Review Article 2019, **10**(11), 786-792 Advanced Materials Letters

Investigating the Machinability of Metallic Matrix Composites Reinforced by Carbon Nanotubes: A Review

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Received: 28 March 2019, Revised: 30 June 2019 and Accepted: 02 July 2019

DOI: 10.5185/amlett.2019.0025
www.vbripress.com/aml

Abstract

The modern manufacturing technology tends to innovate different materials with simultaneous low density in weight, porosity, high toughness, corrosion resistance, thermal and electrical properties etc. Metallic matrix-based carbon nanotubes composites (CNTs) are a relatively new material concept. The CNT reinforced composite materials harvest the dual benefit of alloying metals with high mechanical properties of CNTs. Besides, the materials being innovated must have good forming or machining characteristics. However, no machining data or machining model are yet available for these newly developed composites. In this work, the mechanical machining of metal-matrix/CNTs composites has studied to review the available data and better understanding the material removal behaviour. The work also concludes on the suggestive machining techniques adopted that will not affect the structural deformation, mechanical, thermal, electrical properties as well as must not alter the mechanical characteristics of the machined surface. The present study will assist in optimizing the manufacturing composites with desirable mechanical properties in future CNT reinforced composite developments. Copyright © VBRI Press.

Keywords: Carbon nanotube, mechanical properties, thermal properties, electrical properties, machining characteristics.

Introduction

Material development needs continuous progression. With the expansion of versatile service of material, a single material hardly satisfies the increasing demands for improved properties. CNTs reinforced in metallic or bimetallic Matrix are the new class of materials [**1**]. CNTs have good mechanical properties, high specific strength, but low direct applicability [**2-4**]. Thus, composites of CNTs are becoming popular and rapidly replacing conventional materials in various industrial and aerospace applications [**5, 6**]. However, metallic composites and reinforced composites are hard to machine [**7-9**]. On occasion, unfavorable chemical reaction of CNTs with the matrix and low compact ability are the most significant challenges, requiring more concentration for strength and machining [**10, 11**].

Besides, high tool wear and inferior surface quality of the specimens during machining of the metal matrix may restrict the application in many areas in spite of their excellent properties [**12, 13**]. CNTs reinforced bimetallic composites machining confronts lack of scientist and supportive research data. However, the presence of CNTs in the metallic matrix influences the machining responses of the composite. Thus, high machinability characteristics is a compulsory criterion for this composite manufacturing and applications.

Pramanik *et al.* [**14, 15**] investigated fracture and fatigue performance of metal matrix composites at different conditions of feeds and speeds. The outcome of the research was the fatigue and fracture of metals for different variable parameters. Xavior *et al.* [**16**] study on the machinability of hybrid metal matrix composite. Sekhar *et al.* [**17**] worked on the turning mechanism metal matrix composites. The team compared chipping, wear, dislocation, bonding, surface roughness, cutting forces for varieties of metal matrix composites. The same variable considered by Dabade *et al.* [**18**] for observing cutting force, feed force, thrust force, surface roughness and micro-hardness variation beneath the machined surface.

Recurrence Plots and Recurrence Quantification Analysis has also used to study the machining characteristics of cast and powder metallurgy of Al, Al-Si alloys (LM6 and LM25), and CNT reinforced Al/Al-Si composites produced by powder metallurgy process [**19**]. In this work, the research group concludes good machining characteristics for composites obtained by powder metallurgy process than cast material. Some researchers are working on the finite element-machining model of CNT reinforced polymer composites [**20-22**]. Kumar *et al.* [**23**] studied on surface roughness measurement for turning of Al7075/10/SiCp and Al7075 hybrid composites by using response surface methodology and artificial neural networking.

Besides this available date, little research has done on the machining of CNTs reinforced composites. It is high time to study the machining of the CNT reinforced metal matrix composites (MMC) and modeling to predict the machining criteria. Based on the above-mentioned discussions, the proposed work must have two focus points. Firstly, microscopic analysis of CNT/MMC composites. Secondly, to study different machining method for various range of composition and collecting relevant data for future reference.

