Surface Characteristics of Tool Steel Machined Using Micro-EDM

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High-speed tool steels are extensively used in tooling industries for manufacturing cutting tools, forming tools, and rolls. Electrical discharge machining (EDM) has been found to be an effective process for machining these extremely hard and difficult-to-cut materials. Extensive research has been conducted to identify the optimum machining parameters for EDM with different tool steels. This paper presents a fundamental study of the surface characteristics of SKH-51 tool steel machined by micro-EDM, with particular focus on obtaining a better surface finish. An RC pulse generator was used to obtain a better surface finish as it produces fine discharge craters. The main operating parameters studied were the gap voltage and the capacitance while the resistance and other gap control parameters were kept constant. A negative tungsten electrode was used in this study. The micro-EDM performance was analyzed by atomic force microscopy to determine the average surface roughness and the distance between the highest peak and lowest valley. The topography of the machined surface was observed using a scanning electron microscope and a digital optical microscope.

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NOMENCLATURE

P-V = distance between the highest peak and lowest valley
R_a = average surface roughness

1. Introduction

In electrical discharge machining (EDM), an electric pulse generator creates a series of short electrical discharges between the tool and the workpiece to remove materials in the presence of a dielectric fluid, which flushes away eroded particles.[1] Micro-EDM is similar to EDM except that the size of the tool, discharge energy, and movement resolution of the axes are at the micron level.[2]

EDM technology has been used extensively in the tool, die, and mold making industries, which require tool steels with high precision and good surface finish. Conventional machining cannot work economically with these difficult-to-cut materials.[3] Amorim and Weingaertner conducted experiments on AISI P200 tool steel to analyze the material removal rate, volumetric relative wear, and workpiece surface roughness as functions of the discharge current, discharge duration, pulse interval time, gap voltage, electrode polarity, and generator mode.[4] Singh *et al.* carried out experiments on EN31 tool steel with different electrodes, and reported the effects of pulsed current on the material removal rate, overcut, electrode wear, and surface roughness.[3] Guu worked with AISI D2 tool steel to analyze the surface roughness (R_a) achieved by varying the pulse current and pulse duration.[5] There have been similar experimental investigations of the surface roughness of different tool steels using EDM technology. SKH-51 tool steel has high wear resistance compared to conventional mold materials for processing thermoplastic, thermosetting, or glass-fiber resins. Unlike molds made from conventional products, SKH-51 molds can be used several times. This reduces mold maintenance, and the difference in total cost becomes significant when small parts are fabricated.[6]

However, for micro slots and micro molds in tool steels, the optimum parameters for surface roughness using micro-EDM have not been completely investigated. Moreover, most of the work with EDM has been conducted using transistor pulse generators.

The aim of this paper is to determine the optimum micro-EDM parameters for generating a good surface finish on SKH-51 tool steel using a relaxation (RC) pulse generator.

2. Experimental Setup

2.1 Machine Tool

A multipurpose miniature machine tool developed at the National University of Singapore[7] was used to investigate micro-EDM of SKH-51 tool steel. By changing attachments, this single machine tool can be used for micro-EDM, micro-electrochemical machining (micro-ECM), micro turning, micro milling, and micro grinding. There is also a provision to switch between RC and transistor pulse generators; an RC pulse generator was used for this experiment. The maximum travel range of the machine tool in the *x*-, *y*-, and *z*-directions are 210, 110, and 110 mm, respectively, with a resolution of 0.1 μm.

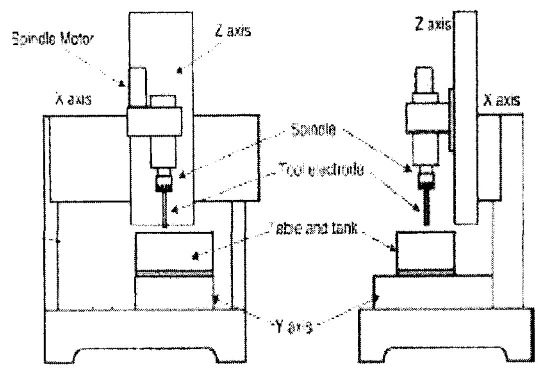


Fig. 1 Block diagram of the multi-purpose miniature machine tool used for micro-EDM

2.2 Workpiece Material

SKH-51 tool steel was used as the workpiece material in this experiment. The workpiece was ground and milled to 42 mm long, 12.5 mm wide, and 3 mm high. Table 1 shows the chemical composition, and Table 2 shows the heat treatment properties and hardness of SKH-51 tool steel.

