



# Powder-mixed electro-discharge machining performance of Inconel 718: effect of concentration of multi-walled carbon nanotube added to the dielectric media

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MS received 25 March 2019; revised 11 October 2019; accepted 21 April 2020; published online 23 May 2020

**Abstract.** The present work reports an experimental investigation on Powder-Mixed Electro-Discharge Machining (PMEDM) of Inconel 718 superalloy using Multi-Walled Carbon Nanotubes (MWCNTs) dispersed in kerosene, as dielectric media. Effects of variation of peak discharge current along with concentration of carbon nanotubes in the dielectric fluid are studied in purview of machining performance indicators including material removal efficiency, tool wear rate, and surface integrity of the machined part. The obtained results are compared to that of conventional EDM which utilizes kerosene as dielectric media. Morphology and topography, these two aspects of machined surface integrity are deliberated. The following surface morphological features: uneven fusion structure, globules of debris, molten metal deposition, surface cracks, pockmarks, and recast layer are identified. Topographical study includes surface roughness, severity of surface cracking, recast layer thickness, transfer of foreign elements, surface metallurgical characteristics, residual stress, and micro-indentation hardness. It is observed that application of MWCNT mixed dielectric media substantially improves EDM performance of Inconel 718 over conventional EDM. This is due to excellent thermo-physical properties of carbon nanotubes.

**Keywords.** Powder-mixed electro-discharge machining (PMEDM); Inconel 718; superalloy; multi-walled carbon nanotubes (MWCNTs); surface integrity.

## 1. Research background

Inconel 718 is nickel-iron-chromium based super alloy possessing high strength at extreme temperatures. Machining of Inconel 718 is very difficult using conventional methods due to its material properties which include poor thermal conductivity, extreme work hardening tendency, high strength and toughness, tendency to get welded tool-workpiece interface (due to localized temperature). It also contains hard and highly abrasive carbide particles which promote rapid tool wear [1]. More recently, potential aspects of conventional machining (grinding) of Inconel 718 were studied in [2] with application of nanofluids under Minimum Quantity Lubrication (MQL). Lesser grinding force, favorable frictional coefficient, and superior surface integrity were experienced than dry machining. In another reporting [3], grinding characteristics of Inconel 718 were studied under soluble oil MQL and liquid nitrogen (LN<sub>2</sub>)

environments. Application potential of clean and ecological grinding was reported therein.

In contrast, non-conventional methods are also employed for machining of Inconel 718 work material. Though material removal rate is less in case of non-conventional machining but it can produce desired shape, intricate contour, and complex dimensional features with satisfactory surface quality. Amongst various non-conventional methods, Electro-Discharge Machining (EDM) has vivid applications especially in die and mould making industries.

Effects of EDM process parameters on machining responses of Inconel 718 were explored in [4]. EDM process parameters were optimized in [5] during electro-discharge drilling of Inconel 718. Influence of process parameters on machining responses was investigated in [6] during EDM of Inconel 825 using Analysis of Variance (ANOVA) method. Experimental investigations regarding effects of process parameters on machining responses such as Material Removal Rate (MRR), Tool Wear Rate (TWR), and surface roughness (SR) were carried out in [7] with

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varied polarities during EDM of Inconel 600 with copper electrode. Among selected parameters, peak current showed significant influence on MRR and SR.

However, machining of hard and low-conductive materials, through conventional EDM, experiences high tool wear rate, and results in disappointing surface finish. In order to reduce TWR and to achieve better surface finish, few modifications are recommended over conventional EDM procedure. This includes cryogenic cooling of electrode and modifications of tool electrode. Influence of cryogenic cooling of tool electrode on surface roughness, and tool wear during EDM process was examined by [8]. Cryogenic cooling offered the lowest tool wear rate as well as surface roughness than conventional EDM. EDM experiments were performed on Inconel 718 and Ti-6Al-4V work materials using single channeled and multi-channeled electrodes (brass and copper) [9]. Single channeled electrode resulted in higher MRR, and lower tool wear rate. On the contrary, multi-channeled electrode offered better surface finish than single channeled electrode due to efficient flushing.

EDMed surface in general consists of cracks, pockmarks, craters and re-deposited layer. Due to existence of aforesaid surface irregularities, inferior surface quality is obtained. Few researchers [10, 11] suggested that adding micro-sized conductive powder particles into the dielectric medium during EDM operation could enhance machining efficiency with better surface characteristics than conventional EDM. But, different powders perform differently. It depends on the properties of powder, particle size, powder concentration, compatibility of work/tool material. Popularity of powder addition in various EDM techniques was delineated in [10]. Salient properties of different powder particles which are commonly used in PMEDM process were also provided in [11].

EDM experiments were performed by [12] using Si, Al, and graphite powders added to the dielectric media. Addition of these powders into dielectric media resulted in improved MRR, formation of hardened layer just beneath the machined surface, reduced SR, minimal surface cracks than conventional EDM. In another reporting [13], authors observed that with increasing powder concentration (0 to 6g/l), crack density and surface roughness values were declined. It was concluded in [14] that Si powder mixed EDM process enhanced MRR and reduced TWR, SR, cracks and white layer thickness than conventional EDM of Ti-alloy. As reported in [15], process responses were optimized during titanium powder-mixed EDM process using Taguchi-TOPSIS method. Effect of addition of aluminum powder into dielectric media on EDM responses of Inconel 718 was explored in [16]. Topographical features of machined Inconel 718 were investigated in [17] for SiC powder-mixed EDM with copper tool. Addition of SiC powder into dielectric media offered improved MRR, surface finish and declined TWR as well as SCD than conventional EDM process.

Aerospace structural components require superior surface finish with desired surface properties. Therefore, researchers further extended their research towards usage of nanopowders (instead of micropowders) mixed within dielectric media to achieve better surface characteristics. Surface morphology of Inconel 825 work material was studied in [18] for conventional EDM as well as PMEDM operation. Authors reported that, Carbon Nano Tube (CNT) mixed EDM offered superior surface finish with minimal micro-cracks than conventional EDM. Finally, authors confirmed that magnitude of pulse current remarkably influenced surface roughness and depth of micro-cracks. Effect of suspended MoS<sub>2</sub> powder particles in dielectric media during machining of Inconel 718 material with tungsten electrode was explored in [19]. In [20], PMEDM experiments were conducted on AISI-D2 die steel, and observed that CNT mixed dielectric (4g/l) enhanced MRR up to 80%, and reduced surface roughness up to 67% than conventional EDM.

It was concluded in [21] that addition of CNT in dielectric media reduced MRR as well as surface cracks at EDMed Ti-6Al-4V specimen. In [22], authors compared conventional EDM responses with Nano-Powder EDM (NPEDM) responses during machining of Inconel 825 material with copper electrode. Addition aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) nanopowders into dielectric media provided higher MRR, lower surface roughness, and thinner recast layer thickness than conventional EDM.

In the context of PMEDM, appropriate size and concentration of powder particles added to the dielectric medium enhances overall machining performance than conventional EDM [19]. Varieties of conductive powders are available in the marketplace in the form of micro and nanopowders. Many researchers explored micropowder added dielectric media and observed better performance than conventional EDM. However, during EDM with micropowders, problem arises due to local agglomeration of powder particles at the bottom of the dielectric tank due to its high specific gravity. In order to avoid this, use of stirrer is recommended. However, getting homogeneous mixing of powder particles in the dielectric media cannot be ensured. Therefore, local agglomeration and sedimentation of powders adversely affect machining performance. In order to avoid this, use of nanopowders is suggested. Recently, Carbon Nano Tubes (CNTs) are being used for its excellent thermo-electrical properties and lower specific gravity than micropowders. Therefore, CNTs can easily spread over the dielectric media thus ensures uniform dispersion.

CNTs possess high thermal conductivity, low specific gravity, and excellent mechanical and electrical properties. CNTs are mainly classified into two categories; Single Walled Carbon Nano Tubes (SWCNTs) and Multi-Walled Carbon Nano Tubes (MWCNTs). SWCNTs appear as a seamless cylinder of average diameter of 1 to 4 nm; it contains single layer of graphene. In contrast, MWCNTs

are composed of multiple concentric graphene layers with cylindrical shape having average diameter of 9.5 nm [23]. Additionally, MWCNTs possess better thermal and chemical stability than SWCNTs. In addition, MWCNTs can be produced in mass production basis and therefore processing cost is less than SWCNTs. Moreover, MWCNTs have higher strength and corrosion resistance; prone to lesser oxide formation as compared to the case of SWCNTs.

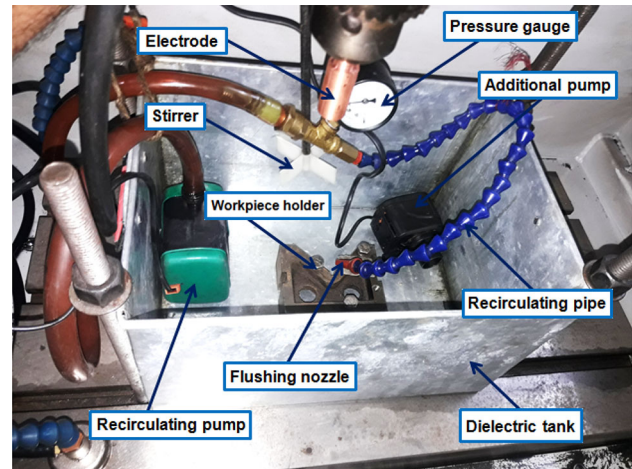
In this context, EDM experiments are performed on Inconel 718 work material using MWCNT suspended dielectric medium. In addition, complete study of machined surface integrity was carried out which is explained in subsequent sections.

