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Study of the Diffusion of Carbon, Its Sources, and Effect on Finishing Micro-EDM Performance of Cemented Carbide

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Apart from the necessity of surface modification based on different applications, in most of the cases, diffusion of carbon or foreign particles on the workpiece surface during micro-electrodischarge machining (micro-EDM) is avoidable, especially in finishing micro-EDM. This study aims to investigate different sources of materials that migrate to the machined surface during fine-finishing of micro-EDM of cemented tungsten carbide (WC-Co). The machined surfaces have been examined under scanning electron microscope and energy dispersive x-ray to investigate the changes in chemical composition. It has been observed that during finishing of micro-EDM, the major source of materials' transfer to both the workpiece and electrode is the diffusion of carbon that comes from the decomposition of the hydrocarbon dielectric. In addition, materials from both workpiece and electrode transfer to each other based on machining conditions and discharge energy. The migration occurs more frequently at lower gap voltages during die-sinking with micro-EDM because of low spark gap and stationary tool electrode. Milling micro-EDM results in lower amount of carbon migration and fewer surface defects that improve the overall surface finish significantly.

Keywords carbon diffusion, materials' transfer, micro-EDM, surface defect, WC-Co

1. Introduction

Electrical discharge machining (EDM) is one of the most popular non-conventional machining processes that remove electrically conductive materials by means of rapid, repetitive spark discharges from electric pulse generators with the dielectric flowing between the tool and the workpiece. Currently, EDM is a technique widely used because of its high-precision machining ability in respect of all types of conductive materials such as hard metals, metallic alloys, composites, or even some ceramic materials, regardless of their hardness. The non-contact machining process has been endlessly evolving from a mere tools-and-dies-making process to a microscale application machining. Micro-EDM is the application of EDM on micro-field. Micro-EDM has similar characteristics as EDM except that the size of the tool, discharge energy, and movement resolutions of the axes are in micron levels. Since EDM has the ability to manufacture complicated shapes with high accuracy and process any conductive material without regard for hardness, micro-EDM has become one of the most important methods of choice for manufacturing micro-features and sub-micrometer-sized parts.

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Although EDM is essentially a material removal process, there is always some movement of materials both from workpiece and electrode to each other. During the EDM process, owing to rapid heating and cooling effects induced on workpiece and electrode, the two materials will melt, vaporize and subsequently result in materials movement (Ref 1). Moreover, pyrolysis of the hydrocarbon dielectric contributes carbon to the plasma channel and aids the process of material deposition (Ref 2, 3). As the dissolution of the electrode takes place during the process, the constituents of the electrode material may get deposited on the machined surface depending on the process parameters (Ref 4). Furthermore, the white layer and migration of materials change the composition of the base material, while rapid heating and cooling result in residual tensile stress on the machined surfaces (Ref 5). The extensive literature review indicates that a few studies have been carried out on the migration of materials during conventional EDM. Soni and Chakraverti (Ref 5) investigated the migration of materials during EDM of die-steel and reported that there is a migration of iron and chromium from the workpiece [die steel T215-Cr12] to the copper-tungsten [80/20] tool during EDM process. It has been demonstrated by Marafona (Ref 3) that there is the formation of black layer on electrode surface by migration of materials from the workpiece and dielectric fluid. However, this black layer on the tool surface was found to lower the tool electrode wear based on the machining conditions (Ref 3). Simao et al. (Ref 6) showed that the use of partially sintered electrode of WC/Co resulted in the formation of a uniform alloyed surface layer as a result of material migration, with relatively fewer micro-cracks.

Owing to the above phenomenon of migrating materials in conventional EDM, several researchers have tried to use the conventional EDM process as a surface modification technique

(Ref 7-14), which can add important and required materials by using composite electrode materials (Ref 8, 11, 13), powder-metallurgy electrodes (Ref 9), and powder-mixed dielectric (Ref 14). In powder-mixed dielectric EDM, at high temperatures of the plasma, the powder particles combine with carbon (which comes from the breakdown of the hydrocarbon dielectric) to form hard carbides on the machined surface (Ref 12, 14). Experimental investigation has also been carried out on the feasibility of depositing solid powder materials to incorporate desired properties on the workpiece by means of electrical discharges (Ref 7). However, apart from surface modification, the relocation of materials and deposition on the workpiece or electrode surface during EDM can hamper the physical and mechanical properties of the parent materials, as well as deteriorate the surface finish. In most of the cases, uncontrolled migration of materials causes surface and subsurface damage (Ref 5). At the same time, the white layer, caused by rapid heating and cooling, also results in high residual and tensile stresses, heat-affected zone, and surface cracking (Ref 15). The white layer and cracks, as they are not deep enough, may be removed using fine cutting conditions and subsequent polishing.

Although several researches have been carried out on the transfer and deposition of materials, most of the studies considered conventional EDM. None of the researchers has considered studying the diffusion of carbon and other materials onto the electrode and workpiece surface during micro-EDM, which seems to be more important. In conventional EDM, comparatively larger discharge energies are used for machining. Therefore, the amount of migrated materials is higher, and it is also difficult to control the migration of materials because of breakdown of dielectric at higher energy. In most of the cases, post-EDM processes are used to remove migrated materials from the surface, and hence to improve the performance of the product. However, unlike conventional EDM, post EDM processes are difficult to apply in the micro-features machined by micro-EDM, because of huge chance of destroying the structures. Micro-EDM requires minimization of the pulse energy supplied into the gap to obtain micro-components with high dimensional accuracy and improved surface finish. The migration of materials and deposition onto small micro-features can have a negative effect on the product performance. Therefore, investigating the ways of reducing migration and deposition of materials in microstructures during micro-EDM is of great significance, especially in the application of micro-electromechanical systems (MEMS), micro-molds, and dies.

In recent years, WC and its composites (WC-Co) are of great demand in the production of molds and dies, cutting tools, and components due to its high hardness, strength, and wear resistance over a wide range of temperatures (Ref 16). Some of these applications of WC often demand higher quality and integrity of the surface finish resulting from the EDM process. Moreover, in the production of dies and moulds using WC material by EDM, the surface finish of the cavities is reflected in the final products. Thus, the surface quality is of prime importance in the micro-EDM of WC. Moreover, it is preferable to obtain a better surface when hardened materials are machined, so that subsequent polishing can be avoided. For this reason, research has been carried out in the hope of obtaining fine surface finish in the microfeatures and final products fabricated by micro-EDM of WC. Koshy et al. (Ref 17) attempted grinding of cemented carbide with electrical spark assistance. Lee and Li (Ref 18) have studied the integrity of the machined WC surface during the EDM of WC. The correlation between EDM and surface integrity and its influence on the sliding contact response of a fine-grained WC-Co has been discussed by Llanes et al. (Ref 19). In addition, investigation has been carried out on the capability of different electrode materials to obtain improved surface in the micro-EDM of WC (Ref 20). Further investigation has been carried out on the feasibility of achieving nano-level surface finish in micro-EDM of carbide (Ref 21). To date, no study has considered investigating the diffusion and deposition of carbon or other materials, their sources, and effects on surface finish during micro-EDM of tungsten carbide.

The objective of this study is to investigate the sources of unwanted particles like carbon, understanding the mechanism of depositing particles on the workpiece and its effect on final surface finish during micro-EDM of cemented carbide. Investigation has also been carried out for the solution of this problematic phenomenon and to find the ways of achieving satisfactory surface finish by reducing the material transfer. The effect of migrated materials on the surface topography and roughness are also studied. Finally, a comparison of average surface roughness and peak-to-valley surface roughness between die-sinking and milling micro-EDM are presented to understand the effect of discharge energy and materials' migration.

2. Experimental

A multi-purpose miniature machine tool has been developed for high-precision micro-machining at the National University of Singapore (NUS), which is capable of micro-EDM, micro-turning, micro-milling, micro-grinding, and micro-ECM by changing a suitable attachment. This machine is energized by a pulse generator which can be switched to both transistor-type and RC-type. 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 the accuracy of up to sub-micron. Figure 1(a) and (b) show the schematic diagram and photograph of the setup with multi-purpose miniature machine tool. The magnified view of the micro-EDM arrangement is shown in Fig. 1(c).

The workpiece material used in this study was tungsten carbide with a composition of WC-10 wt.%Co. The tool electrode material was tungsten electrode (99% W) of 500-μm diameter. The tungsten electrode has been used for its high melting point and high wear resistance, which will help in reducing the migration of materials from electrode. 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. The important properties of workpiece, electrode, and dielectric fluid are listed in Tables 1, 2, and 3, respectively. A low-pressured side flushing system was used to avoid any tool deflection or vibration of the workpiece.

