A Comparative Study of Transistor and RC Pulse Generators for Micro-EDM of Tungsten Carbide

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Micro-electrical discharge machining (micro-EDM) is an effective method for machining all types of conductive materials regardless of hardness. Since micro-EDM is an electro-thermal process, the energy supplied by the pulse generator is an important factor in determining the effectiveness of the process. In this study, an investigation was conducted on the micro-EDM of tungsten carbide (WC) to compare the performance of transistor and resistance/capacitance (RC) pulse generators in obtaining the best quality micro-hole. The performance was measured by the machining time, material removal rate, relative tool wear ratio, surface quality, and dimensional accuracy. The RC generator was more suited for minimizing the pulse energy, which is a requirement for fabricating micro-parts. The smaller-sized debris formed by the low-discharge energy of RC micro-EDM could be easily flushed away from the machined zone, resulting in a surface free of burrs and resolidified molten metal. The RC generator also required much less time to obtain the same quality micro-hole in WC. Therefore, RC generators are better suited for fabricating micro-structures, producing good surface quality and better dimensional accuracy than the transistor generators, despite their higher relative tool wear ratio.

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1. Introduction

The growing trends towards miniaturization of machined parts, developments in the area of microelectromechanical systems, and requirements for micro-features in difficult-to-cut materials have made micro-electrical discharge machining (micro-EDM) an important and cost-effective manufacturing process. EDM is a well-established method for manufacturing geometrically complex or hard material parts that are extremely difficult to machine by conventional machining processes. This non-contact machining process has evolved from a mere tool-and-die making process to micro-scale application machining. Micro-EDM is the application of EDM on a very small scale using low energy. Since micro-EDM has the ability to manufacture complicated shapes with high accuracy and can process any conductive material without regard for hardness, it has become one of the most important methods for manufacturing micro-features and sub-micrometer-sized parts.[1]

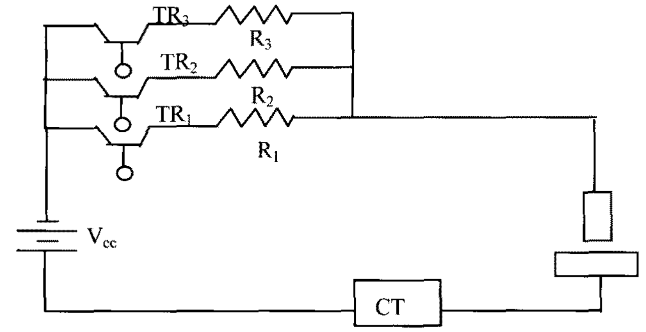
Tungsten carbide (WC) and its composites (*e.g.*, WC-Co) are important in the production of cutting tools, dies, and other special tools and components due to their hardness, strength, and wear resistance over a wide range of temperatures.[2] Although WC is difficult to machine using conventional processes, it can be formed in different complex shapes by the micro-EDM process. Therefore, extensive research has been carried out on the micro-EDM of WC and its application to micro-features. Pandey et al.[3] studied the effects of pulse parameters and carbide composition on the material removal rate (MRR), relative electrode wear, and the shape and size of the craters produced. The influence of intensity, pulse time, and duty cycle on the surface quality of WC-Co material, as well as the MRR and electrode wear, have also been studied.[4] Mahdavinejad et al.[2] investigated the process instability and its causes in the EDM of WC-Co composites, and introduced a way of controlling it. Yan et al.[5] examined micro-hole machining of carbide with a copper electrode tool to show the effects of polarity, tool electrode shape, and rotational speed. Micro-holes are the most basic machined features in micro-machining, and are found in many industrial applications such as fuel injection nozzles, spinneret holes, and biomedical filters, and are standard defects for testing material.[1,6,7]

Although there has been some interest in the EDM of WC, extensive research on the micro-EDM of WC using a resistance/capacitance (RC) pulse generator is still scarce. Transistor pulse generators have been used in most cases to supply the discharge energy as this works well for conventional EDM.[8] In micro-EDM, however, the fabrication of micro-parts requires minimizing the pulse energy supplied into the gap, and the performance of micro-EDM is directly related to the discharge energy. Since an RC pulse generator can produce a very small amount of energy compared to a transistor generator, some study of micro-EDM of WC using an RC pulse generator is required, focusing on the production of quality micro-holes.

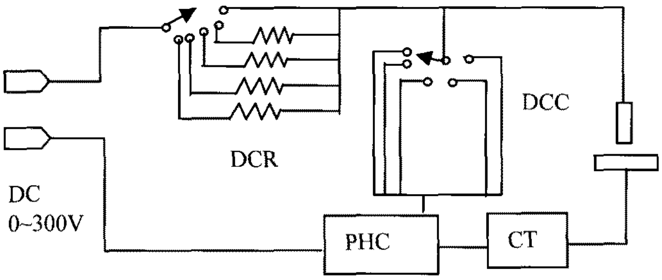
We conducted investigations to obtain quality micro-holes in WC with good surface finish, better dimensional accuracy, and improved circularity using both transistor and RC pulse generators. This study compares the performance of the two types of generator.

2. Overview of conventional transistor and RC pulse generators

The pulse generator is the most important part of the EDM setup as it supplies the electrical energy required for the EDM operation. Transistor and RC pulse generators are used widely in EDM.

