applications

Copper and its alloys are extensively utilized in many industries due to its physical and mechanical properties. They are used in many applications, for example, electrical, marine, automotive, aircraft, and aerospace applications. Also, due to new advancements in electronics technology, the need for a material with higher strength and higher electrical conductivity is increased. The copper alloys are the commonly used materials for these purposes.³¹⁻³⁵⁾

1.2 Aluminum applications

Aluminum alloys and aluminum matrix composites have used in numerous applications in many industries such as automotive, aircraft, aerospace, military, electricity, and marine parts, such as engine, cylinder blocks, pistons, and piston insert rings.³⁶⁻³⁸⁾ Aluminum alloys and their composites have advantageous properties for industrial applications, such as high specific strength,³⁹⁾ good corrosion resistance,⁴⁰⁾ high thermal conductivity,⁴¹⁾ low coefficient of thermal expansion,³⁸⁾ low electrical resistivity,⁴²⁾ and high damping capacity.⁴³⁾ So, aluminum alloys are the most

important material in the aircraft construction industry, such as, in the aircraft body and airfoil wings.^{44,45)} Also, Aluminium composite materials (ACMs) have excellent properties for wear resistance, temperature creeps resistance and fatigue strength.³⁸⁾ ACMs are substituted with cast iron and bronze alloys where the tribology properties are very high for wear and seizure resistance.^{46,47)} Applications of aluminum alloys in the automobile and aircraft industries have been created with regard to decreasing fuel consumption and insulating the environment, where they can effectively substitute steel and cast iron components,⁴⁸⁾ for example in, cylinder blocks, brake drums, cylinder liners and drive shafts, with the aim of decrease fuel and pollution.³⁶⁾ Aluminum alloys have low mechanical properties and tribological properties. This can be overcome by inserting ceramic particles, such as Al₂O₃,⁴⁹⁾ silicon carbide (SiC),⁵⁰⁾ BN,⁵¹⁾ and carbon nanotubes (CNTs) materials depending on their applications.

1.3 Magnesium applications

Magnesium has great attention due to its material density (1.74 g/cm³) which is lighter in weight than aluminum density (about 35%).^{52,53)} Also, it has a high strength to weight ratio and specific modulus with good machinability.⁵⁴⁾ Magnesium comes in an eighth of its abundance on the earth⁵⁵⁾ and has the lightest structural metal material with high chemical activity and energy density.⁵⁶⁾ All of those features, encourage aircraft industry, automotive⁵⁶⁾ and field of battery^{57,58)} to use it widely. On the other hand, the magnesium has low corrosion, wear resistance and inferior ductility due to its hexagonal closed packing (HCP) structure.^{59,60)} Researchers have investigated those problems by improving magnesium composites with reinforcements of particulate.⁶¹⁻⁶³⁾ Al₂O₃, SiC, and B₄C are commonly used in the scale of micro-size particulate reinforcements but those reinforcements improve the modulus and hardness while they stabilize ductility.⁶⁴⁾ In the main time, Nano-size reinforcement such as CNTs and nanoparticles have proven enhancement in mechanical properties.⁶⁵⁾

*Corresponding author, E-mail: dr.husseinzein@qec.edu.sa

Magnesium is the third most commonly used structural metal following iron and aluminum.⁶⁶⁾ Magnesium is used in super-strong, lightweight materials and alloys. For instance, when implanted with silicon carbide nanoparticles, it has an extremely high specific strength.⁶⁷⁾ In the past, magnesium was one of the major aerospace structure metals and was utilized for German military aircraft since World War I and widely used for German aircraft in World War II. The Germans gave the name “Elektron” for magnesium alloy, a term which is still utilized today. In the marketable aerospace industry, magnesium was generally limited to engine-related elements, because of fire and corrosion problems. Now, magnesium alloy is utilized in aerospace is increasing, driven by the importance of fuel economy.⁶⁸⁾ Improvement and assessment of new magnesium alloys carry on notably Elektron 21, which (in the evaluation) has been proven appropriate for the aerospace engine, internal, and airframe components.⁶⁹⁾

From the 1950s to the current time, magnesium alloys and magnesium matrix composites have utilized in many applications in many industries such as an automobile, aircraft, aerospace, military, and electrical components. For the automobile industry, due to high corrosion resistance and high strength in the new magnesium alloys, these alloys are extensively utilized for manufacturing wheels, seat frames, steering wheels, crankcase, and transmission housing. As a result of light weight and high strength properties for magnesium composites, it is used for fabricated aircraft, and aerospace components, such as cast helicopter transmission housings, landing wheels, gearbox housings, and helicopter rotor fittings. Due to low weight and excellent mechanical and electrical properties, magnesium is extensively utilized for the production of mobile phones, laptop, tablet, and camera casings. This trend is a result of enhancement in corrosion resistance of magnesium alloys and development of new alloys withstanding creep, fatigue and elevated temperatures. For environmental protection, magnesium alloys and their composites have many features, such as more fuel-efficient transportation, better recycling capabilities, and better emission protection.^{70–83)}

2. Carbon Nanotubes (CNTs)

In 1991, the carbon nanotubes (CNTs) have been discovered by Iijima.⁸⁴⁾ Because of its extraordinary mechanical properties such as tensile strength and elastic modulus around a (150 GPa) and (1 Tpa) respectively. Since then, a considerable amount of research has been carried out on CNTs which has shown them to have very peculiar electronic and thermal properties such as electric current capacity that exceed that of copper wires by 1000 times,¹⁸⁾ a thermal conductivity greater than that of diamond,⁸⁵⁾ etc. On account of those remarkable characteristics, the CNTs become superior nano-filler (reinforcement) of composites to improve its properties.⁸⁶⁾ According to their shape, the carbon nanotubes (CNTs) were classified into two main categories: (1) single-walled carbon nanotube (SWNT) which contain a one-atom-thick sheet of carbon (graphene) rolled to the tube, and (2) multi-walled carbon nanotubes which contain many graphene layers.⁸⁷⁾ There are some studies on

the influence of geometrical parameters of carbon nanotubes for both types (single-walled and multiwalled) on its mechanical and electrical properties.^{88,89)} Also, Mohsen *et al.* studied the influence of geometrical parameters of multi-walled carbon nanotubes on the mechanical strength and the dispersion of CNTs of cement composites.⁹⁰⁾ Some studies have shown a reinforcement of CNTs into composite materials which have to increase the mechanical properties.^{91,92)} Sónia Simões *et al.* (2017) reinforced MWCNTs into Aluminium due to their results; there was a significant increase in mechanical properties.⁹²⁾ Z.Y. Liu *et al.* (2017) used Al–5Mg composites as a matrix and the results were positive.⁹³⁾ On the other hand, G.Q. Han *et al.* (2016) demonstrated in his research the CNTs reinforced magnesium alloys decrease the strength and yield but improve the ductility of magnesium.⁹⁴⁾

3. Reinforcement or Dispersion Techniques

A metallic powder as matrix composites can be acquired by dispersing reinforcement particles in metallic powder utilizing solid or liquid phase techniques. Carbon nanotubes (CNTs) are favorable reinforcements for lightweight and high strength composites due to their exceptional properties. However, until now, the major difficulty is to get a uniform dispersion of the CNTs in the required material matrix. Relatively a few techniques have been researched to assist to improve the dispersion of CNTs in a polymer matrix. But not much research has been performed on how to disperse CNTs in metal matrices.⁹⁵⁾

The Effectiveness of CNTs on the matrix composites has attracted many researchers. CNTs have turn out to be well-known in the modern materials due to its reinforced enhancement of the mechanical, the thermal, and the electrical properties of Cu and Al,^{94,96)} pure the Mg,⁹⁷⁾ Mg–6Al alloy,⁹⁸⁾ and AZ31/AZ81 alloys.^{99,100)} Figure 1 shows a flowchart of reinforcement CNTs into the metallic matrix in the shape of powders.

Fig. 1 Flow chart of reinforcement CNTs into Metallic Powders.

Table 1 Techniques of CNTs reinforcements into metallic powders.^{95,102–115)}

Technique Name	Technique's Description	Advantages	Disadvantages	Figures
Mixing Techniques	Low Energy Ball Milling	<ul style="list-style-type: none"> • Suitable for research purposes. • Suitable for Solid, dry and wet mixture. 	<ul style="list-style-type: none"> • Breaking the CNTs • A very small amount of powder. • A relatively long time of milling. • Poor mixing [116]. 	Figure 2
	Arc Melting Technique	<ul style="list-style-type: none"> • No need for a secondary process. • Low porosity. • Low energy consumption. • Faster operation 	<ul style="list-style-type: none"> • Big crystal grains 	Figure 3
	Mechanical stirring	<ul style="list-style-type: none"> • Better results in the Semi-solid condition of the dispersed phase. • Simple and low cost. 	<ul style="list-style-type: none"> • The dispersed phase is limited. • Mixtures not always perfectly homogenous. 	Figure 4
Forming or Compaction Techniques	Hot Pressing	<ul style="list-style-type: none"> • High density (low porosity) • Less sensitive to powder's size shape and distribution. • Strong bonding. 	<ul style="list-style-type: none"> • Take a lot of time to heat the mold. • Expensive technique because of the heating and pressure system. • Powders Oxidation • Bonding powder particle inside the cavity. 	Figure 5
	Cold Pressing + Sintering.	<ul style="list-style-type: none"> • Highest safety. • Long life of the die. • Reduce mechanical stress. • Massive production. • Closed tolerance. 	<ul style="list-style-type: none"> • Effect by powder's size shape and distribution. • Limit on the complexity of shapes • The produced sample called Green Compact, Need a secondary operation like sintering. 	Figure 6
	Spark Plasma Sintering.	<ul style="list-style-type: none"> • Uniform and fast sintering process. • Low grain growth • Sintering and compaction in one operation. 	<ul style="list-style-type: none"> • Only simple symmetrical shapes can be prepared. • Expensive technique. 	Figure 7
	Infiltration	<ul style="list-style-type: none"> • Very low residual porosity • Complex shapes can be fabricated. • Low cost. • Short production time. 	<ul style="list-style-type: none"> • The high temperature of molten powders may cause damage to the fibers. • Lower mechanical properties of the resulting composite 	Figure 8

In the last few years, the researchers have been facing two major difficulties in reinforced CNTs into the material: (1) homogenous dispersion of CNTs, and (2) the perfect interfacial bond between CNTs and the material matrix which mainly affect the load transfer which produces high strength material.¹⁰¹⁾ Techniques of CNTs reinforcements into metallic powders are divided into two categories: (1) Mixing Techniques, and (2) Forming or Compaction Techniques. Table 1 presents all the details of these Techniques. While Table 2 displays the comparisons between the results, type of reinforcement and matrix, the used technique, and the description techniques of CNTs.