Table 1 Chemical composition of SKH-51 tool steel

Workpiece Material	Chemical Composition (%)						
SKH 51	C	Si	Mn	Cr	Mo	W	V
	0.80 to 0.90	0.40 max	0.40 max	3.80 to 4.50	4.50 to 5.50	5.50 to 6.70	1.60 to 2.20

Table 2 Heat treatment and hardness of SKH-51 tool steel

Heat Treatment (°C)				Hardness	
Annealing Temp	Hardening Temp	Quenching Medium	Tempering Temp	Annealed HB	Tempered HRC
800 to 880	1160 to 1220	Oil, Salt	540 to 570	255 max	62 min

2.3 Tool Electrode Material

Tungsten rods, 0.500 mm in diameter, were used as the tool electrode in this study. Electrodes with high melting point exhibits little change in its shape after EDM.[8] Small diameter electrodes shift the crack critical line upwards and thus results in enlarged no-crack zone. This allows adopting a wider choice of machining parameters.[9] These two criteria predominated in case of choosing the type and size of electrode materials for performing micro-EDM. Habib et al. fabricated copper electrodes with complex cross sectional shape in localized electrochemical deposition method.[10] However the application of LECD in case of tungsten electrodes needs to be investigated. The properties of tungsten are given in Table 3.

Table 3 Tool electrode properties

Material	Tungsten
Composition	99.9% W
Density	19.3 g/cm^3
Melting point	3370°C
Conductivity (relative to silver)	14.0
Specific resistance	56.5 μΩ
Thermal expansion coefficient	4.6×10^{-6} K^{-1}

2.4 Dielectric

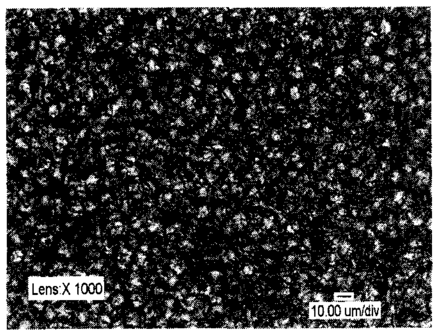
This is a clear mineral oil with good resistance to oxidation; it has a very low aromatic content and a high flash point, low volatility, and a low pour point, which makes outside storage possible. It also has a sufficiently low viscosity so that metal chips can be evacuated easily. The properties of EDM 3 are shown in Table 4.

Table 4 Properties of EDM 3 dielectric fluid

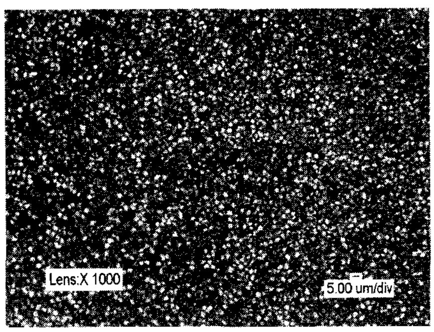
Appearance	transparent
Volumetric mass at 15°C	813 kg/m^3
Saybolt color	+30
Viscosity at 20°C	7.0 mm^2/s
Pensky-Martens flash point	134°C
Aromatic content	0.01% wt
Distillation range, IBP/FBP	277/322°C

3. Experimental Method

A negative-polarity electrode was selected for the micro-EDM of SKH-51 tool steel. Three sets of experiments were conducted using capacitors of 10, 47, and 100 pf, and in each set, four voltage levels were selected: 80, 100, 120, and 140 V. The resistance was fixed at 1 kΩ and the electrode was dressed in two steps before the experiment at each voltage. Since the electrode surface is very rough after it is cut from the bulk, a 0.15-mm thick stainless steel strip was used as a negative polarity tool to perform plate EDM on the rough surface and slice out the rough part. A capacitance of 2200 pf and a voltage of 120 V were used in this process. Since the energy was very high, it resulted in larger craters on the surface of electrode. To make the craters smaller, scan EDM was performed with the same polarity and same tool, but with a capacitance of 47 pf and a voltage of 100 V. Figure 2 shows Keyence images of the dressed electrode.