## 2. Material and methods

Inconel 718 plates of dimension  $(50 \times 50 \times 5) \text{ mm}^3$  are used as workpiece. Properties of work material are furnished in table 1. Commercially available pure copper rod ( $\text{Ø}15 \text{ mm}$ ) is used as tool electrode. Copper is selected as electrode material due to its excellent thermal and electrical conductivity, superior corrosion and wear resistance. Properties of copper are: density: 8.96 g/cc, melting point: 1083.4°C, and thermal conductivity @27°C: 398 W/m.K. Die-Sinking EDM setup (CNC series) (ED30C, Taiwan) is used in this experiment. Execution of machining tests was carried out with the especially designed additional setup integrated to the existing setup for conventional EDM. The additional setup consists of (i) submersible pump (Brand: Polo cool; Rating: 30 W, 165–220 V/ 50 Hz; Make and Country: TMA International, New Delhi, India), (ii) Stirrer (pure copper motor 6001F; rating: 220 V, 50 Hz, 15 W; Venus Aqua, India), (iii) pressure gauge, (iv) nozzle and (v) transparent tank ( $60 \times 54 \times 35$ ) cc. Snapshot of the experimental setup is provided herein (figure 1). MWCNT mixed kerosene is used as dielectric media. Properties of kerosene are: density: 0.81 g/cc, kinematic viscosity: 2.71 cst, flash point: 38°C, and dielectric constant: 1.8. Specifications of MWCNT supplied by Platonic Nanotech Pvt Ltd, Jharkhand, India, are also provided in table 2. FESEM images of MWCNTs at different magnification are given in figure 2.

**Table 1.** Properties of Inconel 718.

Properties	Value
Density	8.912 g/cc
Specific gravity	8.19
Melting range	1260–1335°C
Ultimate tensile strength	800–1360 MPa
Modulus of elasticity	200 GPa
Specific heat capacity @ 23°C	0.435 kJ/kg.K
Thermal conductivity @ 23°C	11.2 W/m.K



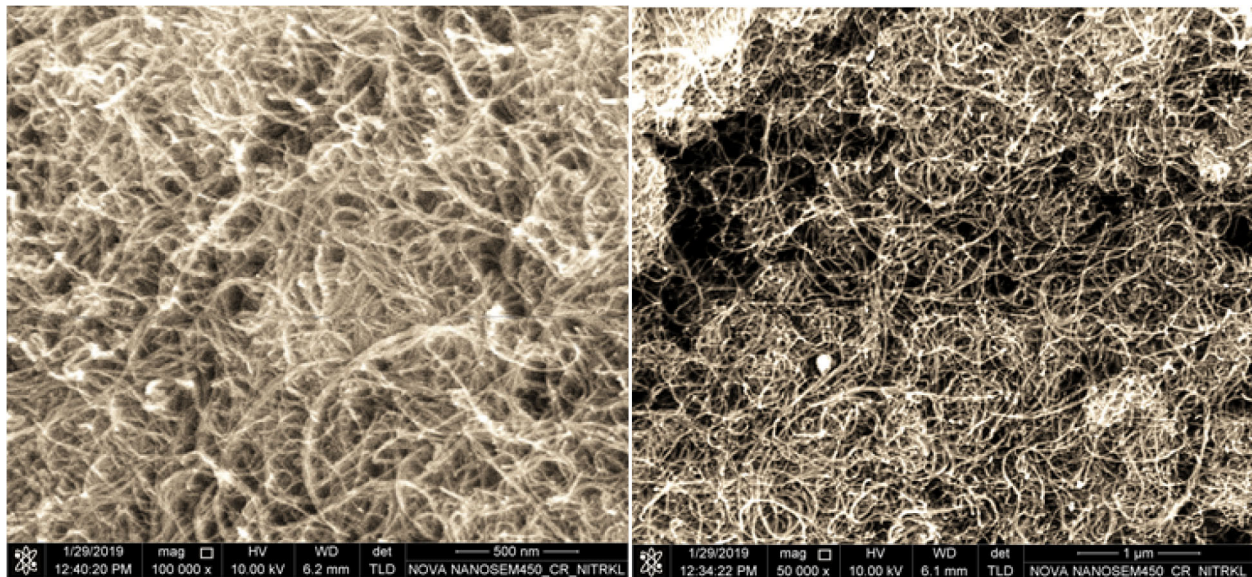
**Figure 1.** Experimental set-up.

**Table 2.** Specifications of MWCNTs.

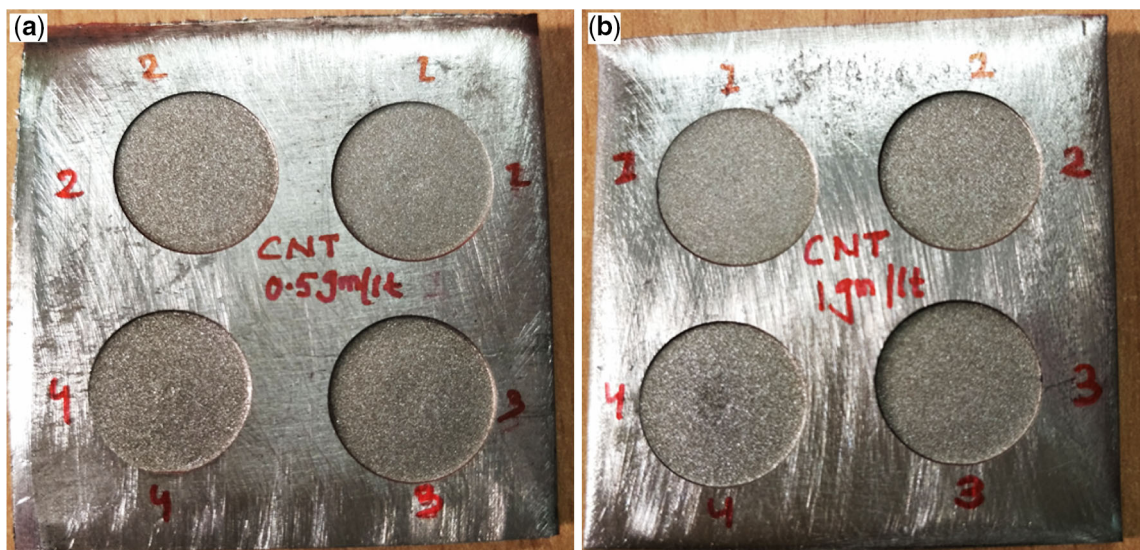
Specification	Unit	Standard
Diameter	nm	10–15
Length	$\mu\text{m}$	2–10
Purity	%	>97%
Ash content	%	<2%
Fe	mg/kg	<4000
Al	mg/kg	<3500
Mo	mg/kg	<800
Specific surface area	$\text{m}^2/\text{g}$	250–270
Bulk density	g/cc	0.06–0.09

Concentration of MWCNT is varied at two levels: 0.5 g/l, and 1 g/l. Four sets of experiments are carried out with varied peak discharge current (2 A, 4 A, 6 A, and 8 A) for each of the concentration values. Level values of peak current are selected based on the recommendations of [18] and [24]. They suggested application of CNT mixed dielectric during EDM at low pulse energy mode (low peak discharge current, short pulse-on duration, and short interval between two consecutive pulses). Apart from peak current, the following process factors are kept constant during experimentation: Gap voltage = 140 V, Pulse-on time = 10  $\mu\text{s}$ , Pulse-off time = 10  $\mu\text{s}$ , Flushing pressure = 0.3  $\text{kg}/\text{cm}^2$ , Workpiece polarity = +ve, Gap between tool and workpiece = 50  $\mu\text{m}$ , depth of cut = 0.75 mm. A snapshot of the machined specimens is provided herein (figure 3).

After experimentation, the following response features are computed: material removal rate, tool wear rate, surface roughness, surface crack density, and recast layer thickness. Material removal rate and tool wear rate are computed based on mass loss. Mass loss of the workpiece as well as tool electrode is computed through mass balance (ABJ



**Figure 2.** FESEM images of MWCNTs at different magnification.



**Figure 3.** Machined specimens produced in MWCNT mixed EDM: (a) MWCNT concentration 0.5 g/l, and (b) MWCNT concentration 1g/l.

120-4NM, KERN and Sohn GmbH, Germany with capacity: 120 g, and accuracy: 0.0001 g). Crater morphology is studied under Optical microscope (Carl Zeiss Microscopy, GmbH 37081, Germany).

Surface roughness of the machined specimen is measured with help of surface roughness tester (Talysurf) with cut-off length ( $L_c$ ) of 0.8 mm and sampling length ( $L_n$ ) of 4 mm. Surface cracks present at the machined surface are observed under Field Emission Scanning Electron Microscope (Nova NanoSEM 450, FEI, USA). Micrographs are used to compute SCD. The same setup is used to study recast layer. Energy Dispersive X-ray Spectroscopy (EDS)

analysis is carried through Scanning Electron Microscope (JEOL, JSM 6480 LV, Japan) in order to reveal chemical composition (elemental analysis) of the machined surface. X-ray Diffraction Microscope (BRUKER, D8 ADVANCE with DAVINCI design, Germany) is used for phase analysis as well as surface residual stress measurements. Microhardness of machined specimens is measured with the help of Vickers microhardness tester (LECO, LM810, USA). In this, pyramid-shaped diamond micro-indenter is used to make indentation on the specimen surface at constant load and dwell time (25 gf, 10 s). Based on the imprint diagonal lengths, hardness value is evaluated.

