Carbon nanofibre assisted micro-electro discharge machining (μEDM) of Ti-6Al-4V alloy

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Abstract: Titanium alloys have found growing applications in aerospace, biomedical and marine industry. However, extreme hardness and strength cause difficulty in machining of titanium alloys. This is further complicated by the requirements of micro-features on hard to machine alloys. Micro-electro discharge machining (micro-EDM) is being investigated to match the requirement. However, slower removal rates and thermal effects are the issues in thermal erosion-based EDM process. In this work, we have investigated the efficacy of using carbon nanofibres (CNFs) mixed with the dielectric fluid for micro-machining of Ti-6Al-4V using micro-EDM. It is observed that the addition of CNFs not only improves electro-discharge frequency, material removal rate but also improves the surface roughness. Added nanofibres lowered the material migration and increased spark gap. We noted a significant influence of mixing CNFs in the dielectric fluid for enhancing machining performance characteristics in μEDM during micro hole generation on Ti-6Al-4V alloy.

Keywords: micromachining; micro-electro discharge machining; micro-EDM; titanium alloys; carbon nanofibres; CNFs; additives; surface integrity.

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1 Introduction

In recent years, the demand for micromachining has increased due to the need for miniaturisation of components. Particularly in the applications like aerospace, electronics, marine and biomedical field as the size of components plays a vital role along with its function. It has been highlighted that microsystem-based products represent key value-added elements for many sectors of industry and are important contributors to a sustainable economy. In order to keep abreast with the increasing sophistication of micro-component design, the capabilities of micro manufacturing processes have to be continuously enhanced to produce the required micro-products economically and reliably (Tan, 2010). However, many of these components required better mechanical properties such as high strength to weight ratio, melting temperature and excellent corrosion resistance. Among the other materials, titanium alloys exhibit unique properties like high strength at a lightweight, useful formability and high corrosion resistance. Between all titanium alloys, Ti-6Al-4V alloy is most commonly used alloy. Advanced applications in aerospace, marine and biomedical domains require innovative processing methods to produce micro features like microholes or micro-textures. However, the low thermal conductivity, low elastic modulus and high chemical reactivity are the main factors for low machinability of titanium alloys. Due to this, micromachining of such materials is currently gaining the interest of multidisciplinary researchers. Specifically, micro-electro discharge machining (micro-EDM) is showing promises in machining of micro-features on Ti alloys.

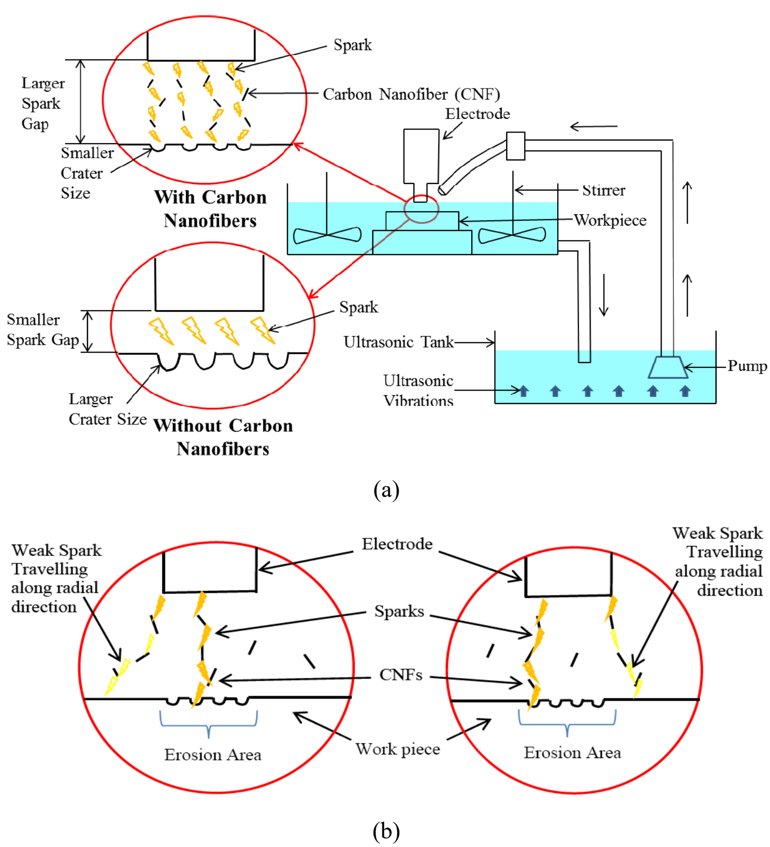
In the micro-EDM process, any type of conductive material can be machined regardless of its hardness. The low energy range is becoming more important as the EDM process is used in the micro-domain. Micro-EDM has similar characteristics as EDM, except that the size of the tool, the discharge energy and axes movement resolutions are in micron levels (Masuzawa, 2000; Jahan et al., 2011). In this process, repetitive spark discharge takes place in the gap between tool and workpiece. Due to the generation of high temperature in the spark zone, tiny amount of metal melts and evaporates. As machining zone has emerged in the dielectric fluid, the melted and vaporised material transforms into tiny particles known as 'debris' upon cooling during pulse off time. This debris is removed from machining zone by flushing pressure of dielectric liquid jet (Kibria et al., 2010). An additional advantage presented by μEDM is the effective ability to perform machining with minimal mechanical stress (Liu et al., 2010), vibrations or chatter (Ho and Newman, 2003; Marashi et al., 2015).