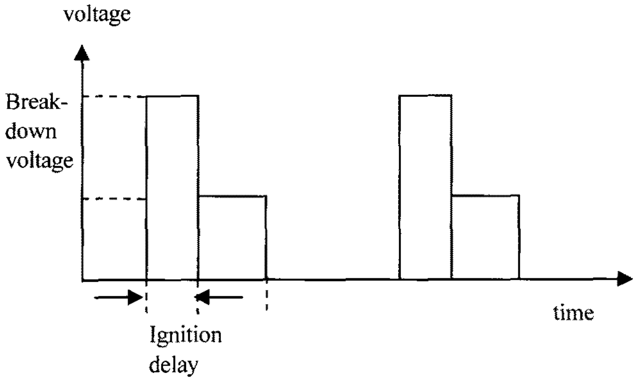


(a) transistor generator

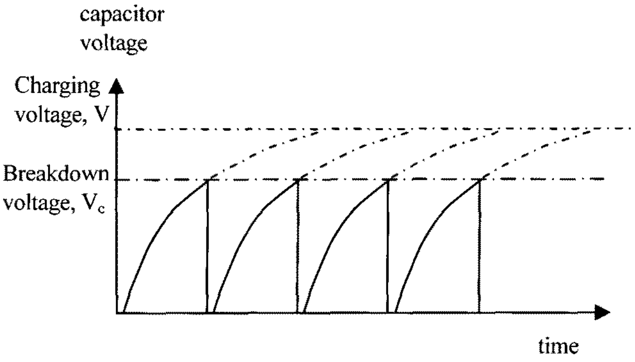


(b) RC generator

Fig. 1 Schematic diagrams of the pulse generators examined in this study



(a) transistor generator

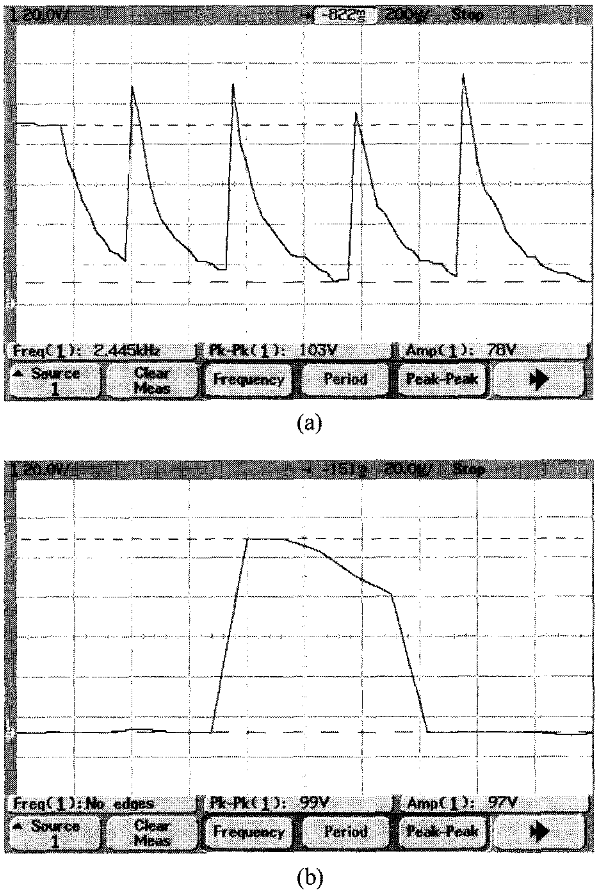


(b) RC generator

Fig. 2 Typical voltage–time characteristic curves[9]

The transistor pulse generator is widely used in conventional EDM and provides a higher MRR due to its high discharge energy. Moreover, the pulse duration and discharge current can be arbitrarily changed depending on the required machining characteristics.[10] Micro-EDM is becoming increasingly important due to the growing demand for very small components. The fabrication of parts smaller than several micrometers requires the minimization of the pulse energy supplied into the gap between the workpiece and the electrode. This means that using micro-EDM for finishing requires a pulse duration of several dozen nanoseconds. Since an RC pulse generator can generate such a small discharge energy simply by minimizing the capacitance in the circuit, it is more suitable for micro-EDM.

Figure 1 shows schematic representations of the transistor and RC pulse generators examined in this study. The main components of a transistor pulse generator are the gate drive circuit consisting of several transistors (TR) and current limiting resistors (R) as well as a current transducer (CT). The main components of an RC generator are the discharge control resistors (DCR), the discharge control capacitors (DCC), the peak hold circuit (PHC), and the CT. Figure 2 shows the typical voltage–time characteristic curves for transistor and RC pulse generators. Figures 3 and 4 show the spark patterns and an analysis of a single spark in transistor and RC generators, respectively. There is a difference between the typical characteristic curves and the oscilloscope signals because the actual signal may change according to the machining characteristics during the micro-EDM process.

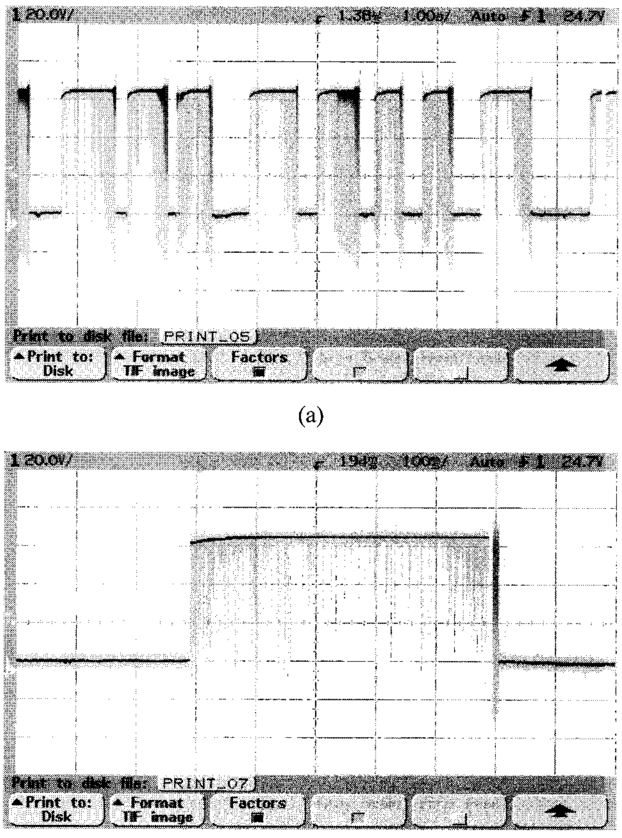


(a)

(b)