In this study, die-sinking and milling micro-EDM at a depth of 5 μm was conducted using 500-μm electrodes with negative polarity. However, to ensure smooth surface facing the workpiece, electrode has been dressed in two steps using positive electrode polarity before each machining. The electrode dressing was done as final surface finish on workpiece also depends on electrode surface in addition to machining

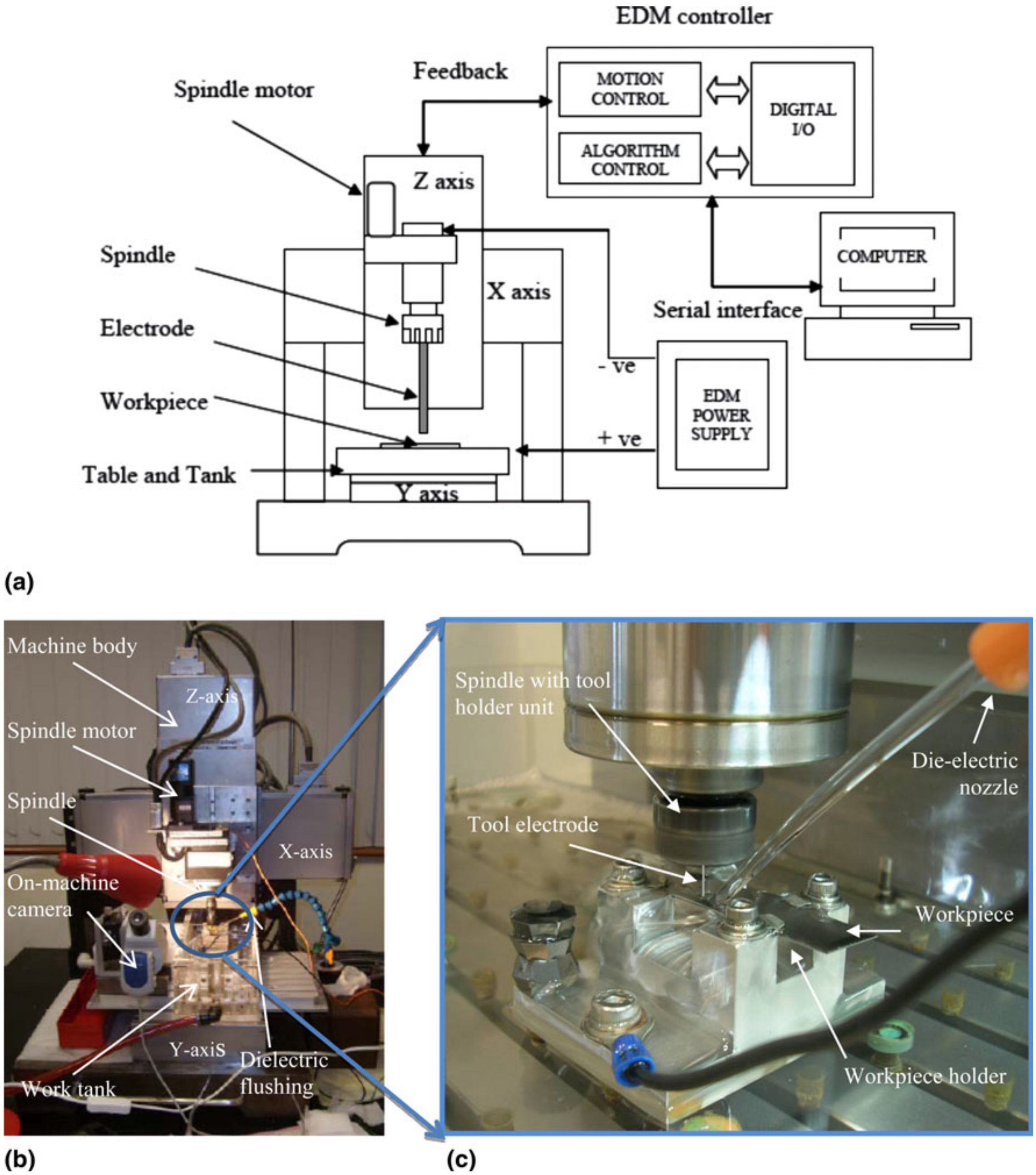

Fig. 1 (a) Schematic diagram of the setup, (b) photograph of the developed multi-purpose miniature machine tool, and (c) magnified view of the micro-EDM arrangement

Table 1 Properties of the workpiece material

Material composition, wt.%	Density, g/cm^3	Hardness, HRa	Melting point, °C	Transverse rupture strength, MPa	Compressive strength, MPa	Thermal expansion coefficient, K^{-1}
WC-10 wt.%Co, 0.6% others	14.5	92.3	2597	4000	6600	5.5×10^{-6}

Table 2 Properties of the electrode material

Material composition, wt.%	Density, g/cm^3	Melting point, °C	Relative conductivity (to silver)	Specific resistance, μΩ	Thermal expansion coefficient, K^{-1}
99.9% W	19.3	3370	14.0	56.5	4.6×10^{-6}

Table 3 Properties of the dielectric fluid

Material	Volumetric mass at 15 °C, kg/m^3	Viscosity at 20 °C, mm^2/s	Flash point Pensky-Martens, °C/°F	Auto ignition temperature, °C/°F	Aromatics content, wt.%	Distillation range, IBP/FBP, °C
EDM oil 3	813	7.0	134/259	243/470	0.01	277/322

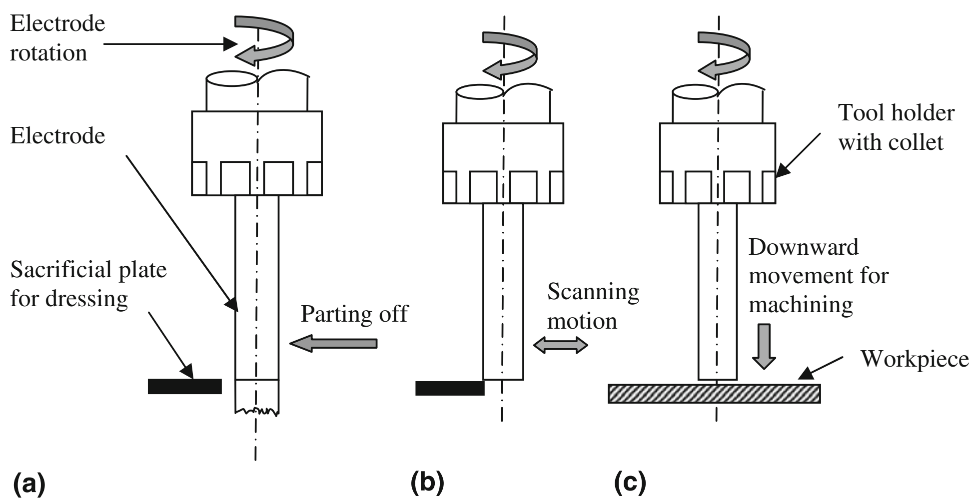

Fig. 2 Electrode dressing using plate EDM: (a) first step: slicing horizontally to remove the rough surface, (b) second step: surface finishing by scanning using very low energy, and (c) smooth surface of the electrode approaching for micro-EDM

conditions. First, 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). Second, to make the crater smaller and to smooth the surface of the electrode facing the workpiece, a finish dressing is performed by scanning micro-EDM at comparatively lower discharge energy of 0.15 μJ (80 V, 47 pF). Figure 2 shows the schematic representation of the approaches taken for electrode dressing and fine-finish micro-EDM of tungsten carbide. Figure 3 shows the optical micrograph of side and top view of electrodes before and after first step dressing. The comparison of crater sizes and smoothness after first and second step dressings is presented in Fig. 4. The machining conditions were selected for finishing micro-EDM using RC-generator where the gap voltage is varied from 60 to 120 V, and capacitance from stray C (7 pF) to 100 pF, while keeping the resistance fixed to 1 kΩ. The experimental conditions are listed in Table 4.

In order for the analysis of materials' transfer between the electrode and workpiece, the surfaces of the samples were observed and analyzed by scanning electron microscope (SEM) and energy dispersive x-ray (EDX). Moreover, to study the effect of migrated materials on surface finish, average surface roughness (R_a), and peak-to-valley roughness (R_{max}) were measured using atomic force microscope (AFM), which scans the samples over an area of 40 μm × 40 μm. A Seiko scanning probe was used for this purpose. It was observed that roughness measuring along a line in AFM analysis always gives lower R_a than that obtained by scanning the area. To get more accurate idea of the surface roughness, the average roughness of the entire scanned area was used.

3. Results and Discussion

In this study, the diffusion of carbon, its sources, as well as migration of materials from tool and workpiece has been analyzed for finishing micro-EDM using a RC-type pulse generator. The RC-type pulse generator produce lower discharge energy compared with transistor-type pulse generator and hence, more suitable in the finishing regime of micro-EDM (Ref 22, 23). There is more chance of depositing debris particles and carbon on the surface, when a transistor-type pulse generator with comparatively larger discharge energies is used in micro-EDM (Ref 16). The discharge energy in RC-type