Mixing of additives in dielectric fluid is one of the promising methods to improve machining performance of μEDM, however the material removal via erosion process on titanium alloys is still a challenge. Jahan et al. (2011) compared μEDM sinking and milling operations with nano-graphite powder in EDM oil. It was found that micro-EDM milling provides smoother and defect-free surface compared to micro-EDM sinking. In addition, material removal rate found to be improved with the reduction in the electrode wear rate. Experimental results reported by (Prihandana et al., 2009a, 2011). Better surface roughness is observed with MoS_2 while machining with powder assisted EDM, such as copper, MoS_2 and SiC. For evaluation of different tool electrode materials, Jahan et al. (2011) used W, CuW and AgW electrodes on WC material with EDM3 dielectric oil. It was concluded that the AgW electrode produces smoother and defect free surface among the other electrodes. Tungsten electrode has the lowest tool wear followed by copper-tungsten and silver-tungsten. Prihandana et al. (2011) worked for accuracy improvement in μEDM with the addition of nano-graphite powder to the dielectric fluid. A discharge pulse counting was carried out by current probe sensor and inaccuracies related to the powder-assisted μEDM have been reduced by providing the same number of pulses for the machining operation. In addition, the inclusion of graphite nano-powder reduces the machining time up to 35%. Chow et al. (2003, 2008) performed Al and SiC powder assisted slitting operation on Ti-6Al-4V with kerosene and deionised water as dielectric fluid. It was observed that the addition of Al and SiC powder increases material removal depth. Al powder with kerosene yields better surface finish and it gives largest working gap resulting in largest slit expansion. Sabur et al. (2015) worked with tantalum carbide powder on zirconium oxide with kerosene as a dielectric fluid. It was observed that the gap voltage and the powder concentration have the significant effect on the surface roughness. Kuriachen and Mathew (2015) studied the effect of SiC powder on machining of Ti-6Al-4V; capacitance, voltage and powder concentration were identified as the significant factors, which influences the material removal rate. Prihandana et al. (2009b) performed machining on copper, copper-tungsten and silver-tungsten with different electrodes and different concentrations of MoS_2 powder. It is observed that the presence of MoS_2 powder produces a flat surface free of black spots in the centre, unlike pure dielectric fluid.

Recently, carbon nanofibres (CNFs) have shown potential to be used as an additive to the dielectric fluid. Compared to the conventional EDM with powder assisted EDM, the tendency to form micro chains by the arrangement of bridging network makes CNFs better to transmit spark energy in the spark gap. One of the significant purpose to include additives in dielectric fluid is to reduce insulating strength of dielectric fluid, the CNFs suits the purpose due to its excellent electrical conductivity (Liew et al., 2013). Liew et al. (2013) performed machining on the ceramic material; reaction bonded silicon carbide with CNF as additives in EDM oil. The surface finish and material removal rate were improved. Shabgard and Khosrozadeh (2017) machined Ti-6Al-4V using 10 mm diameter copper electrode by using carbon nanotubes as additives. Considerable betterment of machining stability is observed. Material removal rate is reduced for short pulse duration and increased for larger pulse durations. Khosrozadeh and Shabgard (2017) machined Ti-6Al-4V with copper electrode by using three hybrid techniques ultrasonic-assisted EDM (USEDM) and powder-mixed dielectric EDM (PMEDM) and US-PMEDM. It is observed that the material removal rate increases by introduction of the hybrid processes.

In this paper, we have investigated the effect of CNF assisted µEDM of Ti-6Al-4V with CNF in EDM oil. The discharge principle of EDM with pure dielectric and CNF assisted dielectric along with the experimental setup as shown in Figure 1. Furthermore, to maintain the homogeneous mixture of CNF in dielectric oil the experiments utilised ultrasonic vibrations followed by fan type stirring to dielectric fluid. In this work, investigations are carried out in terms of the behaviour of electro-discharge frequency, spark gap, material removal rate, material migration and surface finish.

