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ORIGINAL ARTICLE

Study on the nano-powder-mixed sinking and milling micro-EDM of WC-Co

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Abstract Present study investigates the feasibility of improving surface characteristics in the micro-electric discharge machining (EDM) of cemented tungsten carbide (WC–Co), a widely used die and mould material, using graphite nano-powder-mixed dielectric. In this context, a comparative analysis has been carried out on the performance of powder-mixed sinking and milling micro-EDM with view of obtaining smooth and defect-free surfaces. The surface characteristics of the machined carbide were studied in terms of surface topography, crater characteristics, average surface roughness (R_a) and peak-to-valley roughness (R_{max}). The effect of graphite powder concentration on the spark gap, material removal rate (MRR) and electrode wear ratio (EWR) were also discussed for both die-sinking and milling micro-EDM of WC–Co. It has been observed that the presence of semi-conductive graphite nano-powders in the dielectric can significantly improve the surface finish, enhance the MRR and reduce the EWR. Both the surface topography and crater distribution were improved due to the increased spark gap and uniform discharging in powder-mixed micro-EDM. The added nano-powder can lower the breakdown strength and facilitate the ignition process thus improving the MRR. However, for a fixed powder material and particle size, all the performance parameters were found to vary significantly with powder concentration. Among the two processes, powder-mixed milling micro-EDM was found to provide smoother and defect-free surface compared to sinking micro-EDM. The lowest value of R_a (38 nm) and R_{max} (0.17 μm) was achieved in powder-mixed milling micro-EDM at optimum concentration of 0.2 g/L and electrical setting of 60 V and stray capacitance.

Keywords Powder-mixed sinking micro-EDM · Powder-mixed milling micro-EDM · Surface characteristics · Graphite nano-powder · Cemented carbide (WC–Co)

1 Introduction

In recent years, micro-electric discharge machining (EDM) is considered as one of the most promising non-conventional machining processes in terms of size and precision of product. It has advantage over other fabrication process, such as LIGA, laser, ultrasonic ion beam etc., because of its lower cost, although the majority of such non-conventional processes are slower and limited in planar geometries. However, the main drawback of using micro-EDM in industries is that micro-EDM of hard metals usually yields a relatively poorer surface finish and integrity including craters, micro cracks and unfavourable residual stress due to the thermal action [1]. Although a number of researches are being carried out to improve the quality of surface for the EDM and micro-EDM of WC, most of the cases, for improving the surface quality of WC, diamond grinding and polishing are used after EDM [2]. Many manufacturers worldwide are still using hand lapping to finish the EDM surface in order to achieve a high level of surface finish [3]. However, most of these processes of hand lapping or polishing are difficult to apply in micro-components, micro-moulds and micro-dies, as there is a chance of destroying the structures. A new approach to a practical and efficient finish process comes in the form of machining in presence of suspended powder dispersed

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uniformly in the dielectric medium. Apart from the other EDM-based methods of improving the surface finish such as planetary EDM, multi-electrode EDM and high-resistance coated electrode, powder-mixed EDM/micro-EDM has been found to affect the spark gap between the electrodes in addition to discharging process, thus significantly influencing the performance of the process [4].

There have been numerous researches on the conventional powder-mixed EDM with an intension of improving the surface finish. One of the earliest researches on powder-mixed EDM has been reported by Erden and Bilgin [5] who investigated addition of powdered form of copper, iron, aluminium and carbon into commercial kerosene oil as impurities for EDM of steel. The results indicated that added powder improves the breakdown characteristics of dielectric fluid and machining rate. Jeswani [6] investigated with graphite powder into kerosene oil at a concentration of 4 g/L for the EDM of steel and reported that the interspace for electric discharge initiation was increased while breakdown voltage was lowered. An improvement in machining process stability resulted in 60% increase in material removal rate (MRR) and 28% reduction in electrode wear ratio (EWR). Narimuya et al. [7] reported that aluminium and graphite powder generates better surface finish in EDM of steel than silicon powder at specific machining conditions. Mohri et al. [8] used silicon powder of 10–30 μm size uniformly in dielectric fluid and performed machining using lower discharge current and discharge duration and was able to produce surface with roughness less than 2 μm. However, to achieve this performance even distribution of debris and short discharge time are required. Kobayashi et al. [9] also reported that silicon powder improves the surface finish of SKD-61 tool steel. Yan and Chen [10] studied the process with aluminium and silicon carbide powder-mixed dielectric to EDM on SKD-11 and Ti-6Al-4V and reported improvement in MRR and surface roughness. Uno and Okada [11] reported that silicon powder mixed with dielectric reduces the impact force acting on the workpiece and results in smaller undulation of craters, hence glossy surface. Wong et al. [4] used fine powders of silicon, graphite, molybdenum, aluminium and silicon carbide with dielectric. Aluminium powders was found to produce mirror finish on SKH-51 tool steel but failed to produce mirror finish on SKH-54 steel. Rather semi-conductive silicon and graphite powders were able to produce very fine finish condition. Wang et al. [12] investigated with Al and Cr powder in kerosene fluid and found these powders can reduce isolation, increase the gap between tool and workpiece and thus stabilise the process. Tzeng and Lee [13] applied Al, Cr, Cu and SiC with working fluid and performed EDM on SKD-11 material. It was reported that machining performance is significantly affected by concentration, size, density, electrical resistivity and thermal conductivity of added powder. Moreover, it was also revealed that due to its higher density Cu powder has almost no effect in EDM. Pecas and Henriques [14] applied silicon powder at a concentration of 2 g/L and found that operating time and surface roughness decreases. It was also reported that average surface roughness depends on machining area and machining time.

Besides, powder-mixed EDM of different types of steel, recently Kung et al. [15] studied the MRR and EWR during the conventional powder-mixed EDM (PMEDM) of cobalt-bonded tungsten carbide (WC–Co) using Al powder of 1.5–2 μm and 10–20 g/L. However, this study only presented the effect of Al powder on MRR and EWR with no focus in surface finish, although the main purpose of using PMEDM is to improve the surface finish.

Although there has been extensive research on improving the surface finish of EDMed surface, very few works have been done in case of micro-EDM. Chow et al. [16] has applied PMEDM for machining of micro-slit in a titanium alloy (Ti-6Al-4V) and has obtained better performance in terms of MRR and surface finish. However, although the study aims for fabricating micro-structures, they used conventional EDM machining conditions. Tan et al. [17] have investigated the effect of nano-powders additives on the surface roughness and discharge gap distances during the micro-EDM of AISI 420 stainless mould steel. It has been reported that SiC and Al_2O_3 nano-powders can reduce the surface roughness during the micro-EDM of stainless steel. In addition, Jahan et al. [18] studied on the graphite powder-mixed micro-EDM of SKH-51 tool steel and found that the surface finish improves. However, only one fixed concentration (2 g/L) was used in this study as conventional EDM suggests 2–4 g/L concentration provide improved surface finish [18]. Nevertheless, the optimum concentration of micro-EDM may be different from that of conventional EDM and therefore the effect of concentration is important to study in micro-EDM.

It has been found from the extensive literature survey that most of the researcher focused on improving the surface finish of different types of tool steel as it is widely used in die and mould industries. However, very few researches have been carried out on powder-mixed EDM with no reported research on powder-mixed micro-EDM of WC–Co, although it is extensively used in tool and die industries. Therefore, present study intends to investigate the feasibility of achieving fine surface finish in the micro-EDM of WC–Co using graphite nano-powder additives in dielectric oil, as this powder has been reported to provide improved surface finish in different studies. In this regard, a comparative evaluation of powder-mixed sinking and milling micro-EDM has been carried out on the basis of spark gap, MRR, EWR, R_a, R_{max} and overall the surface topography. The surface characteristics in WC–Co without and with powder-mixed micro-EDM were studied in terms of surface topography, crater characteristics, average surface roughness (R_a) and peak-to-valley roughness (R_{max}).