Literature review

Composites of bimetallic-CNTs are obtained by powder metallurgy process usually. This process integrates sophisticated mechanical properties like toughness, fatigue, fracture, and strength for its uniform particle's distribution and chemical homogeneity. This also includes fabricating corrosion resistant films or coatings, micro/nano dispersion, the bonding process, chemical treatment etc. Therefore, the selected machining process should not alter or adversely affect any of the above-mentioned characters.

In the preliminary study, it is required to a systematic study of the interrelationship between powder metallurgy, compacting techniques, dispersion, CNTs formation, bimetallic matrix formation, bonding, chemical analysis, mechanical properties, fatigue, robustness, microstructures etc. The relevant cutting tool materials, geometry will be studied. It will provide guidance to select optimum cutting conditions with appropriate cutting methods. The study will consist of the method of cutting, feed, depth of cut, cutting speed, chip formation, lubricating/cooling, tool materials etc. in a precise manner. The work will also address surface generation, cutting forces, particle fracture, particle pullout, de-bonding, dislocation phenomena, thermal softening and wear modes.

For selecting optimum machining parameters and high cutting performance, necessary charts, table will be provided for reference. Finally, mathematical modeling and simulation data will provide a flexible machining process relating mechanical data. The electrical discharge machining process of CNTs-Alumina has tried for 2.5 to 12.5 vol. % CNTs. The low concentration of CNTs at 2.5, 5 vol. %, effective machining is not possible. Proper machinability is observed with increase CNTs concentration in the composite around 7.5 vol. % or more [**24**].

A large number of the metallic particle is mixed with CNTs for composite formation. At the same time, separate processing techniques are available/adopted for better mechanical processing. A list of MMC constituents and processing methods are listed in **Table 1**. Composites formed by CNTs and metals provide a superb mechanical property due to nano diameters of CNTs, high Young's modulus (≈ 1 TPa), tensile strength (≈ 200 GPa) and high elongation (10-30%) [**28**]. In this work, researchers have used equal channel angular pressing (ECPA) concept to develop Cu-CNTs composite. The resulting hardness is given below in **Fig. 1**.

Table 1. Types of CNT/metal matrix composites and processing techniques [25-27].

Reinforced Metal	Processing Techniques
Al, Cu, Mg, Ni, Ti, Ag, Sn, W-Cu, Fe_3Al	Powder metallurgy (Mechanical alloying and sintering, Mixing/mechanical alloying and hot pressing, Spark plasma sintering)
Zr, Mg, Al, $Fe_{82}P_{18}$	Melting and solidification route (Casting, Melt spinning Laser deposition, Metal infiltration)
Al	Thermal spray (Plasma spraying and high velocity oxy-fuel, Cold spraying)
Ni, Cu, Ni-P, Ni-B, Ni-Fe-P, Ni-Cu-P	Electrochemical (Electro-deposition and Electro less deposition etc.) process

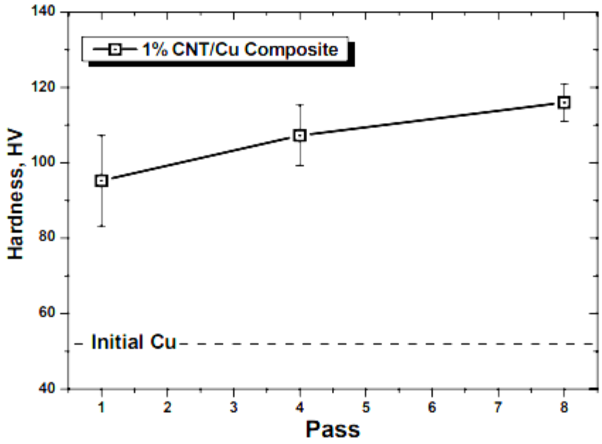

Fig. 1. Hardness with the number of ECAP passes for 1 vol.% CNT/Cu nanocomposites [28].