Figure 1 Experimental setup and principle of micro-EDM, (a) with and without CNFs (b) scattering of weak discharges in the radial direction leading to stray sparks (see online version for colours)



2 Experimental methods

2.1 Machine tools

The experiments were performed on the micro-EDM machine (Mikrotools DT110i). The electro-discharge mechanism is controlled through resistor-capacitor (RC) type circuit.

2.2 Electrodes

While choosing an electrode material, the electrical, thermal and structural properties are major considerations. Tool wear is an important factor because it affects dimensional accuracy of the machined profile. Since EDM is a thermal process, tool wear is related to thermal properties of the electrodes, the tool and the workpiece; lower the melting point of the material, higher will be the material removal or tool wear rate. Considering the properties like density, tensile strength and melting point, the pure tungsten was selected as a tool material for the experiments. The tungsten electrode of 400 μm diameter was prepared by turning of 3 mm diameter rod using polycrystalline diamond (PCD) tool [refer to Figure 2(a)]. To achieve a uniform face, each electrode was further cut by μWEDM using a zinc coated brass electrode of 70 μm diameter as shown in Figure 2(b).

Figure 2 Preparation of tool electrode, (a) micro-turning operation to yield 400 μm diameter electrode (b) micro-WEDM operation to achieve uniform face of the electrode (see online version for colours)

2.3 Workpiece

An aerospace grade Ti-6Al-4V was used as a workpiece material for the experiments. Composition of the material is as given in Table 1. Received samples were of 20 mm × 20 mm × 1.1 mm dimension. A die-sinking EDM operation was carried out by a tungsten electrode of 400 μm on Ti-6Al-4V alloy to achieve 150 μm depth.

2.4 Carbon nanofibres

In this study, CNFs are used as additives in the dielectric fluid. The diameter of CNFs was in the range 500 nm to 5 μm and the standard length range was about 10–40 μm.

The properties of CNFs are given in Table 3. Figure 3 shows the scanning electron microscope (SEM) micrograph of CNFs. The CNF concentration was 0.25 g/l of the dielectric fluid.

Table 1 Composition of Ti-6Al-4V alloy

Element	*Percentage (%)*
Carbon	0.029
Nitrogen	0.029
Ferrous	0.360
Vanadium	3.8
Aluminium	6.1
Oxygen	0.138
Hydrogen	0.00198
Titanium	Balance

Table 2 Experimental conditions

Workpiece material	Ti-6Al-4V
Tool material	Pure tungsten
Polarity	Workpiece (positive)
	Tool electrode (negative)
Dielectric fluid	EDM oil
Additive	Carbon nanofibre
Feed rate	0.125 mm/min
Capacitance	1,000 pF
Concentration	0.25 g/L
Cavity depth	150 µm
Rotational speed	1,500 RPM
Voltage	90 V, 102 V, 114 V, 126 V

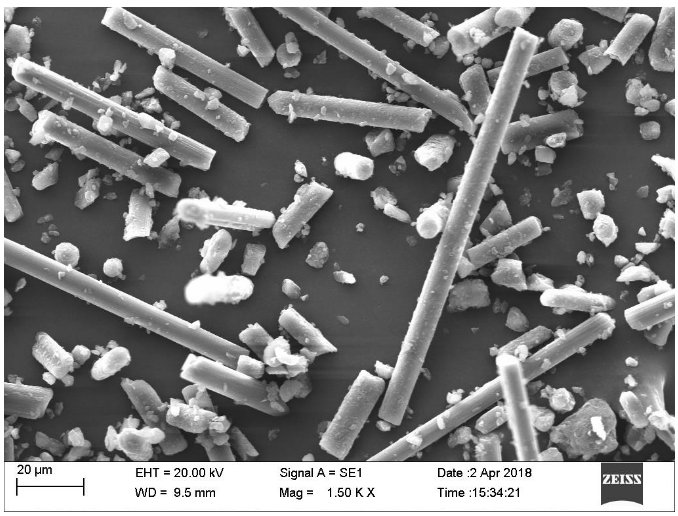
Table 3 Properties of CNF

Property	*Typical value*
Carbon content	99%
Purity	> 96%
Electrical resistivity	0.00061 ohm-inch
Density	0.065 lb/in^3

2.5 *Experimental setup*

The major constraint with the powder-assisted micro-EDM is the density difference between the additives and the dielectric fluid. High density additives tend to sink the in the low density dielectric fluid. To overcome this problem and ensure the uniform distribution of additives in the dielectric fluid, we have developed an external dielectric circulation system as shown in Figure 1(a) and the spark propagation due to CNFs in the spark gap is shown in Figure 1(b). In the external dielectric circulation system, an ultrasonic vessel is used to ensure the uniform dispersion of the CNFs in the dielectric fluid. This mixture is then directed into the machining zone via submersible pump. From the machining zone, the fluid is then re-circulated to the ultrasonic vessel by gravity. In addition, the machining tank was provided with a fan-based stirring mechanism to ensure the homogeneous distribution of CNFs in the dielectric fluid throughout the tank during machining.