2 Experimental setup and methodology

2.1 Materials

The workpiece material used in this study was cemented tungsten carbide with a composition of WC–10wt.% Co. The tool electrode material used was tungsten electrode (99.9% W) of 500 μm diameter. The tungsten electrode has been used for its high melting point and high wear resistance. The dielectric fluid used was the commercially available "Total FINA ELF EDM 3" oil, having relatively high flash point, high auto-ignition temperature and high dielectric strength. A low pressured side flushing system was used in order to avoid any tool deflection or vibration of the workpiece. For the powder-mixed micro-EDM, graphite nano-powder of 55 nm average particle sizes are used. The properties of the workpiece, electrode and dielectric are same as presented in authors' previous study [19]. The important characteristics of the powder material are listed in Table 1.

2.2 Machine tool

A multi-purpose miniature machine tool has been developed for high-precision micro-machining at National University of Singapore. This machine is energized by a pulse generator which can be switched to both transistor-type and RC-type. The machine is capable of micro-EDM, micro-turning, micro-milling, micro-grinding and micro-ECM by changing a suitable attachment. The maximum travel range of the machine is 210 mm (X)×110 mm (Y)×110 mm (Z) with a resolution of 0.1 μm in X, Y and Z directions and full closed-feed-back control ensures accuracy of up to sub-micron.

2.3 Modified dielectric circulation system

In this study of powder-mixed micro-EDM of WC–Co, the dielectric circulation system has been designed carefully. Since the debris particles generated from WC–Co are magnetic, a magnetic filter with a magnet material of 'Ferrite C5' is used to separate the debris and to allow the non-magnetic nano-powder particles to pass through. The core of the magnetic filter collects the debris as smaller as 0.7 μm in diameter. After the filtering of debris particles, only powder-mixed dielectric is recirculated by means of a pump. Figure 1 presents the schematic diagram of the setup with machine tool and modified dielectric circulation system for powder-mixed micro-EDM.

2.4 Experimental procedure

In the experiments to obtain fine surface finish, die-sinking and milling micro-EDM was conducted using 500 μm W electrodes on the surface of WC–Co under different machining conditions. The machining conditions are given in Table 2. In the micro-EDM of tungsten carbide selection of electrode polarity is important. For this reason, the electrode polarity is firstly selected. In the micro-EDM of WC–Co, positive electrode polarity resulted in extensive electrode wear compared with material removal rate from the workpiece. On the contrary, negative electrode polarity gives much better surface finish with comparatively higher material removal rate, lower electrode wear and controlled performance [20–22]. Hence, the experiments were carried out with the electrode as negative polarity. However, in case of electrode dressing reverse (positive) polarity was used as more material is removed from the electrode and dressing process become faster using positive electrode polarity. For the fine-finish micro-EDM the surface of the electrode facing the workpiece is important to consider. In the die-sinking EDM the electrode shape is exactly reflected on to the workpiece. Though in EDM the electrode does not touch the workpiece, the surface finish of the electrode facing the workpiece are required to be smooth specially in finishing micro-EDM. In the micro-EDM process the spark always occurs at the closest point between the electrode and the workpiece. Thus if the surface of the electrode facing the workpiece is rough then the machining depth may not be equal to the anticipated depth. Therefore, in this study of fine-finish micro-EDM, the electrode was dressed in two steps as explained in authors' previous study [19]. In this method of dressing, firstly, the electrode was dressed to cut horizontally using a WC plate of 100 μm thickness to remove the rough surface using discharge energy of 1.5 μJ per pulse (80 V, 470 pF setting). Thereafter, to make the crater smaller and to smooth the surface of the electrode facing the workpiece, a

Table 1 Properties of graphite powder

Average particle size (nm)	Density (g/cm^3)	Thermal conductivity (W cm^{-1}K^{-1})	Electrical conductivity (μΩ^{-1}cm^{-1})	Melting point (°C)	Specific heat (J Kg^{-1}K^{-1})
55	2.25	1.50	3×10^{-3}	3,652	710

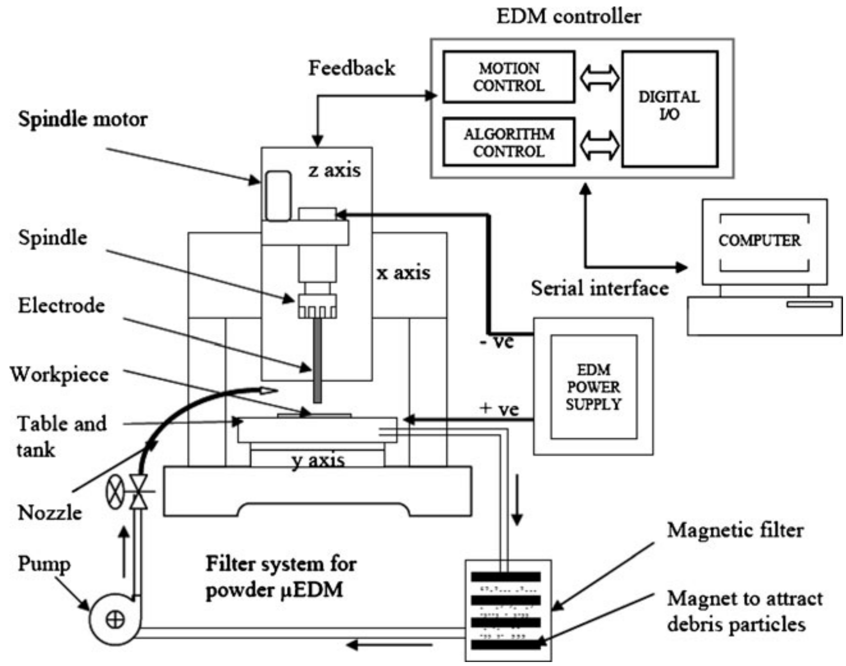


Fig. 1 Schematic diagram of the setup designed for powder-mixed micro-EDM

finish dressing is performed by scanning micro-EDM keeping the same polarity using comparatively lower discharge energy of 0.15 μJ (80 V, 47 pF).

3 Results and discussion

3.1 Selection of optimum concentration of graphite nano-powder

3.1.1 Analysis of spark gap, MRR and EWR

Figure 2a shows the variation of spark gap with different concentration of graphite nano-powder in EDM oil 3. It can be observed that the spark gap increases significantly with the increase of powder concentration for graphite-mixed dielectric. During the micro-EDM, the presence of conductive or semi-conductive powders in the working gap can drastically lower the breakdown strength of dielectric, which eventually results in a higher spark gap [23]. It has been observed from Fig. 2a that the effect of graphite powder properties is more pronounced in milling micro-EDM due to improved flushing and stable machining. Moreover, the concentration of graphite powder in the spark gap reduces in case of die-sinking due to the presence of difficult-to-remove debris particles. Hence, the spark gaps at all concentrations may be lower in die-sinking compared to milling micro-EDM. However, although spark gap is increased, very higher concentration of powder particles in the dielectric can result in series of discharging and arcing thus causing surface defects. It can be also seen from Fig. 2a that the spark gap is higher for milling micro-EDM compared to that of sinking micro-EDM after adding graphite nano-powders in the dielectric. Figure 2b shows the variation of MRR for die-sinking and milling micro-EDM at different concentration of graphite powder in dielectric. It has been found that with the increase of powder concentration the MRR increases gradually both in sinking and milling micro-EDM. This may be due to comparatively earlier breakdown of dielectric at reduced insulating strength in powder-mixed micro-EDM. The effect of increased MRR is more pronounced in case of sinking micro-EDM. This is due to the fact that, at the finishing regime due to low spark gap and stationary tool electrode in die-sinking micro-EDM without powder, the machining become unstable resulting in longer machining time. Therefore, at increased spark gap after adding nano-powder in dielectric, the machining instability reduces significantly which enhance MRR. In addition to increased