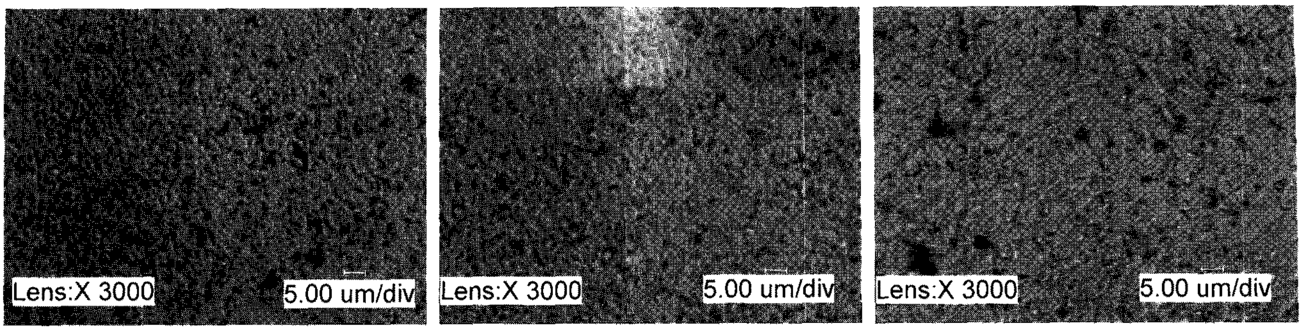
(a) after plate EDM



(b) after scan EDM

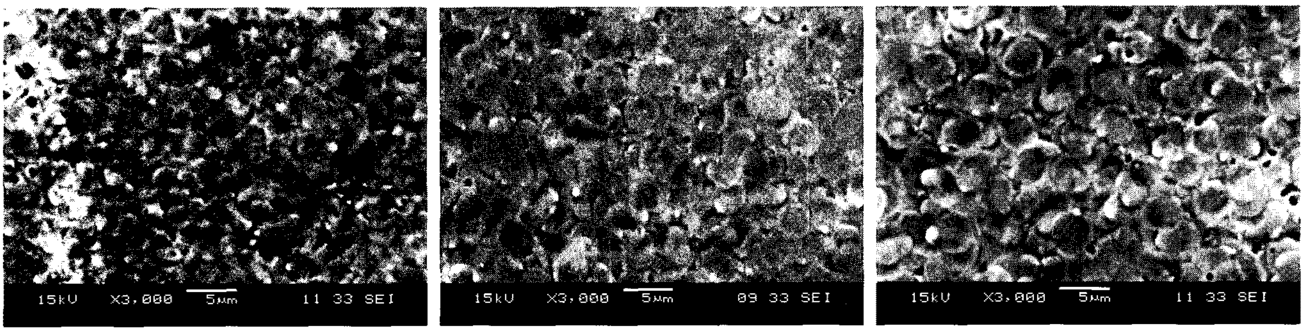
Fig. 2 Keyence image of electrode surface after dressing

For the experiment, die-sinking EDM at a depth of 5 μm was conducted on the surface of SKH-51 tool steel using a tungsten electrode with various parameters. The surface roughness and the distance between the highest peak and lowest valley (P-V) were



(a) 10 pf (b) 47 pf (c) 100pf

Fig. 3 Keyence images of the machined surface using 120 V



(a) 10 pf (b) 47 pf (c) 100pf

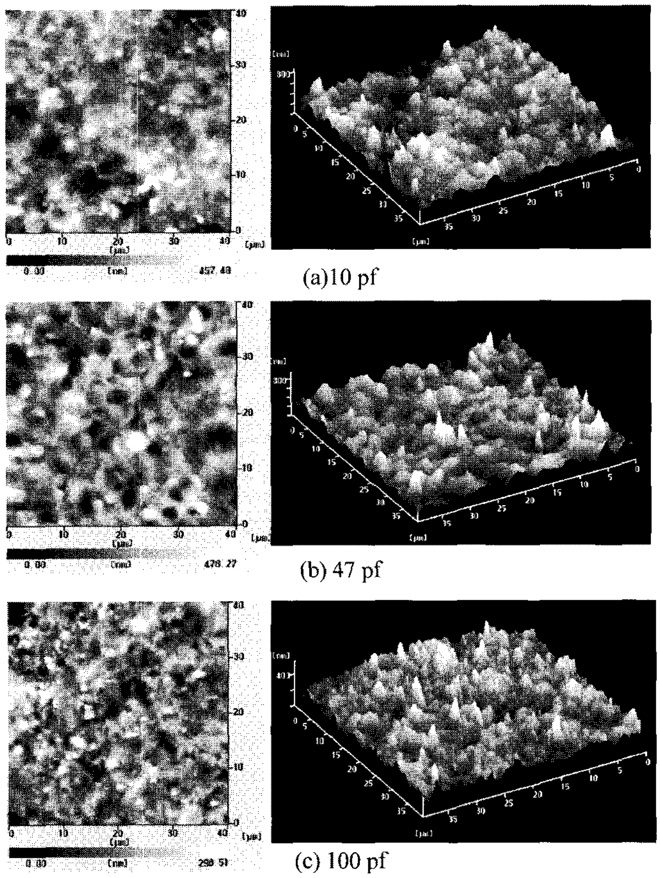
Fig. 4 SEM images of the machined surface using 120 V