Figure 3 SEM micrograph of CNFs



The experiments were conducted at different voltages with CNFs added in the dielectric fluid. The experiments were repeated using the dielectric fluid without any additives in order to assess the influence of addition of CNFs. The same electrodes were used for experiments with CNFs at a particular voltage, which were used for the experiments without CNFs to have a better comparison of the results. Before such reuse of the electrodes, the worn edges of the electrode were cut by µWEDM process as shown in Figure 2(b) to avoid any effect of the worn edges or any EDM related deposition on the tool on the following experimentation.

2.6 Measurements and evaluations

The tungsten electrodes were shaped to 400 µm diameter using a micro turning process as shown in Figure 2(a). Furthermore, the dimensions of micro turned electrodes were confirmed using optical microscope (Zeta 20X microscope). The discharge current and the discharge voltage measured in real time using oscilloscope (Tektronix TPS2014). The surface roughness, the diameter and the depth of the machined cavity on the workpiece after µEDM machining were measured using optical microscope. The machined surfaces of micro-cavities were then examined under SEM and by energy dispersive X-ray (EDX).

3 Results and discussions

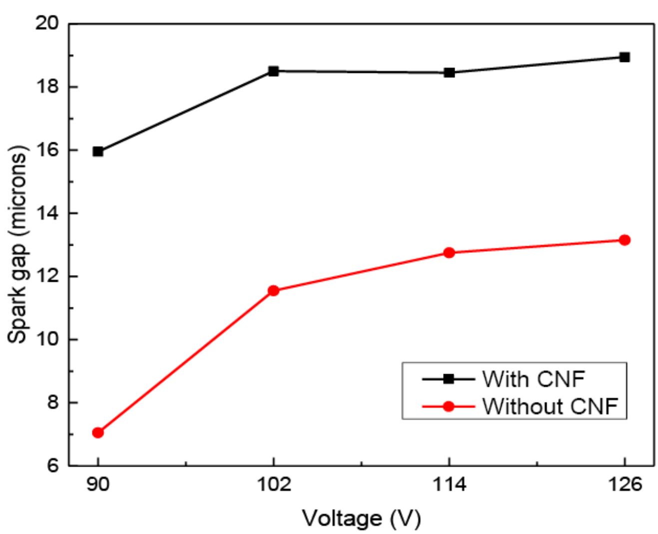
3.1 Spark gap

The spark gap is a maximum distance separated by an anode and a cathode at which the sustainable discharge is possible. The spark gap is influenced by an open circuit voltage and the strength of a dielectric fluid (Tan, 2010). In the present case, the spark gap was calculated by measuring the largest diameter of the cavity observed at the top of the cavity and the diameter of a tool electrode used for machining.

$$\text{Spark gap} = \text{Largest (upper) radius of the cavity} - \text{Tool radius}$$

The spark gap, thus measured, is found to be increasing with the increasing voltage. This is because higher magnitude of voltage easily breaks down the insulating strength of dielectric fluid compared with the small voltage levels. The spark gap is at a higher side with the addition of CNFs as shown in Figure 4. The spark gap is increased from 7.05 µm to 15.95 µm at 90 V. Whereas, at higher voltages, this difference is recorded in the range of 5 to 6 µm. Thus, the addition of conductive particles in the spark gap works as a series of bridges enabling sparks to jump from the tool electrode to the workpiece. The presence of the CNFs also reduces the insulating strength of dielectric fluid resulting in larger spark gap.

Figure 4 Effect of voltage on the spark gap (see online version for colours)



