The Effect of Machining Parameters on Tool Electrode Edge Wear and Machining Performance in Electric Discharge Machining (EDM)

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The main purpose of this study is to investigate the variation of tool electrode edge wear and machining performance outputs, namely, the machining rate (workpiece removal rate), tool wear rate and the relative wear, with the varying machining parameters (pulse time, discharge current and dielectric flushing pressure) in EDM die sinking. The edge wear profiles obtained are modeled by using the circular arcs, exponential and power functions. The variation of radii of the circular arcs with machining parameters is given. It is observed that the exponential function models the edge wear profiles of the electrodes very accurately. The variation of exponential model parameters with machining parameters is presented.

Key Words : EDM, Tool Edge Wear, Machining Rate, Electrode Wear, Exponential Model

1. Introduction

Electric Discharge Machining (EDM) is one of the non-traditional machining processes, which is used commonly to produce the die cavities by the erosive effect of electrical discharges. The electrically conductive tool electrode, which has the male shape of the die cavity, is prepared to machine the die cavity. The technique is especially effective in machining hard die steels, complex form of cavities and small workpieces.

In many research works, the wear ratio or relative wear (ratio of "volume of the tool electrode material removed/volume of the workpart material removed") is the main concern. It is known that the tool and work materials and their geometry, machining current, pulse time, pause (off) time, dielectric flushing conditions, pulse waveforms and machining voltage polarity are the effective parameters on wear ratio. Most of these works are directed towards finding the optimum machining conditions, materials and geometries for the maximum machining rate with minimum tool wear.

The wear of the tool electrodes is not completely eliminated though the tool wear is reduced to small values in today's level of technology. In EDM, the tool wear problem is very critical since tool shape degeneration affects directly the final shape of the die cavity. Some authors (Zingerman, 1959 ; Van Dijck, 1973 ; Koning and Siebers, 1993) claimed that most of the electrode wear and workpiece removal is due to evaporation and fusion. Eubank and Barrufet (1990), however, pointed out that material removal is caused by expulsion of the super heated molten electrode from the craters at the end of the pulse time. Feeney et al. (1978) and Zingerman (1956) have pointed out that relative wear is higher in the early stages of the process and proposed that this is mainly due to the high value of energy density. Mohri et al. (1995) suggested that carbon layer on the electrode surface reduces the wear of the electrode. Kruth et al. (1979) optimised machining settings, namely pulse time, pulse interval, dielectric flushing flow rate and servo

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reference voltage, on-line to obtain a minimum relative wear and a good surface finish. Rajurkar et al. (1989) improved the machining stability by controlling the servo reference voltage and obtained 40% higher workpiece removal rate.

Especially in 70's, many works were published on "front wear" and "side wear" of the tool electrodes. In today's technology, the new EDM machine tools and pulse generators can reduce the wear ratio below 1% (called as "no wear" case) by setting the machining parameters in accordance with the machine tool manufacturers catalogues. At the "no wear" case, the side wear and the frontal wear of the tool electrode are very low but the tool edge wear is still at large quantities [Fig. 1(c)]. In EDM, the electric field in the machining gap has the highest densities at the corners and edges of the tool electrodes. This increases the probability of occurrence of discharge pulses at the corners and edges which results in rapid rounding at these sections. In the literature, there is very limited number of published works on tool electrode shape degeneration (geometrically) concentrating on tool edge wear. In 70's, valuable contributions on geometric modeling of tool wear and degeneration of tool electrodes in EDM were made by Crookall et al. (1973; 1973a; 1973b) and Jeswani (1979). In these studies, the edge wear profiles were represented simply by circular arcs. The geometrical modeling and simulation of the tool shape degeneration in EDM die-sinking process was investigated by Delpetti and Dauw (1988). The wear profiles of the tool and the workpiece were found by displacing the points, which were filled up along both contours, alongside a displacement vector with the length calculated using the predetermined volumetric tool and workpiece removal amounts. The effect of the erosion depth and discharge current on the edge rounding of electroformed copper electrode was investigated by Zerweck and Muller (1983). It was found that a fast rise of edge rounding up to an erosion depth of 10mm, an almost proportional rise results with erosion depth. They also stated that for higher discharge current the electroformed electrodes present higher degree of edge rounding. The shape change of the edge portion of cylindrical electrode with machining time was introduced by Mohri et al. (1994; 1995). In one of his works, the variation of wear of edge portion and whole wear ratio were examined for increasing machining time (Mohri et al., 1995). The wear ratio of edge proportion was found to be decreasing with increasing machining time. In their works, the shape of the edge portion and degeneration of the edge portion with varying machining parameters were not taken into consideration.