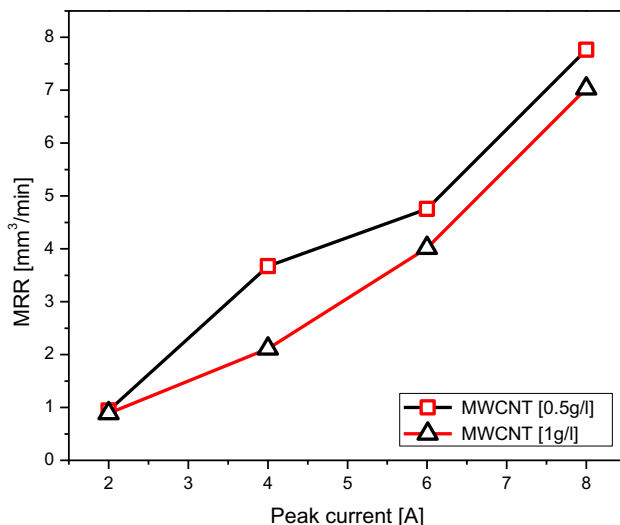
### 3. Results and discussion

#### 3.1 Influence of peak current on MRR

Peak current imposes positive effect on material removal efficiency. As spark energy is directly proportional to the peak current; hence, increase in peak current promotes higher degree of material erosion from the work surface. This improves material removal rate. As compared to conventional EDM, addition of MWCNTs in kerosene results in improved material removal efficiency. This is due to the thermo-electrical properties of CNTs. They act as good conductor in the inter-electrode gap resulting effective transfer of ions to the work surface. Hence, better material removal is accomplished. However, it is noted that when concentration of MWCNTs is 0.5 g/l, MRR is relatively high than the case of 1 g/l concentration (figure 4). High concentration of additives into the dielectric media results in enormous accumulation of machining debris in the discharge gap. This is because high additive concentration to somewhat restricts smooth removal of debris from the discharge gap. Flushing efficiency is hampered. Due to occurrence of abnormal arcing, MRR is decreased at concentration 1 g/l.

#### 3.2 Influence of peak current on TWR

During execution of EDM process, discharge energy not only partially melts the workpiece but also the tool electrode. Melting and vaporization of electrode material causes significant change in mass of electrode before and after machining. This is termed as tool wear. Increase in peak current in turn intensifies spark energy; huge discharge heat results in rapid melting of tool electrode (especially at the bottom surface or edge), hence, tool wear rate is increased.

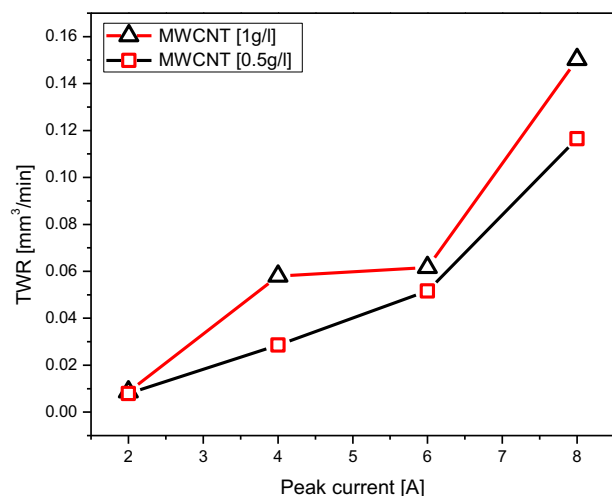


**Figure 4.** Influence of peak discharge current on MRR.

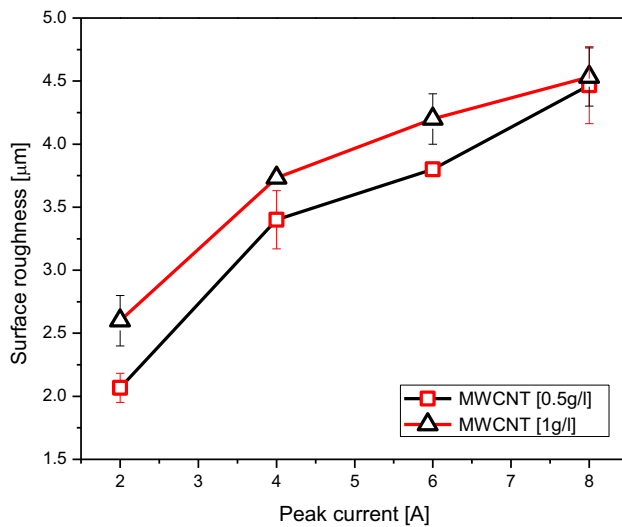
However, it is observed that when MWCNT added dielectric media is used, TWR is decreased than conventional EDM. This is due to the outstanding thermal conductivity which enables CNTs to absorb significant heat thereby reducing the heating effect of the tool electrode. However, it is observed that as compared to conventional EDM and PMEDM with MWCNT concentration 1g/l, minimal TWR is achieved at MWCNT concentration 0.5 g/l (figure 5). This is because higher concentration of MWCNT (1 g/l) restricts efficient heat transfer from the machining zone which further increases TWR. However, magnitude of tool wear rate is affected by foreign material migration and deposition of carbide layer onto the electrode surface due to decomposition of hydrocarbon dielectric media.

#### 3.3 Influence of peak current on surface roughness

Every electrical discharge creates a discharge spot by removing material (spark erosion) at the work surface. Thus, crater is formed whose dimensions are influenced by the discharge energy supplied. Increased peak current causes occurrence of intense spark which further increases degree of material erosion. This promotes formation of large and deep craters which further damages surface finish. Hence, surface roughness is increased with increase in peak current. It is experienced that use of MWCNT added dielectric media offers better surface finish than conventional EDM. This is because in PMEDM, discharge spark is divided into a series of smaller discharges thus increases discharge frequency. This results in formation of overlapped craters (large but shallow) which improves surface finish. However, it is noticed that better surface finish is achieved at MWCNT concentration 0.5 g/l than the case of 1 g/l (figure 6). High concentration of additives prevents



**Figure 5.** Influence of peak discharge current on TWR.

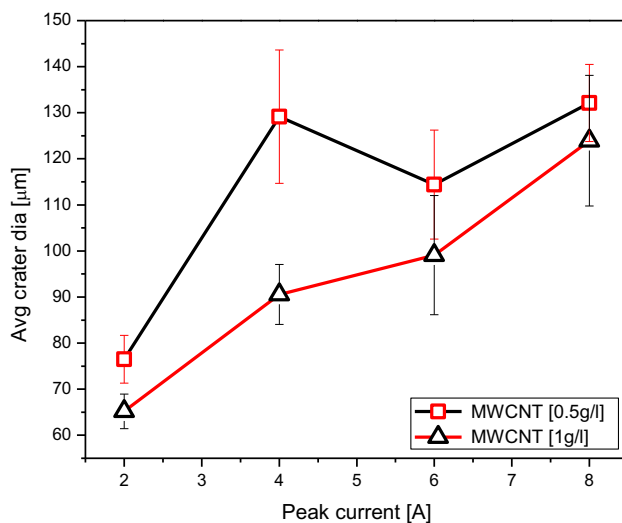


**Figure 6.** Influence of peak discharge current on surface roughness ( $R_a$ ).

adequate circulation and thus causes inefficient debris removal which finally results in abnormal arcing. This affects surface finish adversely.

### 3.4 Influence of peak current on average crater diameter

Optical micrographs are used to study crater morphology of the machined surface. It is observed that crater dimension (average crater diameter) increases with increase in peak discharge current (figure 7). This is due to increased energy input and higher degree of material erosion from the workpiece which is attributed to higher material removal efficiency [25]. However, degree of crater enlargement is



**Figure 7.** Influence of peak discharge current on average crater diameter.

observed relatively more at MWCNT concentration 0.5 g/l than the case of 1 g/l. Therefore, lesser MRR is obtained when MWCNT added dielectric is used with concentration 1 g/l.

### 3.5 Study on surface integrity

EDMed surface exhibited disappointing surface morphology which is further described by presence of uneven fusion structure (overlapped craters), lump of melted material deposition, globules of debris, spherical deposition, pockmarks, surface cracks, and recast layer (figure 8). As compared to conventional EDM, severity of surface cracking appears relatively less than the case when MWCNT added dielectric is used. Occurrence of discharge spark evolves thermal stress at the machined surface. When induced stress exceeds ultimate tensile strength of the specimen, work surface tends to release that stress through surface cracking. Severity of surface cracking is generally described by the term called surface crack density which is total crack length per unit surface area. High thermal conductivity of MWCNT suspended in dielectric increases amount of dissipated heat into dielectric and alleviates the plasma heat flux into the electrodes leading to decrease in the melted material and a reduction of surface micro-cracks in the solidification state. As well, by increasing temperature of dielectric due to high heat input, the temperature difference between the melted material and the dielectric decreases; hence solidification shrinkage lowers that causes less thermal stresses. In this condition, the size and the number of micro cracks are reduced [26, 27]. It is also noticed that the machined surface produced by using MWCNT added dielectric with concentration 0.5 g/l corresponds to relatively less crack density than the case of MWCNT concentration 1 g/l (figures 9, 10). Higher concentration of MWCNT leads to inefficient heat transfer due to accumulation of un-flushed machining debris in the machining zone. Therefore, evolution of thermal stress of higher magnitude promotes formation of crack lines in abundance. Moreover, magnitude of thermal stress increases with increase in discharge energy. Hence, it is observed that with increase in peak current (up to  $I_p = 6$  A), surface crack density assumes an increasing trend (figure 9). However, beyond  $I_p = 6$  A, crack density is drastically declined. This may be due to the fact that increasing peak current removes excess material from the workpiece (MRR is enhanced); but dielectric media being increasingly inefficient to carry sufficient debris from the machining zone. When discharge is seized (during pulse-off duration), debris resolidify forming recast layer, globule of debris, chunk of deposited material etc. which covers surface cracks in the surface and sub-surface region. Therefore, visibility of existence of surface cracks is hampered. This affects value of the crack density computed.