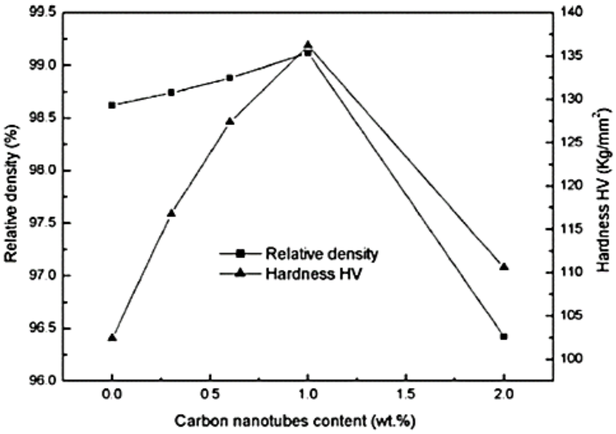

Fig. 2. Hardness and density of different weight percentages of CNT/2024 Al composites [29].

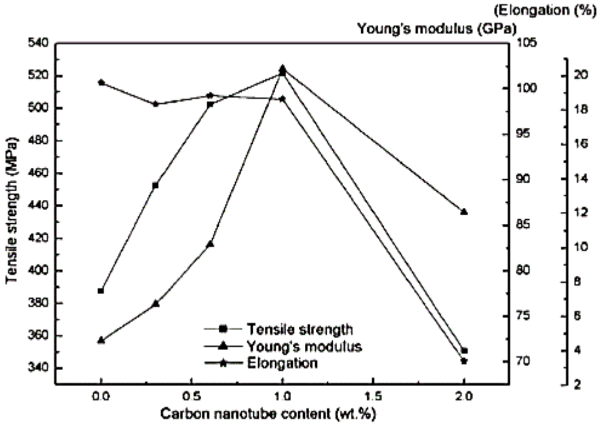

Fig. 3. Effect of CNTs addition on tensile strength, Young's modulus and elongation of an Al matrix [29].

Deng *et al.* [**29**] describe that for Al-CNTs composite, tensile strength, and Young's modulus primarily increase with increasing wt. % CNTs content when CNTs content is below 1.0 wt.%. Both of them decreases obviously with increasing CNTs content as shown in **Fig. 3**. The tensile strength and Young's modulus reach the maximum when CNTs content is 1.0 wt. %. Alongside the tensile strength, Young modulus, hardness Al/CNTs also achieve improved normal stress as shown in **Fig. 4**. Thus, CNTs addition make the metallic composite more ductile. George *et al.* [**31**] study about the MWCNTs/Al and SWCNTs/Al composites. They found the following properties as summarized in **Table 2** and **Table 3**. Esawi *et al.* [**32**] found an enhancement of up to 50% in tensile strength and 23% in stiffness compared to pure Al for 5% CNTs-Al by cold compaction and hot extrusion.

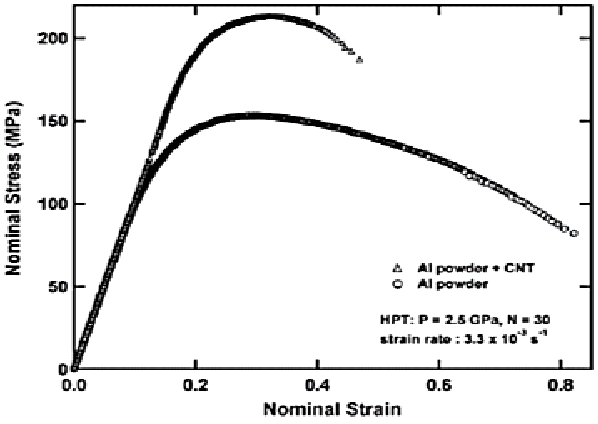

Fig. 4. Stress-strain curve obtained for Al/CNT samples and Al powder samples [30].

Table 2. Effect of MWCNT volume on mechanical properties of Al-MWCNT composites [31].

MWCNT vol%	Shear Lag Young's Modulus (MPa)	Experimental Young's modulus (MPa)	Experimental Yield Strength (MPa)	Ultimate Tensile strength (MPa)
0.5	74.305	78.1	86	134
0.5 + K_2ZrF_6	74.305	75.20	93	150
2	84.376	85.85	99	138

Table 3. Effect of SWCNT volume on mechanical properties of Al-MWCNT composites [31].