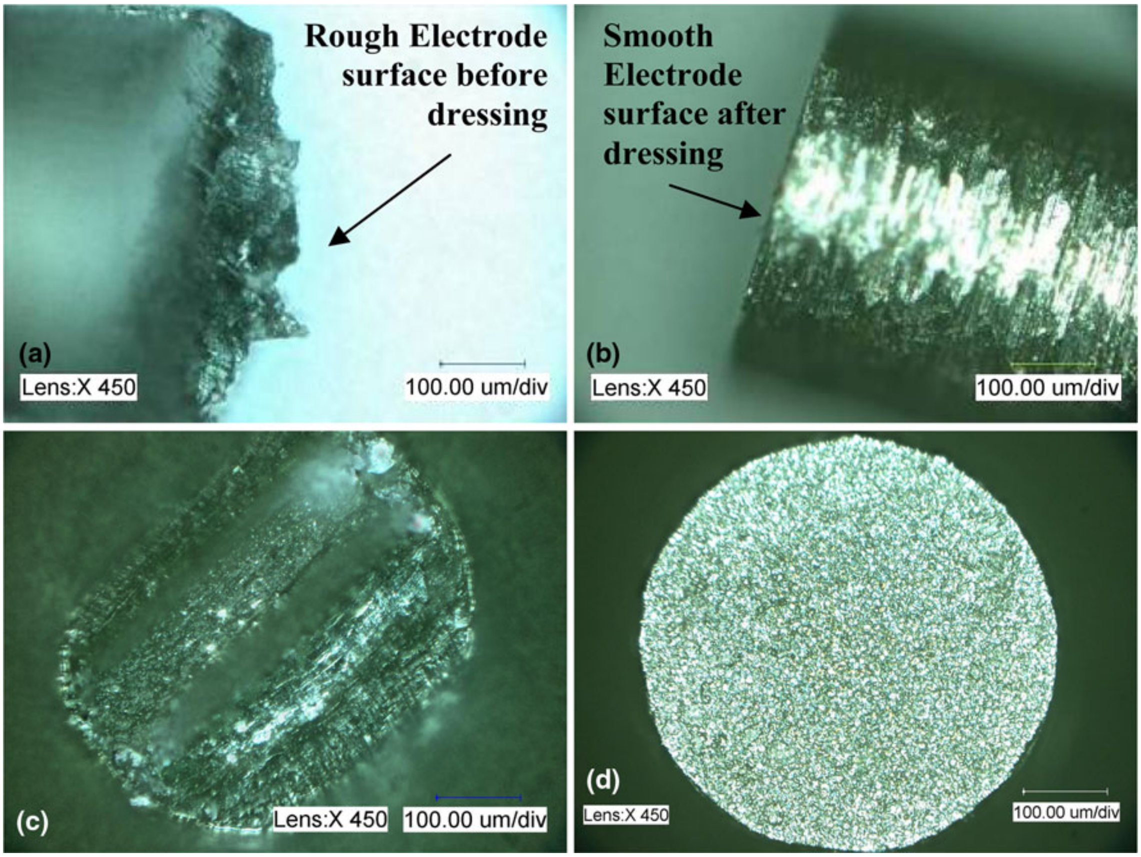

Fig. 3 Optical micrograph of the W electrode before and after first step dressing: (a) side view of electrode tip before dressing, (b) side view after dressing, (c) top view before dressing, and (d) top view of the electrode after dressing

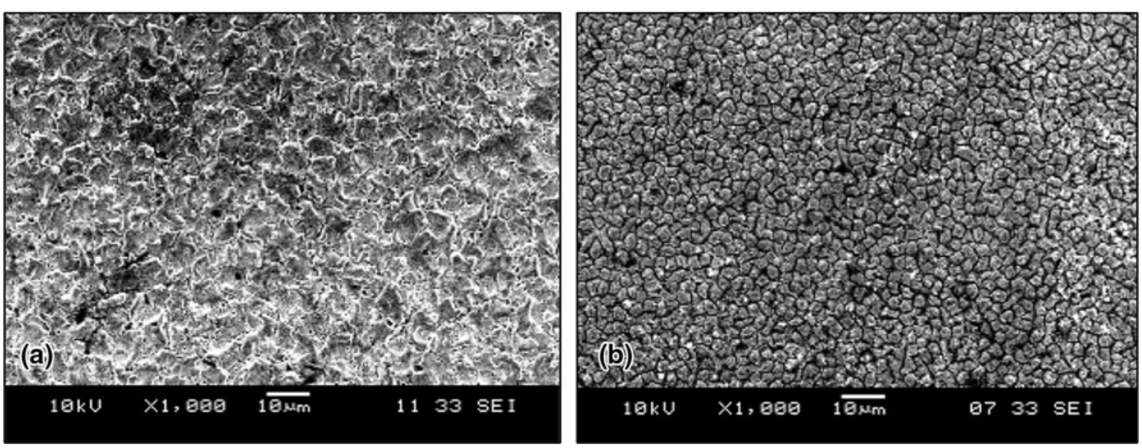

Fig. 4 Electrode surface facing the workpiece for machining: (a) higher crater size after first step dressing and (b) reduced crater size after second step dressing

micro-EDM is reduced by decreasing the values of gap voltage and capacitance, as DE in RC-type pulse generator is expressed by $(1/2)CV^2$. It has already been shown in Fig. 4 that, with the decrease of discharge energy, the crater sizes are lowered which resulted in smoother surface finish. However, it has been found that the lower surface roughness in a particular area does not necessarily indicate the improved surface topography of the entire machined area (Fig. 5), as surface topography also depends on surface and sub-surface defects and deposition of materials onto the surface during machining. During finishing micro-EDM, when the voltage is too low, the gap between tool and workpiece becomes small, as there is an intrinsic relationship between the gap voltage and spark gap (Ref 24). This lower spark gap at finishing regime, leads to improper expulsion of debris from the gap, which results in deposited and molten debris particles on the machined surface (Fig. 5). It has been observed from Fig. 5 that at constant voltage of 60 V, there is very little decrement in the migration of materials with the increase of capacitance at finishing regime. On the other hand, at stray C setting, the migration of materials greatly reduced from 60 to 80 V. Figure 5 also presents a comparison of the deposited carbons and migrated materials to the workpiece after machining at different settings of electrical parameter. The amount of diffused carbon on the surface and percentage of other migrated materials have been obtained from the EDX analysis of the surfaces machined at 60 and 80 V using stray capacitance (Fig. 6). It is seen from Fig. 6 that, the amount of migrated carbon reduced significantly when the gap voltage was set at 80 V instead of 60 V for same setting of capacitance. This is because in the finishing regime, the spark gap increases slightly with increasing gap voltage, although the total discharge energy is still lower. Therefore, the flushing of debris becomes easier at higher spark gap resulting in lesser deposition of migrated materials. Therefore, it can be said that although finishing micro-EDM requires minimization of discharge energy, it is more advantageous to reduce energy by reducing the capacitance. The gap voltage should also be decreased, but should be optimized to achieve defect-free surfaces with improved surface finish.

Table 4 Experimental conditions for micro-EDM of WC

Workpiece material	WC-10 wt.%Co
Tool electrode	Tungsten, ∅ 0.5 mm
Dielectric fluid	Total EDM 3 oil
Pulse generator type	RC-type
Voltage, V	60, 80, 100, 120
Capacitance, pF	Stray C (7 pF), 10, 47, 100
Resistance, kΩ	Fixed to 1 kΩ

It is shown from the EDX analysis (Fig. 6) that, a significant amount of carbon migrates to the workpiece, which came from the decomposition of dielectric or from dislodged debris of carbide workpiece. However, the percentage of parent materials, i.e., W and Co, decreases significantly, which will deteriorate the important properties of carbide: reduced strength and/or hardness. As the EDX analysis only represents the percentage of different materials before and after machining, the addition of one material will certainly reduce the percentage of other. For example, there are certain possibilities that, materials from tungsten tool electrode will migrate to the WC-Co workpiece during machining. However, as the amount of migrated carbon from dielectric is prominent, the EDX analysis showed the increased percentage of carbon. As a result, a decrease in the percentage of tungsten is shown in EDX analysis. However, it does not necessarily indicate that there is no migration of tungsten from electrode to workpiece. Moreover, owing to these materials' transfer from tool electrode and dielectric to the workpiece, the workpiece becomes defective by the presence of micro-cracks, micro-voids on the surface and sub-surface. Figure 7(a)-(d) shows different forms of surface defects obtained during finishing die-sinking micro-EDM. It can be seen from the figure that there are formations of micro-voids (Fig. 7a, c), micro-cracks (Fig. 7b), and micro-grooves (Fig. 7d) at different settings of machining parameters during the die-sinking micro-EDM of tungsten carbide. In addition, there may be formation of other types of surface and

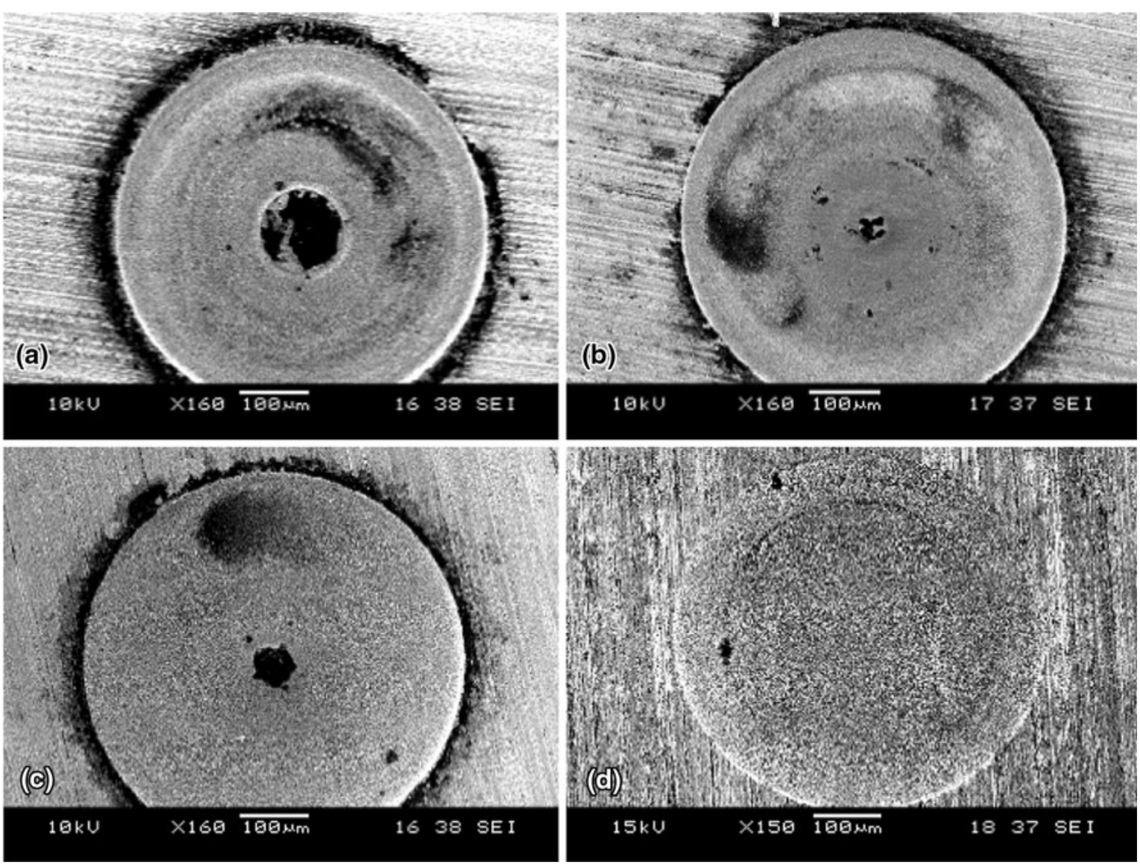

Fig. 5 Comparing the migration of materials to carbide workpiece at different levels of voltage and capacitance: (a) 60 V, stray C; (b) 60 V, 10 pF; (c) 60 V, 47 pF; and (d) 80 V, stray C