4. Research Work on Experimental Methods for the Inspection Process

The current work presents two different experimental methods (destructive and non-destructive) with the purpose of emphasis more researches in this specific field of investigation.

4.1 Destructive testing

In 2003, the primary goal of Thostenson and Chou¹⁴⁴⁾ was to enhance understanding of the structure/size influence of the CNTs on the stability of composites strengthened with nanotube. They came to the conclusion that composite stability is depending on the CNT dimensions.

In 2007, Bakshi *et al.*¹⁴⁵⁾ designed MWCNTs reinforced UHMWPE composite films by electrostatic spraying accompanied by consolidation. Their experimental test demonstrated a decrease in stress to failure from 14.3 to 12.4 MPa, 82% increase in Young's modulus, and strain to failure from 3.9% to 1.4% due to 5% adding of MWCNT. In 2010, Kulkarni *et al.*¹⁴⁶⁾ discovered numerically and experimentally the elastic behavior of a CNT composite reinforced. A multi scale modeling method and the finite element modeling were used for discovering the characteristics of the CNT composite reinforced. By using a multi scale simulation, Savvas *et al.*¹⁴⁷⁾ discovered the effect of interfacial shear stability on the damping and mechanical characteristics of CNT composite reinforced. Their mathematical results

Fig. 2 Schematic diagram of (a) conventional ball milling, (b) Planetary Ball Milling.

Fig. 3 A descriptive diagram of the arc melting Process.

Fig. 5 Schematic diagram of a hot pressing process.

Fig. 4 Schematic diagram of mechanical stirring.

Fig. 6 Schematic diagram of a cold-pressing process.

Fig. 7 Schematic diagram of Spark sintering plasma (SPS).

exposed the substantial impact of the interfacial shear stability and the influence of tube waviness on the damping performance of the CNT composite reinforced. Subsequently, Tsai *et al.*¹⁴⁸⁾ suggested an enhanced surrogate model for checking the stability of CNT reinforced nanocomposites. They also utilized a set of data for MWCNT bison maleimide nanocomposite to study the usefulness of the suggested surrogate method. In conclusion, they calculated the theoretical composite modulus with micromechanical models and measured the experimental modulus by tensile tests. Their findings revealed an enhanced predictive ability in comparison with the traditional micromechanical model. The major target of Bhuiyan *et al.*¹⁴⁹⁾ was to comprehend the reinforcing effectiveness of CNTs in polymers by using finite element modeling. The uniqueness of their work was that the possibility distribution function of CNT diameter, orientation, disposition and waviness, expected through graphic analysis, were integrated into the finite element model. Their graphic analysis technique used scanning electron microscopy (SEM) images of the CNT/polypropylene composites produced by melt mixing and injection modeling.

Laine *et al.*¹⁵⁰⁾ primarily concentrated on sandwich structures produced with polymeric foam core reinforced to get their transverse shear stiffness. In their research, a numerical solution was produced taking into consideration a 2-D unit cell and using the basic principle of energy equivalence. Finally, they likened their numerical results with

experimental values producing from three-point bending tests carried out with different volume fraction of reinforcements. By using a unique technique, Li *et al.*¹⁵¹⁾ manufactured CNTs reinforced Mg matrix composites. After hot extrusion, they checked out the effect of NTs on the microstructure and mechanical performance of an Mg–6Zn matrix. Their results confirmed that the majority of CNTs dispersed uniformly and separately in the composites, and great interfacial bonding was accomplished. In 2015, Alizadeh *et al.*¹⁵²⁾ created specific composites reinforced with CNTs and boron carbide (B4C) by a powder metallurgy method. Also, they studied the surface roughness, wear resistance, hardness, and creep performance of the samples. They demonstrated that as B4C content raises, the hardness values of the composite improve. Additionally, the results of creep tests showed that the addition of NTs increases the creep rate of the Al5083 alloy; however, adding B4C reduces its creep rate. Duarte *et al.*¹⁵³⁾ introduced a novel technique to compose a novel class of closed-cell reinforced metal foams that synergistically is exploring the important properties of both metal foams and CNTs. Their microstructural analysis showed non-agglomerated, well distribution, stretched, and directionally aligned MWCNTs within the Al-matrix of the foams.

4.2 Non-destructive testing

The most significant non-destructive studies relating to the expectation of the mechanical behavior of reinforced composites are shown in this section. In 2003, Ning *et al.*¹⁵⁴⁾ checked out the mechanical behavior of SiO₂ matrix composites reinforced by CNTs. In their analysis, SiO₂ glass powder and CNTs were mixed by ultrasonication in an ethanol solution. Also, they checked out the influence of the NTs content on the mechanical properties. Their major reinforcing methods consist of CNTs pulling out, crack deflexion and bridging. Finally, they detected some faults and aligning the orientation of CNTs in the matrix which were the affecting parameters on the mechanical properties of composites. Subsequently, Ruan *et al.*¹⁵⁵⁾ documented the utilization of MWCNT to reinforce and toughen gel spun UHMWPE fibers. By using a mixture of high-resolution SEM and micro-Raman spectroscopy, they studied the mechanism of reinforcement. Finally, they established that the stability was enhanced via the bearing impact at the tensile strength.

Fig. 8 Schematic diagram of the Infiltration method.

Table 2 The comparisons between the results, type of reinforcement and matrix, the used technique, and the description techniques of CNTs.

Ref.	CNT Type	Dimensions of CNTs	Nanomaterial (Matrix)	Technique's Name	Description	Results
[117]	MWCNTs	Dia: (8-15nm) Length: (0.5-2 μ m)	Cu	<ul style="list-style-type: none"> Chemical vapor deposition. Magnetic stirring Cold press process Microwave sintering Cold rolling process. Annealing process 	<ul style="list-style-type: none"> The CNTs were acid treated in a concentrated H₂SO₄ and HNO₃ solution at 80 °C for 2 h. then CNTs were sonicated for 2 h in distilled water. Then, adding Cu (CH₃COO)₂.H₂O into the suspension and sonicated for 2 h to form CNTs/Cu ion precursor. Then, the precursor was vaporized by magnetic stirring at 100 °C to get a dried mixture which was calcined in air at 350 °C for 1 h. After that the mixture was cold-pressed under the 300 MPa uniaxial pressure for 120 s then sintered at 1000 °C for 10 min then furnace cool. After that, the samples were cold rolled then annealed at 600 °C for 2 h. 	The subsequent rolling procedure assists better microstructure and performance of sintered composites which displays a tensile strength of 218 MPa, the elongation of 37.75%, and the electrical conductivity of >98% IACS compared to pure copper
[37]	MWCNTs	Dia: (30-50 nm) Length: (1-2 μ m)	Cu-Ti	<ul style="list-style-type: none"> Gas atomization process Reduction process. Hot compaction process (Hot-Press process). 	<ul style="list-style-type: none"> Alloy powders produced by gas atomization. Then CNTs was mixed with Cu-Ti alloy powders by low energy ball milling at a rotation rate of 150 rpm for 4 h. Then, CNTs/Cu-Ti composite powders were acquired by reduction at 573 K for 2 h in a hydrogen atmosphere. CNTs/Cu-Ti composite powders compacted in for 30 min at 850 °C and 70Mpa 	(Ultimate tensile strength (UTS) 352 MPa, elongation 28.2%, the UTS is 39% higher than that of the Cu-Ti alloy, and the ductility increased significantly by 62 %.)
[118]	MWCNTs	Dia: (15 nm $\pm$ 5 nm)	(Cu-1.0Ti) alloy powders	<ul style="list-style-type: none"> Molecular Level Mixing (MLM) Magnetic stirring process Ultrasonic dispersion process. Gas atomization process 	<ul style="list-style-type: none"> The pristine CNTs was impregnated in concentrated sulfuric acid and nitric acid then heated in water for 6 h at 60 °C the dried for 24 h at 250 °C. Ultrasonic dispersion process takes a place to impregnated the CNTs in deionized water. CuAc was dissolved in water and stirred for 30 min the CNTs added to CuAc and heated in water for 5 min at 75 °C. After that, 4 Mole of NaOH was added then stirring for 10 min and add 2 Mole of glucose. The CNTs/Cu₂O was successfully obtained. Cu-1.0Ti alloy powders were ball milled in alcohol for 10 h and 300 rpm. CNTs/Cu₂O mixed with flaked alloy powders by ball milling for 2 h but low energy. The mixture was hot pressed at 50 MPa and 800 °C for 30 min. 	Better dispersion, higher compatibilities of the matrix with CNTs, and enhanced interfacial bonding make 0.8% CNTs/Cu-Ti composites exhibit the increments of UTS being 35.15%,
[119]	MWCNTs		Iron powder (20-200 μ m)	<ul style="list-style-type: none"> Ball milling process Cold Compaction Sintering process 	<ul style="list-style-type: none"> The iron powder and CNT, with liquid paraffin used as a binder, is blended by the ball milling process. After that, the powder was compacted in a hydraulic press. The compacted sample, named green sample, was sintered with a Nitrogen atmosphere. The sintered component with the various composition of CNT is fabricated. 	<ul style="list-style-type: none"> As carbon nanotube increase the compressive strength of the material also improved. 0.75 wt. % CNT yield a maximum compressive strength of 745 MPa. For 0.75 wt.% CNT have the high hardness value 423HV compared to pure Fe which is 328.66.
[120]	MWCNTs		Powders of aluminum (22 $\pm$ 11 μ m)	<ul style="list-style-type: none"> Dispersion ultrasonic bath. Dispersion ultrasonication Dispersion and mixing ultrasonication Cold press process Sintering process 	<ul style="list-style-type: none"> Route 1: The CNT were dispersed in ethanol using an ultrasonic bath for 15-90 min. The CNTs were mixed with Al powders in a Turbula for 60–600 min. Route 2: the CNT were dispersed in isopropanol by ultrasonication for 15–60 min at 20,400 kHz Route 3: The CNT and Al powders were ultrasonicated in isopropanol for 15 to 60 min at 20,400 kHz After that The materials were uniaxially pressed with 100 to 300 MPa and sintered at 500 to 640 °C for 30 to 90 min in a vertical furnace under a vacuum. 	Nano-composites with 0.75 wt.% of CNT exhibit well dispersed and embedded nanotubes and the highest hardness and tensile strength 50HV and 196Mpa respectively. The observed 200% increase in the tensile strength attested
[121]	MWCNTs	Dia:	Aluminum	<ul style="list-style-type: none"> Ball milling process 	<ul style="list-style-type: none"> Aluminum powders and CNT were 	There was no improvement in