SWCNT vol%	Shear Lag Young's Modulus (MPa)	Experimental Young's modulus (MPa)	Experimental Yield Strength (MPa)	Ultimate Tensile strength (MPa)
0.5	79.167	70	79.8	141
0.5 + K_2ZrF_6	79.167	93.7	98.7	181
2	88.355	79.3	90.8	134

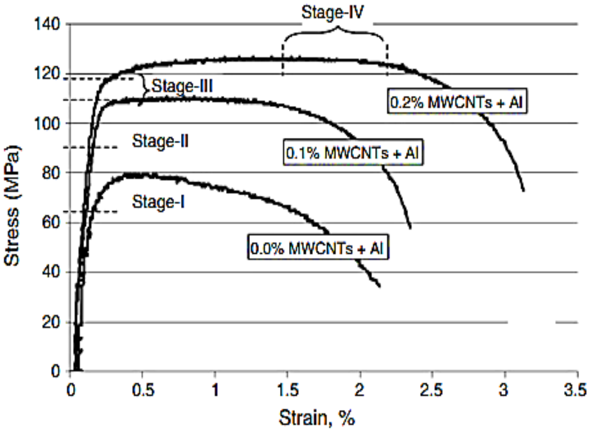

Fig. 5. Experimental stress-strain curves of various specimens [33].

A simultaneous increase in 77% yield strength, 52% tensile strength, 44% ductility, and 45% hardness is observed for Al-0.1% CNTs and Al-0.2% CNTs melted in an induction furnace [**33**]. Cha *et al.* [**34**] reported a 200% increase in the yield strength in 10 vol. % CNT-reinforced Cu composites. Yang *et al.* [**35**] found 2.3- and 2.4-times hardness and tensile strength for 4.5 wt%-CNT/Al composites. However, in most of the case, some CNTs become damaged. Thus, the desired properties somewhat different from the expected results. Hassan *et al.* [**36**] investigated the composites prepared with mildly damaged CNTs are found to have 97.5% higher strength and 14.2% higher modulus than pure Al. Where the strength and modulus of composites with severely damaged CNTs are found to be higher by 71% and 3.3% than pure Al.

However, at high wt. % of CNTs hardness decrease and weight loss increases. According to Yildirim *et al.* [**37**], the best properties are obtained for 1% of CNTs. This is opposite multi-wall CNTs. Tensile strength and micro hardness increase with the increasing amount of MWCNT content, but on the contrary, the elongation decreased [**38**]. Addition of CNTs also improve wear properties of composites. Lu *et al.* [**39**] formed nano-Al_2O_3 particles and CNT reinforced magnesium matrix composites. The research found that, for 1.95 MPa load, the wear of (0.1% Al_2O_3-0.2% CNT)/AZ31 the hybrid composite was considerably lower. Noguchi *et al.* [**40**] found a sevenfold increase in compressive yield strength in 1.6 vol. % CNT/Al composites. Laha *et al.* [**41**] obtained a 71.8% increase in micro-hardness in CNT/6061Al composites when 10 wt. % CNTs was added.

Carreno-Morelli *et al.* [**43**] showed that Young's modulus was increased by 9% in CNT/Mg composites with the addition of 2 wt. % CNTs. The thermal conductivity of CNTs-Metal matrix composite decreases. The presence of an interfacial thermal resistance between the CNT and the metal matrix is the main reason in causing the measured low thermal conductivity. This magnitude may be up to 20% of pure metal [**44**]. Chu *et al.* [**42**] have explained the phenomenon of thermal conductivity for Cu-CNTs as shown in **Fig. 6**. Addition of CNTs in composites leads to extraordinarily low coefficient of thermal expansion. Shin *et al.* [**45**] study about the Al (2024) matrix composites reinforced with MWCNT in the temperature range of 250-430°C. The composites have shown a low thermal expansion coefficient of $\sim 18\times10^{-6}$/K.

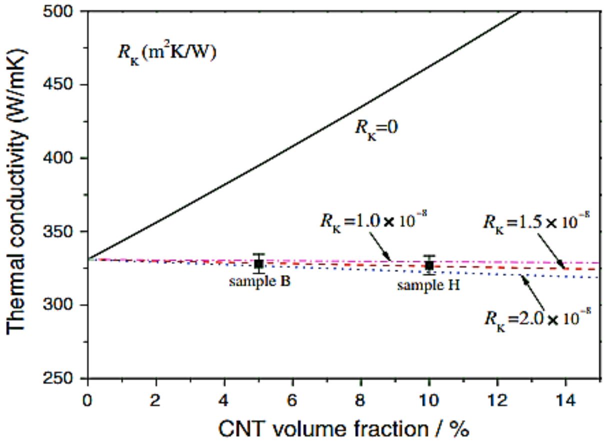

Fig. 6. Predictions of thermal conductivity by effective medium approach for Cu-CNTs composites [42].