Table 2 Experimental conditions for powder-mixed sinking and milling micro-EDM of WC–Co

Workpiece material	WC–10 wt.% Co
Tool electrode	Tungsten
Dielectric fluid	Total EDM 3 oil
Powder materials	Graphite
Pulse generator type	RC-generator
Voltage (V)	60, 80, 100, 120
Capacitance (pF)	47, 10, stray (7 pF)
Resistance (kΩ)	Fixed to 1 kΩ

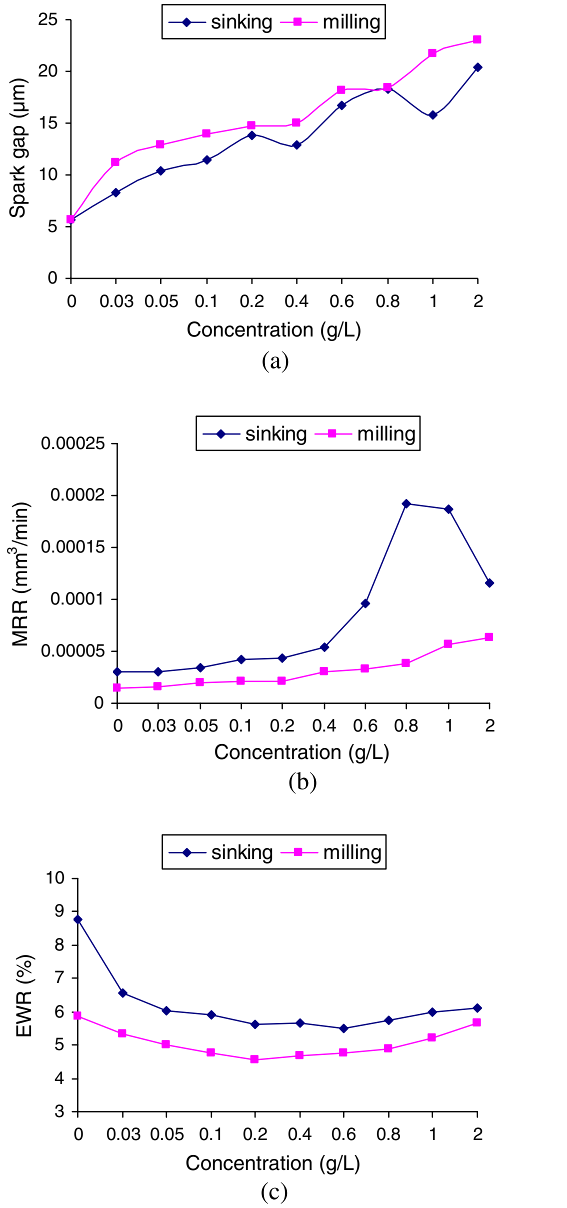


Fig. 2 Variation of **a** spark gap, **b** MRR and **c** EWR with graphite powder concentration in dielectric for die-sinking and milling micro-EDM of WC

spark gap and reduced instability, the mechanism of powder-mixed micro-EDM is also responsible for increased MRR. The addition of powder particles can reduce the electrical discharge power density and gap explosive pressure for a single pulse [23], which result in smaller craters with uniform distribution. However, due to much effective flushing of debris at higher spark gap and reduced size craters, the overall MRR increases. The good flushing condition in milling micro-EDM is associated with the combined rotational and scanning movement of the electrode, which helps in removing the debris from the machined zone more effectively. The rotational movement helps in flushing due to the tangential velocity of the electrodes, which creates disturbance of the dielectric at the machined zone [24, 25]. On the other hand, the scanning movement helps in swiping out the debris from the machined zone [19]. However, at very high concentration, the MRR tends to reduce again in case of die-sinking micro-EDM due to frequent arcing and short-circuiting at deposited powder particles on workpiece surface. Although same machining conditions are used in powder-mixed milling and die-sinking micro-EDM, this phenomenon was not observed in case of milling due to much stable machining. In die-sinking due to stationary tool electrode, these deposited particles cannot be removed out of the spark gap easily causing secondary sparking. This secondary sparking makes the machining unstable and increases machining time. So, the trend of lower MRR at higher concentration in die-sinking is mainly due to the machining instability. The variation of EWR with concentration for both powder-mixed sinking and milling micro-EDM is shown in Fig. 2c. It has been observed that, with the increase of powder concentration the EWR decreases first, then after certain optimum concentration, it tends to increase again. The reduction in EWR with addition of powder is due to the reduction of ineffective pulses at higher spark gap and improved flushing, whereas the increasing trend of EWR at higher concentration is due to settling of powder in spark gap. An optimum range of 0.1–0.4 g/L was found to provide lower EWR.

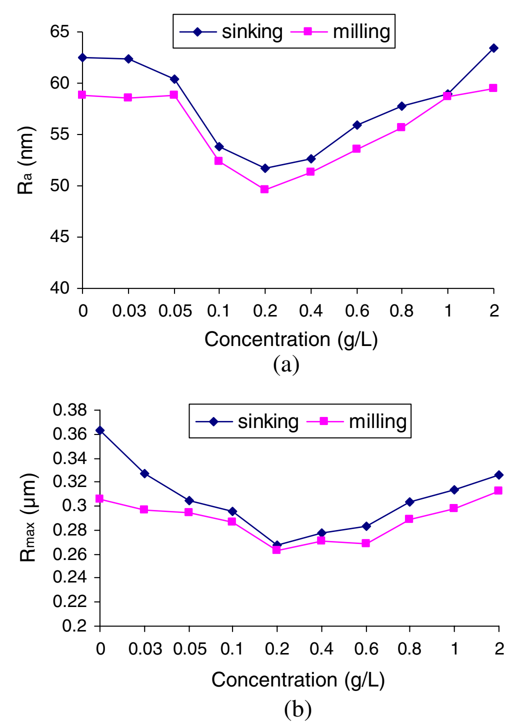


Fig. 3 Variation of **a** R_a and **b** R_{max} with concentration during the powder-mixed sinking and milling micro-EDM of WC

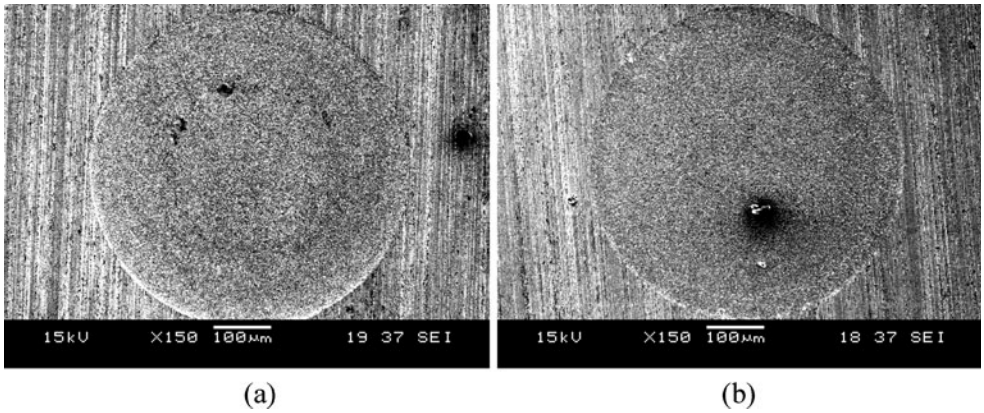


Fig. 4 Comparison of machined surface of WC at 60 V, stray C in powder-mixed sinking micro-EDM for **a** 0.2 and **b** 2 g/L concentration