Fig. 3 (a) Spark patterns and (b) analysis of a single spark in a transistor pulse generator

The RC or relaxation pulse generator was the first type used for EDM, and it is still used in finishing and micro-machining because the more conventional transistor generators do not produce a constant-energy pulse that is sufficiently short.[10] If a transistor pulse generator is used in micro-EDM, it requires at least several tens of nanoseconds for the discharge current to diminish to zero after detecting the occurrence of the discharge because the electric circuit for detecting the discharge, the circuit for generating the signal to switch off the power transistor, and the power transistor itself have a certain delay. Hence it is difficult to achieve a constant discharge duration shorter than several tens of nanoseconds using a transistor pulse generator.[10] This is also the reason why the micro-EDM process becomes unstable when the discharge energy is significantly reduced in a transistor pulse generator. The discharge energy in an RC generator can be significantly reduced and short iso-duration pulses can be generated by decreasing the capacitance to a very small value.[6]



(a)

(b)

Fig. 4 (a) Spark patterns and (b) analysis of a single spark in an RC pulse generator

3. Experimental details

3.1 Experimental setup

A multi-purpose miniature machine tool developed for high-precision micro-machining at the National University of Singapore (NUS)[11] was used for the micro-EDM of WC experiments. Either a transistor or an RC pulse generator may be used with this machine by a simple switch selection.

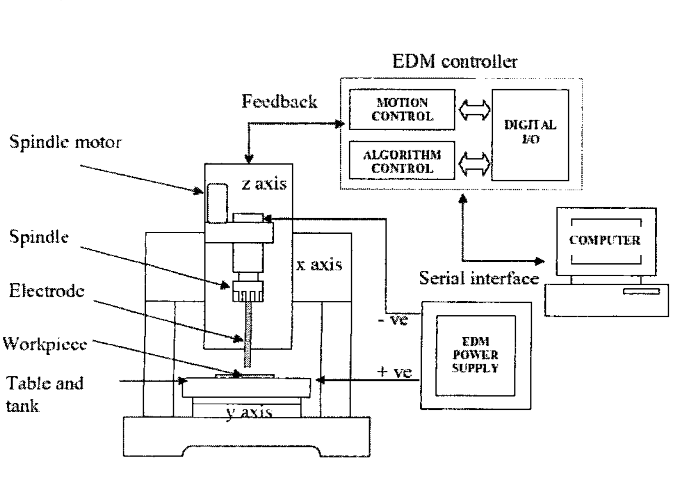


Fig. 5 Schematic diagram of the multipurpose miniature machine tool

The machine is capable of micro-EDM, micro-turning, micro-milling, micro-grinding, and micro-electrochemical machining by the use of suitable attachments. The maximum travel range of the machine is 210 mm (*x*-direction) × 110 mm (*y*-direction) × 110 mm (*z*-direction) with a resolution of 0.1 μm in all three directions. A full closed-feedback control system ensures sub-micron accuracy. Figure 5 shows a schematic diagram of the setup. The WC workpiece used in this study was 60 × 12.5 × 0.1 mm. The tool electrode was pure tungsten, 300 μm in diameter. The dielectric fluid was the commercially available Total EDM 3 oil formulated in France by Total. The properties of the workpiece, electrode, and dielectric fluid are given in Tables 1 to 3.

Table 1 Workpiece material properties

Material	Tungsten carbide
Composition	W: 10 wt% Co, 0.6% others
Grade	MG 18
Average grain size	< 0.5 μm
Density	14.5 g/cm^3
Hardness	92.3 Hra
Melting point	2597°C
Transverse rupture strength	4000 MPa
Compressive strength	6600 MPa
Young's modulus	580 GPa
Thermal expansion coefficient	5.5×10^{-6} K^{-1} (20 to 400°C)

Table 2 Electrode properties

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

Table 3 EDM 3 dielectric fluid properties

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
Aromatics content	0.01 wt%
Distillation range, IBP/FBP	277/322°C

3.2 Experimental method

The choice of electrode polarity is important in the micro-EDM of WC. Negative electrode polarity was used as it gives a much better combination of MRR, low electrode wear, and controlled performance than positive polarity.[12] Reverse polarity was used for the electrode dressing, however, as more material is removed from the electrode and the dressing process is faster. After machining each micro-hole, the electrode was dressed using a sacrificial block of tungsten. The dressing was necessary as the electrodes become tapered after EDM each micro-hole. The worn-out height, *i.e.*, the tapered portion of the electrode, was dressed before starting the next micro-hole.

Even though electrode dressing took place before forming each hole, the entrance and exit diameters of each machined hole were not the same due to corner wear and linear wear of the electrodes. Therefore, to evaluate the dimensional accuracy of the micro-holes, the amount of taper angle and spark gap were measured for both types of generator. The spark gap of the micro-holes in these experiments was calculated as the average of the difference between the diameter of the micro-holes and the electrode diameter. As the electrode became tapered, the spark gap was taken as the average spark gap of the entrance and exit sides of the micro-holes. A

Keyence VHX digital microscope (VH-Z450) was used to measure the dimensions and observe the micro-holes. A scanning electron microscope (JSM-5500, JEOL Ltd.) was also used to take images of the micro-holes. The micro-EDM machining parameters used in this study are listed in Table 4.