3.2 Material removal rates

Material removal rate is a performance measure for the erosion rate of the workpiece and is typically used to quantify the speed at which machining is carried out. It is expressed as the volumetric amount of workpiece material removed per unit time (Tan, 2010). The cavity produced on the workpiece was scanned by the optical microscope; the diameter at the bottom of the cavity found to be smaller than the diameter at the top of the cavity due to the tool wear. The machined cavity assumed to be a perfect frustum and subsequently the volume of the cavity was estimated. Figure 5 shows effect of voltage on the material removal rate with and without addition of CNF. The spark energy increases with the increase in voltage and results in higher material removal rate. When no CNFs were added to the dielectric fluid, the material removal rate was reduced. However, the material removal rate found to be improved with the addition of CNFs. Highest material removal rate of 0.00293 mm^3/min was noted at 126 V under added CNF conditions. It is observed that the crater size obtained under dielectric fluid without any additive is larger than the crater size obtained when CNF added dielectric fluid is used. However, the material removal rate found to be higher in the dielectric fluid mixed with additive. In pure dielectric, i.e., without mixing any additives, the spatial concentration of discharges is high, but the sparking phenomenon is not stable. This resulted in smaller spark gap and hence inefficient removal of the debris from the narrow gap between the tool and the workpiece. The presence of debris in the gap causes short circuits between the electrode and the workpiece. Due to servo control mechanism, the short circuit leads to retraction of the electrode away from the workpiece in order to maintain the spark gap. Such short circuits and the subsequent retraction of the electrode causes rate of material removal to drop. However, with the presence of CNFs in the dielectric fluid, the dielectric strength of the fluid reduces and the dielectric breaks down easily. The spark initiation takes place at larger distance than it used to be in pure dielectric fluid at specific electric parameters. Hence, it results in a larger spark gap when compared to the gap size in pure dielectric fluid conditions. The increase in the spark gap enables the efficient debris removal and hence, the short circuits are minimised. In order to verify the phenomenon, we have monitored the discharge pulses using the oscilloscope (Tektronix TPS2014). The voltage progression is as shown in Figure 6. The plot shows the spark frequency increases with the addition of CNFs when compared with the spark frequency as observed under the dielectric fluid without any additives. Increase in the spark gap and the discharge frequency causes an increase in the material removal rate.

Figure 5 Effect of voltage on material removal rate (see online version for colours)

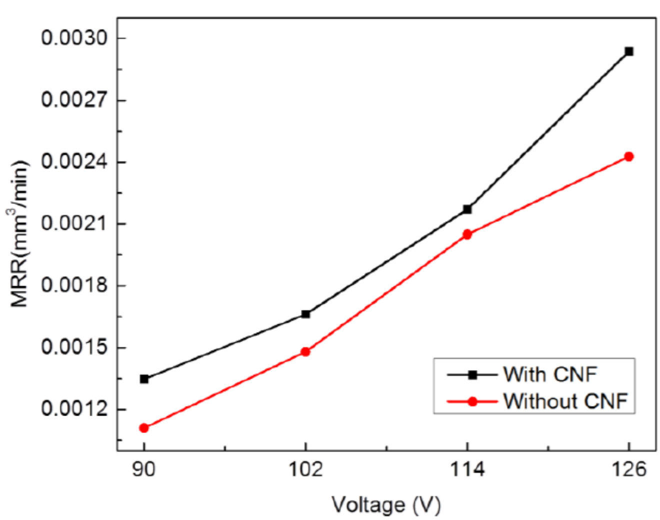
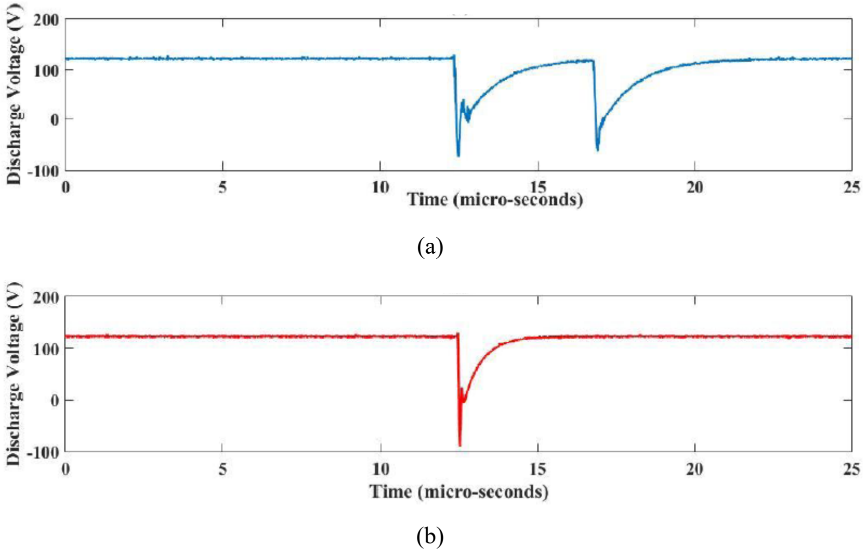


Figure 6 Discharge voltage waveforms at 126 volts, (a) with CNF (b) without CNF (see online version for colours)