3.1.2 Analysis of R_a and R_{max}

Due to increased spark gap and suspension of powder particles in the dielectric during powder-mixed micro-EDM, the electrical discharges are well distributed among the particles, which reduce the energy released from a single spark [4, 23]. The concentrated discharge energies at lower spark gap in normal micro-EDM can result in broader crater size in addition to surface defect due to arcing and short-circuiting. On the other hand, a fine surface with smaller craters due to distribution of discharge energies was observed after applying powder-mixed dielectric. It can be observed from Fig. 3a that unlike spark gap, the average surface roughness (R_a) decreases first with the increase of powder concentration, then again tend to increase at higher concentration of powder particles. Similarly, the R_{max} values also decrease with the concentration up to a certain level; then again tend to increase [Fig. 3b]. Although R_a and R_{max} showed same trend, the R_{max} is important to study in the surface finishing for die/mould making using EDM. The R_{max} provides a good indicator of the shininess of the surface. The overlapped craters with high border height (high R_{max}) may reflect light in multiple directions, causing the surface dull in appearance [14]. On the other hand, lower R_{max} reduces the need of hand lapping or other finishing process. There may be several reasons for higher roughness at high concentration of the powder materials in dielectric. Firstly, at very high concentration, the dielectric loses its ability to distribute uniformly all the powder materials. Therefore, powder settling is a common problem at higher concentration [14], although spark gap increases. In addition, at higher concentration of conductive powders, the bridging of powder particles may occur, which results in arcing and short-circuiting more frequently. The bridging effect can result in more concentrated discharge energy and accumulate carbon on the surface of workpiece, finally deteriorating the surface roughness [26]. Figures 4 and 5 show comparison of the machined surface at two different concentrations for die-sinking and milling micro-EDM respectively at the lowest setting of discharge energy used in this study. It has been found that the surface obtained in sinking micro-EDM at higher concentration (2 g/L) has some resolidified and accumulated carbon compared to that of lower concentration (0.2 g/L) [Fig. 4]. The EDX analysis of the SEM image in Fig. 4 also indicates about 2% increases in carbon percentage at 2 g/L compared to that of 0.2 g/L [Fig. 6]. On the other hand, this accumulation of carbon particles decreases in case of milling micro-EDM significantly, although there is some traces of carbon observed at higher concentration [Fig. 5b]. The EDX analysis of Fig. 5 shows that there is very little (less than 1%) increase in carbon percentage at higher concentration

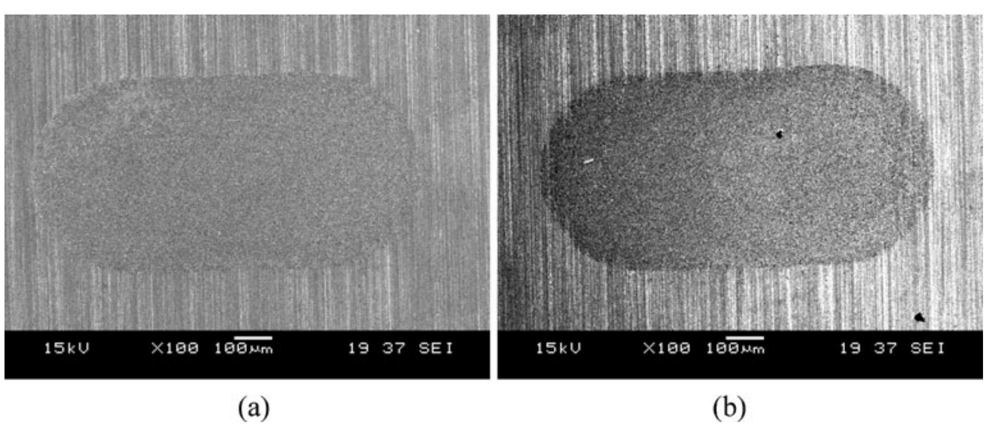


Fig. 5 Comparison of machined surface of WC at 60 V, stray C in powder-mixed milling micro-EDM for **a** 0.2 and **b** 2 g/L concentration

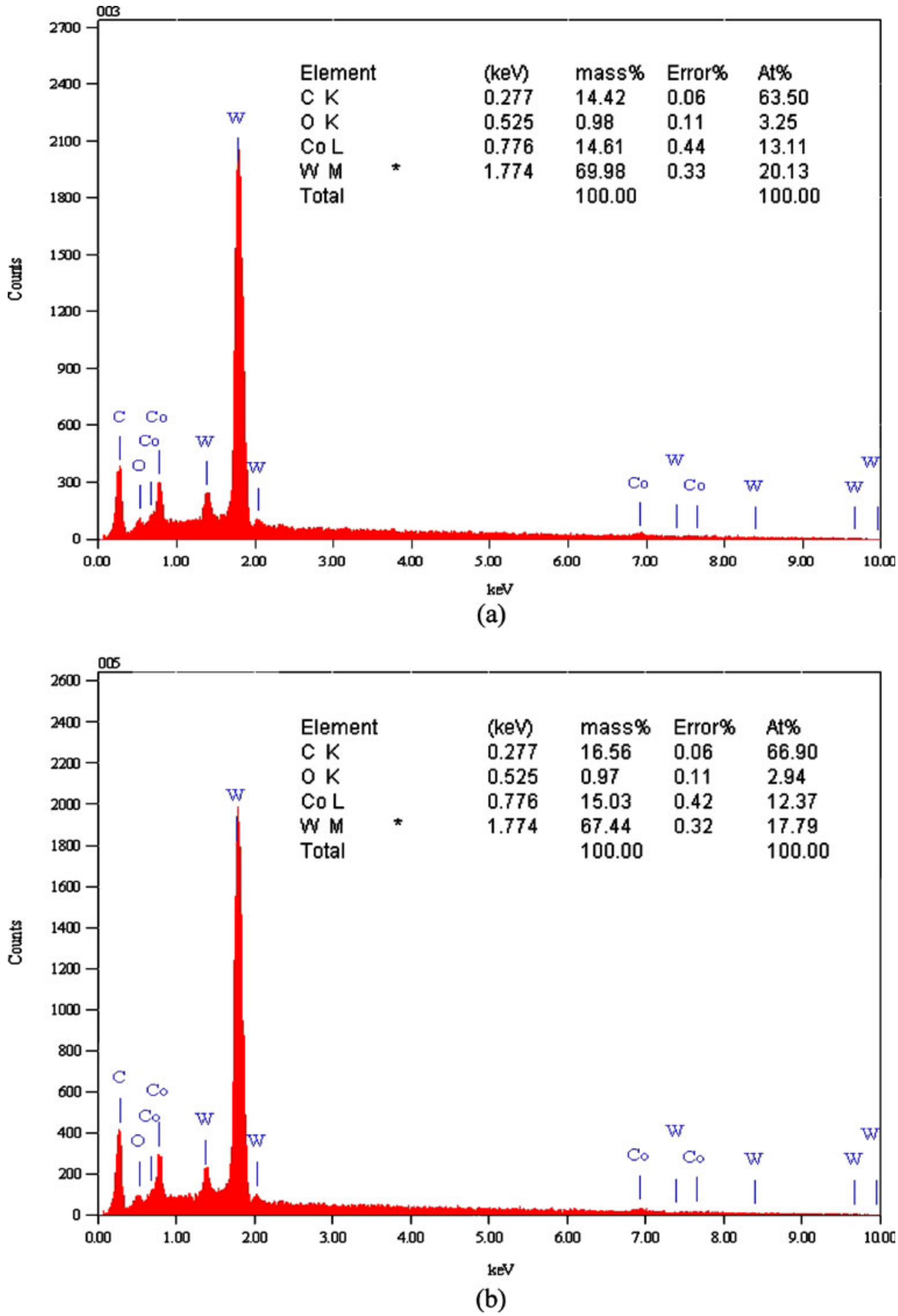


Fig. 6 Comparison of EDX analysis of the machined surface shown in Fig. 4; **a** 0.2 and **b** 2 g/L concentration for die-sinking

of powder particles in milling micro-EDM [Fig. 7]. It has been observed that, for both sinking and milling micro-EDM, a concentration of range 0.1–0.6 g/L provides lower R_a and R_{max} in addition to moderately higher spark gap. The lowest R_a of 48 nm and R_{max} of 0.26 μm were obtained in 0.2 g/L concentration for graphite powder in milling micro-EDM at 80 V and stray capacitance.

