MECHANICAL PROPERTIES OF CARBON NANOTUBES REINFORCED COMPOSITES: A REVIEW

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Abstract-This paper summarises the research work performed in the field of carbon nanotubes (CNT) metal/ceramic matrix composites. Research has been carried out to use CNT as reinforcement material for composites, however the most research has been focussed in polymer matrix based composites, whereas metal matrix based composites have received the least attention. The CNT-metal/ceramic based composites can be used in structural applications for their significant mechanical, thermal and electrical properties. This review discusses fabrication and properties of CNT reinforced metal/ceramic matrix based composites with a focus on composites fabricated by powder metallurgy and thermal spraying techniques. In the end, the effect of different reinforcements on mechanical properties of the composites has been summarised.

Keywords:Carbon nanotubes, reinforcement, composites, powder metallurgy, thermal spray

1. Introduction

A group of researchers first time described the science of fullerenes, which were first time known as pen like structures of carbon (Thostenson et al., 2001). Another researcher Iijima (1991) reported the new structures of carbon particles in the form of tubes, which were having diameters of the order of 20 nm with few microns lengths, and named these as carbon nanotubes (CNT). Since then, a number of researchers have studied this newly found structure of carbon and investigated their mechanical properties. Experiments have shown that CNT have extraordinary properties over other available form of materials, for example, stiffness upto 1000 GPa, tensile strength greater than 100 GPa and elastic modulus greater than 1 TPa(Esawi and Farag, 2007; Bakshi et al., 2010).Lau et al. (2004) and Agarwal et al. (2016) revealed that CNT possess very good thermal and electrical properties. CNT can be thermally stable at high temperatures of the order of 3000^{0}C and are having 1000 times greater current carrying capacity than copper wires (Collins and Avouris, 2000).

In the recent years, a number of researchers have used CNT as reinforcement materials in polymers, ceramics and in metals. The majority of this research has been confined to polymer matrix composites because its processing does not need high temperatures as required in metal or ceramic matrix composites. There is need to review the studies on CNT reinforced metal matrix and ceramic matrix composites and to highlight the effect of CNT reinforcements on the properties of resulting composite materials. This review discusses fabrication and properties of CNT reinforced metal/ceramic matrix based composites with a focus on composites fabricated by powder metallurgy and thermal spraying techniques. In the end, the effect of different reinforcements on mechanical properties of the composites has been summarised. This review may be helpful to highlight the significance possibilities of research and development in this area.