In the literature, there is no published work on the modeling of the shape of the edge portion and variation of tool electrode edge wear with machining conditions in EDM. The authors believe that the rapid rounding (wear) of the tool electrode edges which significantly detoriates the final shape of the produced die cavities should be closely investigated. In this study, the outer and inner edge wear profiles of the tool electrode with a through hole flushing (Fig. 1) are investigated for different machining conditions. The pulse time, discharge current and dielectric flushing pressures are changed and the variations in tool edge wear profiles, machining rate, tool wear and wear ratio are observed and discussed. The edge wear profiles are modeled by using different distribution function than circle (i.e. circular arc). The variation of the model parameters of the distribution function, which best models the edge wear profiles, with machining parameters is introduced.

2. Investigations

2.1 Experimental method

2.1.1 Specimens

In the experiments 60 tool electrodes and workpieces were used. Tool electrodes were prepared by cutting cylindrical copper rods of 20 mm diameter. The electrodes were then turned down to 18 mm diameter. The upper sections of the tool electrodes are turned down to 10 mm diameter for easy fixing to a jig in the workhead side [Fig. 1(a)]. For easier and even flushing

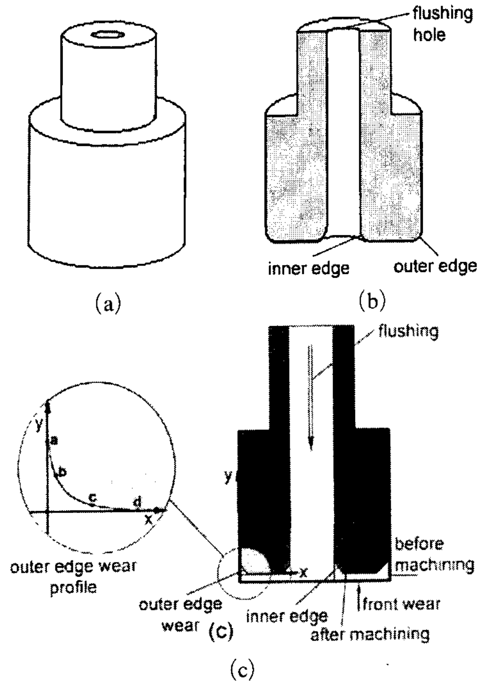

Fig. 1 (a) Tool electrode geometry, (b) Front view of a used tool, which is cut off by wire EDM, (c) Edge wear of a tool electrode

purposes, 5 mm diameter hole was drilled through the centre of the tool electrode [Fig. 1(b)]. As workpiece material, cold rolled die steel 2080 was used. Workpiece electrodes were cut from a 39× 44 mm bar at 9 mm thickness. Two largest parallel surfaces were ground. The densities of the electrolytic copper and 2080 die steel specimens used in the experiments were 8.9 g/cm^3 and 9 g/cm^3, respectively.

2.1.2 Machine tool

The electric discharge machine used in this investigation was the MAKIM25 Model die sinking machine with EDM25A isopulse type generator.

2.1.3 Dielectric flushing

Tellus dielectric was used and positive pressure through hole flushing was applied in the experiments. The effect of flushing on the edge rounding was also tested by using static dielectric (no flushing) for six machining conditions. The tool was retracted in every four seconds for five seconds duration. Low pressure through hole flushing (0.1 bar) was applied to clean the gap for the five seconds, during which the tool was retracted.

2.1.4 Machining parameters

As pulse time (t_p) 25, 50, 100, 200 μs, as discharge current (I) 12, 18, 25 A and as dielectric flushing pressure (P) 0 (static), 0.3, 0.75, 1, 1.25, 1.5 bar were used in the experiments. Static (no flushing) and 0.3 bar dielectric conditions were tested for 12 experiments where discharge current (I) was 18 A (t_p=50 μs, 100 μs and 200 μs) and 25 A (t_p=25 μs, 100 μs and 200 μs). The pause (off) time was 25 μs and open circuit voltage was 80 V with (+) polarity in all experiments. In order to observe the edge wear easily, the same depth of tool sinking (approximately 8 mm) was used.