Forming CNTs-metal matrix composites exhibit a good strength but poor electrical. On the other hand, MWCNTs-metal matrix composites reveal much enhanced electrical conductivity of $3.316 \times 10^7\ \mathrm{Sm}^{-1}$ and thermal conductivity of 172 W/mK [**46**]. For CNTs-Al matrix composites electrical resistivity at room temperature increases slightly with increasing vol% of CNTs [**47**]. In this work, the resistivity was found to be dropped at 80 K by more than 90%. The authors describe the different sample and their electrical properties as shown in **Table 4**. For Ag-6% CNTs composites, the electricity conductive properties have found to be double than the pure Ag. The Ag/CNTs conductivity is shown in the below **Table 4, Table 5** and **Fig. 7** [**48**].

Table 4. Electrical resistivity at room temperature for aluminum and SWCNT-Al metal-matrix composites prepared by the HIP and sintering methods [49].

Sample	Production Method	wt% SWCNTs	Electrical resistivity (Ω cm)
Al (Literature)	NA	0	2.8×10^{-6}
Al (this study)	HIP	0	3.1 ×10-6
SWCNT-A1-v1	HIP	5	5.8 ×10-6
SWCNT-A1-v2	HIP	5	5 ×10-6
Ag@SWCNT-Al Ag:SWCNT=10:1	HIP	0.5	3.7 ×10-6
Al (this study)	Sintering	0	3.1 ×10-6
SWCNT-A1	Sintering	0.66	3.2 ×10-6

Table 5. Density and electrical conductivity of Ag/MW-CNT nanocomposites [48].

Specimen	Conductivity [s/m]	CNT [mg]	Silver nitrate	CNT vol %	Density [mg/cm^3]
Ag	0.4×10^7	0	3 gm	0	8.62
Ag/CNT	0.9×10^7	11	3 gm	6	7.72
Ag/CNT	0.7×10^7	22	3 gm	12	7.46

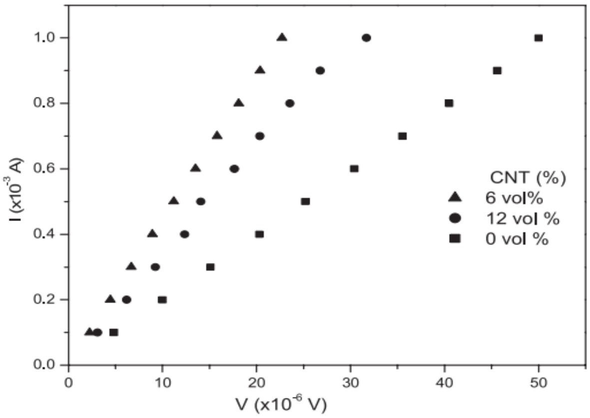

Fig. 7. V-I Characteristics of Ag/MW-CNT nanocomposite [48].

Results and discussions

CNTs reinforced composites materials is a new class of material not spread widely yet. Very few literatures is available for machining characteristics of CNTs based composites. More specifically metal-CNTs based materials have ever tried for machining. Very few numbers of the author have worked on the recurrence quantification analysis (RQA), geometric programming, linear programming, goal programming, sequential unconstrained minimization, technique, dynamic programming, fuzzy logic etc. However, most of the basis of the works are simulation rather than practical. Umashankar *et al.* [**50**] worked on the RQA method for finding machining characteristics in a 1530/1650 lathe **(Table 6)**. For the following RQA parameter, the research team observes the combination of cutting force and corresponding RP as shown in **Fig. 8**. On the other side, CNTs reinforced polymer/polycarbonate composites have tried to machining in several works.