Another important observation is that the trend of decreasing the R_a and R_{max} values are more significant in die-sinking micro-EDM compared to milling, although the values are lower in milling micro-EDM for all the settings of powder concentration. This is due to the fact that the presence of powder reduces the electrostatic capacity which usually forms at lower gap voltage in die-sinking due to stationary tool and workpiece [27]. On the other hand, in milling micro-EDM due to electrode scanning movement, the capacitance cannot form between the electrode and workpiece. The reasons for obtaining smooth surface using

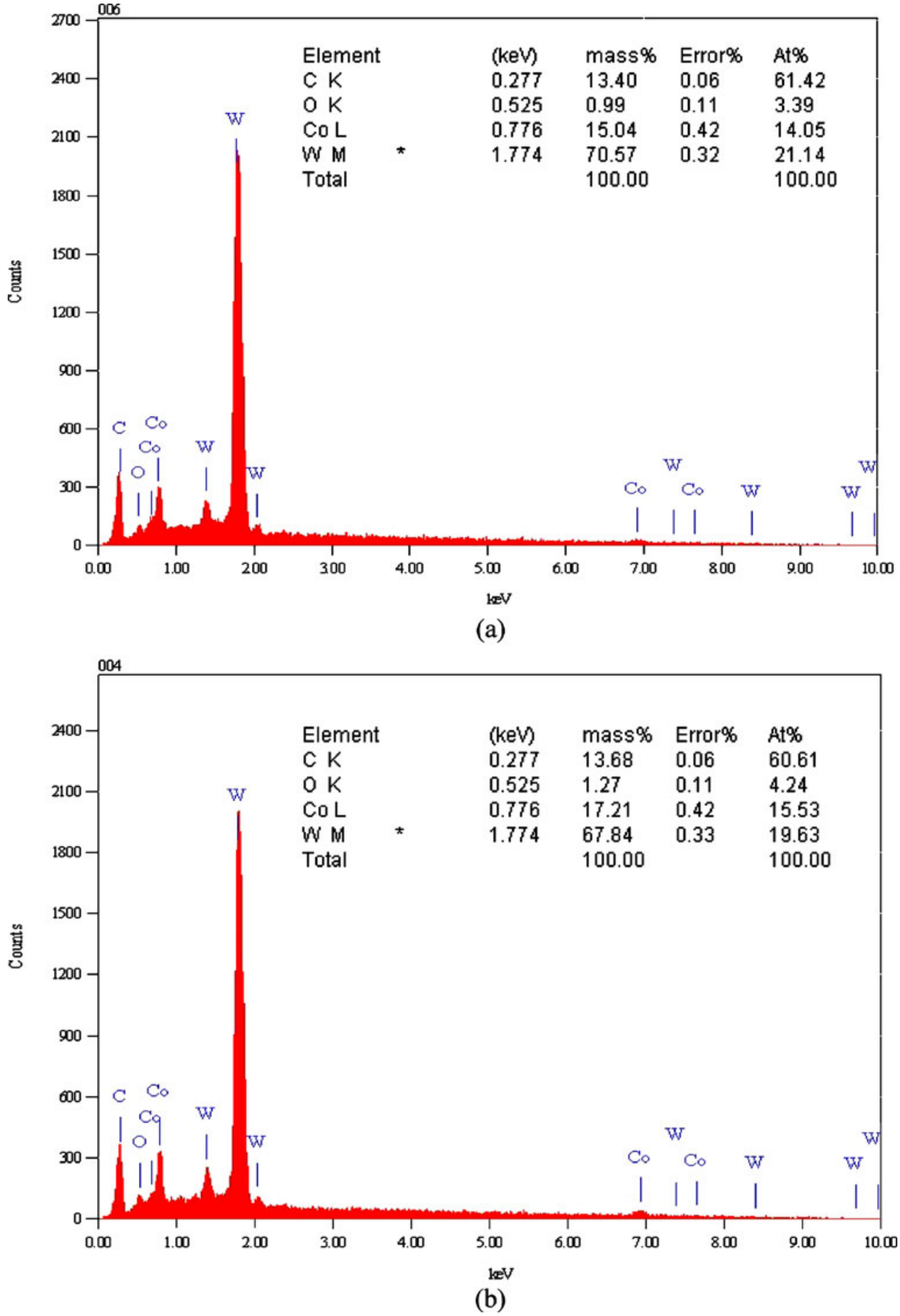


Fig. 7 Comparison of EDX analysis of the machined surface shown in Fig. 5; **a** 0.2 and **b** 2 g/L concentration for milling

graphite nano-powders can be explained by means of the thermo-physical characteristics of graphite powder shown in Table 1. It has been found that being a semi-conductor, the temperature effect on its resistivity can significantly influence the scattering effect [4] during the fine-finish micro-EDM. The conducting electrons increase with the increase of temperature during micro-EDM which reduces the electrical resistivity and results in lowering the breakdown strength. In addition, due to its higher thermal conductivity, more heat is distributed and dissipated to the workpiece surface to limit the size of the craters produced. The lower density of graphite powder makes it suitable to mix uniformly and float within the dielectric fluid. Moreover, the excellent lubricity of graphite may also have some effect on the surface finish

[4]. The wetting of particles by the melted surface may improve the surface finish in addition to make the surface glossier.

The optimum concentration of graphite nano-powder has been selected based on the lowest R_a and R_{max} values obtained in both the sinking and milling micro-EDM, as the primary focus was on improving the surface finish. From the above discussion, it has been observed that graphite nano-powder with a concentration of 0.2 g/L provided lowest R_a and R_{max}. The EWR is also reduced significantly at this concentration (0.2 g/L) and the MRR is moderately higher at 0.2 g/L than without powder (0.0 g/L). Therefore, in the following section investigation will be presented on the surface characteristics of die-sinking and milling micro-EDM without and with addition of graphite nano-powder at different settings of discharge energy using optimum concentration of 0.2 g/L.