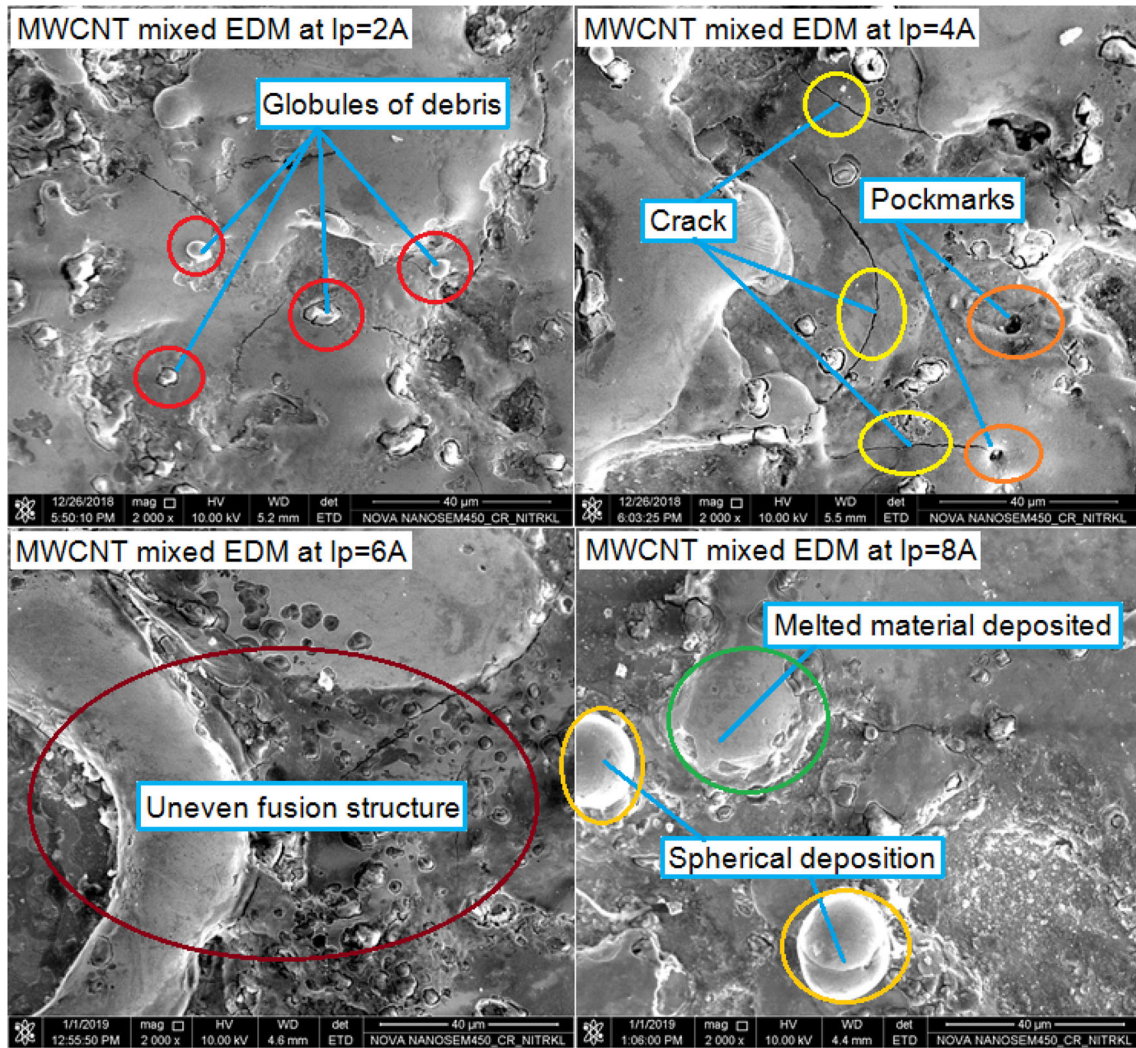


Figure 8. Morphology of the machined surface obtained through MWCNT mixed EDM [1g/l concentration].

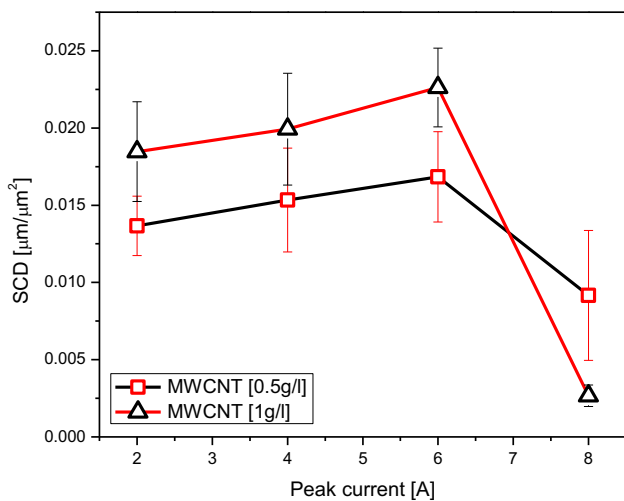
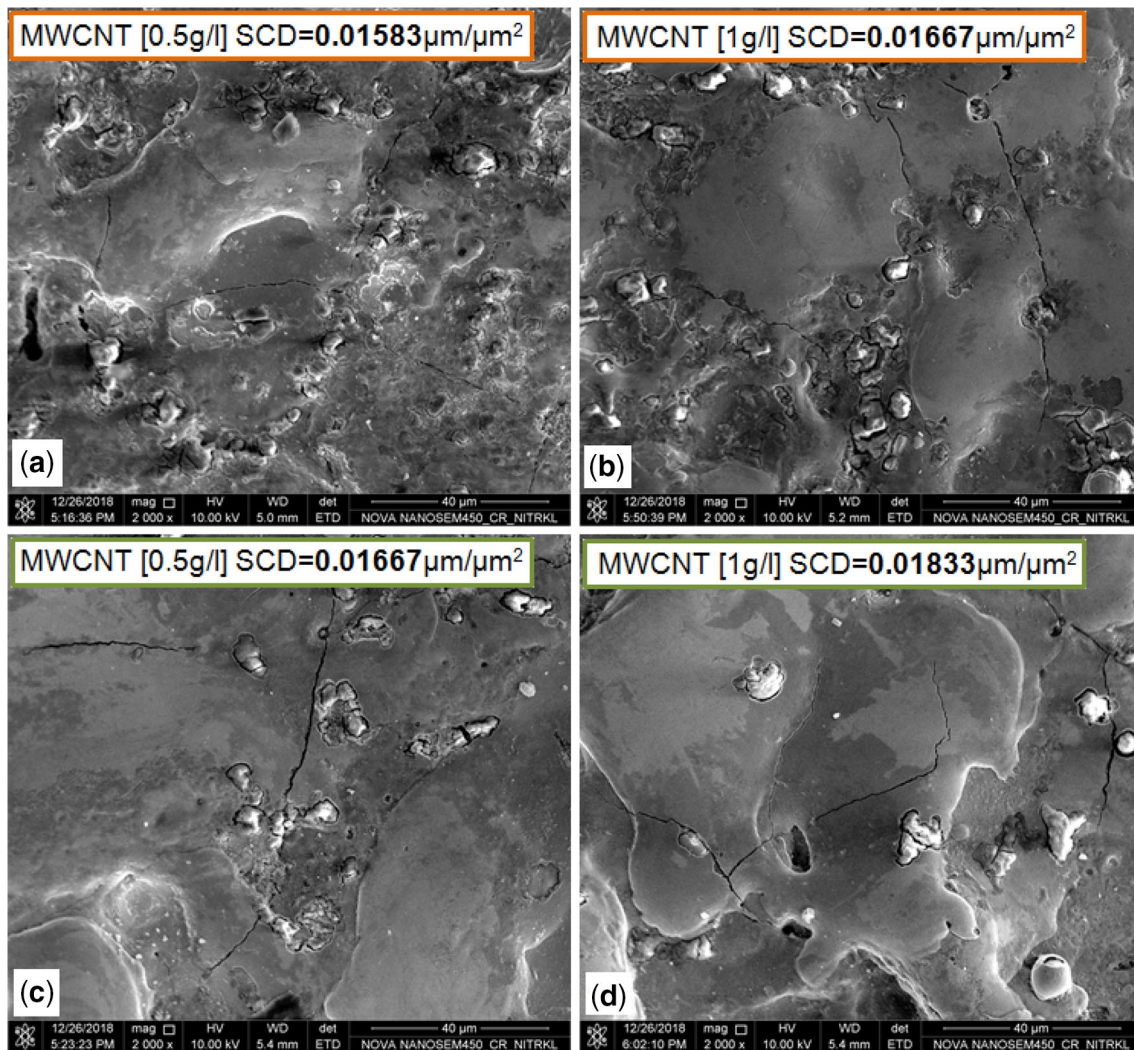


Figure 9. Influence of peak discharge current on surface crack density.