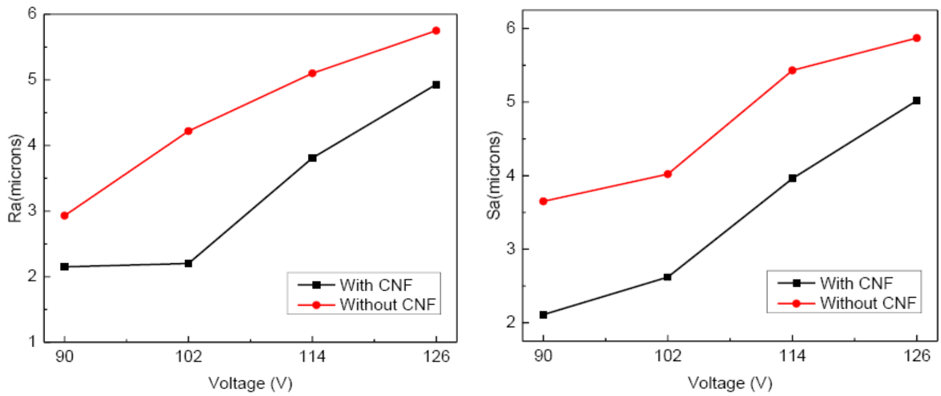


3.3 Surface roughness

Effect of voltage on the roughness of machined surface is as shown in Figures 7(a) and 7(b). The spark energy increases with increase in the voltage, which results in increase of the crater size formed by sparks. Such individual craters formed ultimately give rise to surface roughness, as machined surface is a collection of such overlapped craters formed by multiple discharges. Large size craters forms a rough surface texture. The addition of nanofibres break down the few high energy discharges into multiple low energy discharges. The presence of low energy discharges lead to uniform dispersion of the discharge energy in the spark gap and cause decrease in the crater size. In single discharge experiment (Tan, 2010), it has been reported that the presence of additives in dielectric fluid reduced the crater diameter and produced more consistently shaped craters. The small size craters spread over the discharge zone yield better surface finish. We report an average surface roughness as small as 2.15 μm at 90 V with addition of CNFs. The reduction in the roughness is as high as 47% at 102 V when CNFs are added to the dielectric.

We also observed here that, with the presence of CNFs, the area around the cavity, i.e., around 200 μm from the periphery of the micro hole, outside the direct discharge zone, on the workpiece has been affected (Figure 9). The surface exhibits poor surface finish. This can be attributed to the CNFs being getting organised in different configurations in the spark gap due to flow of dielectric fluid leading to create bridging effects of the sparks. Some stray sparks travel radially outside the machined cavity due to the bridging effect in the presence of nanofibres as shown in Figure 1(b). Such stray sparks moving radially do not carry significant energies, hence there is no significant material removal observed outside the machining domain. However, such weak energy sparks cause deterioration of the surface. Thus, it can be concluded that only few weak sparks may have reached to this area, which have only damaged the surface leading to poor surface quality when compared with the surface finish of the machined region.

Figure 7 Effect of voltage on surface roughness, μm (see online version for colours)



(a) (b)

3.4 Surface topography

In order to investigate the surface integrity of the machined cavity, the machined surfaces are observed under SEM. The SEM micrographs are as shown in Figures 8 and 9. The micrographs are captured at lower magnification (500X) whereas the highlighted and the magnified portion from the cavities shown in Figure 8 and 9 are captured at higher magnification (7,000X). It is observed that the surface at the centre of cavity machined with CNFs in Figure 9 appears to be smoother than the surface of cavity machined without CNFs in Figure 8.

Figure 8 SEM micrographs of cavity machined without CNFs at 114 V (see online version for colours)