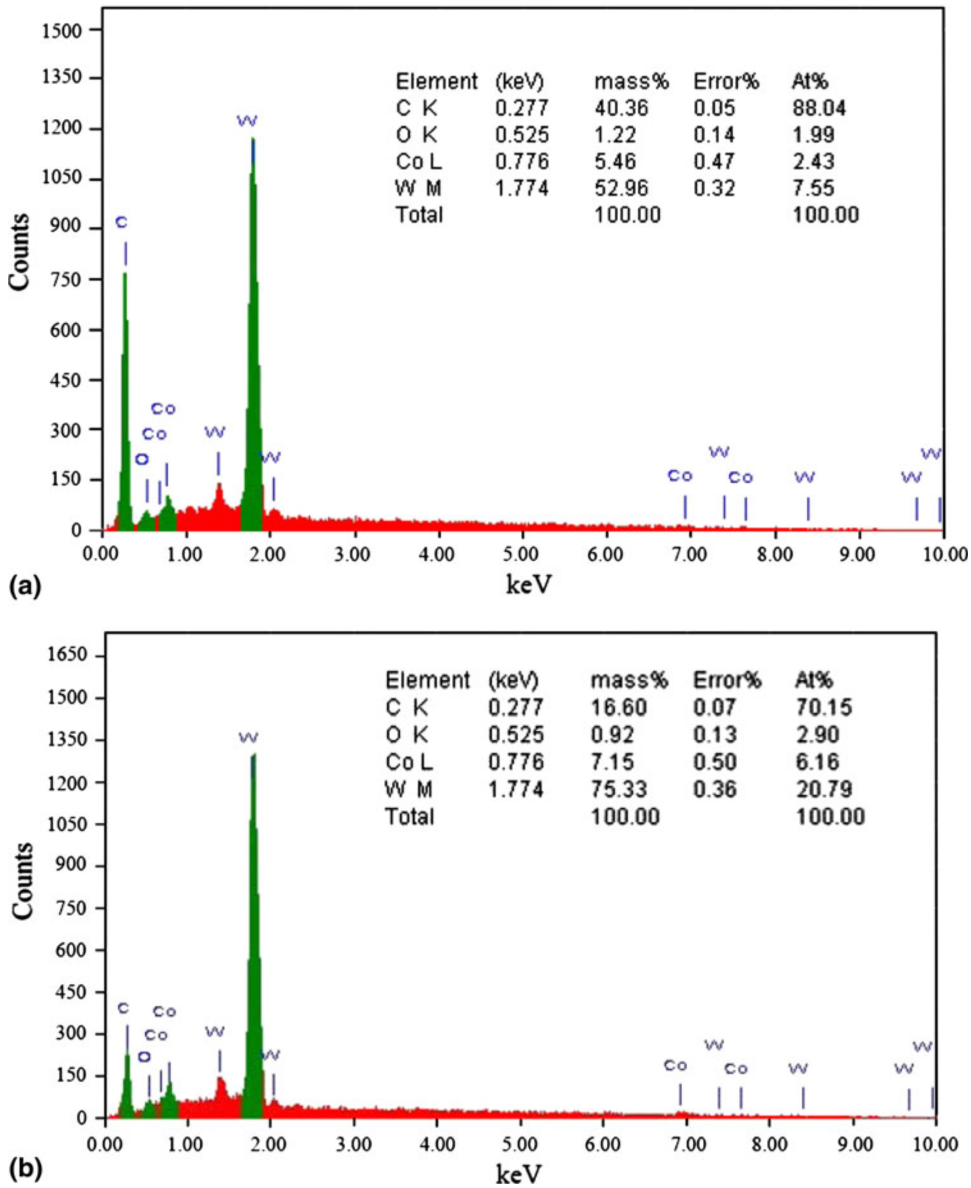

Fig. 6 EDX analysis showing the percentage of materials on the workpiece surface after machining at (a) 60 V, stray C and (b) 80 V, stray C

sub-surface defects like deposited molten materials, globules of debris, pockmarks, etc. during die-sinking (Ref 18). In addition to migrated materials, the formation of capacitance in die-sinking micro-EDM is another reason for surface defects on the workpiece. During die-sinking micro-EDM at lower spark gap, capacitance is formed between the stationary electrode and workpiece (Ref 25). This capacitance causes a rise in peak current during discharging, which eventually damages the final machined surface.

In addition to migration of materials to workpiece, materials also transfer from workpiece and dielectric to the tool electrode during fine-finish micro-EDM. It has been found that unlike the migration of materials to the workpiece, the materials transfer to the tool electrode mainly depends on the discharge energies used during machining. The migrated materials to electrode tip and black layer thickness increase with the increase of capacitance because of the increase in discharge duration and discharging current. The longer discharge duration causes increase in the duration of the decomposition of dielectric hydrocarbon. Therefore, more carbon particles are attracted by the cathode tool electrode. Figure 8 shows a comparison of electrode surface topography after the die-sinking micro-EDM of WC at two different parameters settings. The migration of carbon around the craters of tungsten electrode can be observed more clearly from Fig. 9. It has been observed from Fig. 8 and 9 that the amount of migrated materials increases with the increase of capacitance. The EDX analysis of the electrode surface also proves the migration of materials to the electrode surface. It can be seen from Fig. 10 that there is no existence of carbon material on the tungsten tool electrode before machining. However, interesting finding is that although, at lower gap voltage, there is significant amount of migrated carbons and molten electrode metals on the workpiece surface (Fig. 5), there is little migration of materials to the tool electrode surface (Fig. 8). Therefore, the migration of materials to tool electrode surface mainly depends on discharge duration used during micro-EDM.

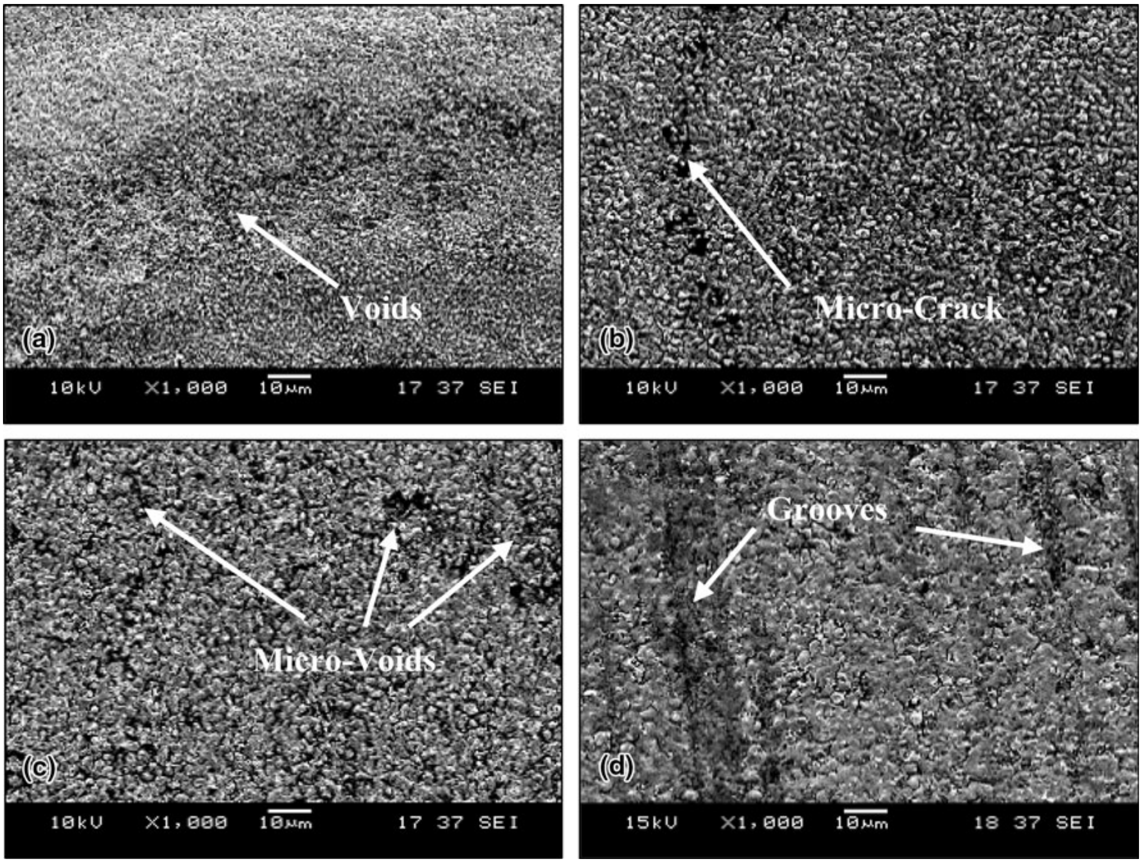

Fig. 7 Examples of surface defects on the workpiece during die-sinking micro-EDM at (a) 60 V, stray C; (b) 80 V, stray C; (c) 60 V, 47 pF; and (d) 60 V, 100 pF