3.2 Comparison of surface characteristics without and with nano-powder-mixed dielectric

3.2.1 Surface topography and crater characteristics

Although the surface roughness decreases with decrease of discharge energy, a common problem during the die-sinking micro-EDM at the finishing regime is the capacitance formed by the electrode and workpiece, as the electrode is stationary [27]. Moreover, the open circuit voltage charges this capacitance. Therefore, during the discharging, the energy accumulated this way is released and adds to the generator discharge current. With increasing active electrode/work-piece surface and decreasing distance between electrode and workpiece (sparking gap), this inherent capacitance increases, and causes an uncontrollable current peak at the moment of discharge, making it impossible to achieve a very low roughness in die-sinking. This problem can be solved to a great extent by the powder-mixed dielectric as the powder particles increase spark gap thus reduce capacitative effect. Figures 8 and 9 present the comparison of machined surface topography for die-sinking and milling micro-EDM for without and with the addition of graphite nano-powders in dielectric oil at electrical setting of 80 V, stray C. It can be seen from the SEM and AFM images that both for sinking and milling micro-EDM, the machined surface topography has been improved and surface becomes smoother after the addition of graphite nano-powders. It can be observed from AFM image of the scanned surface that the maximum scale indicating the crater heights of surface irregularities are lower in the surface machined by powder-mixed micro-

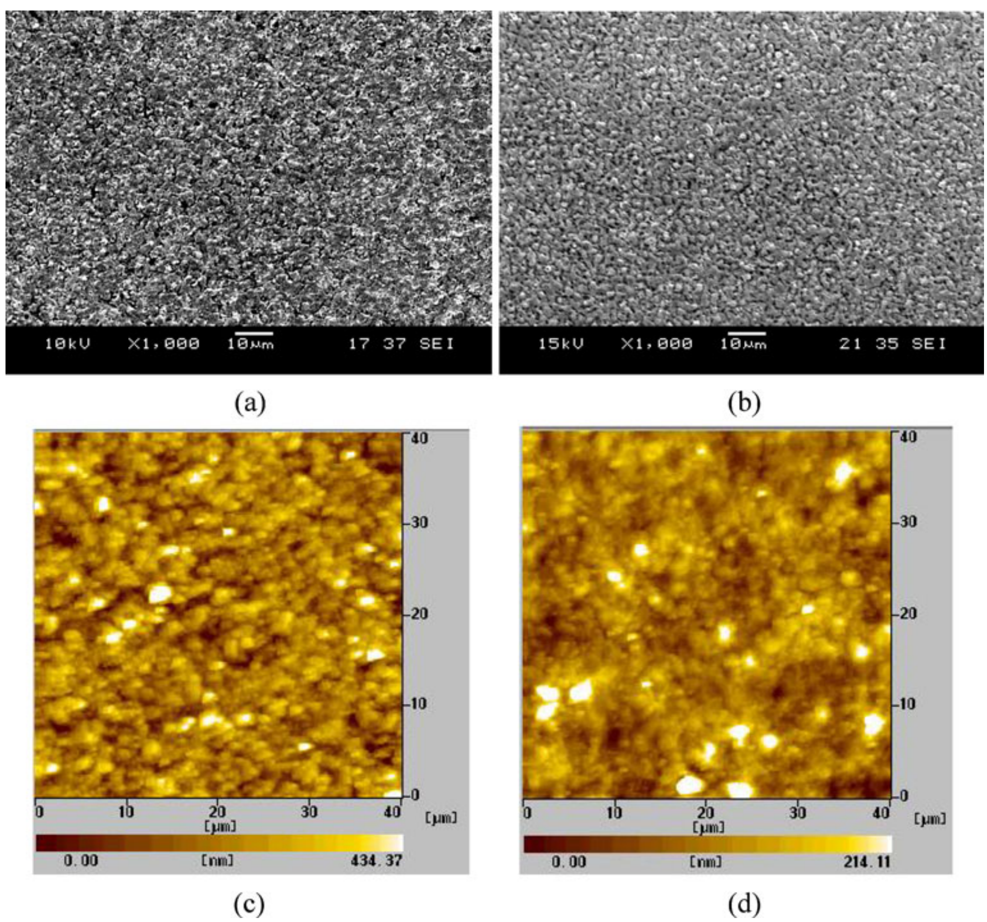


Fig. 8 Comparison of machined surface topography in die-sinking micro-EDM at lower discharge energy: [D.E. 0.022 μJ/pulse, 80 V, stray capacitance] for **a** SEM image without powder, **b** SEM image with graphite powder-mixed dielectric, **c** AFM image without powder, **d** AFM image with powder

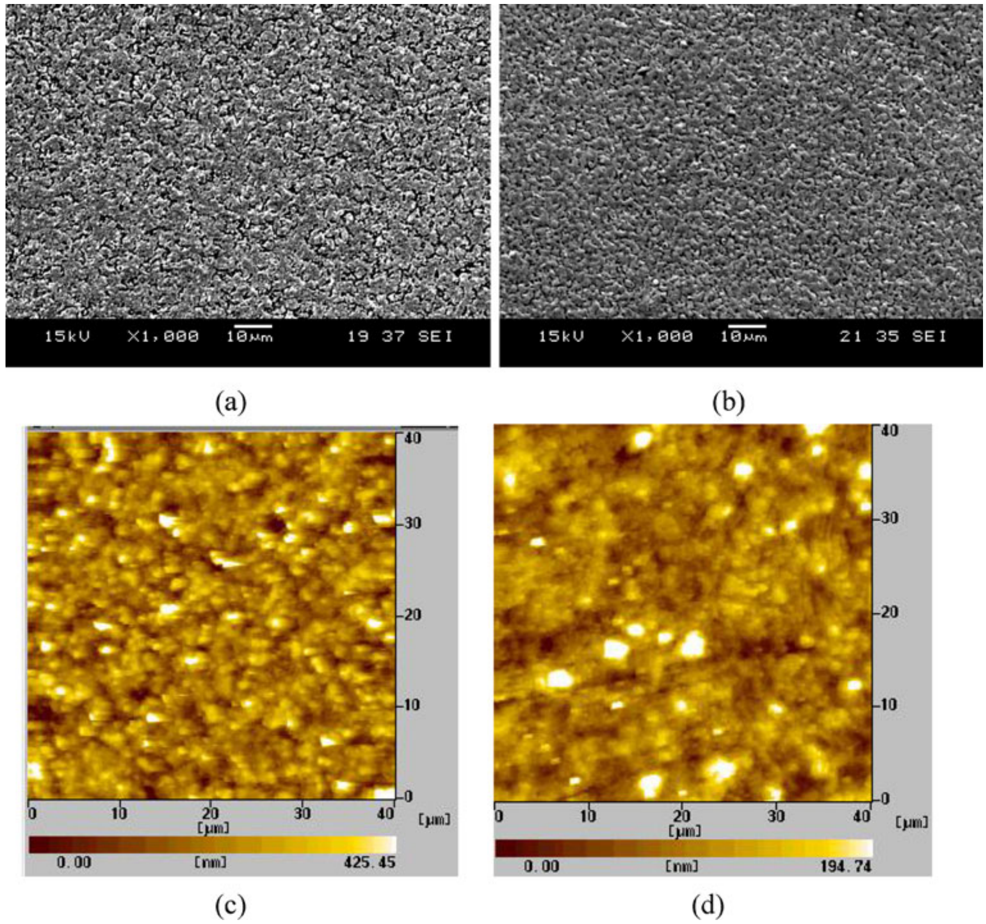


Fig. 9 Comparison of machined surface topography in milling micro-EDM at lower discharge energy: [D.E. 0.022 µJ/pulse 80 V, stray capacitance] for **a** SEM image without powder, **b** SEM image with graphite powder-mixed dielectric, **c** AFM image without powder, **d** AFM image with powder

EDM. For die-sinking micro-EDM, the scale reduced from 434 to 214 nm [Fig. 8c and d], whereas for milling micro-EDM it reduces from 424 to 195 nm [Fig. 9c and d]. The reasons for improving the surface finish can be both primary and secondary effect of powder particles [28]. The primary effect is that the added powder improves the breakdown characteristics of the dielectric fluid. Hence, the insulating strength of the dielectric fluid decreases and consequently, the spark gap between the electrode and workpiece increases which makes the flushing of debris uniform. As a result, the process becomes more stable thereby improving the surface finish at comparatively higher machining rate. The secondary effect is that, sometimes there may be some abrasive action of the powder particles which can improve the surface finish by reducing the deposited debris and also the crater boundary heights. In addition, it can be seen from Fig. 9b and d that powder-mixed milling micro-EDM provides the best surface finish among the four SEM and AFM images of surface topography. The reason behind this is the reduction of crater boundary heights due to the scanning movement of tool