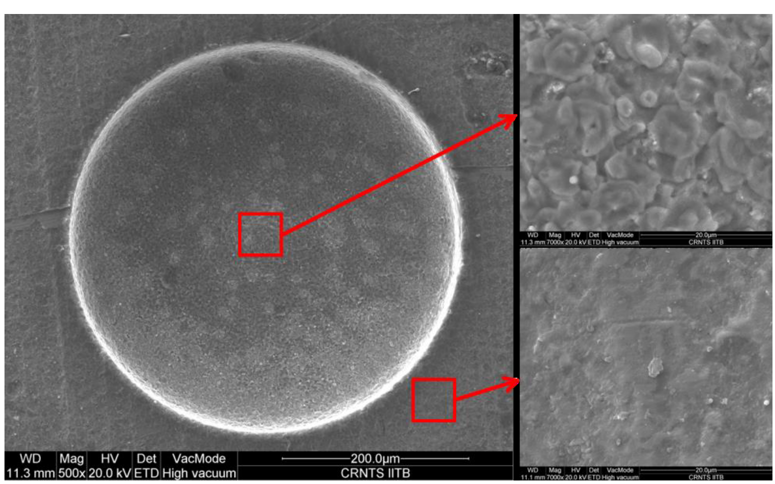
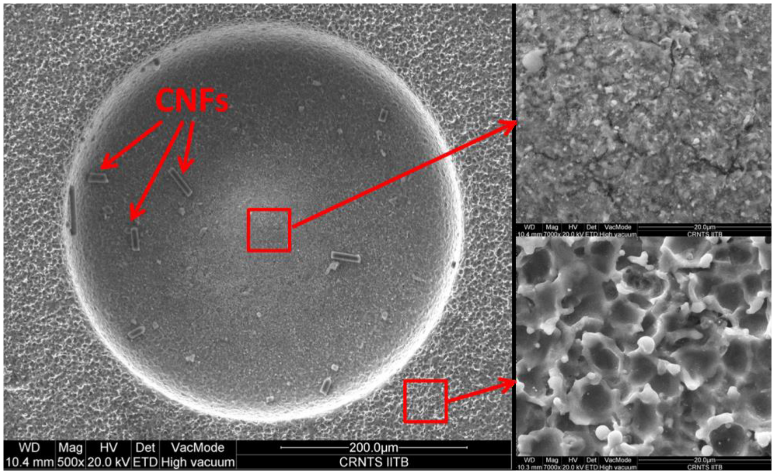


Figure 9 SEM micrographs of cavity machined with CNFs at 114 V (see online version for colours)

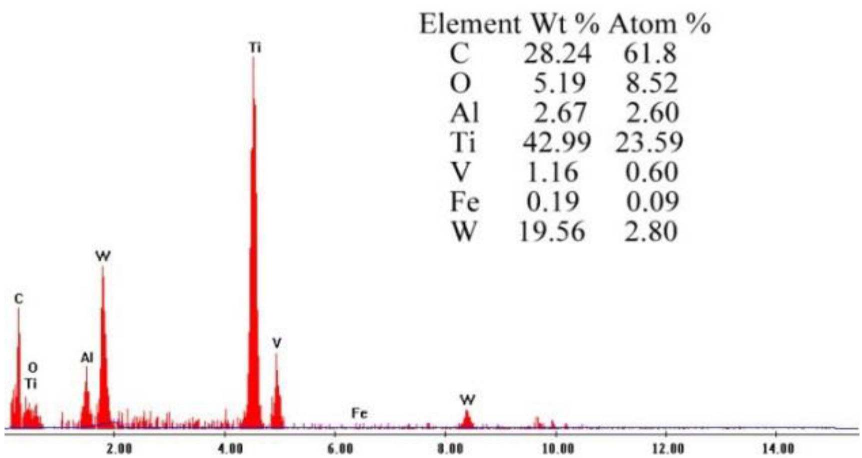


When CNFs are used in the dielectric fluid, the bridging phenomenon leads to uniform dispersion of discharge energy aids in removal of smaller flakes. Thus, the observed surface has small sized craters size and the smooth surface. As discussed in Section 3.1, the spark gap also increases with the presence of CNFs in the dielectric fluid. With increased spark gap, the debris can be efficiently flushed out of the spark gap. Thus, the adhesion and re-solidification of debris on the machined surface reduces. The uniform dispersion of energy due to the bridging effect and better debris flushing together helps to produce better surface topography. In earlier reports (Liew et al., 2013), during machining of machining of reaction bonded SiC with CNF additives, it was observed that the addition of CNFs leads to better surface finish. Otherwise, the machined surface used to be rough without CNFs due to spalling of flakes. The spalling effect generally observed in semiconductors and insulators due to intense discharges causing thermal shocks leading to crack formation (Lee and Lau, 1991; Trueman and Huddleston, 2000; Melk et al., 2016). The subsequent discharges separated large volumes flakes from the workpiece. We must note here that the mechanism of material removal is melting and evaporation assisted by CNFs. The intense discharges are absent due to presence of suspended CNFs as the fibres cause distribution of the spark energy due to 'bridging effect' shown in Figure 1.