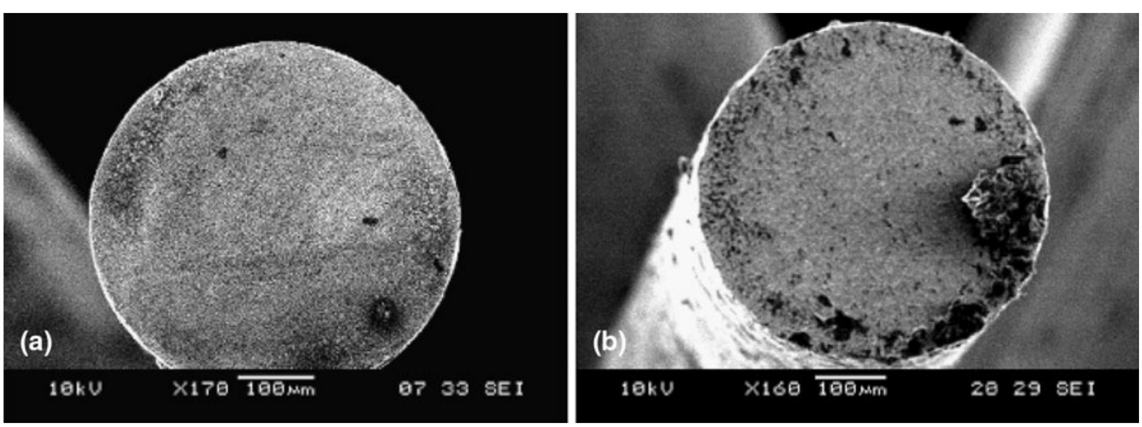

Fig. 8 Comparison of electrode surface topography after the die-sinking micro-EDM of WC at (a) 60 V, stray C and (b) 60 V, 47 pF

The migration of materials and deposition of carbon is significantly reduced during the fine-finish micro-EDM by the use of electrode movement instead of stationary electrode in die-sinking. It has been observed from Fig. 11 that unlike die-sinking micro-EDM, the milling micro-EDM suffers lower migration of materials at lower gap voltage. Although the spark gap becomes very lower at low voltage, owing to movement of electrode in milling micro-EDM, the capacitance cannot be formed at lower gap. Therefore, the discharging is more controlled and uniform. In addition, no sudden rise of peak current was observed during discharging, which was the cause for surface defect in die-sinking. Moreover, the continuous change in the spark gap due to scanning motion of electrode helps in flushing all the materials from the machined zone easily, thus reducing the amount of deposited and migrated materials. Figure 11 also represents a comparison of materials deposited to WC workpiece after die-sinking and milling micro-EDM at different settings of electrical parameters. It has been observed that compared to die-sinking, the amount of deposited materials decreased significantly at low gap voltage

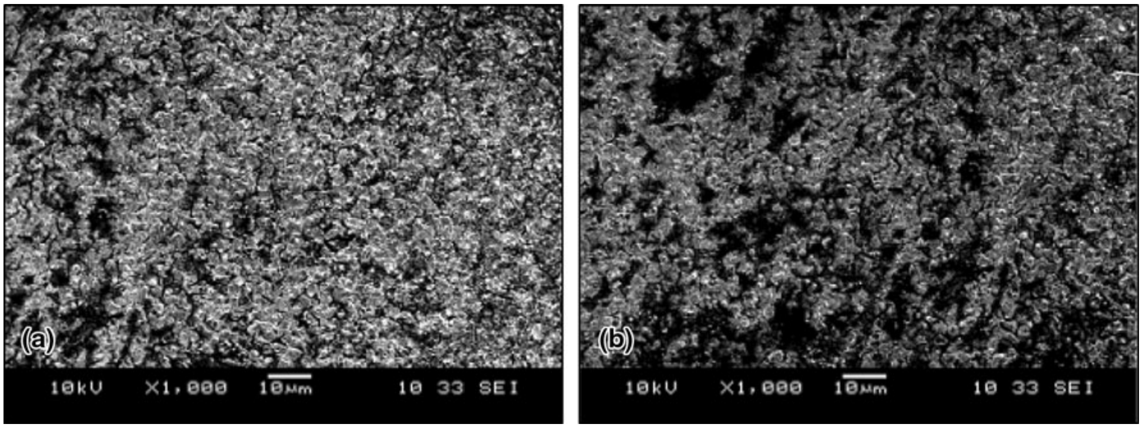

Fig. 9 Migration of carbon around the craters of the tungsten electrode after machining at (a) 60 V, stray C and (b) 60 V, 47 pF

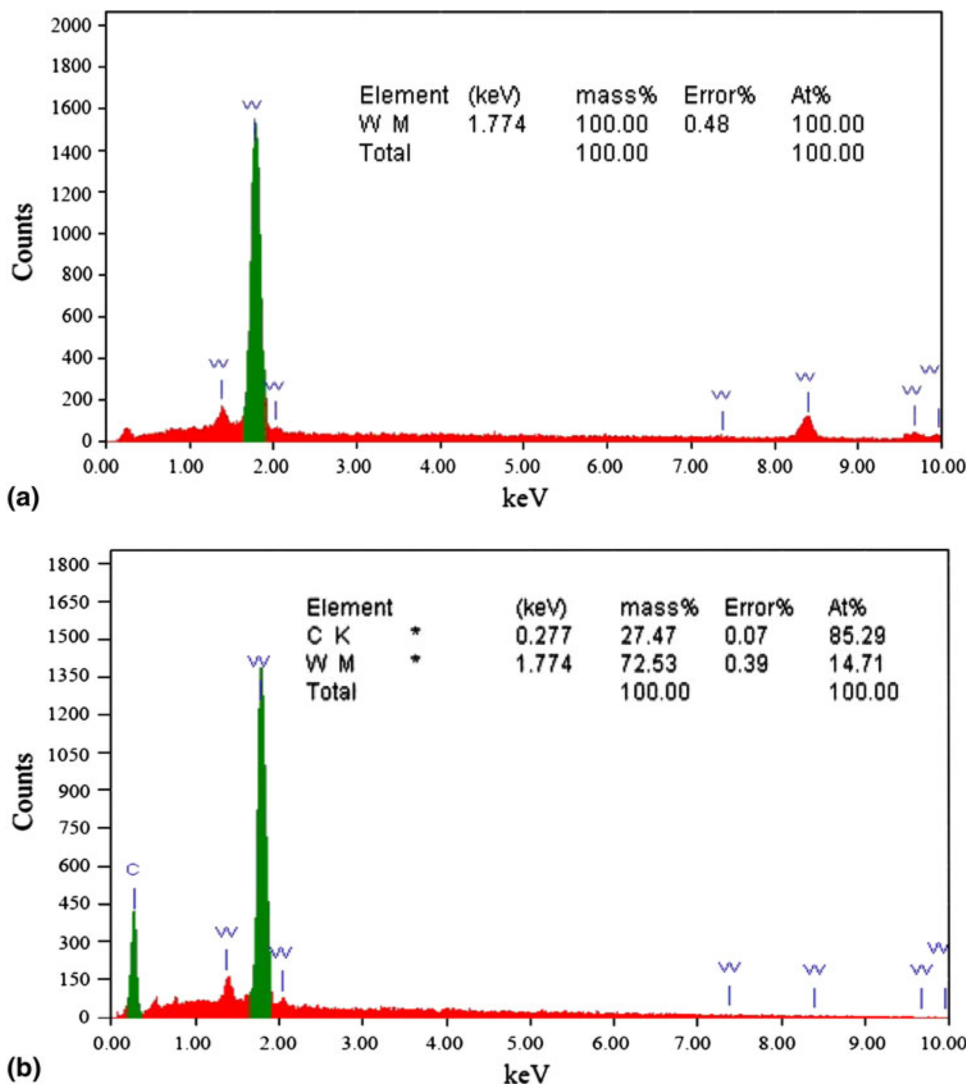

Fig. 10 Comparison of migrated materials to electrode (a) before and (b) after die-sinking micro-EDM at 60 V, stray C

in milling micro-EDM. However, there are some avoidable materials like diffused carbon on the surface, and this amount increases with the increase of discharge energy. This is because, at higher discharge energy, the plasma channel lasts longer which allows greater time for the pyrolysis/decomposition of the dielectric hydrocarbon and deposition of the dislodged carbon particles onto the machined surface (Ref 3). Similarly, the percentage of carbon on the machined surface also