Continued on next page.

Subsequently, Rokni *et al.*^[156] suggested a new principle for enhancing the dynamic response of composite structures. Based on the obtained optimum distribution, they created composite plates and evaluated their effective stiffness, constituent frequencies, and damping ratios by means of

free vibration and static deflection tests. They established that the optimum distribution of NTs lead in an increase of 10.4% and 21.9% in the fundamental damped natural frequency values and the efficient Young's modulus, respectively.

Park *et al.*^[157] carried out a research on explaining

Continued.

		(10-30 nm) Length: (15-30 μm)	(74 μm)	<ul style="list-style-type: none"> • Cold pressing process • Sintering process 	blended by a ball-milling process for 30 min using steel balls at 400 rpm. • Then compacted under a load of 150 kN then the green samples sintered.	hardness of the composite on the addition of CNT. The compressive strength of the composite was increased by 143.58 MPa
[91]	MWCNTs	Dia: (15-35 nm)	Powders of aluminum (50-60 μm)	<ul style="list-style-type: none"> • Ultrasonication process • Ball milling process 	• The CNTs were untangled previously by ultrasonication in propanol for 15 min. • And, then mixed with Al powders by ball milling in propanol during 6 h.	The use of ball milling for mixing CNTs with Al powders can improve the CNTs dispersion by reducing the size of the agglomerates.
[92]	MWCNTs	Dia (19-25nm)	Aluminum powders (65 μm) Nickel powders (60 μm)	using ultrasonication as the dispersion	• The MWCNTs were dispersed and mixed with metallic powders in isopropanol using an ultrasonicator for 15 min. • Then, the mixtures were dried and uniaxially pressed with 300 MPa for Al/CNTs and 900 MPa for Ni/CNTs. • After that, the sintering process was applied for the samples at 640 °C for 90 min under a vacuum atmosphere.	The better dispersion results were observed for the nanocomposites produced with 1.00 vol % of CNTs leading to the highest hardness values. The 50% hardness increase demonstrated the strengthening effect of the CNTs
[122]	CNTs	Dia: (60–100 nm) Length: (5–15 μm)	Al powders	<ul style="list-style-type: none"> • Solution ball milling (SBM) • Spark Plasma Sintering Process 	The isopropyl alcohol (IPA) based solution with -1 wt.% zwitterionic surfactants [18] was used to obtain 1 wt.% CNT solution. Then, the Al powder and CNTs were mixed using a planetary ball milling machine with a speed of 200 rpm for 60 min. Then, dried in an oven at 353 K for 30 min. after that, the sparking plasma sintering process at a temperature of 600 °C for 30 min and pressure of 30 MPa was applied followed by hot extrusion.	The tensile strength of the Al matrix was noticeably enhanced by CNT additions agreeing with the potential strengthening effect predicted by the load transfer mechanism.
[93]	MWCNTs	Dia: (10 nm) Length: (5 μm)	Al-5Mg (Dia: 10 μm)	<ul style="list-style-type: none"> • Ball milling process. • Cold-Compaction. • Hot-press process. • Hot extrusion process • Annealing process 	• CNTs were ball milled with Al-5Mg alloy powders at 300–450 rpm for 2–8 h. • The mixture cold-compacted in a cylinder die, degassed and hot-pressed at 753 K for 1 h then the samples were hot extruded at 723 K. CNT/Al-5Mg composites was annealed at 753 K for 1–4 h • Then, room cooling.	The elastic modulus of the CNT/Al-5Mg composites increased as CNT concentration increased, which can be predicted by the Tsai-Halpin equation. The tensile strength of the composites showed a significant increase compared with the matrix alloy.
[86]	Graphene nanosheets GNSs		Cu powders	<ul style="list-style-type: none"> • Hummers' method • Ball milling process • Hot-press sintering process. 	• The GO nanosheets were dispersed in ethanol for 1 h by the ultrasonic process then added Cu powder. • The mixed powders were obtained in the vacuum drying oven at 80 °C for 24 h to remove ethanol. • After that, the mixture ball-milled at a rotation rate of 400 rpm in an argon atmosphere. • Then, the mixture was pressed and sintered simultaneously at 25 MPa and 850 °C for 1h in a vacuum atmosphere.	When the content of GNSs in the composite is 0.5 wt%, the UTS and ϵ of the composite are the highest. The fracture mechanism changes from ductile to brittle with increasing the GNS contents
[115]	GNSs	Dia: 7.05 μm	Al6063 powder (Dia: 4.7 μm)	<ul style="list-style-type: none"> • High energy ball milling process • Compaction process. • Pressure Infiltration. • Hot Extrusion process 	• Adding The GNSs/Al6063 composite with 500 ml volume zirconia vial into planetary ball milling machine for 1 to 4 hours at a velocity of 150 rpm. • After that, The mixture was pre-compacted and preheated for 700 °C. • Then, a hot-extrusion process was applied.	The Highest tensile strength of 276 MPa was obtained only with 0.3 wt% GNSs, which was 22.5% enhancement over the unreinforced Al matrix with the same preparation process and no decrease in elongation.
[123]	MWCNTs	Dia: 18nm length: 1.6–2.2 μm	Cu ₂ O	<ul style="list-style-type: none"> • Microwave plasma chemical vapor (MPCVD) method. • Deposition. • Ultrasonic with isopropylalcohol. • Sintering process. 	• Ultrasonic for 20 min to agitate the CNTs in isopropylalcohol (IPA) for 20 min. • Then, immersing in a solution of H ₂ SO ₄ /HNO ₃ (3:1 ratio) in order to produce active sites for subsequent reaction with the Cu ions. • Then, add Cu(ac) H ₂ O, Aldrich then sealed and purged in an argon-protected environment for 2 h.	• Mechanical responses (critical strength and hardness) of the CNT/Cu composites depend on both the matrix grain size and the CNT content. • However, of the two factors, the enhanced mechanical response is dominated by CNT addition rather than grain size reinforcement • Addition of CNTs to the Cu matrix improves the wear resistance by a minimum of 40% compared to that of a pure Cu sample
[124]	CNTs	Dia: 20–40 nm Length: 10–30 μm	Cu thickness: 100–120 μm	<ul style="list-style-type: none"> • Composite electrodeposition • Spark plasma sintering (SPS) 	• The CNT dispersant was composed of 10 wt% of CNTs, non-ionic surfactants, and H ₂ O. • Two copper plates were used as the	The YS and UTS of the composites deposited under a current density of 1 A·dm ⁻² are 128 MPa and 244 MPa, respectively, which

Continued on next page.

numerous mechanisms such as the generation of dislocations from the thermal mismatch, the Orowan looping system, and load transfer for clarifying the enhanced characteristics of CNTs reinforced Aluminum. The formulation of covalent

bonds between Aluminum and CNTs walls was verified by Raman spectroscopy, transmission electron microscopy (TEM), and X-ray diffraction measurements. Subsequently, Wang *et al.*^[58] researched the relationship between the filler

Continued.