During EDM process, high temperature is developed near the work surface (surface and subsurface) due to occurrence of series of sparks. Rapid cooling helps the top surface to cool quickly. Hence, molten material, over the top surface is cooled down faster than the subsurface region. Due to this action, higher contraction is experienced by the subsurface region than the top surface. This difference causes evolution of thermal stresses within the material. Whenever, these induced stresses exceed the material's ultimate tensile strength, cracks are generated over the machined surface. The 'as received' work material corresponds to compressive residual stress:  $-639.5 \pm 131.5$  MPa. It is observed that,  $I_p = 2$  A, the EDMed surface corresponds to lower tensile residual stress ( $191.2 \pm 89.9$  MPa) than the surface machined at  $I_p = 8$  A ( $750.8 \pm 79.3$  MPa) through conventional EDM. This means, with increasing peak current values, higher stresses are generated within the specimen. Higher current causes generation



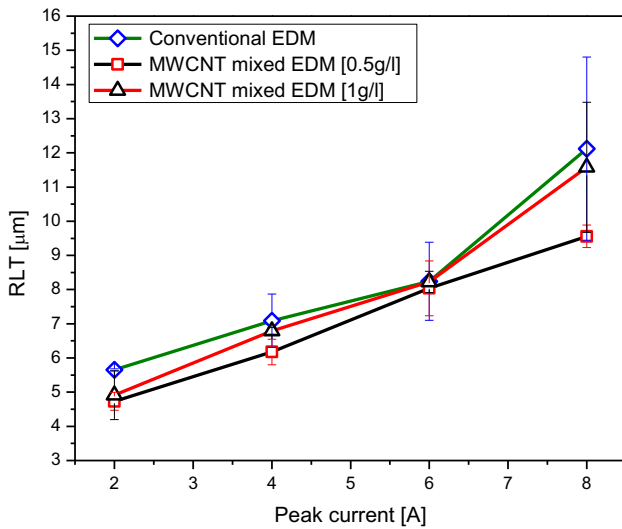
**Figure 10.** Comparison of SCD as observed on EDMed surface produced at (a) and (b)  $I_p = 2A$ ; (c) and (d)  $I_p = 4A$ .

of higher temperature near specimen's top surface. Additionally, dielectric medium cools the machined surface simultaneously; thus, temperature difference is increased. Due to this, residual stresses are increased. For the machined surface obtained through CNT (0.5 g/l) mixed EDM at  $I_p = 8 A$ , ( $408.8 \pm 161.4$ ) MPa residual stress is obtained; which is less than the case of conventional EDM ( $750.8 \pm 79.3$  MPa). According to the theory of PMEDM, energy density is decreased during PMEDM process due to expansion of plasma channel. This means, discharge energy is distributed to the large area than the case of conventional EDM. Hence, uniform machining takes place which reduces the temperature difference within machined surface layers. Therefore, lesser residual stress is obtained at the machined surface. Moreover, during CNT mixed EDM, highly conductive CNTs carry a significant amount of the discharge heat away for the machined surface. This in turn reduces the magnitude of tensile residual stress at the

machined surface. However, 1 g/l CNT concentration yields higher tensile residual stress:  $502.8 \pm 119.8$  MPa at the machined surface produced at  $I_p = 8 A$  than the case of 0.5 g/l CNT concentration ( $408.8 \pm 161.4$  MPa). Higher residual stress increases propensity of surface cracking at the machined surface produced using 1 g/l CNT concentration than 0.5 g/l.

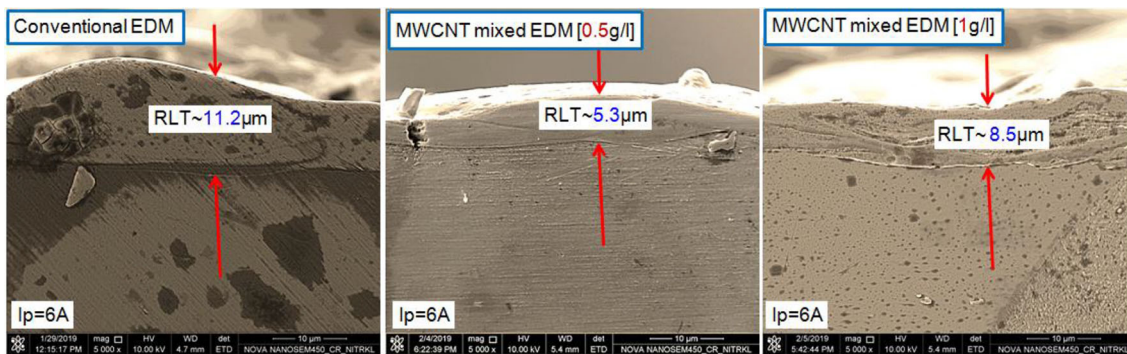
Effect of peak current and CNT concentration (while added to dielectric media) on recast layer thickness (RLT) is shown in figures 11, 12. Recast layer thickness is increased with increasing peak current. Discharge energy is increased with increasing peak current. Due to higher discharge energy, machining zone experiences elevated temperature. Amount of material removed from the workpiece is more. But due to the insufficient flushing by the dielectric media, the rate of re-deposition of molten debris over the machined surface is increased; which enhances recast layer thickness. Hence, RLT is enhanced with increasing peak





**Figure 11.** Influence of peak discharge current on recast layer thickness.

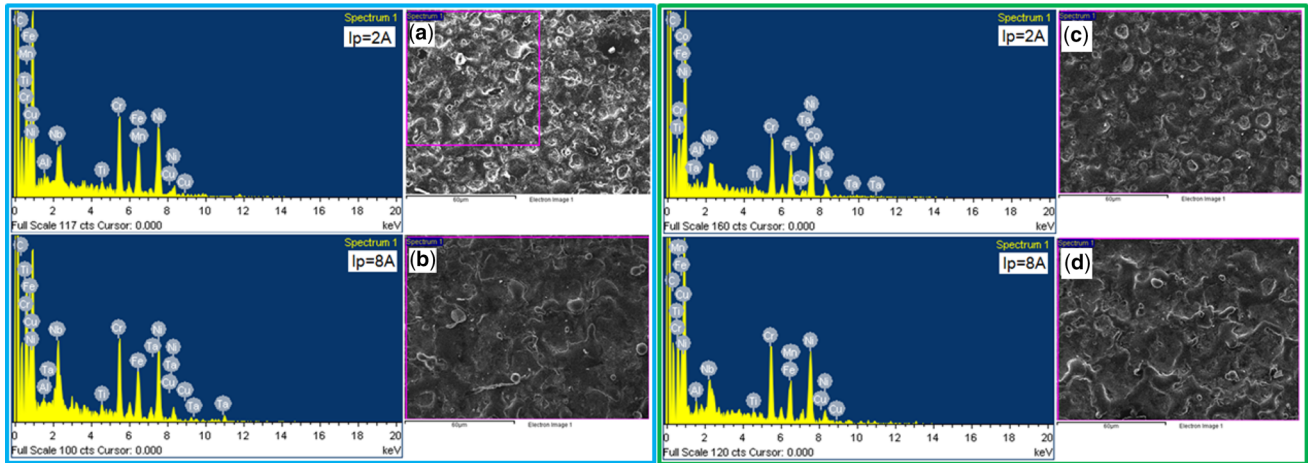
current values in all experimental conditions: conventional EDM as well as MWCNT mixed EDM with varied concentration of CNTs. Results reveal that, MWCNT mixed EDM offers thinner recast layer than conventional EDM. According to the theory of PMEDM, inter-electrode gap is increased due to presence of conductive powder particles. Because of this enlarged gap, wider plasma channel is created resulting reduced energy density [13]. Additionally, flushing efficiency is also improved in PMEDM process due to the enlarged gap size. Hence, rate of re-depositing of debris over the machined surface is reduced in additive mixed EDM. Thermal properties of MWCNTs allow a good absorption of heat, during EDM, thus leading to reduce the thickness of recast layer (also called white layer) and increasing the quality of surface finish by reduction in the roughness value. During MWCNT mixed EDM, discharge takes place covering wider volume and in a uniform manner. This helps debris to spread over the machined surface uniformly, thus producing tiny recast layer. Moreover, thicker recast layer is observed at MWCNT concentration 1



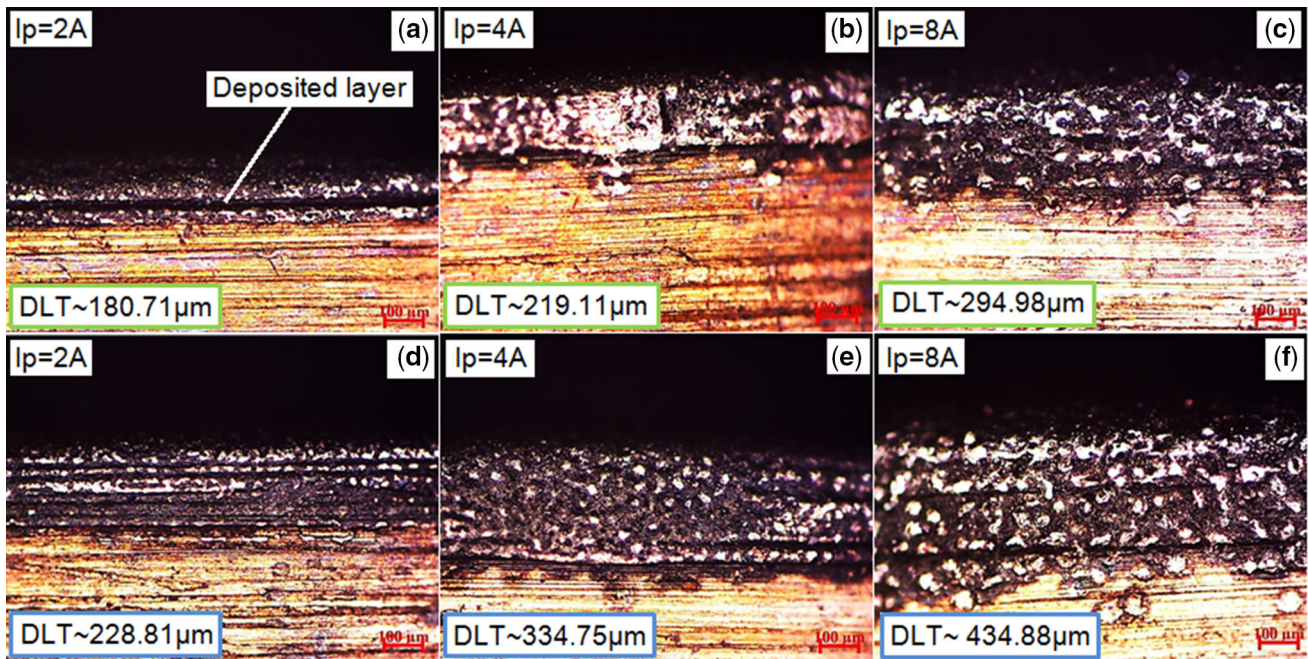
**Figure 12.** Comparison on RLT obtained through conventional EDM and MWCNT mixed EDM (with varied concentration).