measured using atomic force microscopy (AFM) (scanning probe microscope, Seiko Instruments, Japan) to scan samples in an area of 40 × 40 μm. The sample surfaces were observed with a digital microscope (model VHZ-600 with VH-Z450 lens, Keyence) at a magnification of 3000×. To obtain a better image of the surface, some of the samples were also analyzed using a scanning electron microscope (SEM) (JSM-5500, Jeol Ltd., Japan) at a magnification of 3000×.

4. Results and Discussion

4.1 Surface Topography

In EDM applications, an RC pulse generator produces low discharge energy with a short pulse duration, which results in a small unit of removal per discharge and small craters on the surface.[11] The maximum discharge energy per pulse that can be obtained from an RC circuit is $(1/2)CE^2$, where C is the capacitance and E is the gap voltage.[12] Low values of voltage and capacitance are required for fine finishing since a low discharge energy results in smaller craters and better surface finish. Figure 3 shows the distribution of craters using 120 V and different capacitances. It is clear that an increased voltage resulted in larger craters. A setting of 120 V and 100 pf gave larger craters while a setting of 120 V and 10 pf produced smaller craters. The variation in crater size can be clearly seen in Fig. 4. The SEM images show that 100 pf and 120 V produced larger craters than 10 pf and 120 V. In RC circuit the electrical energy in every discharge is theoretically constant, so it is assumed that uniform volume is removed under this condition.[13, 14] However, practically, in the RC circuit, the discharge energy across the gap between the tool and the workpiece was not uniform. The capacitor stores electrical energy, but as soon as the dielectric breaks down, it discharges the charge stored in the capacitor.[15] Therefore if the dielectric breakdown occurs before the capacitor is fully charged, the energy discharge will vary somewhat and it will not be the maximum possible. For this reason, a lower capacitance gives smaller craters, but the craters may not be uniform. However, if a higher capacitance is used and dielectric breakdown occurs frequently after the capacitor is fully charged, then it is more likely that the craters will be larger but more uniform. This may be the reason that the setting of 100 pf and 120 V gave a more uniform distribution of craters than a setting of 47 pf and 120 V.



(a)10 pf

(b) 47 pf

(c) 100 pf

Fig. 5 AFM images of the machined surface using 120 V

4.2 Surface Roughness

The R_a and P-V were selected as the parameters to be studied to understand the effect of capacitance and voltage on the surface of the workpiece material. In this study, AFM was used to calculate the surface roughness from topographic data obtained by scanning an area of 40 × 40 μm. Figure 5 shows AFM images of the surface profile along with three-dimensional profiles obtained at 120 V using three different capacitors. It is clear that an increase in capacitance resulted in an increase in the difference between the crater heights. For a setting of 10 pf and 120 V, the maximum difference between the heights of the craters was 298.54 nm, while for a setting of 100 pf and 120 V, the height difference was 478.27 nm. Therefore, it is clear that a larger capacitance rating produced a greater maximum crater height. However a setting of 100 pf and 120 V generated a more uniform distribution of craters. Therefore there are two crater parameters, depth and size. For the setting of 10 pf and 120 V, the crater depths were not too deep but their size varied, while for 100 pf and 120 V, the craters were deeper and larger, but uniformly distributed.

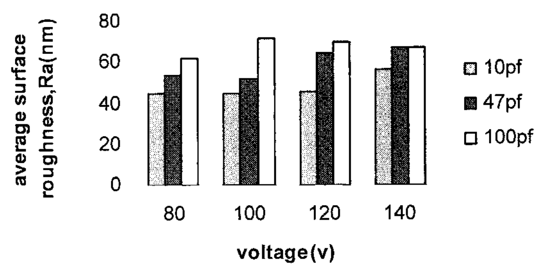
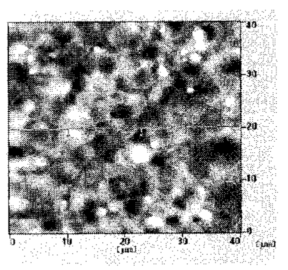
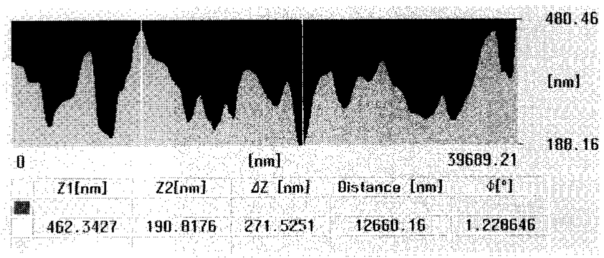