				<ul style="list-style-type: none"> • Cold pressing process • Sintering process 	<p>anodes and a titanium plate was used as the cathode.</p> <ul style="list-style-type: none"> • The as-prepared films, with a thickness of 100–120 μm, were cut into circles with a diameter of 20 mm. • Then, cold pressing was applied then sintered under vacuum. 	
[108]	MWCNTs	Dia: 9.5nm Length: 1.5 μm	6063 Al alloy powders Dia: 94 μm	<ul style="list-style-type: none"> • Powder metallurgy process • Spark plasma sintering (SPS) • Hot extrusion 	<ul style="list-style-type: none"> • A6063 raw powders were mixed with isopropyl alcohol (IPA) solution containing 1 wt.% un-bundled CNTs, • And the elemental mixture slurries were stirred in the pot. • Then, CNTs coated Al alloy composite powders were compacted into the columnar billet via spark plasma sintering (SPS) process at 550 $^{\circ}\text{C}$ for 30mins under the pressure of 30MPa in a vacuum. • Then, hot extruded. 	<ul style="list-style-type: none"> • The as-extruded composite materials with 0.56 and 1.22 vol.% CNTs reveal yield stress (YS) of 134.5 and 135.2 MPa, respectively. There is a very small difference in YS in the composite between 0.56 and 1.22 vol.% CNTs. • In addition, they indicate a small increment of mechanical strength compared to the monolithic alloy with no CNT reinforcement showing 128.7 MPa YS.
[125]	MWCNTs -(type A) -(type B)	Dia(A): 15nm Length(A): 0.5–1 μm . Dia(B): 40nm Length(B): 3–10 μm .)	Pure Mg (99.5% purity) AZ31B Mg alloy powder	<ul style="list-style-type: none"> • Ultra-sonic vibration • The de-binding process was • Spark plasma sintering • Hot extrusion 	<ul style="list-style-type: none"> • Ultrasonic vibration was used to disperse the agglomerated CNTs in ethanol, followed by dipping powder into a zwitterionic surfactant solution, • And subsequently dried in the oven at 353K for 10.8 ks in an argon gas atmosphere. • Each powder coated with CNTs was consolidated by a spark plasma sintering process. • The samples were heated at 673K for 180s in argon gas, and immediately put through hot extrusion. 	When approximately 1vol.% CNTs were added, the extruded pure Mg and AZ31B alloy composites displayed an extremely large increase of the tensile yield stress of 25–40%, compared to Mg materials containing no CNT. the elongation was less than 5%, and the composites exhibited a very poor ductility
[102]	graphene nanosheets (GNS)		AZ91 alloy powders 70 μm and 99.9% in purity.	<ul style="list-style-type: none"> • Modified Hummers method • Ultra-sonic vibration • hyper mechanical-stirring and ultrasonic process. • Press process • Sintering process • Hot extrusion 	<ul style="list-style-type: none"> • The GNS were dispersed into ethanol by ultrasonication for 2 h. • AZ91 powders were added in ethanol under the argon atmosphere with the following ultrasonication for 30 min to obtain a suspension of AZ91 powders. • The ultrasonicated GNS solution was slowly dropped into the suspension of AZ91 powders. • Then, it followed by pressing, sintering and hot extrusion. 	Filling 0.5 wt. % of GNS, the yield strength and elongation of the composite increased by 76.2% and 24.3%, respectively as compared to the matrix alloy
[109]	MWCNTs	Dia: 5–30 nm Length: 1–10 μm	AZ91 alloy powders 75 μm and 99.5% in purity.	<ul style="list-style-type: none"> • Ultrasonication process. • Mechanical stirring process • Mechanical mixing process • Sintering process • Hot extrusion 	<ul style="list-style-type: none"> • First, metal powders were mixed in ethanol solvent using a mechanical agitator under atmospheric air. • Second, MgO@CNTs were dispersed into ethanol by ultrasonication for 2 h. • Then MgO@CNTs and AZ91 were then mixed together and mechanically stirred for 1 h to form AZ91-MgO@CNT composite suspension, which was filtered and dried at 313 K under vacuum for 12 h. • Then, the mixtures were compacted in a 40 mm wide and 200 mm high cylinder mold under a hydraulic pressure of 120 MPa then sintered in a tube furnace at 873 K for 2 h under Ar atmosphere then hot extrusion was applied. 	The yield strength and elongation of AZ91-3.0MgO@CNT composite were enhanced by 69.0% and 22.9%, respectively, when compared with the AZ91 alloy
[110]	MWCNTs	Dia: 20 nm Length: 5 μm	Al2024 powder (99.5% purity)	<ul style="list-style-type: none"> • High-energy ball milling • Cold /hot press • Sintering 	<ul style="list-style-type: none"> • The ball-to-powder weight ratio was 15:1, and the chamber was stirred by horizontal impellers attached to a vertical shaft rotating at a controlled speed of 500 RPM for 5 h in which water was circulated in the chamber surface. • Then uniaxial cold Press process at 560 MPa for 10 min in a cylindrical mold. • For hot pressing, the mixture was press into the mold at 375 MPa and 530 $^{\circ}\text{C}$ for 1.5 h. • Then, sintering at 500 $^{\circ}\text{C}$ for 24 h. 	Tensile and fatigue strength of the Al2024/MWCNT composites increases with increasing the MWCNT content. Al2024/4 vol.% MWCNT composite shows the notably enhanced fatigue strength of 600 MPa at the 2.5×10^6 cycles and the ratio of tensile strength to fatigue strength of 0.78.
[111]	MWCNTs	Dia: 5–20 nm	Aluminum alloy AA5083	<ul style="list-style-type: none"> • Compo-casting method 	Compo-casting were used to produce the composite with uniformly dispersed	Hardness increased from 74 BHN for the alloy AA5083 to 84 BHN for

Continued on next page.

orientation and the resulting relative permittivity of nano-composites reinforced models to achieve an appropriate forecast of the efficient dielectric constant. It was established that the orientation angle factor along the applied electric

field is the major parameter to figure out the efficient dielectric constants. Furthermore, a comparison between the proposed experimental data and random orientation models were carried out to clarify the ability of the suggested models.

Continued.

		Length: 1–10 μm			MWCNT reinforcement in Aluminium alloy AA5083 using stir casting apparatus.	1.75 wt% of reinforced composite and considerably increased for 1, 1.25 and 1.5 wt% addition of MWCNT. -AA5083/MWCNT composite have better corrosion resistance than the AA5083 alloy in HCl (dil) at room temperature
[126]	CNT		Pure Al powders (-200 mesh)	<ul style="list-style-type: none"> In-situ chemical vapor deposition. Powder metallurgy 	Combination of in-situ chemical vapor deposition and powder metallurgy using titanium hydride as a blowing agent to produce Al alloy foam with the improvement of the pore uniformity and reduction of the pore size.	The plateau stress (average stress between 20% and 40% strain) is enhanced from 14.98MPa to 29.25MPa while the energy absorption capacity (50% strain) rises from 7.06MJ/m ³ to 13.66 MJ/m ³ .
[127]	MWCNTs	Dia: 10–30 nm Length: 1–10 μm	Cu–10Sn alloy powder	<ul style="list-style-type: none"> Ball milling. Compaction of the composite powder Sintering Repressing. 	<ul style="list-style-type: none"> The Cu–Sn alloy powder and each mass fraction of CNTs were balls milled in a planetary ball mill at 200 r/min. The mass ratio of the ball to powder is 8:1. the powders were milled for 3 h. powders were cold- compacted for about 5 min under a pressure of 350 MPa. Then, sintered under argon protected atmosphere at 800 °C for about 2 h. 	At an applied load of 5 N, the coefficient of friction and wear loss of 2% CNTs reinforced Cu–Sn alloy nanocomposite decrease by 72% and 68%, respectively,
[128]	MWCNTs	Dia(A): 15–35 nm, Length(A): 10 μm Dia(B): 9.5 nm, Length(B): 1.5 μm	Aluminium 60 μm	<ul style="list-style-type: none"> Ultrasonication process Compaction Process Sintering process 	<ul style="list-style-type: none"> Using ultrasonication to disperse and mix CNTs and Al powders. Then compacted. Then, the green samples sintered 640 °C for 90 min. 	Improve the dispersion and promote the production of nanocomposites with better mechanical properties. Vickers microhardness tests using a 98 mN load
[129]	MWCNTs	Dia: 3–5 nm Length: 8–15 μm	Mg AZ61	<ul style="list-style-type: none"> Water atomization Ultrasonication Ball Milling Microwave sintering 	<ul style="list-style-type: none"> Atomized Mg AZ61 alloy to produce a powder (150 – 300 μm). Reduce the particle size of AZ61 to 50 μm by Mechanical Milling. Then, applied ultrasonication for 20 min for the complete dispersion of CNTs in the solution. And use microwave sintering. 	Significant improvement in both compressive and energy absorption properties have been observed in CNT-re- enforced Mg composite foams. For samples with 3% CNTs fraction and 49% porosity level, improvements in compressive strength and energy absorption are 93% and 153%, respectively.
[130]	MWCNTs	Dia: 16 nm Length: 900 nm	The coarse-grained AA and nano-crystalline are structured of powders AA 4032.	<ul style="list-style-type: none"> Energy ball milling Electric arc discharge. Compacted process. Sintering process. 	<ul style="list-style-type: none"> The powder prepared by ball milled for 30hr then MWCNTs added into ball milling for 15 min to avoid the damage of CNTs. Then, compacted under a uniaxial load of 650 MPa for 2 min. Finally, they were sintered under an argon atmosphere at 520oC for 90 min 	The yield strength of the AA4032 was double when the CNT was added by 2 wt % its' jump from 300 MPa to 600MPa
[131]	CNTs		Fe-50Co-0.2Si alloy powder(23.4 μm)	<ul style="list-style-type: none"> Gas atomization High energy ball-milling. Spark plasma sintering (SPS) 	<ul style="list-style-type: none"> The powder was produced by gas atomization, Then, entered the high energy ball milling to achieve the uniform dispersion at 6th hour. Finally, the specimens goes into A spark plasma sintering SPS furnace 22mins.at 50 MPa and vacuum atmosphere. 	As the ball-milling time increased, the yield strength increased in the composites; a maximum 50% relative increase in tensile strength due to the addition of CNTs was achieved after 1 h ball-milling, which then decreased with further ball-milling.
[112]	MWCNTs	Dia: 5-30 nm Length: 1-10 μm	AZ91D alloy (75 μm)	<ul style="list-style-type: none"> Ball milling with stirring casting 	<ul style="list-style-type: none"> CNTs were previously dispersed in AZ91 alloy powder by ball milling Then, applied compact under a hydraulic pressure of 100 kN. Then, the alloy was melted at 993 K and preheated CNTs block (393K). Then, CNTs added into alloy melt 1073K then cooled down to 933K and stirred for 3min with 100 r/min. 	Homogeneously distributed in the matrix and maintained the integrated structure. The yield strength and ductility of AZ91D/CNTs composite were improved by 47.2% and 112.2%,
[132]	MWCNTs	(Dia: 40 nm Length: 2 μm	AZ91D alloy (75 μm)	<ul style="list-style-type: none"> Powder metallurgy method. Mechanical agitator Vacuum drier Compact process Sintering process 	<ul style="list-style-type: none"> CNTs were dispersed in ethanol using an ultra-sonication process for 1 h. And the powder was dissolved in ethanol to make a slurry Then CNTs dispersion was added dropwise into powder slurry by using mechanical agitator at 1500 rpm for 1h then the slurry was put in vacuum dried at 65 °C for 10 h After that, the powder mixture was 	The composite exhibited an impressive increase in microhardness (about 23%) and tensile failure strain value (about 98%) without significant compromise in tensile strength, compared to the un-reinforced Mg–3Al–1Zn alloy. The synthesized composites can be used