2. Processing CNT reinforced metal/ceramic matrix composites

2.1 Powder metallurgy techniques

Several investigations have been reported in which aluminium and copper matrix based CNT reinforced composites have been prepared using the powder metallurgy method. A few studies are also available in which MG, Ti, AG, Sn and Ni have been used as matrix in the composites. In the powder metallurgy technique, the CNT are mixed with metal/ceramic powder by mechanical alloying or grinding, and subsequently the mixture is compacted and sintered to achieve uniform reinforcements and proper bonding of CNT in the matrix. Chen et al. (2003a), Wang et al. (2003a), Goh et al. (2005), Kumar et al. (2017), and Tan et al. (2017) used mechanical alloying in powder metallurgy to fabricate CNT reinforced composites. Albaaji et al. (2017) and Liu et al. (2017) reported that using a ball mill is very effective in mixing the composite powders in ratios 0.1 to 50% by volume, and it gives a uniform reinforcements of carbon nanotube fibres in metal matrix composites. He et al. (2007)used chemical vapour deposition process to grow CNT on aluminium powder, and subsequently compacted and sintered at 640^{0}C to achieve 5 wt.%CNT reinforcements with homogeneous dispersion. Yang and Schaller (2004)mixed CNT and magnesium powders in alcohol and acid mixture by sintering at 550^{0}C. The CNT were treated with acid to get rough surface to achieve strong bonding in Ag matrix based composites (Feng et al., 2005). Zhong et al. (2003)have reported that hot pressing method for fabricating aluminium matrix based composite resulted in clustering of carbon nanotubes. Kuzumaki et al. (2000)restricted the milling for 5 hours to prevent damage to CNTs during fabrication of Ti matrix based composite by hot pressing. CNT reinforced composites have shown enhanced hardness, compressive strength and bend strength due to uniform dispersion of CNT and proper interlocking of CNT in the metal matrix (Pang et al., 2007). Kim et al. (2009)investigated the friction and wear characteristics of carbon nanotubes composites based on the dispersion condition, fabrication method and carbon nanotubes content in the composites. The specimens were fabricated using spark plasma sintering (SPS) method and hot pressing (HP) method with the best dispersion condition. The composite with 1% CNT was found to have the lowest friction and wear characteristics.Esawi et al. (2010)fabricatedCNT-Al composites by with powder metallurgy and friction stir processing and found that CNT were uniformly dispersed in the Al matrix. The spectroscopy results revealed the formation of aluminium carbide during fabrication. The yield strength of CNT based composites was enhanced by 45%. Feng et al. (2005)fabricatedCNT-Ag composites with powder metallurgy method and investigated the effects of different carbon nanotube contents on the relative density, hardness, bend strength and electrical resistivity of the composites. The results revealed that the addition of 8% by volume of CNT had enhanced the Vickers hardness and the bend strength by 27% and 9%, respectively. Asl et al. (2016)fabricated ZrB_2–20 vol% SiC and ZrB_2–20 vol% SiC–10 vol% CNT composites by powder metallurgy. It was found that indentation fracture toughness of CNT reinforced composite was 5.1 MPa, which was much higher than pure ceramic due to the uniform dispersion of CNT in the composite matrix. Mallikarjuna et al. (2016)developed CNT-Cu-Sn mixed nano-composite with powder metallurgy and found that increase in CNT content resulted in decrease in density of composite. The hardness of CNT based composite was much higher than pure alloy, and found to be increasing with increase in CNT content in the matrix. The surface roughness decreased with coefficient of friction found to be reduced by 72% with 2 wt.% CNT addition, which resulted in reduction in wear loss by 68% as compared to Cu-Sn alloy. Esawi et al. (2009)used ball mill to mix 2 wt.% CNT in Al powder and investigate the properties of unannealed and annealed composites. The extruded samples were annealed at 400^0C and 500^0C for 10 hours, and found to have more ductility. The ball milling for 3 hours with hot extrusion and annealing at 500^0C exhibited 21% enhancement in tensile strength in comparison to pure aluminium. The transmission electron microscopy results revealed the uniform presence of CNT in the aluminium matrix, which resulted in the increase in mechanical properties of the composites. Bhaskar et al. (2016)synthesised the magnesium matrix reinforced with various different wt% (0–0.45) of multi wall carbon nano tubes and micro SiC particles prepared through powder metallurgy route. The microhardness of SiC was 61 Hv, whereas the microhardness of 0.45 wt% carbon nanotubes based composite was 78 Hv. The Energy-dispersive X-ray spectroscopy confirmed that SiC and carbon nanotubes were present within the composites.

2.2 Thermal Spraying Technique

Thermal spraying techniques have been used to develop CNT reinforced metal matrix composites (Laha et al., 2004; Laha et al., 2005; Pialago et al., 2015; Moonngam et al., 2016; Ariharan et al., 2017; Goyal et al., 2018). Laha et al. (2004)reported the feasibility of developing CNT reinforced aluminium coatings with uniform dispersion. Laha et al. (2007)analyzed the interfacial phenomenon in aluminium-silicon-CNT reinforced composites developed by plasma and high velocity oxy fuel spraying technique.

Table 1: Effect of CNT reinforcements on properties of composites

Researcher	Reinforcements	Matrix	Improvement in Mechanical properties of composite in comparison to matrix
(Deng et al., 2007)	1.0 wt. % CNT	Al	Strength-35%, Moudulus-41%
(Esawi et al., 2010)	5.0 wt. % CNT	Al	Strength-50%, Stiffness-23%
(Feng et al., 2005)	8.0 vol. % CNT	Ag	Hardness-27%, Bend Strength-9%
(Bhaskar et al., 2016)	(0–0.45) wt. % CNT and micro SiC	Mg	Hardness-28%
(Mallikarjuna et al., 2016)	2.0 wt. % CNT	Cu-Sn alloy	Coeff. of friction- 72% Wear rate-68%
(Chu et al., 2013)	10.0 wt. % CNT	Cu-0.76 wt% Cr	Yield Strength-76% Hardness-98%
(Pérez-Bustamante et al., 2009)	1.75 wt. % CNT	Al	Yield Strength-36% Hardness-29%
(Goh et al., 2006)	1.3 wt. % CNT	Mg	Yield Strength-11% Ultimate tensile strength-9% Elongation-68%
(Liu et al., 2012)	1.0 wt. % CNT	2009Al	Yield Strength-28%
	3.0 wt. % CNT	2009Al	Yield Strength-45%
(Ramesh et al., 2013)	25 vol. % CNT	Al 6061	Hardness-27% Wear rate-75%
(Ramesh and Prasad, 2008)	2.0 wt. % CNT	Al-17%Si	Yield Strength-10% Hardness-4%
(Kim et al., 2007)	5 vol. % CNT	Cu	Wear rate-60%
	10 vol. % CNT		Wear rate-95%
(Wang et al., 2003b)	4 vol. % CNT	Cu	Wear rate-40%
	8 vol. % CNT		Wear rate-52%
	12 vol. % CNT		Wear rate-60%
	16 vol. % CNT		Wear rate-62%
(Chen et al., 2003b)	5 vol. % CNT	Ni	Hardness-3.2% Wear rate-33%
	10 vol. % CNT		Hardness-21.4% Wear rate-66%
	11 vol. % CNT		Hardness-39% Wear rate-60%
	12 vol. % CNT		Hardness-5.5% Wear rate-66%