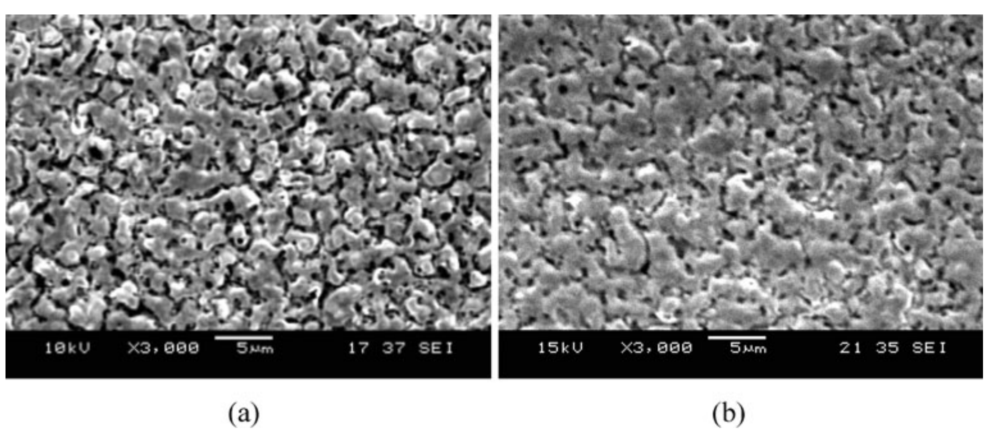
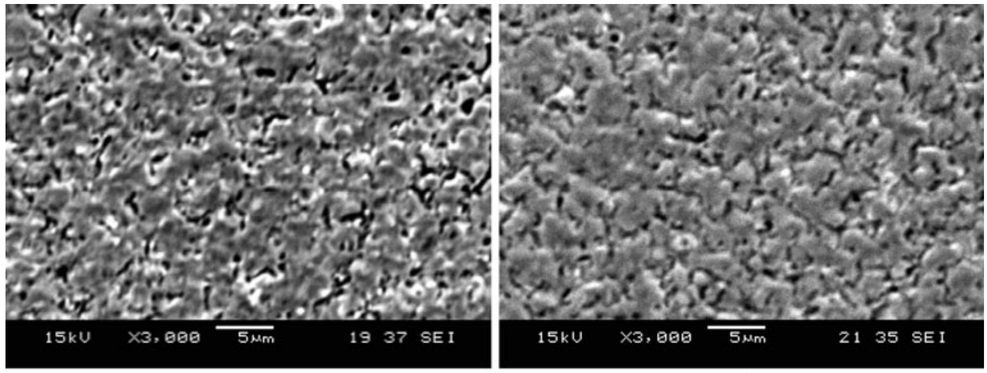


Fig. 10 Comparison of crater size and distribution in die-sinking micro-EDM at comparatively higher discharge energy: [D.E. 0.035 µJ/pulse, 100 V, stray capacitance] for **a** without powder, **b** with graphite powder-mixed dielectric



(a) (b)

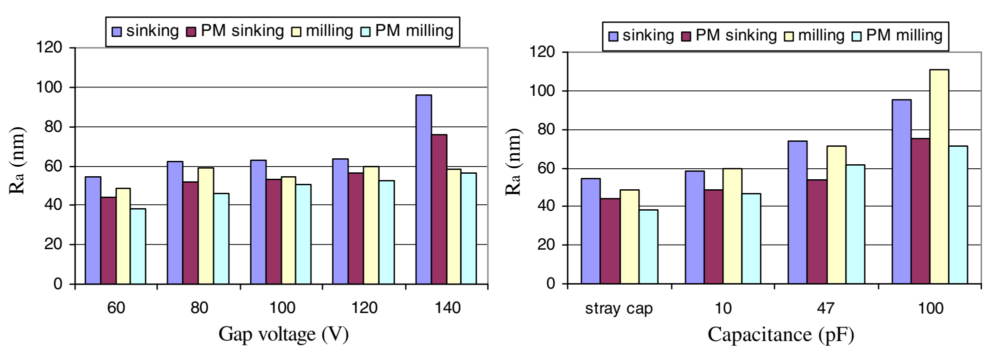
Fig. 11 Comparison of crater size and distribution in milling micro-EDM at comparatively higher discharge energy: [D.E. 0.035 µJ/pulse, 100 V, stray capacitance] for **a** without powder, **b** with graphite powder-mixed dielectric

electrode in addition to secondary abrasive effect of powder particles.

Another important reason for improving the surface finish and topography in powder-mixed micro-EDM is the improvement in crater uniformity. It has been proved that for smooth and glossy surface both the crater size and crater distribution play an important role [19]. In order for the machined surface to be smooth and glossy, the surface micro-structures should be characterised by the presence of well-defined, uniformly sized and smoothly overlapping craters [4, 19]. This is due to the fact that, when applying powder-mixed dielectric, the discharging process becomes more uniform in addition to the enlarged spark gap. The sparking is uniformly distributed among the powder particles, hence electric density of the spark decreases. Due to uniform distribution of sparking among the powder particles, shallow craters are produced on the workpiece surface which results in an improved surface finish. The crater distribution is more important in determining the glossiness of the surface. Figures 10 and 11 show SEM images of the surface showing crater uniformity and distribution in sinking and milling micro-EDM at 100 V, stray capacitance for without and with powder. Though in the SEM images, the difference in crater distribution is not significantly observable, it is easily noticeable that the intensity of black pock marks are lower in powder-mixed sinking and milling micro-EDM, which can significantly increase the reflectivity, thus making the surface shinier.

3.2.2 Average surface roughness (R_a)

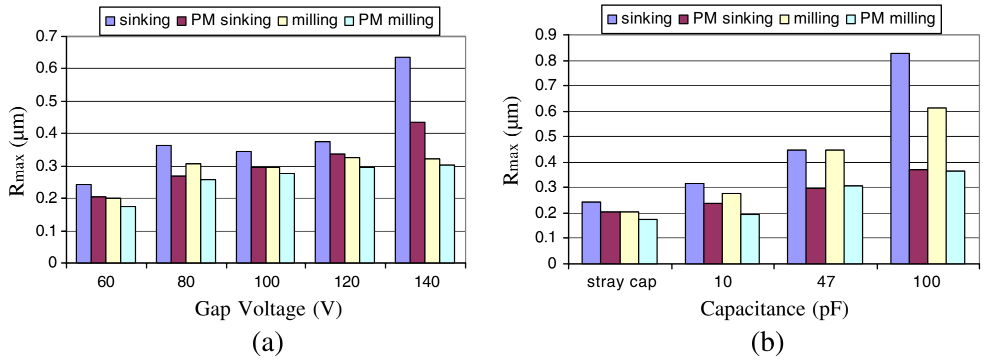
Figure 12(a) show the variation of average surface roughness with different settings of gap voltage using stray capacitance for sinking and milling micro-EDM with and without powder-mixed dielectric. The variation of R_a with capacitances at 60 V is shown in Fig. 12b. It has been found for all the settings of gap voltage and capacitance the average surface roughness reduces after adding graphite nano-powders in dielectric oil. An average reduction of 20–30% in R_a was obtained after using powder-mixed dielectric. The lowest value of R_a (38 nm) was obtained in powder-mixed milling micro-EDM, which was found to be about 49 nm without powder. It can be seen from both Fig. 12a and b that there is a significant reduction of R_a at 140 V, stray capacitance and 60 V, 100 pF settings also, which enables powder-mixed micro-EDM to be suitable for semi-finishing regime also. As the spark gap is mainly influenced by the gap voltage without powder-mixed micro-EDM [29], it has been found that there is a significant reduction of R_a at 60 V and 100 pF settings (Fig. 12b). In 60 V, due to low spark gap, the surface becomes rougher at 100 pF, though the discharge energy is