Continued on next page.

5. Conclusion

Despite all the previous encouraging dispersion and inspection techniques that were presented, challenges exist

with regards to uniformly dispersing the CNTs within the metal matrix. This dispersing problem is a result of the bundling of CNTs and the meagre compatibility properties between CNT's and metals. While some degree of success

Continued.

					compact with the pressure of 550 MPa finally the sintering process takes 2h at 630 °C.	
[133]	MWCNTs	Dia: 9.5 nm Length: 1.5 µm	Mg chips/Al	<ul style="list-style-type: none"> Ball Milling Cold pressing Hot extrusion 	<ul style="list-style-type: none"> Mg chips ball-milled under an argon atmosphere at 300 rpm for 3 h. Al powders used as a good binder in the recycling of Mg chips containing CNTs through a hot extrusion process 	<ul style="list-style-type: none"> The microstructure, mechanical properties and corrosion behavior of Mg/Al without CNT (base alloy) and composites were evaluated. A small addition of CNTs (0.5 wt.%) to the base alloy improved the hardness and corrosion resistance.
[113]	MWCNTs	Dia: 20-40 nm Length: 1-5 µm	Mg AZ91D	<ul style="list-style-type: none"> Mechanical stirring Ultrasonic dispersion processing 	<ul style="list-style-type: none"> The melting was carried out using a resistance heating furnace. The mechanical stirring was applied And CNTs were added into the stirring vortex with speed 300–500 rpm in 2 min to ensure complete dispersion a high-intensity ultrasonic wave with a 20 kHz, a maximum 1.4 kW power for 15 min, Then, the melted mixture was heated to 700 C then cooled down. 	The microstructures and mechanical properties of the nanocomposite were investigated. the tensile strength, yield strength, and elongation of the 1.5%CNTs/AZ91D nanocomposite are improved by 22%, 21%, and 42% respectively.
[134]	MWCNTs	(Dia: 50 nm Length: 1-5 µm	Al-Si alloys 325±15 µm	<ul style="list-style-type: none"> Ball Milling Shot-blasting process Cold spray process 	<ul style="list-style-type: none"> Mixing MWCNTs in aqueous dispersion medium then alumina powders were mixed with CNTs And dry-milled using a planetary ball mill. Pretreated using a shot-blasting process. Then cold sprayed by a bond coat. mixtures were Then, coated by a cold spraying process 	The optimum properties in the hardness and wear resistance were observed
[135]	MWCNT _{Gr}	Dia: 20-30 nm Length: 10-30 µm	Ti64 25 µm	<ul style="list-style-type: none"> Gas atomization process High energy ball milling Spark plasma sintering (SPS) technique Vacuum sintering process 	<ul style="list-style-type: none"> High energy ball mill (HEBM), was adapted for the mixing and dispersion of MWCNT_{Gr} in the Ti64 metal matrix for 6h and 50 rpm. Composite powder mixtures were sintered in vacuum at constantly applied pressure, heating rate and isothermal holding time of 50 MPa, 100 °C/min and 5 min. 	<ul style="list-style-type: none"> The relative density of the sintered MWCNT_{Gr}/Ti64 composites was enhanced with increased sintering temperature but deteriorated with increased wt% MWCNT_{Gr} in the metal matrix. Vickers microhardness composites improved with increasing sintering temperature and weight fractions of MWCNT_{Gr}.
[136]	MWCNT	Dia: 20 nm Length: 10-30 µm	Copper 300 mesh	<ul style="list-style-type: none"> Ultrasonication High energy milling Spark plasma sintering. Annealing treatment 	<ul style="list-style-type: none"> Powders fabricated by ultrasonication and mechanical milling with a rotation speed of 300 rpm for milling time of 9 to achieve homogeneously mixture. Then, Spark plasma sintering applied on composited with 40 MPa uniaxial vacuum, 800 C and heating rate of 100 C/min. Then, it cooled down and annealed for 1 h at 800 °C. 	<ul style="list-style-type: none"> The hardness and mechanical properties of the composites were improved by the addition of CNTs. Hardness and tensile tests demonstrated that the homogeneous dispersion of CNTs and high densification are the critical problems that have to be solved to enhance the mechanical properties of Cu-CNTs nanocomposites.
[137]	MWCNT	Dia: 20 nm Length: 1-3 µm	6061Al powder (30 µm)	<ul style="list-style-type: none"> Ball Milling High energy ball milling Sintering process Hot extrusion process Hot rolling process 	<ul style="list-style-type: none"> The 6061Al powder and MWCNTs mixed were balls milled by integration of low energy ball milling (135 rpm for 8h). And high energy ball milling (270 rpm for 1 h) Then, sintered at 550 °C for 2 h and hot extruded into a plate after that the plate was hot rolled into the thinner plate. 	The average grain size was reduced from 580 nm to 300 nm with better homogeneity after cold rolling, and elongation to failure at 400 °C and 4.17E–1s-1 was improved by 40%
[138]	MWCNT	Dia: 15-30 nm Length: 1-5 µm	Al powders (30 µm)	<ul style="list-style-type: none"> Gas atomization Ball milling process Cold press process Sintering process Hot extruded process 	<ul style="list-style-type: none"> Atomized spherical Al powders. The Al powders and stearic acid (as agent) mixed in a 3D mixer for 1 h. Then, the CNT/Al mixed in different ball milling conditions. Then, cold pressed into u40mm columns at 500 MPa, sintered at 550 °C for 2 h and hot extruded. 	CNTs, SSBM CNT/Al composites doubled or tripled the ductility of Low-Speed Ball Milling (LSBM) and High-Speed Ball Milling (HSBM) CNT/Al, while their strength was nearly similar.
[139]	CNT		Al	<ul style="list-style-type: none"> Ball milling process Compact process Sintering process Hot extrusion 	<ul style="list-style-type: none"> The powders with different CNT content were a mill for 90 min with a velocity of 500 rpm in planetary ball mill filled with Ar. Compacted under 600 MPa. Then, sintered for 1h at 630 °C. 	<ul style="list-style-type: none"> The 4.5 wt%-CNT/Al composites exhibit the largest hardness and tensile strength, which is 2.3 and 2.4 times higher than that of starting Al.

Continued on next page.

has been reported in each of these methods, there are, however, still many issues that are being investigated (such as alignment of the CNTs, damaging of the CNTs etc.) and research continues in these areas.

REFERENCES

- 1) J.N. Coleman, U. Khan, W.J. Blau and Y.K. Gun'ko: *Carbon* **44** (2006) 1624–1652.

Continued.