**Table 3.** Results of EDS analysis.

Element(s)	Composition [wt%]			
	Surface produced by MWCNT mixed EDM [0.5g/l]		Surface produced by MWCNT mixed EDM [1g/l]	
	Ip = 2A	Ip = 8A	Ip = 2A	Ip = 8A
C	22.45	30.62	25.30	35.66
Ti	1.48	1.13	1.73	0.84
Cr	17.58	14.82	15.42	15.79
Fe	15.83	12.03	14.64	10.39
Co	–	–	0.58	–
Ni	33.73	26.79	33.96	28.39
Nb	5.40	11.82	4.64	6.55
Ta	–	1.72	2.33	–
Al	1.40	–	1.42	0.99
Cu	1.52	0.75	–	0.54
Si	–	–	–	–
Mn	0.60	–	–	0.84



**Figure 13.** EDS result of the machined surface produced by MWCNT mixed EDM: (a) and (b) CNT concentration: 0.5 g/l; (c) and (d) CNT concentration 1 g/l.

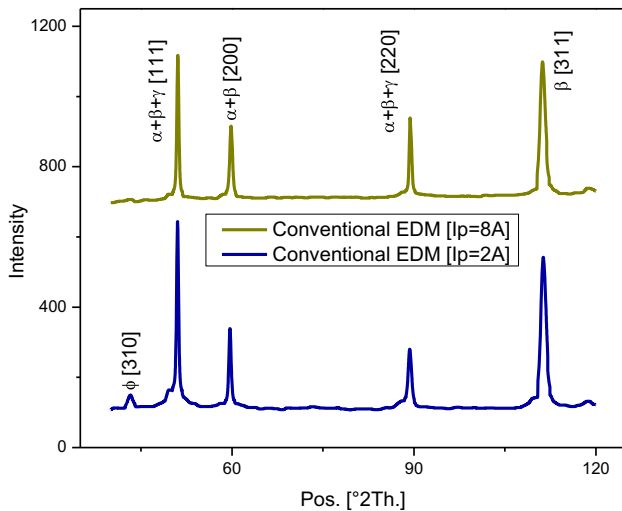


**Figure 14.** Optical micrographs exhibiting deposited layer (probably carbides) at the edge of copper electrode: (a), (b), (c) MWCNT mixed EDM (0.5 g/l), and (d), (e), (f) MWCNT mixed EDM (1 g/l).

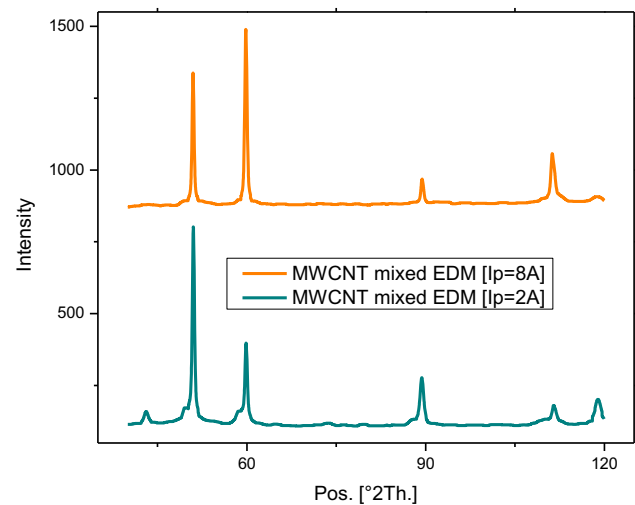
g/l than 0.5 g/l concentration (figure 12). This is because, high MWCNT concentration leads to unstable and inefficient EDM operation, resulting in abnormal arcing or short circuiting, thereby increasing the amount of deposited material.

Significant migration of C and Cu element onto the machined surface is detected through EDS analysis. Transfer of C takes place due to decomposition (pyrolysis) of kerosene used as dielectric media. Addition of CNTs into dielectric media also influences C content at the machined surface. Transfer of Cu is due to wear of tool electrode. It is also observed that increase in peak current results in

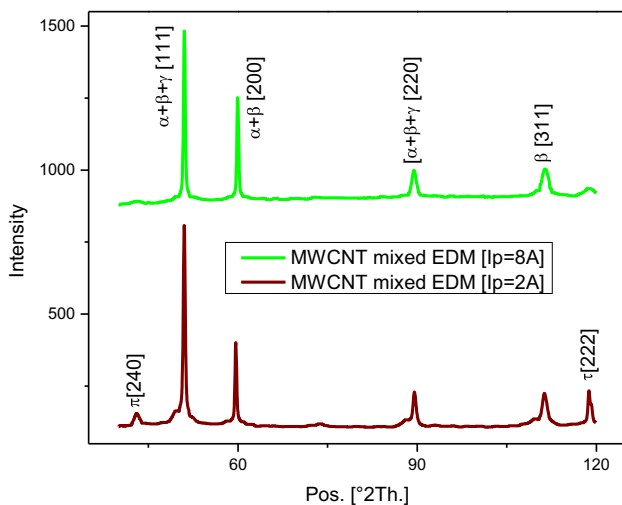
increased carbon content at the machined surface (table 3; figure 13). Additionally, the machined surface produced by using MWCNT added dielectric with concentration 1 g/l corresponded to higher carbon content than the case of MWCNT concentration 0.5 g/l. Migration of carbon atoms onto the machined surface is likely to cause formation of carbon-rich (may be carbides) layer, both at the machined surface as well as bottom surface/edge of tool electrode. Hence, it is observed that Deposited Layer Thickness (DLT) at the edge of tool electrode increases with increase in peak discharge current (figure 14). Additionally, DLT is found relatively less when MWCNT added dielectric is



**Figure 15.** XRD analysis for the machined surface obtained through conventional EDM.



**Figure 17.** XRD analysis for the machined surface obtained through MWCNT mixed EDM (MWCNT concentration = 1 g/l).



**Figure 16.** XRD analysis for the machined surface obtained through MWCNT mixed EDM (MWCNT concentration = 0.5 g/l).

used with concentration 0.5 g/l than the case of MWCNT concentration 1 g/l. This observation also infers higher degree of tool wear rate attributed to the case of MWCNT concentration 1 g/l as described earlier.

Through XRD analysis, no dominant phase alteration is retrieved due to thermo-mechanical effect of the EDM process. However, dielectric media promotes migration of carbon atoms due to its decomposition (figures 15, 16, 17). As a result residues of carbides (mainly NiC and Ni<sub>3</sub>(Al, Ti)C) are traced at the machined surface (table 4). Cu<sub>0.81</sub>-Ni<sub>0.19</sub> is also detected as a result of wear of copper tool electrode. The machined surface produced through conventional EDM at Ip = 2 A reveals presence of Ni<sub>8</sub>Nb at the machined surface. On the contrary, presence of Taenite (Fe, Ni), and Niobium Oxide (Nb<sub>2</sub>O<sub>5</sub>) is detected at the

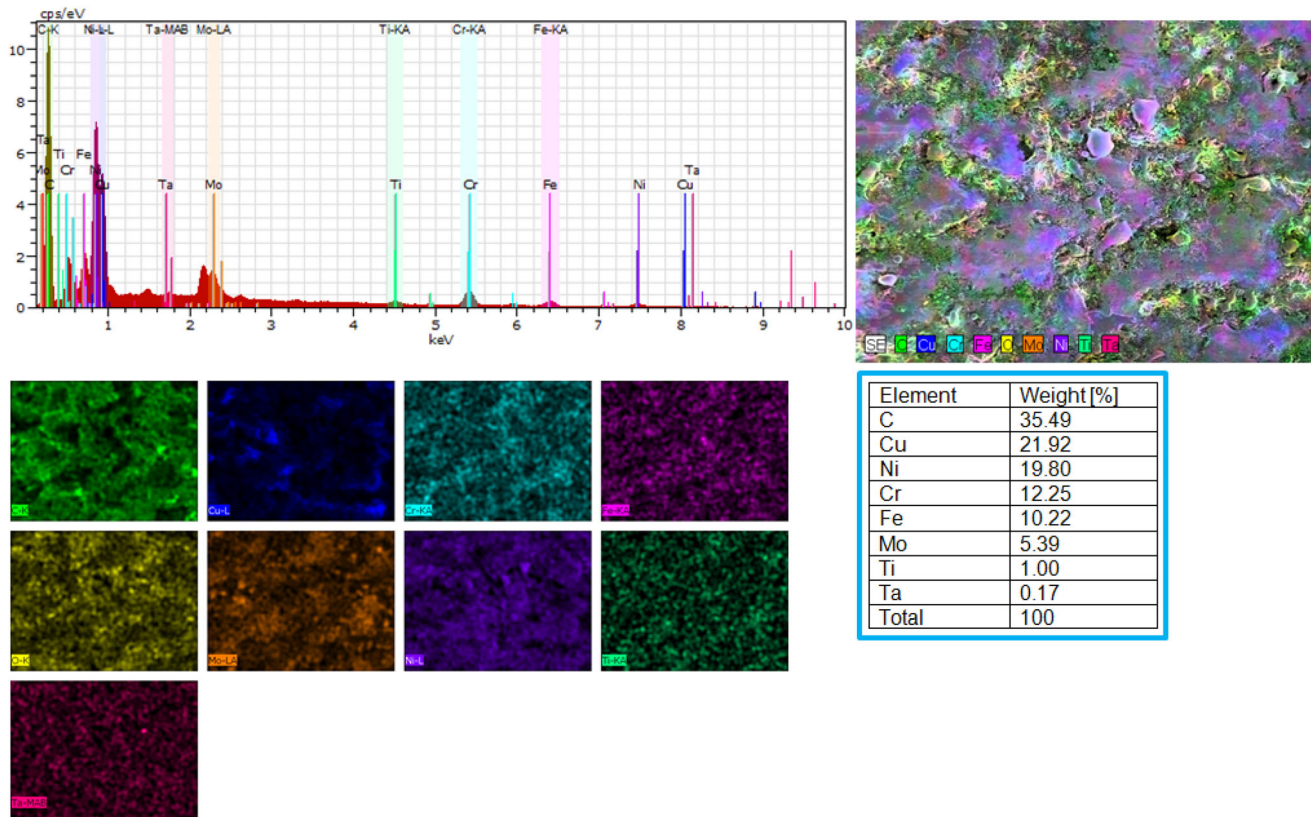
machined surface produced through MWCNT mixed EDM with additive concentration 0.5 g/l. Formation of carbides, oxides and other intermetallic compounds are expected to influence hardness of the surface and sub-surface region of the machined specimen. Similar observation is made during XRD analysis of the machined surface produced at MWCNT concentration 1 g/l.