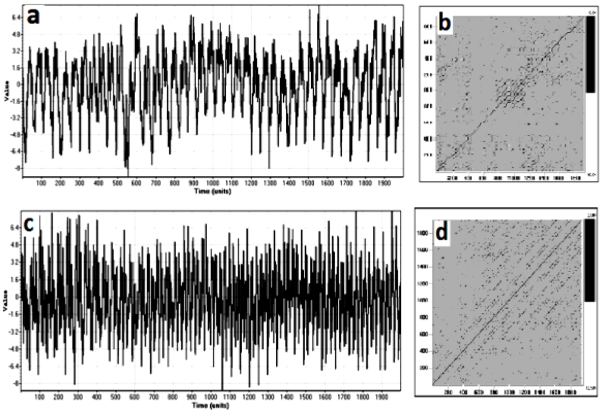

Fig. 8. (a, b and c, d) Time domain cutting force signal and corresponding RP for (a and b) without reinforced Al and (c and d) 0.5 wt % MWCNT reinforced Al nanocomposite samples [50].

Table 6. Parameter for RQA observation [50].

RQA Parameters	Material		
	Al	**LM6**	**LM25**
DET (%)	3.04	17.51	4.98
L	2.72	2.25	2.63
ENTR	1.17	0.62	1.08
LAM (%)	1.99	9.56	1.46
TT	2.34	2.47	2.33

The researchers have developed a finite element analysis (FEA) based machining model for CNTs-Polymer composites. Jiang [**51**] and Basavanahalli [**52**] worked on the FEA machining model of 5% CNTs-polymer composites. The researcher describes the interfacial bonding and phase characteristics between polymer and CNTs for major machining challenge to keep intake the mechanical properties of any composites. Mahmoodi *et al.* [**8**] studied the metal removal rate of CNTs nanocomposites. They concluded that machinability of CNT nanocomposites is better than pure polymer. The research group use injection-moulded sample to observe the micro-mechanical milling effect with the following condition as shown in the **Table 7** below. **Fig. 9** depicts the required cutting force for feed per tooth (FPT).

Table 7. Milling conditions [8].

Tool	Coated tungsten carbide (WC) 508 µm diameter
Axial depth of cut (µm)	200
Feed per tooth (µm/flute)	0.05, 0.2, 1, 2, 3, 4, 5
Spindle speed (rpm)	60,000
Material	Plain PC, 5 wt% MWCNT-PC

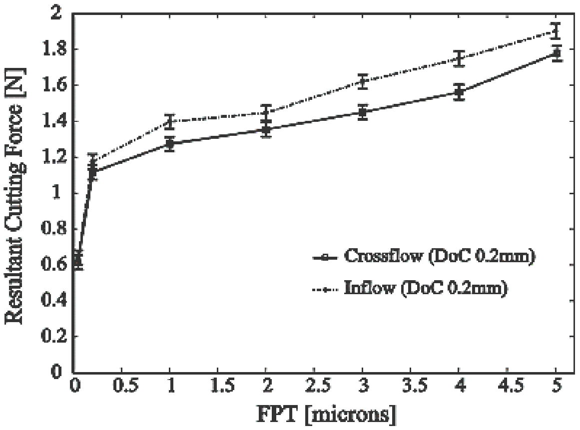

Fig. 9. Comparison of the resultant cutting forces for inflow versus crossflow micro milling for PC-MWCNT (5% by weight) [8].

Pashaki *et al.* [**53**] develop a new approach of cryogenic machining of CNT reinforced nanocomposites at high speed. Results show that at 60 m/s cutting speed, cryogenic cooling has caused a decrease of work piece plastic strain by 12%. Dikshit *et al.* [**54**] model a continuum-based simulation of polycarbonate CNT composite machining. The simulation results were justified by the dynamic mechanical analyser and compression tests. Mahmoodi *et al.* [**55**] measured and compared the magnitude of the cutting forces for graphene nano-platelet and MWCNT filled nanocomposites. A few years ago, Jiang [**51**] attempted to understand the machinability of CNT-polymer composites. The researcher develops an elemental machining model that considers two distinct phases.

Table 8. Comparative table for a different type of CNTs reinforced composites and available machining methods.