					<ul style="list-style-type: none"> Finally, hot extrusion was conducted at 500 °C. 	<ul style="list-style-type: none"> The coefficient of thermal expansions (CTEs) of the composites decreased with the increase of CNT content at the temperature range of 100–300 °C.
[140]	MWCNT	Dia: 15–30 nm Length: 1–5 µm	Copper 35µm	<ul style="list-style-type: none"> The high-energy ball milling process Flake powder metallurgy Hot-pressing process Hot-rolling process 	copper flaky powder (60 g) was thoroughly mixed with dodecyl trimethyl ammonium bromide (20 mg) at room temperature in 800mL deionized water in 0.5 h. after filtration and drying they re-dispersed in deionized water to produce slurry then MWCNTs aqueous suspension was added into the slurry slowly finally The MWCNTs /Cu flaky powder was dried. then compacted in hot-pressing applied at 950°C under 50 MPa then hot-rolling process at 800 °C.	The ultimate tensile strength of 1.0 vol% MWCNTs/Cu composite reaches 395 MPa, with an electric conductivity of 90% IACS and an elongation rate of more than 20%.
[114]	MWCNT	Dia: 9.5 nm Length: 1.5 µm	AA 7075	<ul style="list-style-type: none"> -Stir casting method 	<ul style="list-style-type: none"> Al 7075 alloy were melted in the furnace at 850°C then (MWCNT) powder was preheated to a temperature of 200°C and added to the molten metal Ar atmosphere then the mixture was stir for 15min at 300 rpm 	The wear loss tends to decrease with an increasing weight percentage of reinforcement, which confirms that the addition of MWCNT into the base Aluminium matrix aids in reducing the loss due to wear of the composite.
[141]	MWCNT	Dia: 1–1.2 nm Length: 5–20 µm	Cu	<ul style="list-style-type: none"> Gas Atomization process. Pre-bending process. Compact process. Sintering Process. 	Cu and CNTs blended in a shear type mixer for 60 mins then the mixture compacted at room temperature with pressure 80kN after that the sintering takes place of temperature 900 °C for 90 mins in an argon atmosphere.	<ul style="list-style-type: none"> The green density of copper compact and composite compacts was 8.71 and 8.63 g/cm³ for 1% and 2% carbon nanotubes. The sintered density of the copper and composites was also measured and found to be 8.76 and 8.67 g/cm³ for 1% and 2% carbon nanotubes.
[142]	MWCNTs	Dia: 60–100 nm Length: 5–15 µm	Al powder 5 µm	<ul style="list-style-type: none"> High energy ball milling. Low energy ball millings. Polyester binder-assisting. Spark plasma sintering process. Hot extrusion process. 	<ul style="list-style-type: none"> -Al-0.5 wt.% CNT powders were mixed by stirring then the mixture was added into high energy ball milling at 200 rpm for 4h. -Al-CNTs powders and balls as used in high energy ball milling but in a plastic container then blended by horizontal roller machine. -polyethylene glycol (PEG) in a form of a flake was hand mixed with CNTs. The mixture was transferred into a Haake twin-screw mixer. After that, all the mixture obtained by spark plasma sintering follows by hot extrusion. 	<ul style="list-style-type: none"> The results of mechanical properties revealed that the powder mixing was successful. A small addition of CNTs (0.5 wt.%) could evidently enhance the strength and hardness of the composite compared with the pure matrix. The TS and HV was PBA(165,48) LEBM(174,50) HEBM(206,58) Respectively
[143]	MWCNTs	Dia: 20–50nm, length: 0.5– 1.0µm	Cu-0.5Ti (150 µm)	<ul style="list-style-type: none"> Water atomization Powder Metallurgy Process Spark plasma sintering process 	composites were prepared by dipping raw Cu-0.5Ti powder into the zwitterionic surfactant water solution with CNTs. Cu-0.5Ti/CNTs composite powders were sintered by using spark plasma sintering at 950 °C for 30 mins under 30MPa pressure in a vacuum atmosphere. Then the compacts samples were preheated to 800 °C in Ar gas then immediately extruded.	<ul style="list-style-type: none"> Cu-0.5Ti/0.19 mass% CNTs composite alloy had 175.8MPa YS. It was about 2 times as YS of pure copper. The electrical conductivity of Cu-0.5Ti/ 0.19 mass% CNTs composite alloy was 83.5 IACS%. The electrical conductivities of Cu-0.5Ti/CNTs composite alloys were increased compared to the monolithic Cu-0.5Ti alloy.

- 2) P.M. Ajayan: *Chem. Rev.* **99** (1999) 1787–1800.
- 3) J.N. Coleman *et al.*: *Carbon* **45**(2) (2004) 167–173.
- 4) M. Moniruzzaman and K.I. Winey: *Macromolecules* **39** (2006) 5194–5205.
- 5) M. Cadek, J.N. Coleman, K.P. Ryan, V. Nicolosi, G. Bister, A. Fonseca, J.B. Nagy, K. Szostak, F. Béguin and W.J. Blau: *Nano Lett.* **4** (2004) 353–356.
- 6) M.-K. Yeh, N.-H. Tai and J.-H. Liu: *Carbon* **44** (2006) 1–9.
- 7) A. Peigney, C. Laurent, E. Flahaut and A. Rousset: *Ceram. Int.* **26** (2000) 677–683.
- 8) A. Peigney, E. Flahaut, C. Laurent, F. Chastel and A. Rousset: *Chem. Phys. Lett.* **352** (2002) 20–25.
- 9) Z. Xia, L. Riester, W.A. Curtin, H. Li, B.W. Sheldon, J. Liang, B. Chang and J.M. Xu: *Acta Mater.* **52** (2004) 931–944.
- 10) C.L. Xu, B.Q. Wei, R.Z. Ma, J. Liang, X.K. Ma and D.H. Wu: *Carbon* **37** (1999) 855–858.
- 11) T. Noguchi, A. Magario, S. Fukazawa, S. Shimizu, J. Beppu and M. Seki: *Mater. Trans.* **45** (2004) 602–604.
- 12) Q. Liu, L. Ke, F. Liu, C. Huang and L. Xing: *Mater. Des.* **45** (2013) 343–348.
- 13) A. Esawi and K. Morsi: *Compos., Part A* **38** (2007) 646–650.
- 14) A.M.K. Esawi, K. Morsi, A. Sayed, A.A. Gawad and P. Borah: *Mater. Sci. Eng. A* **508** (2009) 167–173.
- 15) S.R. Bakshi, D. Lahiri and A. Agarwal: *Int. Mater. Rev.* **55** (2010) 41–64.
- 16) S.R. Bakshi and A. Agarwal: *Carbon* **49** (2011) 533–544.
- 17) S.R. Bakshi, A.K. Keshri and A. Agarwal: *Mater. Sci. Eng. A* **528** (2011) 3375–3384.
- 18) L. Jiang, Z. Li, G. Fan, L. Cao and D. Zhang: *Scr. Mater.* **66** (2012) 331–334.
- 19) N. Nouri, S. Ziaei-Rad, S. Adibi and F. Karimzadeh: *Mater. Des.* **34** (2012) 1–14.
- 20) H. Li, J. Kang, C. He, N. Zhao, C. Liang and B. Li: *Mater. Sci. Eng. A* **577** (2013) 120–124.
- 21) D.J. Woo, B. Sneed, F. Peerally, F.C. Heer, L.N. Brewer, J.P. Hooper and S. Osswald: *Carbon* **63** (2013) 404–415.
- 22) S.J. Yoo, S.H. Han and W.J. Kim: *Scr. Mater.* **68** (2013) 711–714.
- 23) N. Silvestre, B. Faria and J.N.C. Lopes: *Compos. Sci. Technol.* **90**