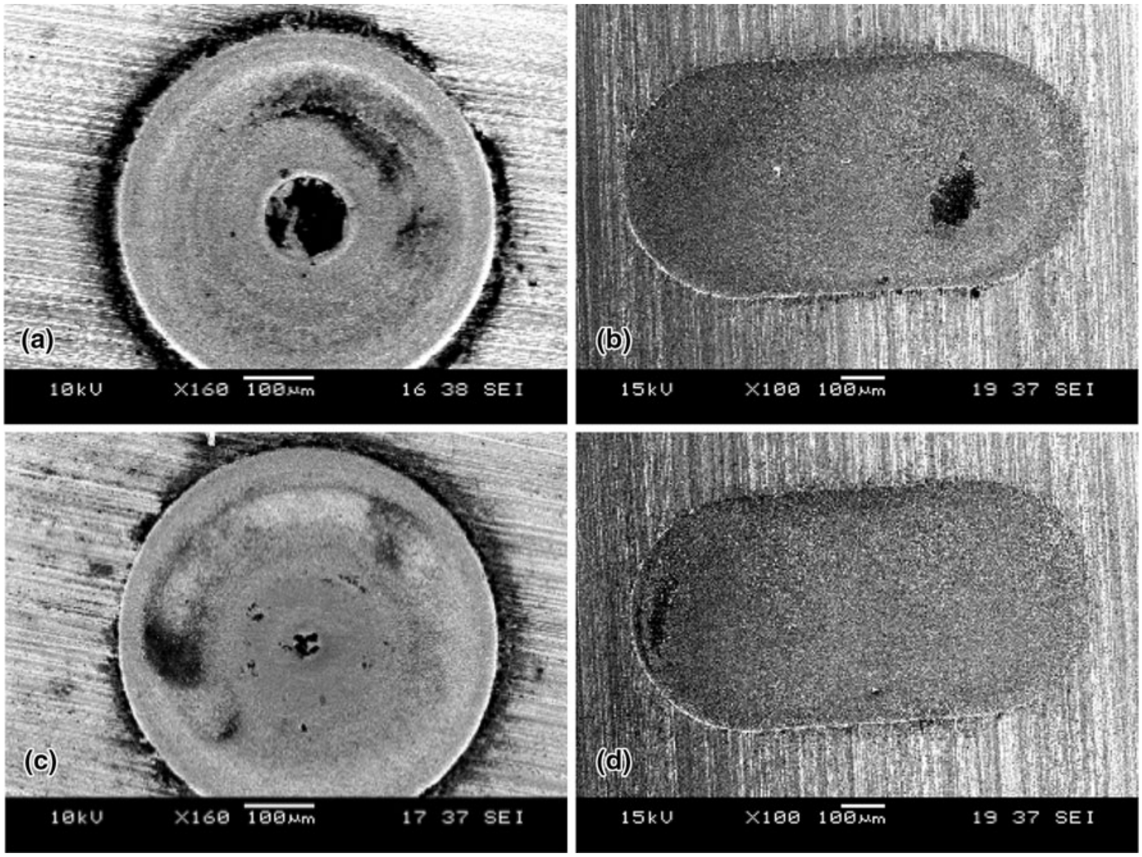

Fig. 11 Comparison of migration of materials to WC workpiece surface between die-sinking and milling micro-EDM: (a) 60 V, stray C, sinking; (b) 60 V, stray C, milling; (c) 60 V, 10 pF, sinking; and (d) 60 V, 10 pF, milling

increased with the increase of capacitance because of increase in discharging current and pulse duration. In addition to reduction of diffused carbon to the workpiece, the surface defect also reduces significantly in milling micro-EDM. Figure 12 shows a comparison of surface defects obtained in sinking and milling micro-EDM for different settings of gap voltage and capacitance. It has been observed from Fig. 12 that at the same discharge energy setting, the surface obtained in milling micro-EDM contains lesser defects compared to that of die-sinking. It can be observed from Fig. 12(a) that at 60 V, stray C setting, the surface obtained in die-sinking micro-EDM contains some micro-voids. On the other hand, at the same setting the surface obtained by milling micro-EDM is smoother and free from any surface defects (Fig. 12b). Similarly, the machined surface at 80 V, stray C obtained by die-sinking micro-EDM contains micro-cracks as shown in Fig. 12(c), whereas the surface obtained in milling micro-EDM is defect free (Fig. 12d). The percentage of migrated carbon reduces significantly in milling micro-EDM compared to sinking micro-EDM at same electrical setting of 60 V, stray C. This statement could be confirmed later from the EDX analysis. The improved performance of milling micro-EDM for the finishing operation is attributed to the inherent good flushing conditions, such as small and less contact area, effective side flushing, and simultaneous scanning and rotational movement of the electrode.

Figure 13 shows a comparison of electrode surface after die-sinking and milling micro-EDM of carbide using 60 V and stray capacitance. The comparison of migrated carbon around the craters for die-sinking and milling micro-EDM are presented in Fig. 14. It is found from Fig. 13 that compared to the electrode surface after machining in die-sinking micro-EDM, the electrode surface is smoother after milling micro-EDM. The deposited and migrated materials also reduced significantly (Fig. 13, 14). Moreover, it has been observed from Fig. 13 that although the percentage of carbon materials on tool surface reduces significantly, there are some migrations of "W" and "Co" particles at the edge of the tool surface. This has been confirmed from the EDX analysis of the electrode surface, as shown in Figure 15(b). It can be seen from Fig. 10 and 15 that, the amount of migrated carbon to the electrode materials is higher (27.47%) for die-sinking micro-EDM compared to that of milling micro-EDM (16.74%). However, there are some migrations of cobalt and oxide materials to the electrode surface during milling micro-EDM as observed from Fig. 15. This migrated "Co" material comes from the dislodged debris of workpiece, and got attached to the electrode edge during the scanning movement of electrode. The reduction of carbon on the electrode surface after milling micro-EDM is also understood from Fig. 14(b).

Finally, comparative studies of the achieved average surface roughness (R_a) and peak-to-valley heights of craters (R_{max}) in die-sinking and milling micro-EDM at different settings of voltage and capacitance are presented in Fig. 16 and 17. It has been found that milling micro-EDM provides lower R_a and R_{max} compared with die-sinking at lower settings of voltage and capacitance. It is seen from Fig. 16 and 17 that the reduction of surface roughness in milling micro-EDM is

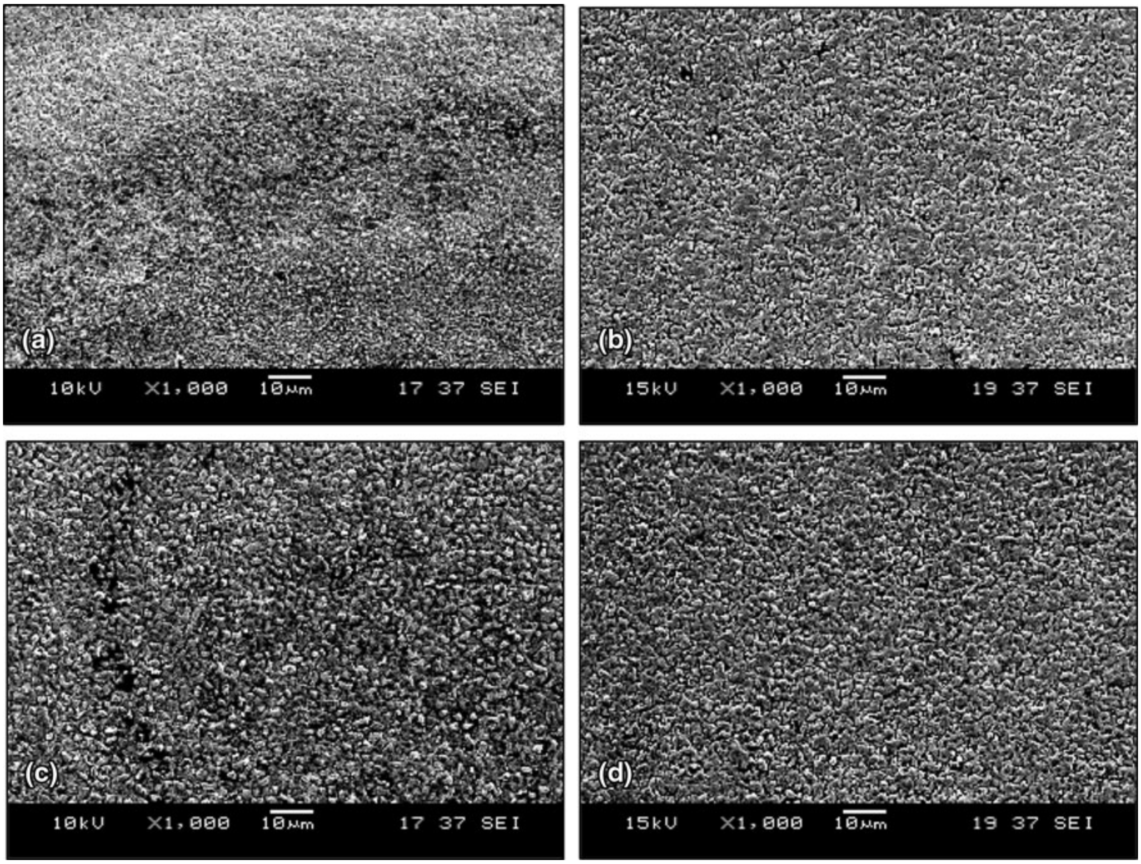

Fig. 12 Comparison of surface defects obtained in sinking and milling micro-EDM: (a) 60 V, stray C, sinking; (b) 60 V, stray C, milling; (c) 80 V, stray C, sinking; and (d) 80 V, stray C, milling micro-EDM