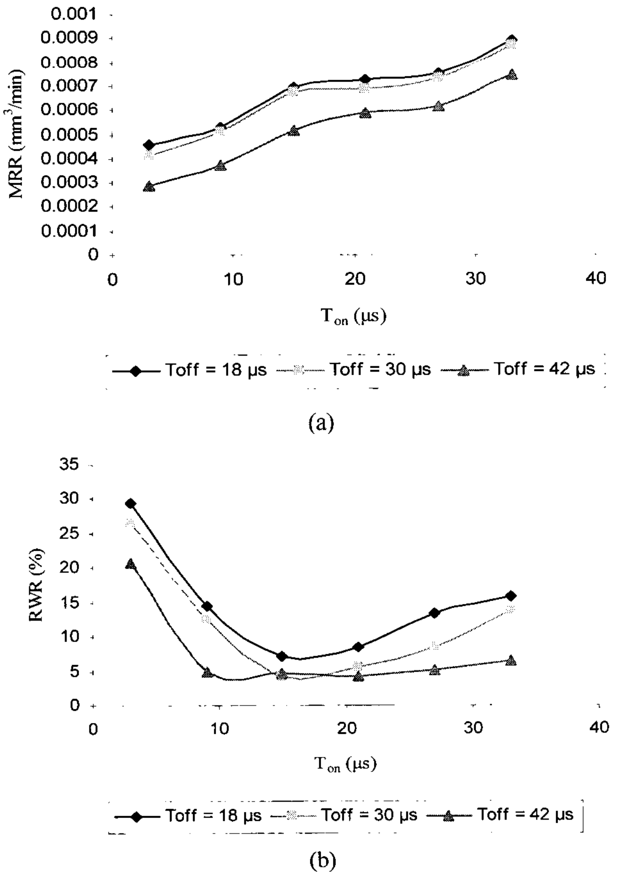
Table 4 Machining parameters for micro-hole EDM in WC

Pulse generator type	transistor
Voltage	60, 80, 100, 120 V
Resistance	6.8, 33, 100 Ω
Pulse on-time	3, 9, 15, 21, 27, 30, 33 μs
Pulse off-time	6, 18, 30, 42, 54, 66, 72 μs
Pulse generator type	RC
Voltage	60, 80, 100, 120 V
Capacitance	4700, 470, 100 pf
Resistance	1 kΩ (fixed)

4. Results and Discussion

4.1 General discussion

The performance of micro-EDM is highly dependent on the discharge energy supplied into the gap by the pulse generator. The discharge energy per pulse for a transistor generator can be calculated as $q = u_e i_e t_e$, where u_e is the discharge voltage, i_e is the discharge current, and t_e is the pulse duration.[10] The discharge energy for a RC generator can be calculated as $E_{ds} = 1/2CV^2$, where C is the value of the capacitor and V is the discharge voltage. Machining in this study was conducted using the lowest possible discharge energy for the setup to obtain the best micro-hole surface quality. The micro-EDM of WC was unstable below 60 V in the setup used. The reason for this may be that the working gap between the electrode and the workpiece was very small at very low voltages, so debris and gaseous bubbles were not removed from the discharge gap. Contaminants that collect in the gap cause short-circuiting or DC arcing, which prevent progress of the machining process.[13]



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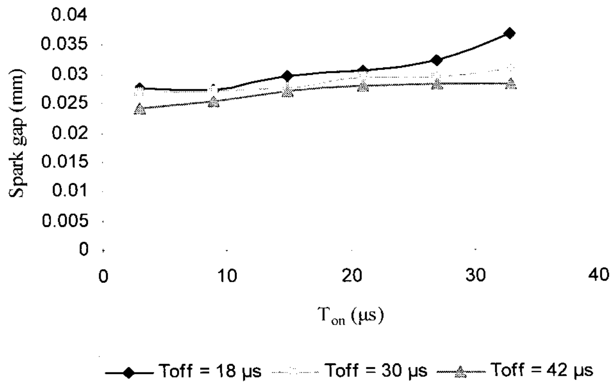
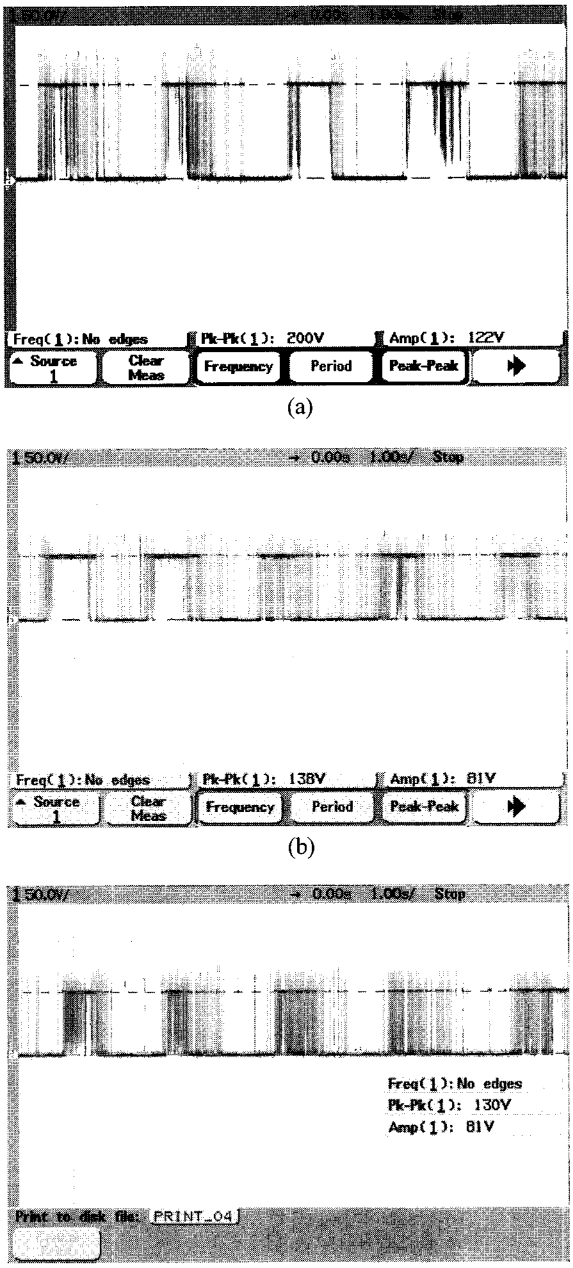


(c)

Fig. 6 Effect of pulse duration and pulse interval on the (a) MRR, (b) RWR, and (c) spark gap for the micro-EDM of WC



(a)

(b)

(c)