Fig. 6 Variation of surface roughness as a function of the gap voltage and capacitance

Figure 6 shows the surface roughness of the machined surface. For a fixed voltage, an increase in capacitance increased the surface roughness. This implies that a smaller capacitance will generate a better surface finish for a given voltage. However, at 10 pf and 47 pf, the surface roughness increased with an increase in voltage, while for 100 pf, a voltage of 100 V produced the greatest surface roughness. This may be attributed to the fact that at a setting of 100 pf and 100 V, the dielectric breakdown occurs after the capacitor is fully charged. Therefore, it is able to discharge the maximum energy across the gap. As the maximum energy discharges more frequently for this setting, it results in a greater surface roughness.



(a) Surface profile



(b) Cross-section profile

Fig. 7 Peak-to-valley distance along a line drawn on the surface profile for 100 pf and 120 V

A horizontal line was drawn across the surface generated by AFM, from which the P-V was measured to be 275.2 nm. Figure 7 shows that the P-V taken along the cross-section agreed with the result obtained directly using AFM. Using the same process, a line was drawn across the surface profile of other capacitance-voltage settings, and the results are shown in Fig. 8. The P-V variation can be divided into two categories, as the results for 80 and 100 V were different than for 120 and 140 V, independent of the capacitance. The P-V increased with an increase in capacitance when the voltage was kept constant at 80 or 100 V. However, for 120 or 140 V, the P-V increased when the capacitance increased from 10 to 47 pf but decreased when the capacitance was increased further from 47 to 100 pf. This implies that the variation in the discharge energy is higher for capacitance-voltage settings of 47 pf and 120 V, and 47 pf and 140 V.

For 80 and 100 V, an increase in capacitance resulted in an increase in the P-V. Therefore for lower voltage values, an increase in capacitance and voltage resulted in a higher P-V. This implies that at lower voltage levels (80–100 V), the P-V increases with the increase in maximum discharge energy that can be obtained at the capacitance-voltage setting.

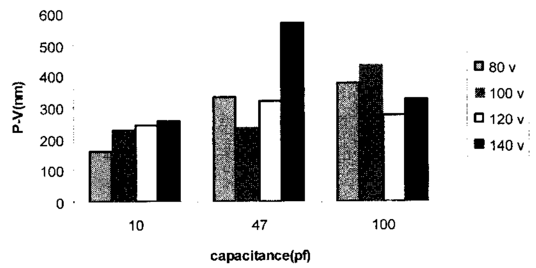


Fig. 8 Variation of distance between the highest peak and lowest valley with gap voltage and capacitance

5. Conclusions

The aim of this study was to determine the optimum parameters that give the best possible surface finish using an RC circuit, and also to discuss the advantages and limitations of micro-EDM using RC circuits. The following conclusions can be drawn from the study.

1. When the gap voltage was fixed, the surface roughness increased with an increase in capacitance.

2. There was a variation in the discharge energy across the gap between the tool and the workpiece when using an RC circuit. The discharge energy depended on the dielectric breakdown of the capacitor. When the dielectric breakdown occurred, the capacitor discharged the energy stored in it, and this was dependent on the flushing conditions, presence of debris, and servo control. Therefore, it was difficult to obtain a uniform surface finish since the capacitor discharges energy randomly depending on the dielectric breakdown. However, since a very short pulse duration could be achieved using an RC circuit, it was useful for fine finishing operations.

3. A higher but more uniform discharge energy produced deeper craters of uniform size on the surface of the workpiece. A lower but more random discharge energy produced shallower craters whose sizes varied.

4. A minimum surface roughness of 44.78 nm was obtained using a setting of 10 pf and 80 V. A maximum surface roughness of 71.68 nm was obtained using a setting of 100 pf and 100 V. Guu obtained a surface roughness in the range 103–172 nm for EDM of AISI D2 tool steel by varying the pulse current and

pulse on-time duration using a pulse generator.[5]

5. The P-V was 158.9 nm for a setting of 10 pf and 80 V, and 566.3 nm for a setting of 47 pf and 140V. Guu reported a P-V in the range 1272–1873 nm for AISI D2 tool steel using a pulse generator.[5]

6. The SEM and AFM images showed that a setting of 100 pf and 120 V generated a uniform surface finish.

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