(a) (b)

Fig. 12 Comparison of R_a values for sinking and milling micro-EDM without and with graphite nano-powder at different settings of **a** gap voltage and **b** capacitance

Fig. 13 Comparison of R_{max} values for sinking and milling micro-EDM without and with graphite nano-powder at different settings of **a** gap voltage and **b** capacitance

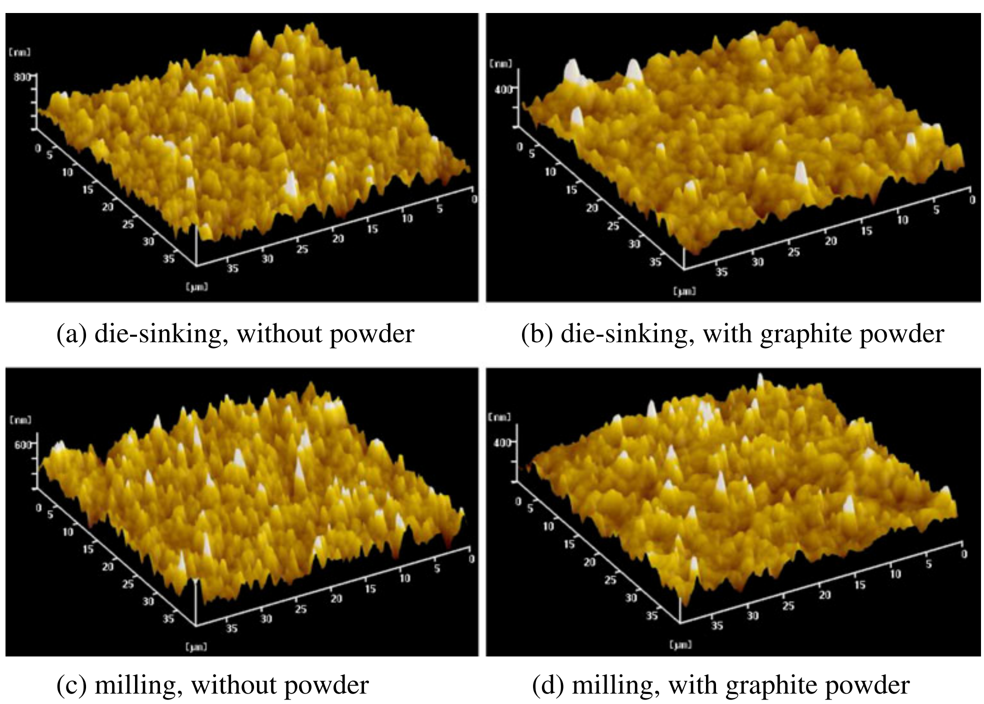


only 0.18 μJ/pulse. After applying powder-mixed dielectric about 20 nm reduction of R_a has been observed. However, it can be said that, although there is a significant reduction of surface roughness after adding powder in dielectric, the discharge energy is the main contributing factor determining the average surface roughness of a micro-EDMed surface. The surface roughness increases with an increase of both gap voltage and capacitance, as the discharge energy is increased.

3.2.3 Peak-to-valley surface roughness (R_{max})

Figure 13a and b show the variation of peak-to-valley roughness (R_{max}) with gap voltage and capacitance. It has been found that, both for sinking and milling micro-EDM, the values of R_{max} decreases after mixing graphite nano-powders in dielectric. The primary reason for obtaining glossy surface in powder-mixed micro-EDM lies in the reduction of R_{max} values. A surface may not be glossy, although it has lower average surface roughness if the surface has non-uniform crater distribution and variations in crater boundaries which scatter light in multiple directions making the surface dull [4, 14, 19]. However, in powder-mixed micro-EDM, due to uniform distribution of discharge energy associated with suspended powder particles, more uniform craters are formed. In addition, due to increase in spark gap and hence better flushing, no depositions of molten metal at crater boundaries are observed which keeps the border height lower. The smallest value of R_{max} (0.17 μm) was obtained in PM milling micro-EDM at 60 V, stray capacitance. This is due to the fact that, in milling micro-EDM, there is also influence of electrode scanning movement, which contribute in reducing the crater heights. Figure 14a and b illustrate the 3D surface texture of the machined surface for die-sinking micro-EDM without and with powder-mixed dielectric. Similar for milling micro-EDM is shown in Fig. 14c and d. It has been found from the AFM images that the crater heights for both

Fig. 14 AFM images of 3D surface texture using **a** die-sinking micro-EDM without powder, **b** powder-mixed sinking, **c** milling without powder and **d** powder-mixed milling micro-EDM at 60 V, stray capacitance



(a) die-sinking, without powder
(b) die-sinking, with graphite powder
(c) milling, without powder
(d) milling, with graphite powder

sinking and milling micro-EDM have been reduced significantly by the addition of graphite nano-powders to the dielectric. The maximum scale indicating crater height was 800 nm for die-sinking micro-EDM at 60 V, stray capacitance which got reduced to 400 nm using the powder-mixed dielectric. Similarly, for milling micro-EDM the maximum scale of crater height decreases from 600 to 400 nm. It has been observed that although both the scales showing the crater height is the same for powder-mixed sinking and milling micro-EDM, some deposited debris and molten metals are indicated in powder-mixed die-sinking [white peaks in Fig. 14b], which are reduced greatly in the case of milling micro-EDM due to the scanning motion of the electrode. It can be seen from Fig. 14d that the white peaks are greatly reduced on the AFM scanned surface in case of powder-mixed milling micro-EDM, which are favourable for lower R_{max} values and smoother surface.

4 Conclusions

The main objective of this study was to investigate the feasibility of improving surface characteristics of carbide in fine-finish sinking and milling micro-EDM using graphite nano-powder-mixed dielectric. The following conclusions can be drawn from this experimental investigation:

- During the fine-finish powder-mixed micro-EDM of WC–Co, addition of semi-conductive graphite nano-powder in dielectric oil provides smooth and defect-free nano-surface in both sinking and milling micro-EDM. Arising from uniform distribution of sparking among powder particles, relatively shallower craters with improved crater distribution are produced on the workpiece surface to result in smooth and glossy surface finish.
- The R_a and R_{max} decreases with increase of powder concentration up to a certain level then again increases after optimum concentration due to powder settling problem and bridging effect. The spark gap and MRR increases with increased amount of powders added in dielectric. The EWR also reduces in powder-mixed micro-EDM, but tends to increase again at higher concentration. Graphite nano-powder of concentration 0.2–0.6 g/L was found to provide lower R_a and R_{max}, lower EWR and moderately higher MRR in the powder-mixed micro-EDM of WC–Co.
- For all the concentration levels, powder-mixed milling micro-EDM was found to provide lower R_a and R_{max}, higher spark gap and lower EWR compared to powder-mixed sinking micro-EDM. The MRR becomes higher in powder-mixed sinking micro-EDM due to more surface area exposed to machining at improved machining stability.
- The powder-mixed milling micro-EDM was found to suffer from less surface defects and migration of materials compared to sinking, as scanning movement of the electrode improve the flushing conditions, can assist in some abrasive action of the powder particles in addition to reducing the capacitive effect between electrode and workpiece.
- In addition to powder characteristics and concentration, the values of R_a and R_{max} vary with discharge energy settings used in powder-mixed micro-EDM. The lowest value of R_a (38 nm) and R_{max} (0.17 μm) was achieved in powder-mixed milling micro-EDM at concentration 0.2 g/L using electrical setting of 60 V and stray capacitance.

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