Fig. 7 Oscilloscope waveforms of collective sparks for different settings of T_{on} and T_{off} in a transistor pulse generator: (a) T_{on} = 15 μs, T_{off} = 72 μs; (b) T_{on} = 30 μs, T_{off} = 6 μs; and (c) T_{on} = 15 μs, T_{off} = 30 μs

The pulse duration (T_{on}) is an important parameter affecting the discharge energy in a transistor generator. However, the pulse interval (T_{off}) is also an important consideration for stable and effective machining. In this study, the performance of the transistor generator was compared with that of the RC generator for the same value of gap voltages using lower peak currents and optimum values of T_{on} and T_{off}. Figure 6 shows the effect of T_{on} and T_{off} on the MRR, the relative tool wear ratio (RWR), and the spark gap during the micro-EDM of WC. Figure 6(a) shows that the MRR increased as T_{on} increased and T_{off} decreased. However, Fig. 6(b) shows that for all values of T_{off}, the RWR decreased at first and then increased as T_{on} increased. The lowest RWR occurred for a T_{on} value of 10–20 μs. The RWR decreased as T_{off} increased. This is because the molten metal and debris could be flushed away from the machined zone with an increase in the pulse interval, thereby reducing the arcing that caused the increased RWR. On the other hand, the spark gap was not much affected by variations in T_{on} and T_{off}. Figure 6(c) shows that the spark gap increased slightly with a decrease of T_{off} and an increase of T_{on}. Therefore, low values of T_{on} and moderately high values of T_{off} should be used for the lower spark gap of the micro-holes, and it is clear than an optimum combination of T_{on} and T_{off} should be selected for proper machining. In the specific case of micro-EDM of WC, a T_{on} of 15 μs and a T_{off} of 30 μs were the optimum combination.

The machining stability was highly dependent on the selection of T_{on} and T_{off}. Figure 7 shows the oscilloscope waveforms of collective sparks for different combinations of T_{on} and T_{off}. A suitable combination of T_{on} and T_{off} is required for proper and stable machining. Figure 7(a) shows that little sparking occurred for very high values of T_{off}; this resulted in a longer machining time. If T_{off} is very low, as shown in Fig. 7(b), continuous sparking may occur, and molten material cannot be removed from the machined area due to the insufficient flushing time. Under these conditions, the process becomes unstable. The sparking process was very stable for a T_{on} of 15 μs and T_{off} of 30 μs, as shown in Fig. 7(c). Therefore, during the comparative study presented in the following sections, T_{on} and T_{off} were maintained constant at 15 μs and 30 μs, respectively. The comparison of performance parameters was conducted at the same gap voltages by varying the discharge energy.

4.2 Comparison of surface quality

Figure 8 shows the surface quality at the entrance side of the micro-holes produced using the transistor pulse generator for gap voltages of 120 and 60 V. The surface quality of the micro-holes using the RC generator at same gap voltages is shown in Fig. 9. Using 60 V and 100 Ω (the lowest possible setting at which micro-EDM is practical) for the transistor generator provided micro-holes with better surface quality. The discharge energy at this setting was 540 μJ per pulse. There were burrs on the micro-holes under these conditions due to a recast layer formed at the rim of the hole that degraded the surface quality. A large discharge energy will cause violent sparks and result in deeper erosion craters on the surface. Residues remained at the periphery of the crater due to the cooling process that accompanied the spill of molten metal.

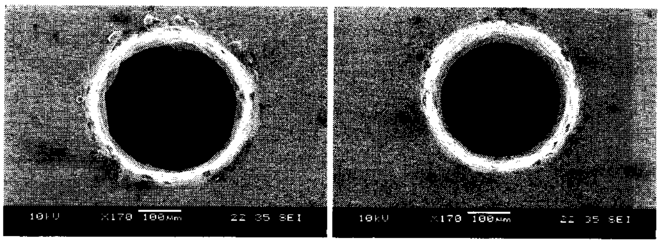

(a) (b)

Fig. 8 Entrance side of micro-holes fabricated by the transistor pulse generator at (a) 120 V, 33 Ω, T_{on} = 15 μs, T_{off} = 30 μs; and (b) 60 V, 100 Ω, T_{on} = 15 μs, T_{off} = 30 μs

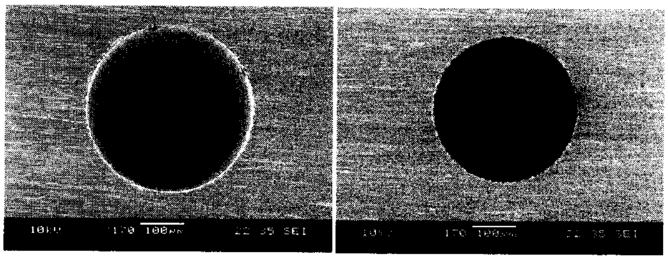
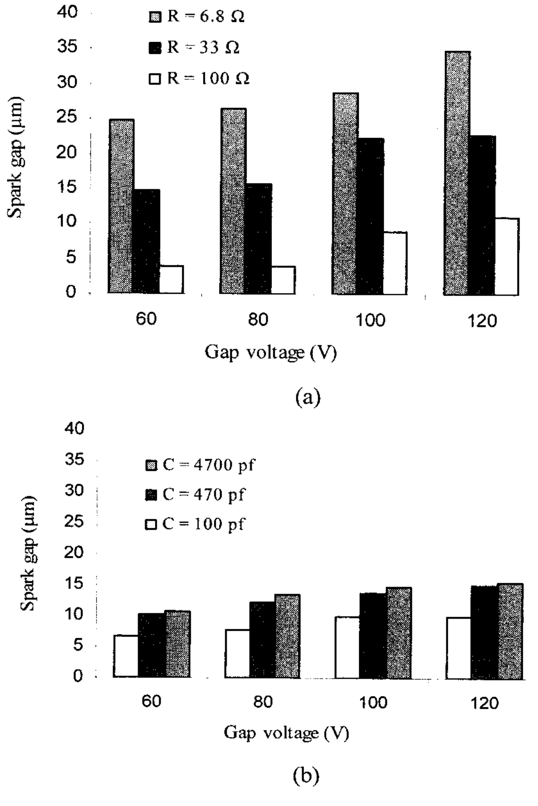