- (2014) 16–24.
- 24) J. Stein, B. Lenczowski, E. Anglaret and N. Fréty: *Carbon* **77** (2014) 44–52.
 - 25) A.M.K. Esawi, K. Morsi, A. Sayed, M. Taher and S. Lanka: *Compos. Sci. Technol.* **70** (2010) 2237–2241.
 - 26) A.M.K. Esawi, K. Morsi, A. Sayed, M. Taher and S. Lanka: *Compos., Part A* **42** (2011) 234–243.
 - 27) H.J. Choi, J.H. Shin and D.H. Bae: *Compos. Sci. Technol.* **71** (2011) 1699–1705.
 - 28) H.J. Choi, J.H. Shin and D.H. Bae: *Compos., Part A* **43** (2012) 1061–1072.
 - 29) Z.Y. Liu, S.J. Xu, B.L. Xiao, P. Xue, W.G. Wang and Z.Y. Ma: *Compos., Part A* **43** (2012) 2161–2168.
 - 30) S.E. Shin and D.H. Bae: *Mater. Charact.* **83** (2013) 170–177.
 - 31) *ASM Handbook: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, Vol. 2, (American Society for Metals, Materials Park, OH, 1990).
 - 32) Y.-J. Kwon, M. Kobashi and N. Kanetake: *Mater. Trans.* **45** (2004) 3163–3171.
 - 33) M. Wąsik and J. Karwan-Baczewska: *Key Eng. Mater.* **682** (2016) 270–275.
 - 34) J. Stabik and A. Dybowska: *Compos., Part B* **127** (2017) 36–43.
 - 35) X. He, G. Zou, Y. Xu, H. Zhu, H. Jiang, X. Jiang, W. Xia, J. Chen, J. Wu and S. Yang: *Prog. Nat. Sci. Mater. Int.* **28** (2018) 416–421.
 - 36) G. Li, Y. Ma, X. He, W. Li and P. Li: *Trans. Nonferrous Met. Soc. China* **22** (2012) 1112–1117.
 - 37) P.K. Saha: *Aerospace Manufacturing Processes*, (CRC Press, Boca Raton, 2016).
 - 38) T. Dursun and C. Soutis: *Mater. Des.* **56** (2014) 862–871.
 - 39) G.B.V. Kumar, C.S.P. Rao and N. Selvaraj: *J. Miner. Mater. Charact. Eng.* **10** (2011) 59–91.
 - 40) M. Kathiresan and T. Somakumar: *Ind. Lubr. Tribol.* **62** (2010) 361–371.
 - 41) S. Srivastava, S. Mohan, Y. Srivastava and A.J. Shukla: *Int. J. Mod. Eng. Res.* **2**(2) (2012) 25–42.
 - 42) H. Beygi, S.A. Sajjadi and S.M. Zabarjad: *Mater. Sci. Eng. A* **607** (2014) 81–88.
 - 43) A.J. Knowles, X. Jiang, M. Galano and F. Audebert: *J. Alloy. Compd.* **615** (2014) S401–S405.
 - 44) M. Yamaguchi, F. Meng, K. Firestein, K. Tsuchiya and D. Golberg: *Mater. Sci. Eng. A* **604** (2014) 9–17.
 - 45) B. Liu, W. Huang, H. Wang, M. Wang and X. Li: *J. Compos. Mater.* **48** (2014) 355–364.
 - 46) B. Huang, J.M. Zeng, Z.L. Hu, H. He, C.Y. He and J.L. Yan: *Adv. Mater. Res.* **900** (2014) 794–797.
 - 47) P. Gudlur, A. Boczek, M. Radovic and A. Muliana: *Mater. Sci. Eng. A* **590** (2014) 352–359.
 - 48) A. Ahmadi, M.R. Toroghinejad and A. Najafizadeh: *Mater. Des.* **53** (2014) 13–19.
 - 49) M. Murali, M. Sambathkumar and M.S.S. Saravanan: *Univers. J. Mater. Sci.* **2** (2014) 49–53.
 - 50) M. Nagaral, V. Bharath and V. Auradi: *J. Mater. Sci. Eng.* **2** (2013) 2–5.
 - 51) K. Edalati, M. Ashida, Z. Horita, T. Matsui and H. Kato: *Wear* **310** (2014) 83–89.
 - 52) M. Rashad, F. Pan, J. Zhang and M. Asif: *J. Alloy. Compd.* **646** (2015) 223–232.
 - 53) M. Rashad, F. Pan, M. Asif and A. Tang: *J. Ind. Eng. Chem.* **20** (2014) 4250–4255.
 - 54) Q.C. Jiang, H.Y. Wang, B.-X. Ma, Y. Wang and F. Zhao: *J. Alloy. Compd.* **386** (2005) 177–181.
 - 55) E.F. Emley: *Principles of Magnesium Technology*, (Pergamon Press, New York, London, 1966).
 - 56) M. Rashad, F.S. Pan, M. Asif and A. Ullah: *Mater. Sci. Technol.* **31** (2015) 1452–1461.
 - 57) T. Zhang, Z. Tao and J. Chen: *Mater. Horiz.* **1**(2) (2014) 196–206.
 - 58) H. Xiong, K. Yu, X. Yin, Y. Dai, Y. Yan and H. Zhu: *J. Alloy. Compd.* **708** (2017) 652–661.
 - 59) J. An, R.G. Li, Y. Lu, C.M. Chen, Y. Xu, X. Chen and L.M. Wang: *Wear* **265** (2008) 97–104.
 - 60) M. Rashad, F. Pan, A. Tang, M. Asif, J. She, J. Gou, J. Mao and H. Hu: *J. Compos. Mater.* **49** (2015) 285–293.
 - 61) J.C. Viala, P. Fortier, G. Claveyrolas, H. Vincent and J. Bouix: *J. Mater. Sci.* **26** (1991) 4977–4984.
 - 62) Y. Kagawa and E. Nakata: *J. Mater. Sci. Lett.* **11** (1992) 176–178.
 - 63) F. Wu, J. Zhu, Y. Chen and G. Zhang: *Mater. Sci. Eng. A* **277** (2000) 143–147.
 - 64) M. Rashad, F. Pan, A. Tang, Y. Lu, M. Asif, S. Hussain, J. She, J. Gou and J. Mao: *J. Magnes. Alloy.* **1** (2013) 242–248.
 - 65) A.D. Moghadam, E. Omrani, P.L. Menezes and P.K. Rohatgi: *Compos., Part B* **77** (2015) 402–420.
 - 66) D. Segal: *Materials for the 21st Century*, (Oxford University Press, Oxford, 2017).
 - 67) “UCLA researchers create exceptionally strong and lightweight new metal | UCLA.” [Online]. Available: <http://newsroom.ucla.edu/releases/ucla-researchers-create-exceptionally-strong-and-lightweight-new-metal>. [Accessed: 01-Jan-2019].
 - 68) E. Aghion and B. Bronfin: *Mater. Sci. Forum* **350–351** (2000) 19–30.
 - 69) K.U. Kainer: *Magnesium: Proceedings of the 7th International Conference on Magnesium Alloys and their Applications*, (John Wiley & Sons, Hoboken, 2007).
 - 70) S. Fleming: Master Thesis, Eng. Mech. Eng. Fac. Rensselaer Polytech. Institute, Rensselaer Polytech. Inst. (2012).
 - 71) E.F. Horst and B.L. Mordike: *Magnesium Technology: Metallurgy, Design Data, Application*, (Springer-Verlag, Berlin Heidelberg, 2006).
 - 72) G. Cole: *IMA-PROCEEDINGS-*, (1995), pp. 1–5.
 - 73) S. LeBeau and R. Decker: Paper presented at the 5th Int. Conference on Semi-Solid Processing of Alloys and Composites, (Colorado School of Mines, Denver, Colorado, 1998) pp. 387–395.
 - 74) T. Ito, M. Sato and Y. Kojima: Annual World IMA 2000 Magnesium Conference, (2000) pp. 33–40.
 - 75) G.V. Raynor: *The Physical Metallurgy of Magnesium and Its Alloys*, (Pergamon Press, London Google Sch., 1959).
 - 76) C.S. Roberts: *Magnesium and its Alloys*, Vol. 180, (Wiley, Hoboken, New York, 1960).
 - 77) D. Eliezer, E. Aghion and F.H.S. Froes: *Adv. Perform. Mater.* **5** (1998) 201–212.
 - 78) E. Aghion, B. Bronfin, F. Von Buch, S. Schumann and H. Friedrich: *JOM* **55**(11) (2003) 30–33.
 - 79) M.K. Kulekci: *Int. J. Adv. Manuf. Technol.* **39** (2008) 851–865.
 - 80) B. Gwynne and P. Lyon: “Magnesium alloys in aerospace applications, past concerns, current solutions,” in Trienn. Int. Aircr. Fire Cabin Saf. Res. Conf., (2007).
 - 81) W.A. Monteiro, S.J. Busoi and L.V. da Silvai, *Application of Magnesium Alloys in Transport, New Features on Magnesium Alloys*, (InTech, 2012).
 - 82) S.C. Erickson: *SAE Trans.* **86** (1977) 1418–1429.
 - 83) E. Aghion, B. Bronfin and I. Schwartz: Israel Annual Conference on Aerospace Sciences, (1996) pp. 353–362.
 - 84) K. Chu, C. Jia, W. Li and P. Wang: *Phys. Status Solidi* **210** (2013) 594–599.
 - 85) H. Dai: Carbon Nanotubes: Synthesis, Structure, Properties, and Applications, *Topics in Applied Physics*, Vol. 80, (Springer, Berlin, 2001).
 - 86) H. Yue, L. Yao, X. Gao, S. Zhang, E. Guo, H. Zhang, X. Lin and B. Wang: *J. Alloy. Compd.* **691** (2017) 755–762.
 - 87) G.Q. Han, J.H. Shen, X.X. Ye, B. Chen, H. Imai, K. Kondoh and W.B. Du: *Mater. Lett.* **181** (2016) 300–304.
 - 88) H. Zein: *World J. Appl. Chem.* **3** (2018) 17–27.
 - 89) Y. Li, M. Li, M. Pang, S. Feng, J. Zhang and C. Zhang: *J. Mater. Chem. C* **3** (2015) 5573–5579.
 - 90) M.O. Mohsen, R. Taha, A. Abu Taqa, N. Al-Nuaimi, R.A. Al-Rub and K.A. Bani-Hani: *J. Nanomater.* **2017** (2017) 6927416.
 - 91) S. Simões, F. Viana, M.A.L.L. Reis and M.F. Vieira: *Microsc. Microanal.* **22**(no. S4) (2016) 52–53.
 - 92) S. Simões, F. Viana, M.A.L. Reis and M.F. Vieira: *Metals* **7** (2017) 279.
 - 93) Z.Y. Liu, B.L. Xiao, W.G. Wang and Z.Y. Ma: *Compos., Part A* **94** (2017) 189–198.
 - 94) J.M. Tao, X.F. Chen, P. Hong and J.H. Yi: *J. Alloy. Compd.* **717** (2017) 232–239.
 - 95) Q. Li, A. Viereckl, C.A. Rottmair and R.F. Singer: *Compos. Sci.*