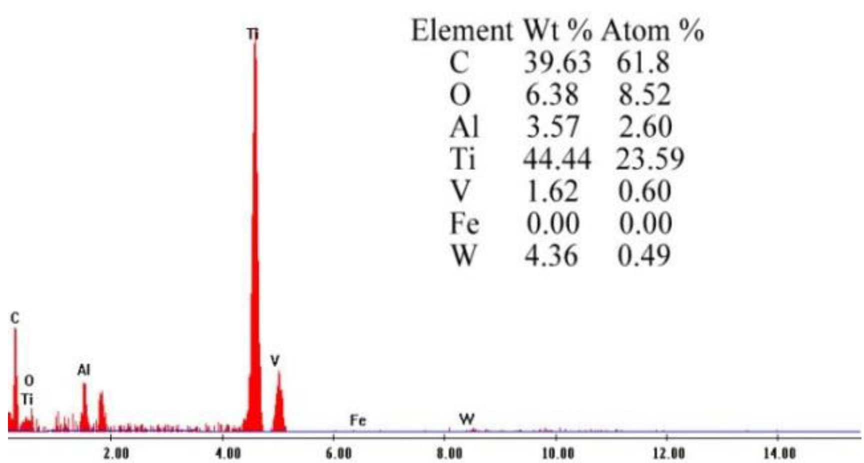
3.5 Material migration phenomenon

In EDM, impingement of plasma comprising of electrons and ions during the break down of dielectric fluid takes place with high velocity and pressure on the tool electrode and the workpiece. The relative impact on the tool electrode largely depends on the EDM polarity, which enables the conversion of the kinetic energy into heat energy. In addition, the evaporation point, melting point, thermal conductivity and thermal diffusivity are the important properties that influence the electrode wear of an electrode. It has been found from the study that the electrode wear rate is almost inversely proportional to the melting point of the electrode material (Chow et al., 2003). Thus, high temperature develops not only at workpiece but also at the tool electrode. Hence, the erosion of tool electrode cannot be completely avoided in the electro discharge action. The eroded particles then partly migrate from the tool electrode to the workpiece in the machining domain. We have studied the effect on material migration with pure dielectric as well as using CNFs using EDX analysis. The EDX analysis results are as shown in Figure 10. EDX of the machined In addition to the basic constituents of Ti-6Al-4V alloy, the presence of the tungsten element is observed in the machined cavity when no CNFs were used as shown in Figure 10(a). This is an evidence of the material migration from the tungsten tool electrode. However, the EDX analyses of the machined cavity machined with CNFs added to dielectric, as seen from Figure 10(b), the tungsten percentage has reduced significantly compared to the cavities, which were machined without addition of CNFs to the dielectric. This fact proves that the addition of CNFs in dielectric fluid is helpful in preventing the material migration to the workpiece and hence assists in improving the surface integrity of the machined surfaces.

Figure 10 EDX analysis of the machined area, (a) at 114 V without CNFs (b) at 114 V with CNFs (see online version for colours)



(a)



(b)

4 Conclusions

CNFs proposed as additives in dielectric fluid for micromachining of Ti-6Al-4V using μEDM process. The external dielectric supply system with fan and ultrasonic vessel was developed in order to maintain a homogeneous distribution of CNFs in the dielectric fluid. Through the experimental investigation, it was found that there is significant influence on machining performance of μEDM when CNFs were added in the dielectric fluid. Performance measures such as electro discharge behaviour, material removal rate, spark gap, surface roughness, material migration and surface damage during micro-machining of Ti-6Al-4V has been investigated via optical, SEM and EDX analysis. The major conclusions of this research are as follows:

- The material removal rate and surface roughness increases with increase in voltage. The higher value of voltage leads to higher spark energy and broader crater size.
- Due to early initialisation of sparks, attributed to bridging effect of CNFs, increases the discharge gap. This allows better flushing between the discharge gap, easy removal of debris and reduced tendency of re-deposition of the debris in the machining zone.
- At lower values of voltage, specifically at 90 V and 102 V, an arcing and short circuiting were observed, which results in reduction in the material removal rate. Addition of CNFs reduced the tendency of arcing and enabled better flushing leading to higher material removal rate.
- Better surface finish observed at lower values of voltages as less spark energy associated with the low voltage leads to a smaller crater size. The surface finish is further improved by adding CNFs to the dielectric fluid. The roughness has reduced by 47% maximum with addition of CNFs, at 102 V. The lowest surface roughness of 2.15 μm was achieved at 90 V with the addition of CNFs.
- Material migration phenomenon observed from tungsten tool electrode to the machined cavity of Ti-6Al-4V via EDX analysis. Obstacles offered by CNFs to the migrating particles and easy flushing of the same due to increase in the spark gap leads to reduction in material migration when compared to machining using dielectric fluid without addition of CNFs.
- It is observed that the top surface of workpiece adjacent to the machined micro hole, approximately 200 μm from the periphery of the hole, is deteriorated. This was due to stray, weak energy discharges carried away radially from the machining domain via bridging effect assisted by CNFs present in the dielectric.

The present investigation will open up challenging possibilities for exploring improvement in the machining of titanium alloys. Future work can be based on fundamental investigation of discharge action in the presence of CNFs.

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