(a) (b)

Fig. 9 Entrance side of micro-holes fabricated the RC pulse generator at (a) 120 V, 4700 pf; and (b) 60 V, 100 pf

The micro-holes machined using the RC generator have a better surface finish and good circularity. Figure 9 shows that the obtained micro-holes were free of burrs and recast layers at both the low and high gap voltage settings. In addition, the circularity of the micro-holes was better. Therefore, micro-holes with a better surface quality can be achieved using the RC generator. The discharge energy for the 60 V and 100 pf setting was 0.18 μJ, much lower than that of the transistor generator. As the energy per pulse is smaller in the RC circuit, smaller craters are generated, which means that a smaller amount of material is removed per cycle. Thus, it is easier for the low-pressure side-flushing to wash the debris away from the machining zone with its dielectric flow. The average discharge energy of the RC generator was much lower than that of the transistor generator for the same gap voltage. On the other hand, the larger energy per pulse in the transistor generator resulted in larger craters, and thus a larger amount of material removed per cycle. The dielectric flow pressure in the machine may not be sufficient to wash it away from the machining zone in the short time available. This allows the debris to re-solidify around the surface, resulting in a poor surface profile.

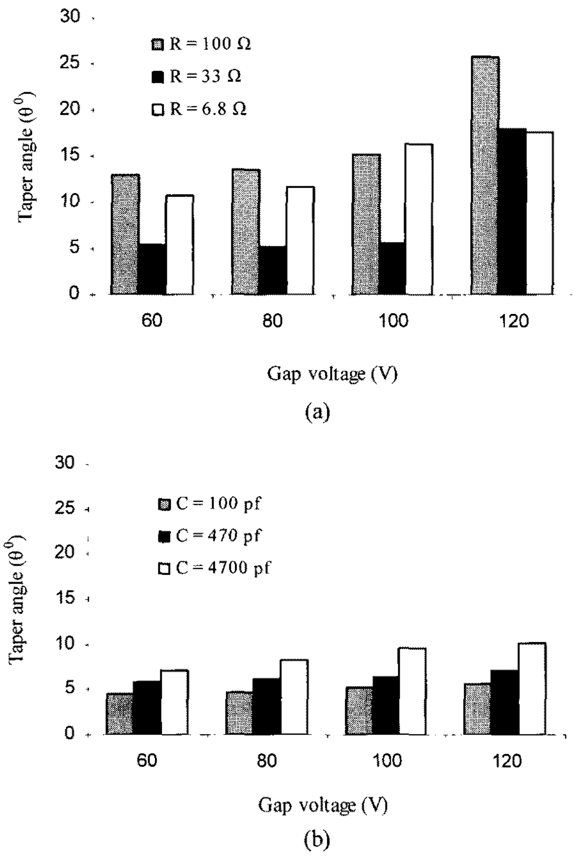
4.3 Comparison of dimensional accuracy



(b)

Fig. 10 Spark gap for different machining parameters using the (a) transistor and (b) RC pulse generators

Dimensional accuracy is an important criterion to consider in the fabrication of micro-structures. In this study, the dimensional accuracy of the micro-holes was evaluated by the average spark gap and the taper angle between the entrance and the exit holes. The RC pulse generator performed well from a dimensional accuracy perspective. Even though the spark gap can be lower at lower energy levels for transistor generators, the value of the spark gap varies very roughly with different combinations of machining conditions. A smaller spark gap is always required to obtain good dimensional accuracy. Figures 10(a) and (b) show the spark gap values for the transistor and RC circuits, respectively, as functions of the gap voltage during the machining of the micro-holes. Except for the 100 Ω resistance, a higher spark gap was obtained using the transistor pulse generator. The lowest spark gap obtained using the transistor circuit was about 5 μm. However, at 120 V and 6.8 Ω, the spark gap was about 35 μm. As the energy per pulse is lower for the RC pulse generator, the crater size is also lower, which resulted in a smaller spark gap as well as better surface quality. The spark gap did not vary significantly with different settings of the operating parameters in the RC circuit. This is a good indication of repeatability that is very important in the evaluation of dimensional accuracy. The average spark gap for the RC circuit was about 10 μm, with the lowest value of 6 μm at 60 V and 100 pf.



(a)

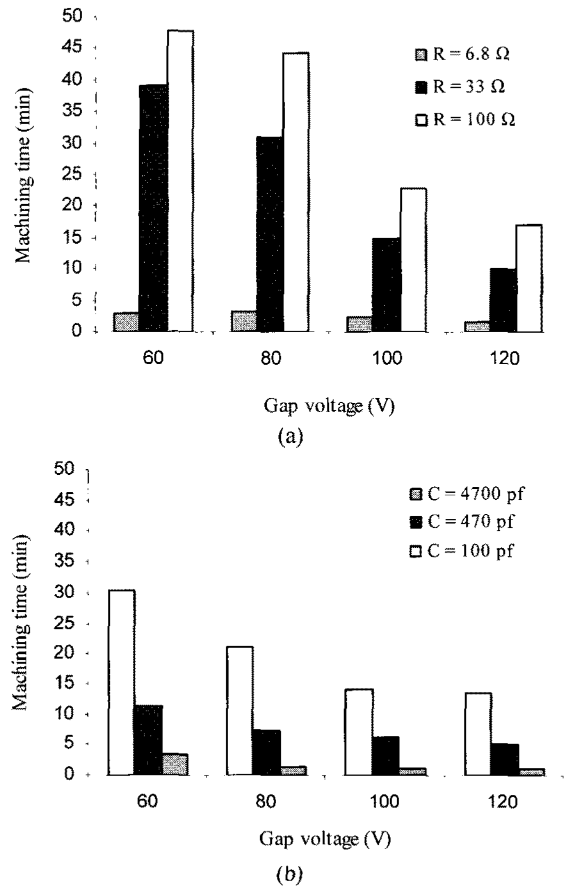
(b)