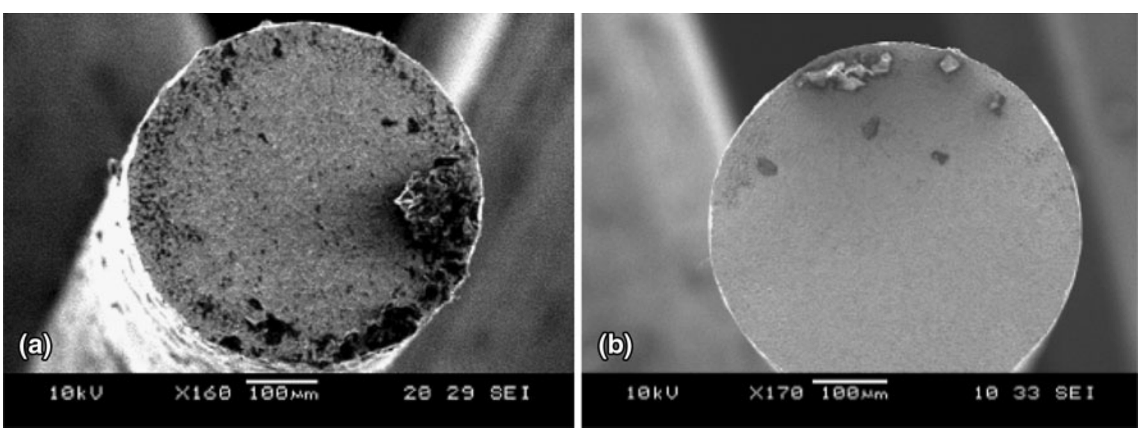

Fig. 13 Comparison of electrode surface topography after machining at 60 V, stray C for (a) die-sinking; and (b) milling micro-EDM

more pronounced at low settings of gap voltages, as the migrated materials decreased significantly because of tool scanning movement. Another important observation from Fig. 17(a) is that the $R_{\max}$ values are higher for 60 and 80 V at 100 pF than those obtained at other gap voltages at same capacitance, although the discharge energies are lower at these settings. This is because at low gap voltage and higher capacitance, the migration of materials to workpiece is very high due to the combined effect of lower spark gap and longer pulse duration. Finally, the reduction in migrated materials in milling micro-EDM contributes significantly in improving the surface roughness and topography. Therefore, it can be concluded that milling micro-EDM is more suitable for finish machining at lower settings of gap voltage and capacitance. However, for rough machining using higher gap voltage and capacitance die-sinking micro-EDM may provide lower roughness, as the spark gap is higher. Owing to higher spark gap, the number of short circuits and arcing reduces as well as the flushing of debris particles improves, which reduces the overall migration of materials.

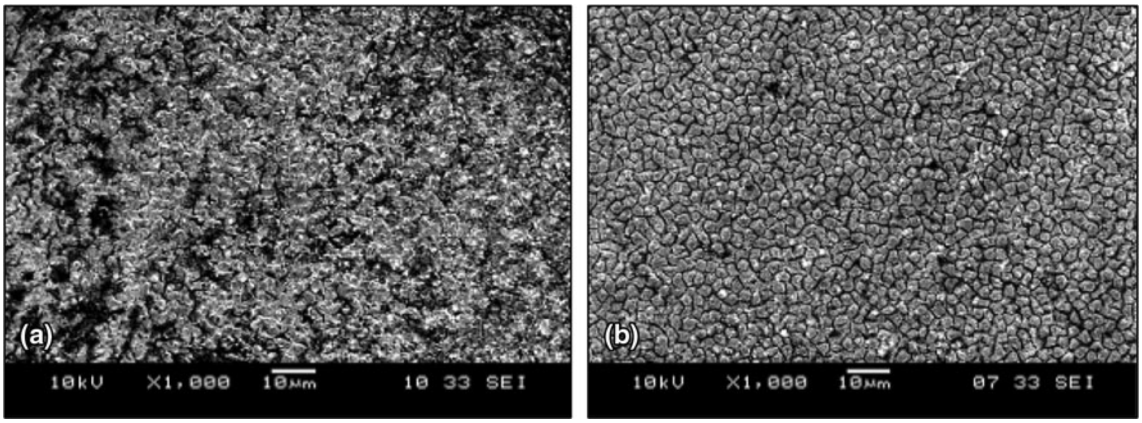

Fig. 14 Migration of carbon around the craters on the electrode surface after machining at 60 V, stray C for (a) die-sinking; and (b) milling

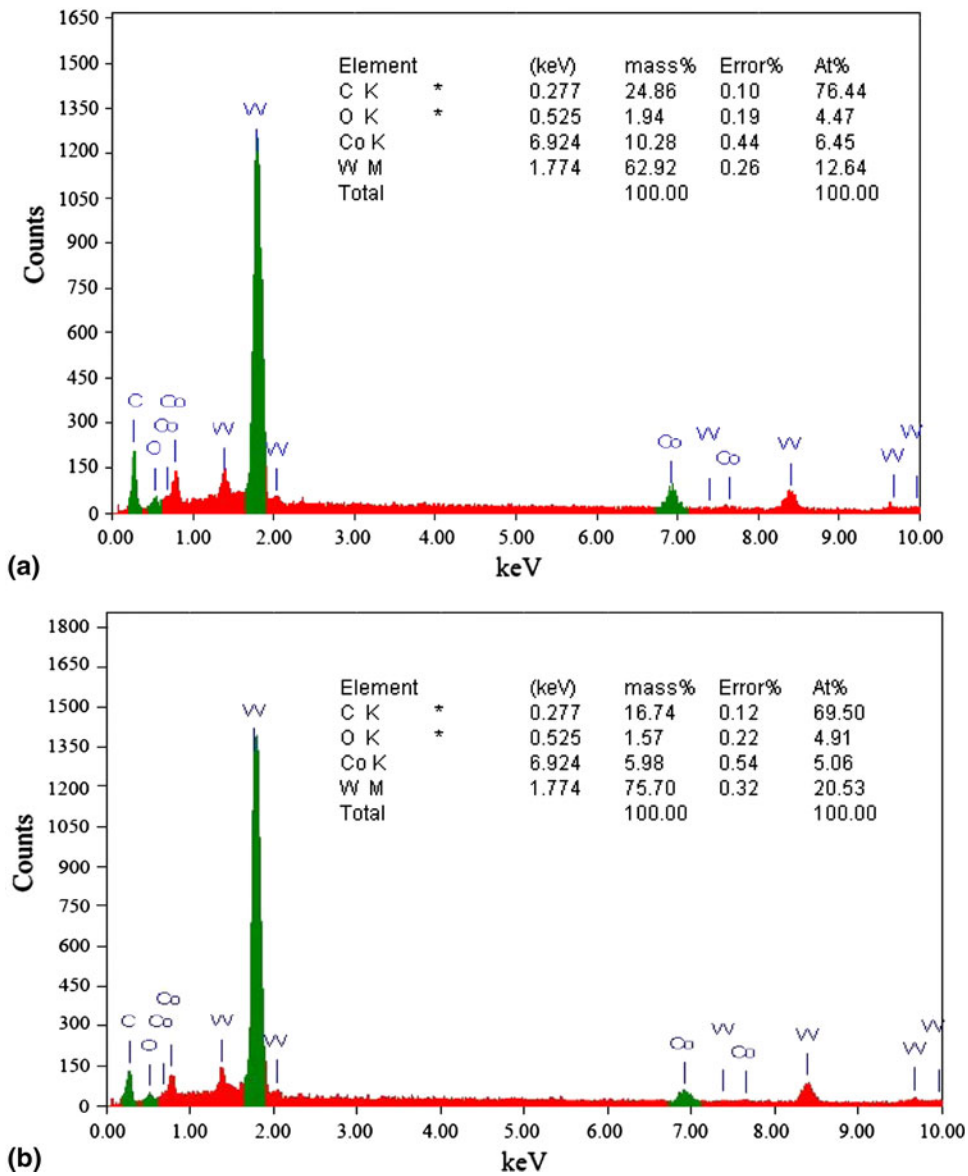

Fig. 15 EDX analysis showing amount of migrated materials after milling micro-EDM at 60 V, stray C into the (a) WC workpiece; and (b) W electrode surface

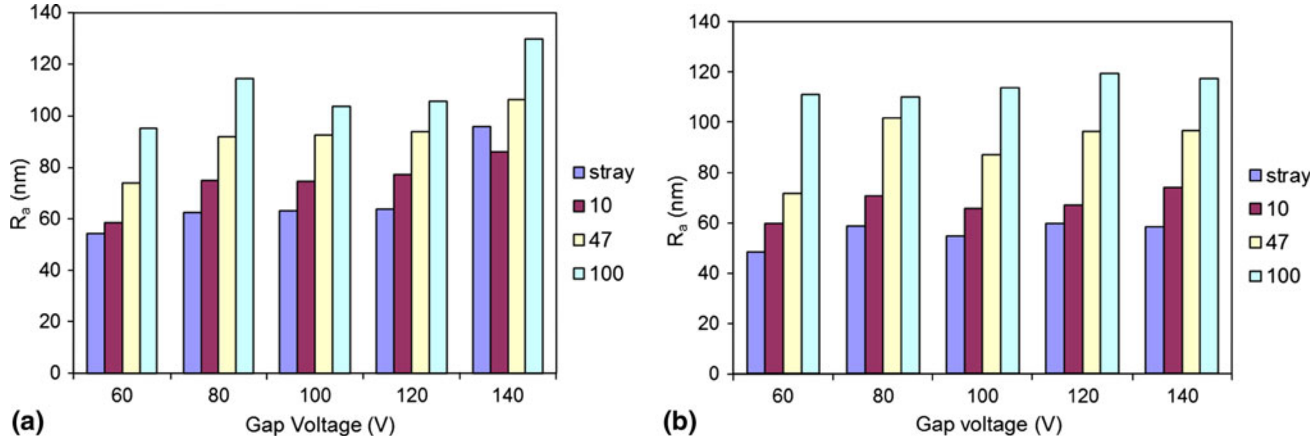

Fig. 16 Comparison of average surface roughness of the carbide workpiece during (a) die-sinking and (b) milling micro-EDM