### 3.6 Aspects of electrode wear

Optical micrographs exhibiting edge of wear out tool electrode are depicted in figure 14. Formation of deposited layer (blackish in color) is distinctly visible; thickness of which is termed here as Deposited Layer Thickness (DLT). The layer is formed due to reactivity of the electrode material at higher temperatures and inefficient flushing condition. Mostly, deposited layer consists of adhered carbon (mostly carbides), tool and workpiece elements. Effect of peak current and powder concentration on DLT is shown in figure 14. It is noticed that with increasing peak current, DLT is increased. Increased peak current causes generation of high temperature at the machining zone; consequently, increased degree of melting (even evaporation) of the work material. Dielectric circulation flushing pressure being constant, extent of re-solidification of debris is enhanced not only over the machined surface but also at the bottom surface/edge of tool electrode. In addition to this, at higher temperature, rate of decomposition of dielectric media is also increased. Thus, carbon atoms are separated from kerosene and are transferred over the tool electrode. However, 0.5 g/l CNT concentration exhibits formation of thin deposited layer than 1 g/l CNT concentration. At higher CNT concentration (1.0 g/l), the mobility of suspended additives (and also debris) is somewhat decreased. Because of this reason, chances of re-

**Table 4.** XRD results of the machined surface.

Sl. no.	Symbol	PDF index name	Reference code	Chemical formula	Crystal system
1	$\alpha$	Nickel carbide	14-0020	NiC	Cubic
2	$\beta$	Copper nickel	47-1406	Cu <sub>0.81</sub> Ni <sub>0.19</sub>	Cubic
3	$\gamma$	Nickel aluminum titanium carbide	19-0035	Ni <sub>3</sub> (Al, Ti)C	Cubic
4	$\phi$	Nickel niobium	23-1274	Ni <sub>8</sub> Nb	Tetragonal
5	$\tau$	Taenite	47-1417	(Fe, Ni)	Cubic
6	$\pi$	Niobium oxide	27-1312	Nb <sub>2</sub> O <sub>5</sub>	Monoclinic

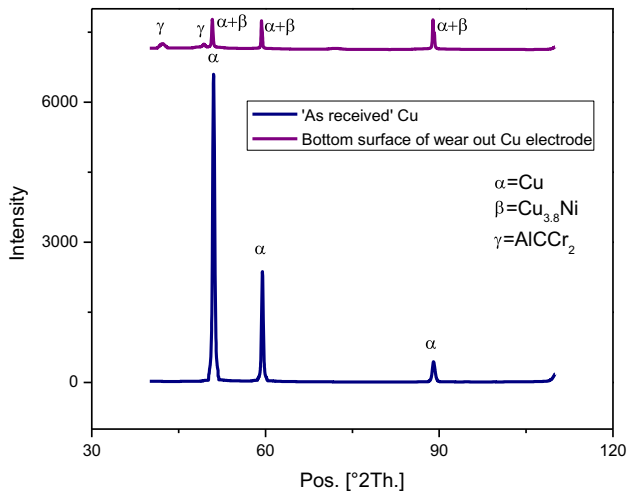
**Figure 18.** Elemental analysis made on bottom surface of the wear out tool electrode.

solidification of debris, adherence of carbon atoms (from kerosene) and CNTs over the tool surface is enhanced. Formation of such deposited layer over the tool surface is detrimental in purview of tool life and tool shape retention capability. Because carbon-rich deposited layer possesses low thermal conductivity; hence, acts as barrier towards transfer of discharge heat through bulk of the tool material. This causes rapid tool wear.

Elemental analysis (EDS maps) made at the bottom surface of wear out tool electrode reveals existence of significant amount of C along with constituents of work material (Ni, Cr, Fe, Mo, Ti, Ta) (figure 18). Pyrolysis of dielectric media causes transfer of C atoms to the tool surface. On the other hand, some amount of molten work material also re-solidifies over the tool.

Results of XRD analysis made of the bottom surface of wear out tool electrode are shown in figure 19. As compared to 'as received' copper, residues of Copper Nickel: Cu<sub>3.8</sub>Ni (Reference Code: 09-0205), Aluminum Chromium Carbide: AlCCr<sub>2</sub> (Reference Code: 29-0017) are observed at the bottom surface of tool electrode after machining operation. Formation of Copper Nickel is due to transfer of workpiece material to the tool surface. On the other hand, carbide formation is incurred due to cracking of dielectric fluid. Moreover, presence of CNT (dispersed within kerosene) contributes to the formation of carbides at the tool surface.

EDS line scan is carried out starting from edge of the machined specimen through recast layer depth up to interior of parent material (along cross section of the machined



**Figure 19.** XRD analysis made at the bottom surface of wear out tool electrode after machining at  $I_p = 8A$ , MWCNT concentration = 0.5 g/l.

specimen) as shown in figure 20. As moving towards interior of bulk of the base material from recast layer, counts for Ni and Cr elements is gradually increased up to a certain limit and afterwards they remain constant. But, it is observed that counts for C element is relatively high near the edge (recast layer depth) and relatively low in base material. Counts of other elements such as Fe, Cu, Ti, Ta etc. remain constant throughout the scanned length.

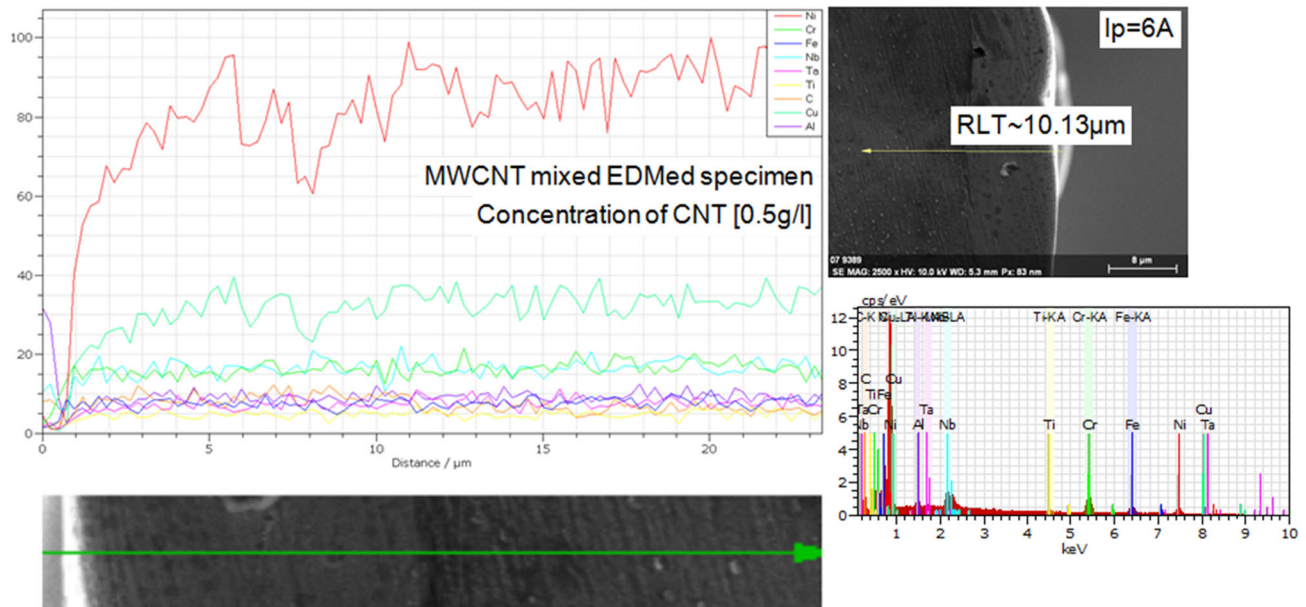
The variation of crystallite size ( $L$ ) of (0) *as received* Inconel 718; and machined surface of Inconel 718 obtained through (1) Conventional EDM, (2) MWCNT mixed EDM with additive concentration 0.5 g/l, and (3) MWCNT mixed

EDM with additive concentration 1 g/l at  $I_p = 8 A$  is observed. The crystallite size ( $L$ ) is calculated from X-ray diffraction profiles of strong reflections with intensity % by measuring the Full Width Half Maximum (FWHM). The formula as provided by *Debye Scherrer* (known as *Scherrer equation*) for computing the crystallite size.