Fig. 11 Micro-hole taper angle for different machining parameters using the (a) transistor and (b) RC pulse generators

Another important observation is the reduction of the taper in the micro-holes produced using the RC generator. The reason for the micro-hole taper is the corner wear of the electrode that reduces the dimensional accuracy. The taper of the micro-holes was dependent on the discharge energy. More material was removed at a higher energy, and thus deeper and larger discharge craters were created on the workpiece surface. An unusual second discharge spark can be induced when debris piles up. This phenomenon causes the entrance of the micro-holes to be larger and makes the machining process unstable.[14] However, when the discharge energy was reduced, the diameter of the micro-hole entrance was not enlarged as much, thus reducing the taper angle. Figures 11(a) and (b) show the taper angle of the micro-holes produced using transistor and RC pulse generators, respectively. The average taper angles were much lower in micro-holes produced using the RC generator. Earlier (Fig. 8(b)), we showed that the transistor generator produced a better surface quality micro-hole with relatively few burrs and a lower spark gap using the 100-Ω setting. However, those micro-holes had considerable taper, as shown in Fig. 11(a). This is due to the fact that the electrode wear was very high due to the longer machining time at 100 Ω. Thus, the electrode became more tapered due to corner wear. However, the micro-holes obtained using the RC generator had less taper and thus better dimensional accuracy. The maximum taper angle using the transistor generator was about 26° at the 120-V and 100-Ω setting, whereas the highest taper angle using the RC circuit was only 10° using the 120-V and 4700-pf setting. The average taper angles were also much lower using the RC circuit. Thus, there was a consistency in the dimensions of the micro-holes as well as their circularity.

4.4 Comparison of machining time

Besides producing a poorer surface quality, the transistor pulse generator required a much longer machining time. The voltage range is 0 to 150 V with resistance settings of 6.8, 15, 33, and 100 Ω for the transistor pulse generator developed at the NUS. The best quality micro-hole was obtained at the lowest practical energy. It was very difficult to perform micro-EDM of WC below 60 V using the transistor pulse generator. It took 48 min to make a micro-hole using the 60-V and 100-Ω setting; this is clearly not economical. Even at the 80-V and 33-Ω setting, it took 30 min to produce a similar quality micro-hole, which is also time-consuming. Figure 12 shows the machining times for fabricating micro-holes in WC. The RC pulse generator was faster and produced micro-holes with a fine quality surface finish.



(a)

(b)

Fig. 12 Machining time for different parameters using the (a) transistor and (b) RC pulse generators

A good quality surface finish was obtained in only 11 min using the 60-V and 470-pf setting. A hole with good dimensional accuracy and a completely burr-free surface required only 15 min using the 60-

V and 100-pf setting. The machining time was inversely proportional to the applied discharge energy for both types of generator. However, the machining (erosion) efficiency also increases with decreasing discharge energy,[15] because if the energy is low, the pulse duration is less, and so the possibility of heat transfer to the surrounding media is also less. This is an indication of the good performance of the RC generator for fine finishing and may be another reason why the MRR of the RC generator was higher in the finishing regime (Fig. 13), even though the discharge energy was higher for the transistor generator. However, for both generators, the machining time increased as the discharge energy decreased even though the erosion efficiency increased, as the higher machining efficiency was mostly related to the machining stability and consistency of the volume and size of craters rather than the machining time.[15]

4.5 Comparison of MRR

The aim of micro-EDM is to achieve good surface quality at the highest possible MRR. This is goal was met by using the RC pulse generator. If the MRR is increased by increasing the discharge energy in the transistor pulse generator, the surface quality begins to degrade. In the RC circuit, however, the MRR can be higher than that achieved by the transistor circuit without reducing the surface quality. The MRR for different operating parameters of the transistor and RC pulse generators are shown in Figs. 13(a) and (b), respectively.

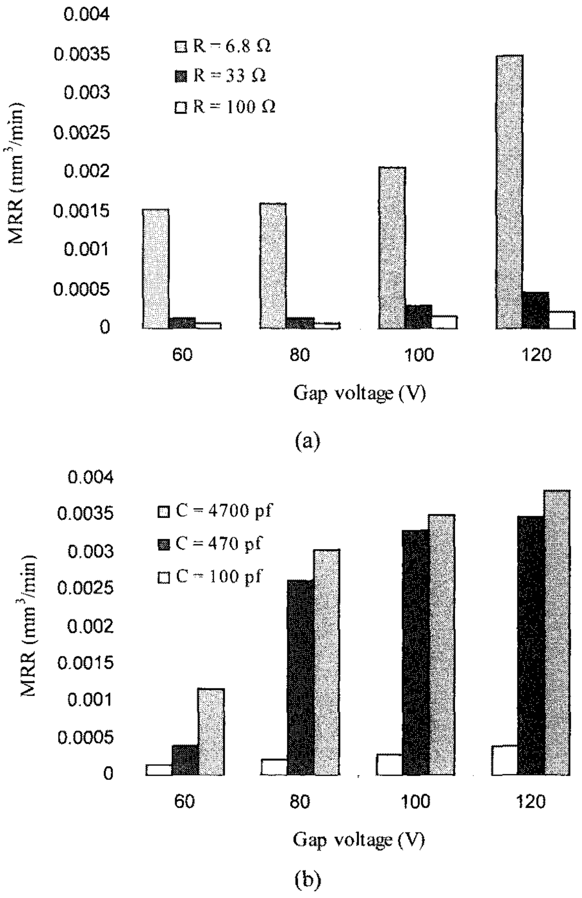


Fig. 13 MRR for different machining parameters using the (a) transistor and (b) RC pulse generators