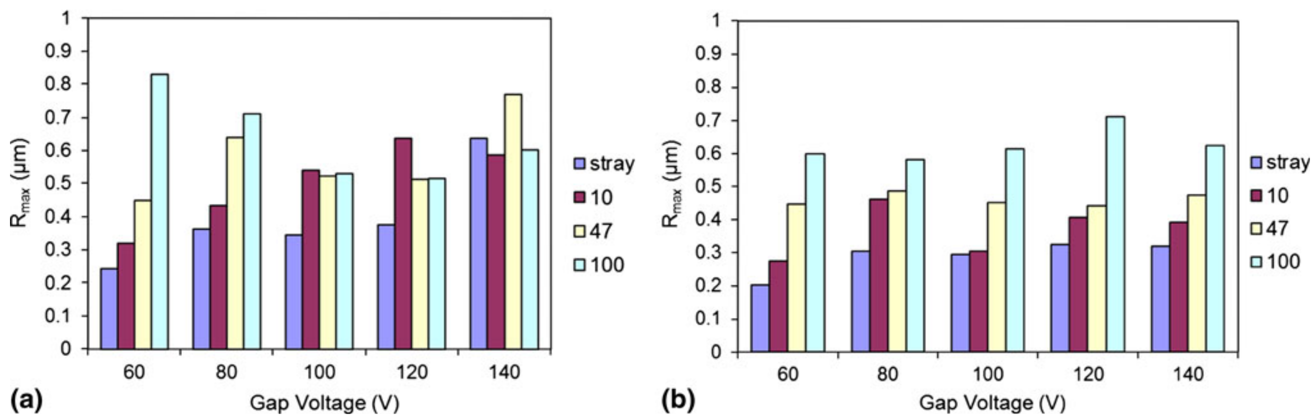

Fig. 17 Comparison of peak-to-valley surface roughness of the carbide workpiece during (a) die-sinking and (b) milling micro-EDM

4. Conclusions

From the above study, it has been concluded that a significant amount of carbon diffuses from the dielectric oil to the workpiece and electrode. The movement of carbon occurs more frequently at low gap voltages during die-sinking micro-EDM because of stationary tool electrode. The intensity of carbon diffusion and migration of particles from either electrode or workpiece increases further if the capacitance is increased keeping the voltage constant. These diffused carbons once deposited on the surface can make the surface faulty in addition to generating surface and sub-surface defects.

The present study also investigated the ways of reducing the migration of carbon and other materials, thus reducing the surface defects into the finished product. It has been concluded that, for reducing diffusion and deposition of carbon onto the workpiece in finishing die-sinking micro-EDM, the discharge energy should be minimized by reducing the capacitance and keeping the gap voltage at moderately low setting for maintaining enough spark gap, so that better flushing can takes place. Low setting of gap voltage can be used more effectively in fine-finish milling micro-EDM, as there is less migration of diffused carbon due to the scanning movement of the tool and better flushing conditions, although the spark gap remain same as in die-sinking.

Finally, this study compared the process of materials migration; sources and effect on surface roughness for two different processes of die and mold fabrication: sinking and milling micro-EDM. It has been concluded that the machined surface defects reduced significantly in finish milling micro-EDM and the surface becomes smoother because of low migrated carbon. Owing to reduction of migrated carbon and improved flushing conditions, the lowest R_a and R_{max} were obtained in milling micro-EDM and were 48 nm and 0.2 μm, respectively, during finish machining at 60 V, stray C setting.

References

1. B.H. Yan, H.C. Tsai, and F.Y. Huang, The Effect in EDM of a Dielectric of a Urea Solution in Water on Modifying Surface of Titanium, *Int. J. Mach. Tools Manuf.*, 2005, **45**(2), p 194–200
2. B.N. Lahiri, S.K. Mukherjee, and B.K. Mullick, Loss of Energy in Pyrolysis of Dielectric in EDM Process, *J. Inst. Eng. (India)*, 1981, **62**, p 66–69
3. J. Marafona, Black Layer Characterisation and Electrode Wear Ratio in Electrical Discharge Machining (EDM), *J. Mater. Process. Technol.*, 2007, **184**(1–3), p 27–31
4. S. Kumar and T.P. Singh, Improving the Surface Properties of OHNS Die Steel Using EDM Process, *Manuf. Technol. Today*, 2006, **5**(6), p 7–11

5. J.S. Soni and G. Chakraverti, Experimental Investigation on Migration of Material during EDM of Die Steel (T215 Cr12), *J. Mater. Process. Technol.*, 1996, **56**(1–4), p 439–451
6. J. Simao, H.G. Lee, D.K. Aspinwall, R.C. Dewes, and E.M. Aspinwall, Workpiece Surface Modification Using Electrical Discharge Machining, *Int. J. Mach. Tools Manuf.*, 2003, **43**(2), p 121–128
7. P. Topală, L. Slătineanu, O. Dodun, M. Coteată, and N. Pınzaru, Electrospark Deposition by Using Powder Materials, *Mater. Manuf. Process.*, 2010, **25**(9), p 932–938
8. Y.F. Chen, H.M. Chow, Y.C. Lin, and C.T. Lin, Surface Modification Using Semi-Sintered Electrodes on Electrical Discharge Machining, *Int. J. Adv. Manuf. Technol.*, 2008, **36**(5–6), p 490–500
9. A. Gangadhar, M.S. Shunmugam, and P.K. Philip, Surface Modification in Electrodischarge Processing with Powder Compact Tool Electrode, *Wear*, 1991, **143**(1), p 45–55
10. T. Miyazaki, S. Yoshioka, T. Kimura, and N. Kinoshita, Surface Modification of Steel by a Small Diameter Plasma Arc, *Ann. CIRP*, 1995, **44**(1), p 161–164
11. N. Mohri, N. Saito, and Y. Tsunekawa, Metal Surface Modification by Electrical Discharge Machining with Composite Electrodes, *Ann. CIRP*, 1993, **42**(1), p 219–222
12. S. Kumar, R. Singh, T.P. Singh, and B.L. Sethi, Surface Modification by Electrical Discharge Machining: A Review, *J. Mater. Process. Technol.*, 2009, **209**(8), p 3675–3687
13. J. Marafona and C. Wykes, A New Method of Optimising Material Removal Rate Using EDM with Copper-Tungsten Electrodes, *Int. J. Mach. Tools Manuf.*, 2000, **40**(2), p 153–164
14. K. Furutani, A. Saneto, H. Takezawa, N. Mohri, and H. Miyake, Accretion of Titanium Carbide by Electrical Discharge Machining with Powder Suspended in Working Fluid, *Precis. Eng.*, 2001, **25**(2), p 138–144
15. F. Roethel, L. Kosec, and V. Garbajs, Contribution to the Micro-Analysis of the Spark Eroded Surfaces, *Ann. CIRP*, 1976, **25**(1), p 135–140
16. R.A. Mahdavinejad and A. Mahdavinejad, ED Machining of WC-Co, *J. Mater. Process. Technol.*, 2005, **162–163**, p 637–643
17. P. Koshy, V.K. Jain, and G.K. Lal, Grinding of Cemented Carbide with Electrical Spark Assistance, *J. Mater. Process. Technol.*, 1997, **72**(1), p 61–68
18. S.H. Lee and X.P. Li, Study of the Surface Integrity of the Machined Workpiece in the EDM of Tungsten Carbide, *J. Mater. Process. Technol.*, 2003, **139**(1–3), p 315–321
19. L. Llanes, E. Idanez, E. Martinez, B. Casas, and J. Esteve, Influence of Electrical Discharge Machining on the Sliding Contact Response of Cemented Carbides, *Int. J. Refract. Met. Hard Mater.*, 2001, **19**(1), p 35–40
20. M.P. Jahan, Y.S. Wong, and M. Rahman, A Study on the Fine-Finish Die-Sinking Micro-EDM of Tungsten Carbide Using Different Electrode Materials, *J. Mater. Process. Technol.*, 2009, **209**(8), p 3956–3967
21. M.P. Jahan, M.M. Anwar, Y.S. Wong, and M. Rahman, Nanofinishing of Hard Materials Using Micro-EDM, *Proc. IMechE Part B: J. Eng. Manuf.*, 2009, **223**(9), p 1127–1142
22. M.P. Jahan, Y.S. Wong, and M. Rahman, A Comparative Study of Transistor and RC Pulse Generators for Micro-EDM of Tungsten Carbide, *Int. J. Precis. Eng. Manuf.*, 2008, **9**(4), p 3–10
23. M.P. Jahan, Y.S. Wong, and M. Rahman, A Study on the Quality Micro-Hole Machining of Tungsten Carbide by Micro-EDM Process Using Transistor and RC-Type Pulse Generator, *J. Mater. Process. Technol.*, 2009, **209**(4), p 1706–1716
24. F.L. Amorim and W.L. Weingaertner, The Influence of Generator Actuation Mode and Process Parameters on the Performance of Finish EDM of Tool Steel, *J. Mater. Process. Technol.*, 2005, **166**(3), p 411–416
25. P. Bleys, J.P. Kruth, B. Lauwers, B. Schacht, V. Balasubramanian, L. Froyen, and J.V. Humbeeck, Surface and Sub-Surface Quality of Steel After EDM, *Adv. Eng. Mater.*, 2006, **8**(1–2), p 15–25