- Technol. **69** (2009) 1193–1199.
- 96) J.L. Song, W.G. Chen, L.L. Dong, J.J. Wang and N. Deng: *J. Alloy. Compd.* **720** (2017) 54–62.
 - 97) S.C. Tjong: *Mater. Sci. Eng. Rep.* **74** (2013) 281–350.
 - 98) H. Fukuda, K. Kondoh, J. Umeda and B. Fugetsu: *Compos. Sci. Technol.* **71** (2011) 705–709.
 - 99) G. Han, Z. Wang, K. Liu, S. Li, X. Du and W. Du: *Mater. Sci. Eng. A* **628** (2015) 350–357.
 - 100) M. Paramsothy, X.H. Tan, J. Chan, R. Kwok and M. Gupta: *Mater. Des.* **45** (2015) 15–23.
 - 101) G.Q. Han, J.H. Shen, X.X. Ye, B. Chen, H. Imai, K. Kondoh and W.B. Du: *Mater. Lett.* **181** (2016) 300–304.
 - 102) Q. Yuan, G. Zhou, L. Liao, Y. Liu and L. Luo: *Carbon* **127** (2018) 177–186.
 - 103) H. Lyu, B. Gao, F. He, A.R. Zimmerman, C. Ding, H. Huang and J. Tang: *Environ. Pollut.* **233** (2018) 54–63.
 - 104) M. Tokita: *Spark Plasma Sintering (SPS) Method, Systems, and Applications*, ed. by S. Somiya, 2nd ed., Chap. 11.2.3, S. B. T.-H. of A. C., (Academic Press, Oxford, 2013) pp. 1149–1177.
 - 105) H.-C. Hsu, J.-Y. Chou and W.-H. Tuan: *J. Asian Ceram. Soc.* **4** (2016) 201–204.
 - 106) Y. Huang, J. Li, L. Wan, X. Meng and Y. Xie: *Mater. Sci. Eng. A* **732** (2018) 205–211.
 - 107) J. Liang, H. Li, L. Qi, W. Tian, X. Li, X. Chao and J. Wei: *J. Alloy. Compd.* **728** (2017) 282–288.
 - 108) K. Kondoh, H. Fukuda, J. Umeda, H. Imai and B. Fugetsu: *Carbon* **72** (2014) 15–21.
 - 109) Q.H. Yuan, X.S. Zeng, Y. Liu, L. Luo, J.B. Wu, Y.C. Wang and G.H. Zhou: *Carbon* **96** (2016) 843–855.
 - 110) S.E. Shin and D.H. Bae: *Compos., Part B* **134** (2018) 61–68.
 - 111) P.S. Samuel Ratna Kumar, D.S. Robinson Smart and S. John Alexis: *J. Asian Ceram. Soc.* **5** (2017) 71–75.
 - 112) Q. Yuan, D. Fu, X. Zeng and Y. Liu: *Trans. Nonferrous Met. Soc. China* **27** (2017) 1716–1724.
 - 113) S.Y. Liu, F.P. Gao, Q.Y. Zhang, X. Zhu and W.Z. Li: *Trans. Nonferrous Met. Soc. China* **20** (2010) 1222–1227.
 - 114) O. Aranke, C. Gandhi, N. Dixit and P. Kuppam: *Mater. Today Proc.* **5** (2018) 7748–7757.
 - 115) Z. Yu, W. Yang, C. Zhou, N. Zhang, Z. Chao, H. Liu, Y. Cao, Y. Sun, P. Shao and G. Wu: *Carbon* **141** (2019) 25–39.
 - 116) S. Sud and A. Kamath: *Int. Res. J. Pharm.* **4** (2013) 57–64.
 - 117) B. Duan, Y. Zhou, D. Wang and Y. Zhao: *J. Alloy. Compd.* **771** (2019) 498–504.
 - 118) L. Liu, R. Bao, J. Yi, C. Li, J. Tao, Y. Liu, S. Tan and X. You: *J. Alloy. Compd.* **726** (2017) 81–87.
 - 119) C. Parswajinan, B. Vijaya Ramnath, M. Vetrivel, A. Ranjith, B.K. Rohit, S. Vasanth and S. Vignesh: *Mater. Today Proc.* **5** (2018) 1176–1185.
 - 120) S. Simões, F. Viana, M.A.L. Reis and M.F. Vieira: *Compos. Struct.* **108** (2014) 992–1000.
 - 121) B. Vijaya Ramnath, C. Parswajinan, C. Elanchezian, S. Venkatesan Pragadeesh, C. Kavin, P.R. Ramkishore and V. Sabarish: *Appl. Mech. Mater.* **680** (2014) 7–10.
 - 122) B. Chen, S. Li, H. Imai, L. Jia, J. Umeda, M. Takahashi and K. Kondoh: *Mater. Des.* **72** (2015) 1–8.
 - 123) P.C. Tsai, Y.R. Jeng, J.T. Lee, I. Stachiv and P. Sittner: *Diamond Related Materials* **74** (2017) 197–204.
 - 124) X. Chen, J. Tao, J. Yi, C. Li, R. Bao, Y. Liu, X. You and S. Tan: *Mater. Sci. Eng. A* **712** (2018) 790–793.
 - 125) K. Kondoh, H. Fukuda, J. Umeda, H. Imai, B. Fugetsu and M. Endo: *Mater. Sci. Eng. A* **527** (2010) 4103–4108.
 - 126) Y. Ma, X. Yang, C. He, K. Yang, J. Xu, J. Sha, C. Shi, J. Li and N. Zhao: *Mater. Lett.* **233** (2018) 351–354.
 - 127) H.M. Mallikarjuna, K.T. Kashyap, P.G. Koppad, C.S. Ramesh and R. Keshavamurthy: *Trans. Nonferrous Met. Soc. China* **26** (2016) 1755–1764.
 - 128) S. Simoes, P.J. Ferreira, F. Viana, M.A.L. Reis and M.F. Vieira: *Microsc. Microanal.* **23**(no. S1) (2017) 1942–1943.
 - 129) A.D. Akinwekomi, W.-C. Law, M.-T. Choy, L. Chen, C.-Y. Tang, G.C.-P. Tsui and X.-S. Yang: *Mater. Sci. Eng. A* **726** (2018) 82–92.
 - 130) T. Nagaraj, A. Abhilash, R. Ashik, M.S. Senthil Saravanan, S.P.K. Babu and M. Rajkumar: *Mater. Today Proc.* **5** (2018) 6717–6721.
 - 131) A.J. Albaaji, E.G. Castle, M.J. Reece, J.P. Hall and S.L. Evans: *Mater. Des.* **122** (2017) 296–306.
 - 132) M. Rashad, F. Pan, M. Asif and L. Li: *Prog. Nat. Sci. Mater. Int.* **25** (2015) 276–281.
 - 133) H. Mindivan, A. Efe, A.H. Kosatepe and E.S. Kayali: *Appl. Surf. Sci.* **318** (2014) 234–243.
 - 134) W. Winarto, D. Priadi, N. Sofyan and A. Wicaksono: *Procedia Eng.* **170** (2017) 108–112.
 - 135) A.O. Adegbenjo, P.A. Olubambi, J.H. Potgieter, M.B. Shongwe and M. Ramakokovhu: *Mater. Des.* **128** (2017) 119–129.
 - 136) H. Deng, J. Yi, C. Xia and Y. Yi: *J. Alloy. Compd.* **727** (2017) 260–268.
 - 137) G. Fan, H. Huang, Z. Tan, D. Xiong, Q. Guo, M. Naito, Z. Li and D. Zhang: *Mater. Sci. Eng. A* **708** (2017) 537–543.
 - 138) R. Xu, Z. Tan, D. Xiong, G. Fan, Q. Guo, J. Zhang, Y. Su, Z. Li and D. Zhang: *Compos., Part A* **96** (2017) 57–66.
 - 139) X. Yang, T. Zou, C. Shi, E. Liu, C. He and N. Zhao: *Mater. Sci. Eng. A* **660** (2016) 11–18.
 - 140) J. Liu, D.-B. Xiong, Z. Tan, G. Fan, Q. Guo, Y. Su, Z. Li and D. Zhang: *Mater. Sci. Eng. A* **729** (2018) 452–457.
 - 141) G. Goudah, F. Ahmad and O. Mamat: *J. Eng. Sci. Technol.* **5** (2010) 272–283.
 - 142) J. Liao and M.J. Tan: *Powder Technol.* **208** (2011) 42–48.
 - 143) H. Imai, K. Kondoh, S. Li, J. Umeda, B. Fugetsu and M. Takahashi: *Mater. Trans.* **55** (2014) 522–527.
 - 144) E.T. Thostenson and T.-W. Chou: *J. Phys. D* **36** (2003) 573.
 - 145) S.R. Bakshi, J.E. Tercero and A. Agarwal: *Compos., Part A* **38** (2007) 2493–2499.
 - 146) M. Kulkarni, D. Carnahan, K. Kulkarni, D. Qian and J.L. Abot: *Compos., Part B* **41** (2010) 414–421.
 - 147) D.N. Savvas, V. Papadopoulos and M. Papadrakakis: *Int. J. Solids Struct.* **49** (2012) 3823–3837.
 - 148) C.-H. Tsai, C.-J. Chang, K. Wang, C. Zhang, Z. Liang and B. Wang: *IIE Trans.* **44** (2012) 590–602.
 - 149) M.A. Bhuiyan, R.V. Pucha, J. Worthy, M. Karevan and K. Kalaitzidou: *Comput. Mater. Sci.* **79** (2013) 368–376.
 - 150) C. Lainé, P. Le Grogne, S. Panier and C. Binetruy: *Eur. J. Mech.* **47** (2014) 231–245.
 - 151) C.D. Li, X.J. Wang, W.Q. Liu, K. Wu, H.L. Shi, C. Ding, X.S. Hu and M.Y. Zheng: *Mater. Sci. Eng. A* **597** (2014) 264–269.
 - 152) A. Alizadeh, A. Abdollahi and H. Biukani: *J. Alloy. Compd.* **650** (2015) 783–793.
 - 153) I. Duarte, E. Ventura, S. Olhero and J.M.F. Ferreira: *Mater. Lett.* **160** (2015) 162–166.
 - 154) J. Ning, J. Zhang, Y. Pan and J. Guo: *Mater. Sci. Eng. A* **357** (2003) 392–396.
 - 155) S. Ruan, P. Gao and T.X. Yu: *Polymer* **47** (2006) 1604–1611.
 - 156) H. Rokni, A.S. Milani, R.J. Seethaler and K. Stoeffler: *Compos. Struct.* **94** (2012) 2538–2547.
 - 157) J.G. Park, D.H. Keum and Y.H. Lee: *Carbon* **95** (2015) 690–698.
 - 158) Y. Wang, S. Kim, G.P. Li and L.Z. Sun: *Comput. Mater. Sci.* **104** (2015) 69–75.