Figure 13(a) shows that the MRR was higher for the transistor generator only for 6.8 Ω, *i.e.*, for a higher value of the peak current. However, the MRR was very low for the 33-Ω and 100-Ω settings. Even though the discharge energies for the RC generator were much lower, the MRR rate was higher compared to that obtained using the 33-Ω, and 100-Ω settings for the transistor generator (Fig. 13(b)). This is attributed to the smaller craters created by the RC generator due to the lower energy per pulse, and the debris flushing from the machining zone by the low-pressure dielectric used in the set-up. However, large debris volumes cannot be flushed away properly by low-pressure dielectric fluid. The debris affects the machining stability and rate, while also reducing the surface quality by adhering to the surface of the micro-holes. In addition, the reduction of discharge energy in the transistor generator meant that the machining became unstable, which also reduced the MRR. The average MRR of the RC circuit was higher than that of the transistor circuit at the low voltage settings. The highest MRR in the transistor circuit was 0.0035 mm^3/min at 6.8 Ω and 120 V, whereas the rate was very low for other settings. However, micro-holes with much better surface quality were been obtained at 0.0025 mm^3/min using the 80-V and 470-pf setting with the RC pulse generator. Moreover, the 120-V and 4700-pf setting produced micro-holes with a better surface quality and a rim free of burrs (Fig. 9(a)) at the same MRR of 0.0035 mm^3/min as the transistor generator at 120 V and 6.8 Ω.

4.6 Comparison of RWR

The RWR is an important issue to consider for micro-EDM to be economical. The electrodes used should have excellenthigh physical, thermal, and electrical properties, thus sometimes may be very expensive when applying micro-EDM to extremely hard materials. Therefore, one of the goals of micro-EDM is a low consumption of the electrode material. Even so, a higher electrode consumption rate is sometimes tolerated when the surface quality of the workpiece is the primary consideration. The RWR was calculated to provide some indication of electrode consumption during the micro-EDM of WC using both the transistor and RC circuits. The RC circuit produced a good quality surface finish at the cost of a comparatively high RWR.

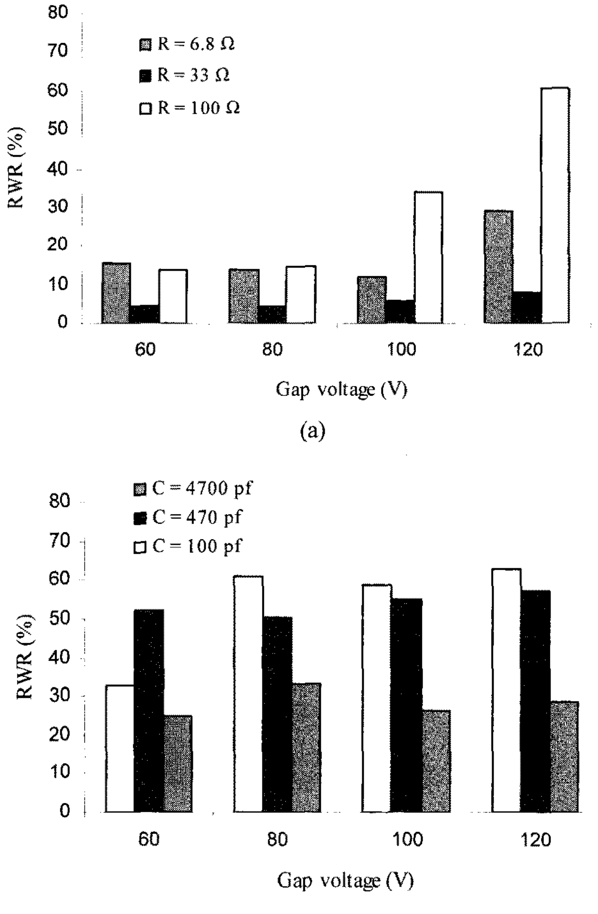


Fig. 14 RWR for different machining parameters using the (a) transistor and (b) RC pulse generators

Figure 14 shows that the average RWR value was higher in the RC circuit than in transistor circuit. This was due to the very high peak current at the instant of spark initiation, followed by a rapid rate of decline. Therefore, the spark temperature resulting from this high current peak was much higher than that required to remove a particle from the workpiece, which can result in thermal damage to the tool electrode.[9] The minimum RWR using the RC circuit was about 25% compared to only 4% using the transistor circuit. The RWR was lower in the transistor generator only for 33 Ω at all voltage settings. At 6.8 Ω, the RWR was higher due to the high peak current, and at 100 Ω the wear was again very high due to the long machining time. Although a large resistance can decrease the discharge energy, it also prevents sparks from taking place and thus results in discontinuous discharging, which causes extensive tool wear.[16] Micro-holes with a better surface can be obtained using comparatively low discharge energies at the expense of higher RWR for both types of generator. For the RC generator, the maximum electrode wear occurred at the 100-pf setting, while for the transistor generator, the RWR was higher for the 100-Ω settings. The maximum RWR was about 60% and 62% for the transistor and RC pulse generators, respectively.

5. Conclusions

A detailed experimental comparison was conducted using micro-EDM with transistor and RC pulse generators to produce good quality micro-holes in WC. Based on the experimental results obtained in this study, the following conclusions can be drawn.

1. The RC pulse generator could produce better quality micro-holes in WC with a good surface finish, a burr-free rim, and good circularity.
2. The spark gap did not vary significantly in the RC circuit; this is an indication of good repeatability. In addition, the average values of the spark gap were smaller when using the RC generator, and the taper of the micro-holes was lower, indicating better dimensional accuracy.
3. Although the MRR was higher for the transistor generator at higher discharge energy levels, the RC generator could provide a higher MRR for micro-EDM finishing at a lower discharge energy. The RC generator required much less machining time to obtain a micro-hole with the same quality surface finish. However, the average RWR was higher for the RC generator.
4. The RC generator micro-EDM was more suitable for fabricating micro-structures in WC, especially where dimensional accuracy and surface finish are of prime importance.

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