Ref.	Composition & Machining	Remarks
[56], [57]	CNTs-Al_2O_3 Drilling	Significant exposures to nanoscale particles and fibers observed. Need to monitor exposures and to adopt a proactive attitude.
[58]	CNTs-Al_2O_3 Turning	Monolithic Al_2O_3 tool inserts for metal cutting. Cutting conditions shows promising applicability in the machining industry.
[59]	CNT-Polymer EDM	EDM of CNT reinforced composite was investigated experimentally. Micro-EDM was found to be an ideal process for obtaining burr-free machined micron-size features.
[60]	CNTs Cluster ESEM	A portion of the electron beam interacts with the water vapor in the vicinity of the CNT sample. Less carbon residue with native structural morphology of the CNT forest.
[61]	CNTs-Polymer	Continuum-based microstructural material model to simulate machining of CNT reinforced composites using a micro-level FE model.
[62]	CNTs-Gr-Al_2O_3 Micro EDM	Effective machining performance for alumina with CNTs and Gr reinforcement.
[63]	CNTs Cluster	CNTs cluster was precisely machined in a low-pressure water vapor ambient using the electron beam of an ESEM.
[64]	CNTs-Si_3N_4 EDM	CNTs-Si_3N_4 can be effectively machined. Material removal rate, electrode wear ratio, and surface roughness of the machined pieces are analyzed.

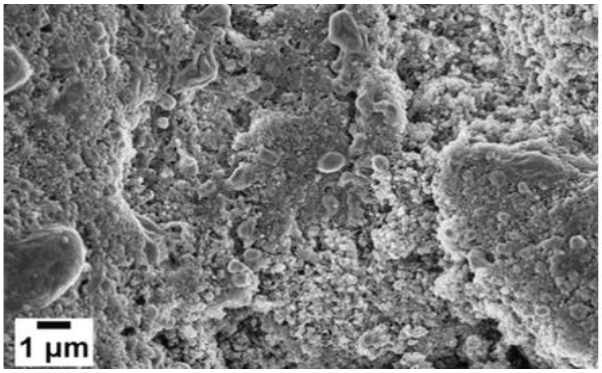

Fig. 10. SEM picture showing the presence of submicron debris on the EDM surface of the composite with 2 wt% CNT content [68].

Samuel *et al.* [**65**] investigated the machinability of a polycarbonate/MWCNT composite with a conventional carbon fibre composite. Recently, the researcher studied the Electrical Discharge Machining (EDM) of zirconia/CNTs [**66**], and 5% Al_2O_3/CNTs [**67**]. Due to many tangles of CNT in 5% Al_2O_3/CNTs composites, a rigorous spark occurs during EDM causing poor dimensional accuracy and circularity. For Zr/CNTs, the material removal in EDM is melting/evaporation and spalling [**68**]. High temperature is produced during machining and thus a debris form on the machined work piece as shown in **Fig. 10**. Singh *et al.* [69] have observed the same in their work. Up to 2.5 wt % of CNTs, Al-CNTs are hard to machine. As like 5% Al_2O_3/CNTs composite, more than 5 wt % CNTs/Al composite provide better machining quality and undergo the same spalling effect. The groups also found wire lag for EDM.

Conclusion and future perspectives

The main research outcome of this anticipated project is the optimization of the composite for better machinability without sacrifice any mechanical properties. The appropriate cutting tools, material, cutting conditions, wear, and finishing are the subsequent results of the project. This review finds that with the increase of CNTs up to 10% depending on the metallic constituents (Al/Ag/Mg/Zr etc.) cause cutting tougher. As the reinforced composites reach its CNTs percolation value, machining withers conventional or unconventional provides poor surface quality. In addition, the post-treatment and strengthening mechanism widely affect the machining quality and magnitude of cutting force. However, the % amount of CNTs drastically change the wear and friction coefficient. RQA and FEA model of CNTs/MMC machining is becoming more popular and seems to be convenient to implement. However, the proposed machining model have not sufficient validating date at different machining conditions. For soft compacting machining is quite impossible. On the other side, for compact hardening and post-treatment, surface quality deteriorates as well as cutting tools. Tungsten wire or carbide tools both groups have the cutting capability. But most research models are based on EDM and wire cutting tools. Appropriate cooling or separate cooling agent has not proposed by any research.

Acknowledgments

The authors like to thanks Dr. Xusheng Yang, Assistant Professor, The Hong Kong Polytechnic University, Hong Kong for his inspiration to work on carbon nanotubes.

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