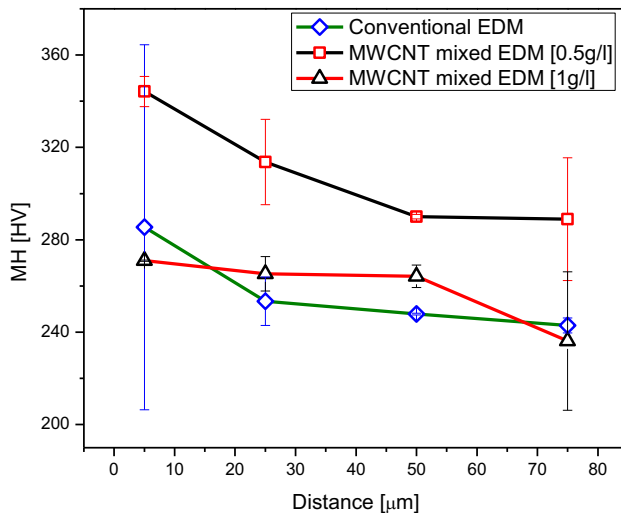
It is observed that *as received* Inconel 718 corresponds to 57.63 nm crystallite size. As compared to *as received* Inconel 718; relatively less crystallite size is attributed to the EDMed surface: 28.81 nm for conventional EDM, 32.39 nm for CNT mixed EDM (CNT concentration: 0.5 g/l), and 26.99 nm for CNT mixed EDM (CNT concentration: 1 g/l). Reduction of crystallite size indicates occurrence of grain refinement; which is strongly related to the micro-hardness value. Hence, micro-hardness of the machined specimen is expected to be more than '*as received*' work specimen.

Considering formation of carbon-rich recast layer up to certain depth beneath the machined surface, micro-hardness is measured on the cross section of machined specimens to study changes in mechanical properties till 75  $\mu m$  depth. Micro-hardness depth profile is shown in figures 21, 22. According to this profile, higher micro-hardness is observed near the surface and sub-surface due to rapid quenching of recast layer by the dielectric media and enrichment of foreign elements (especially carbon) on the cutting surface. Afterwards, micro-hardness values assume gradually decreasing trend as depth is increased towards interior of the bulk material. Similar observations were reported in [28].

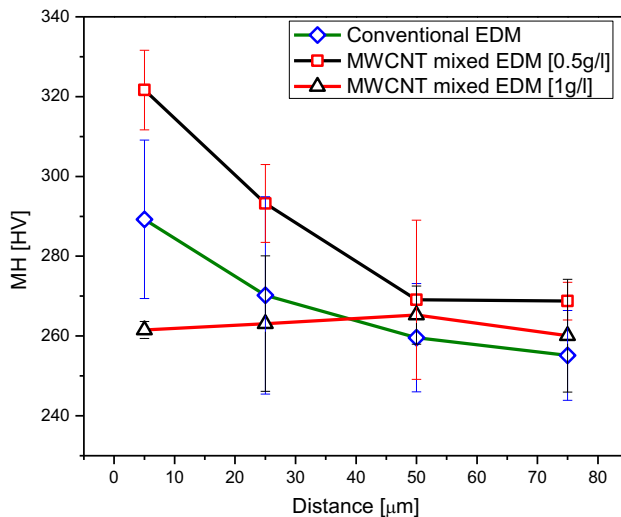
According to [29], three different layers are formed during spark-erosion process: recast layer, Heat Affected



**Figure 20.** EDS line scan starting from edge of the machined specimen through recast layer depth up to interior of parent material (along cross section of the machined specimen).



**Figure 21.** Micro-hardness depth profile: Specimens produced at  $I_p = 2A$ .



**Figure 22.** Micro-hardness depth profile: Specimens produced at  $I_p = 8A$ .

Zone (HAZ), and converted layer. Harder surface is observed in recast layer due to formation of carbides which can be seen in table 4. Below the recast layer HAZ gives less hardness. Hardness is further truncated in converted layer. This is because converted layer is negligibly affected during machining and hence exhibits hardness equal to base material hardness [30, 31]. It is also observed that the machined specimen produced by conventional EDM corresponds to less micro-hardness values than the case of MWCNT mixed EDM. However, it is observed that 1 g/l CNT concentration yield lower micro-hardness value than 0.5 g/l concentration. This is due to abnormal arcing followed by inefficient flushing and hence severe thermal degradation of the machined specimen. Higher micro-

hardness as obtained in case of 0.5 g/l CNT concentration improves wear and corrosion resistance of the end product.

In general, the optimal concentration of CNTs for addition in the dielectric media depends on the tradeoff between process performance (product quality), and the cost of addition of CNTs into the dielectric media [18]. Concentration of additives and machining time are interrelated as pointed out in [24]. High concentration consequences conductivity of the network; however, beyond certain concentration, prolonged machining time needs to be compromised. Hence, the application is limited to low pulse energy (low peak discharge current, short pulse-on duration, and short interval between two consecutive pulses). It is inferred that too high CNT concentration leads to unstable and inefficient EDM operation, resulting in abnormal arcing or short circuiting, thereby deteriorating the surface. The outcome of the present research reveals application potential of MWCNT mixed dielectric media in the context of EDM of Inconel 718 work material. In contrast to conventional EDM, MWCNT mixed EDM exhibits improved process performance. However, 0.5 g/l CNT concentration ensures better performance than 1 g/l.

#### 4. Conclusions

1. During EDM of Inconel 718, use of MWCNT added dielectric media enhances material removal rate than conventional (no additives) EDM. However, higher MRR is achieved at MWCNT concentration 0.5 g/l than 1 g/l. For 0.5 g/l concentration, improvement of MRR is found maximum at  $I_p = 4 A$  ( $\sim 73.91\%$ ).
2. MWCNT mixed EDM seems favorable in purview of reduced tool wear rate than conventional EDM. However, at MWCNT concentration 1 g/l, abnormal arcing makes the process unstable. Therefore, TWR is increased when compared to 0.5 g/l MWCNT concentration. Maximum reduction in tool wear rate is noticed at  $I_p = 8 A$  ( $\sim 29\%$ ) for 0.5 g/l concentration than 1 g/l.
3. Surface finish appears relatively more satisfactory for 0.5 g/l when compared to 1 g/l concentration of MWCNTs added into the dielectric media. Maximum reduction in surface roughness value is noticed at  $I_p = 2 A$  for concentration 0.5 g/l ( $\sim 20.5\%$ ) while compared to that of 1 g/l concentration.
4. Increase in peak current causes crater enlarging. With increase in peak current, average crater diameter is increased resulting higher degree of material erosion from the workpiece. This improves MRR. However, higher MRR is experienced at MWCNT concentration of 0.5 g/l than 1 g/l.
5. Machined surface exhibited poor surface morphology characterized by uneven fusion structure, globules of debris, melted material deposition, pockmarks, surface cracks, and recast layer. Increase in peak current in turn

increases discharge energy. This energy is distributed through workpiece, tool, debris (eroded material), dielectric media, and MWCNTs (additives) added to the dielectric media. Increased energy input causes evolution of huge thermal stress at the machined surface, and consequently higher crack density. MWCNTs, due to their excellent thermal conductivity, carry significant amount of discharge heat away from the machining zone. Therefore, workpiece experiences lesser thermal stress and hence reduced crack density. Due to that, crack density obtained in additive mixed EDM appears truncated than conventional EDM. It is also noticed that, MWCNT added dielectric at concentration 0.5 g/l offers lesser crack density than 1 g/l concentration. High concentration of additives restricts efficient flushing and smooth removal of debris. Heat, thus accumulated near the machining zone is responsible towards increase in crack density.

6. Due to outstanding thermal properties, MWCNTs act as good absorbent of heat during occurrence of discharge sparks. This results in significant truncation in the recast layer thickness, in case of MWCNT mixed EDM when compared to conventional EDM. It is also observed that tiny recast layer is developed for CNT concentration 0.5 g/l than 1 g/l.
7. Significant transfer of C and Cu element is detected through EDS analysis of the machined surface. Tool wear promotes migration of Cu atoms onto the machined surface. Transfer of C atoms is due to pyrolysis of kerosene (used as dielectric fluid) during spark discharge. Presence of MWCNTs in the dielectric media also influences carbon content at the machined surface. Higher MWCNT concentration yields higher carbon content.
8. XRD analysis traces out formation of NiC,  $\text{Cu}_{0.81}\text{Ni}_{0.19}$ ,  $\text{Ni}_3(\text{Al}, \text{Ti})\text{C}$  precipitates over the machined surface. In addition to this, presence of  $\text{Ni}_8\text{Nb}$  is detected in case on conventional EDM. In contrast to this, residues of Taenite (Fe, Ni), and  $\text{Nb}_2\text{O}_5$  are identified at the machined surface obtained in MWCNT mixed EDM.
9. Decomposition of dielectric media and presence of MWCNTs in the dielectric media promote a layer deposition (especially carbides) at the bottom surface as well as tool electrode. Formation of such layer is indeed unwanted since carbides due to their low thermal conductivity act as heat barrier thus preventing transfer of heat through bulk of the electrode material. This causes increase in tool wear rate. Deposited layer thickness (at the edge of tool electrode) is found relatively less for the case of MWCNT concentration 0.5 g/l than 1 g/l.
10. As compared to conventional EDM, formation of carbon-rich re-solidified layer improves micro-hardness of the machined specimen obtained through MWCNT mixed EDM (CNT concentration 0.5 g/l).

Future work can be extended in the following directions:

1. Apart from peak current, effects of other process variables on EDM response may be studied.
2. Variation of residual stress along cross section of the EDMed specimen (depth profile) may be studied in the context of EDM with and without CNT.
3. Voltage and current waveforms may be studied in the context of EDM (with and without CNT; with varying concentration) for better understanding of process physics.

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