The results showed the formation of SiC layer at the interface of Al-Si matrix attributed to the high rate of reaction at tripple point of Al-Si/CNT/vapour. The SiC layer resulted in high interfacial adhesion strength between CNT and Al-Si matrix. Bakshi et al. (2008)prepared the Al-CNT composites with cold spraying. 5 wt.%CNT were blended with aluminium powder before cold spraying, which resulted in the composite coating of 500 μm. The results indicated that carbon nanotubes were uniformly present in the matrix and were fractured due to impact and shearing during deposition process. The elastic modulus was found in the range of 40 -229 GPa, which was attributed to proper mechanical interlocking between CNT and metal particles. Keshri et al. (2009)have fabricated CNT reinforced composites with plasma spray, high velocity oxy fuel and cold spraying methods. The results revealed that CNT were uniformly retained in the metal/ceramic matrix in all thermal spraying processes even at high temperatures of thermal spraying. Some phase transformation of CNT was found in plasma spraying due to high intense heat of plasma. Kaewsai et al. (2010)preparedCNT/stainless steal composite coating with flame spray process. The scanning electron microscopy results revealed the presence of CNT in the stainless steel matrix with lamellar structure. The hardness of CNT reinforced composite coating was found to be 480Hv, which was much higher than hardness of stainless steel. The coefficient of friction was reduced by 3 times with the addition of CNT, which helped to reduce wear rate by 2 times. Bakshi et al. (2011)developed Al-Si-CNT composites with plasma spraying and found that CNT were uniformly dispersed in the composite coating. The 5 wt.% and 10 wt.% addition of CNT were able to enhance elastic modulus by 19% and 30%, and yield strength by 17% and 27% respectively. The 5 wt.%CNT addition has resulted in reduction of wear rate by 68%, while wear rate reduced by 15% with addition of 10 wt.% CNT. The enhancement in mechanical properties was attributed to proper dispersion of CNT and cluster size of CNT in the composite. Keshri and Agarwal (2011)used plasma spraying technique to develop Al_2O_3-CNT composite coatings with 4 wt.% and 8 wt.% CNT content and conducted wear tests at room temperature, 600^0C and in sea water. The microstructure analysis showed the formation of SiO_2 layer due to chemical reaction at room temperature as well as in sea water. Wear rates were found to be increasing with increase in temperature foe all the coatings due to the detachment of SiO_2 layer at high temperature. 8 wt.% CNT addition exhibited highest wear resistance in all the experimental conditions and this behaviour was attributed to the high fracture toughness of CNT reinforced coatings and their uniform dispersion in the coating matrix. The summary of improvements in the properties of CNT reinforced metal matrix composites is given in Table 1.

Conclusion

The increasing interest in development of carbon nanotubes reinforced metal/ceramic matrix based composites can be attributed to the reduced prices, availability and significant mechanical properties. CNT based composites possess a great potential to replace existing metals and their alloys in automobiles, aerospace, and high temperature applications. It has been seen that powder metallurgy, mechanical alloying and thermal spraying techniques have been employed to fabricate CNT reinforced metal or ceramic matrix based composites. Thermal spraying methods can produce these composites at large scale with uniform distribution of carbon nanotubes in the composite matrix. There is lot of scope of research in this field by exploring to fabricate CNT reinforced composites with other metals and ceramic materials as matrix, for example, to use CNT reinforced ceramic composite in high temperature applications.

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