2.1.5 Weighing of specimens

The weight loss of specimens was calculated by weighing the initial and final (after machining) weights of the workpiece and tool electrode specimens by using a Denver Instrument-XE310 type digital scale with 0.001 g accuracy. The weight measurements were repeated three times for each specimen and the average of the values was used in the study. The volumetric removal rates were calculated by dividing the weight losses to the density of the specimen. The machining durations (t_m) measured by a stopwatch were used to calculate machining rate and tool wear rates.

In EDM field, relative wear(RW) value gives much more technologically meaningful result than the TWR, since it is a relative measure including tool wear rate(TWR) and workpiece removal rate(WRR) contributions. Therefore, the RW variations with the pulse time, discharge current and dielectric flushing pressure are also considered and discussed in this study.

2.1.6 Tool electrode edge wear profiles

The used tool electrodes were cut off into two symmetrical parts by using wire EDM [Fig. 1 (b)]. The bottom sections of the cut tool electrodes were optically scanned using Mustek

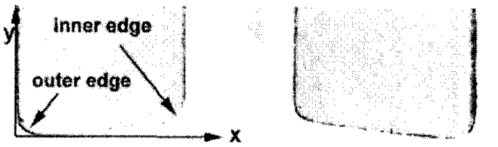

Fig. 2 A scanned tool electrode

1200CP model scanner with 1200 dpi resolution (Fig. 2). The scanned photographs were imported and processed in Photo Shop Pro 5 software. By using the software, the edge wear profiles of the electrodes were examined under magnification of x50. In this study, both outer and inner edge profiles were examined. The x and y axes were placed to the outer and inner edge profiles (Fig. 1(c) and Fig. 2). The x-axis is tangent to the machined front side and y-axis is coinciding to the unmachined cylindrical side. 10 to 18 points were marked on the edge wear profile, and x and y coordinates of these points were recorded by using the graphical capabilities of the Paint Shop Pro 5 software.

The transparent patterns with different diameters were prepared and overlapped to the printed scan images of the edge profiles. The radius of the best-fit pattern was recorded as "edge radius" of the profile.

2.1.7 Mathematical modeling of the edge wear profiles

After the preliminary inspection of the edge profiles, the exponential ($y=ae^{-bx}$) and power functions ($y=ax^b$) were proposed as the possible functions to model the edge wear profiles mathematically. The recorded edge profile coordinates were entered to the STATGRAPH package (1990) to find the model parameters (a and b) and regression values (r2) of the suggested distributions. The regression values were used to check the goodness of fit of the proposed functions (models).

2.2 Results and discussion

Workpiece removal rates (WRR), tool wear rates (TWR) and relative wear (RW) values for the machining settings are represented graphically in Fig. 3. The 8 mm depth of tool sinking is completed at different machining durations (t_m) depending on the used machining settings. The machining is completed at shorter times when high current and/or long pulse time settings are used. This is mainly due to the increased material removal effect of discharge pulses with higher energy contents.

2.2.1 Variation of WRR with machining parameters

The energy of a discharge pulse (E) in EDM can be expresses as $E=V_d\ I\ t_p$ in isopulse generators, where V_d is the constant discharge voltage, I the discharge current and t_p the discharge duration of the pulse. The pulse generator used in the experiments is an 'isopulse' type and in this type of generator, duration of current passes through the machining gap is constant (i.e. pulse time) when the electric discharge initiates. This results in almost identical size of craters on the workpiece surface.

Figure 3(a) indicates that the WRR increases with the increasing pulse time. The rate of increase in WRR is low at low current settings (i.e. 12 A) and becomes high at high current settings. Longer duration discharge pulses produce bigger craters due to their higher energy contents and this results in higher machining rates (WRR) with poor surface quality. The increase in WRR with discharge current is evident from Fig. 3(d). The increase in WRR is due to the increasing energy of a discharge pulse with increasing discharge current I. It is expected that better flushing of the interelectrode gap results in higher removal efficiency of molten material from the workpiece craters. This is validated under static dielectric conditions (i.e. at 0 bar) where the lowest amount of WRRs is observed. At 0.3 bar pressure the WRR increases significantly. The increase of dielectric pressure from 0.3 bar to 0.75 bar also highly improves the WRR. Above 0.75 bar pressure, a very slight increase or no change in WRR is observed with increasing dielectric pressure [Fig. 3(d)]. Further increase in dielectric pressure (to 1, 1.25, and 1.5 bar) does not improve the WRR significantly. It is concluded that the increase of dielectric pressure

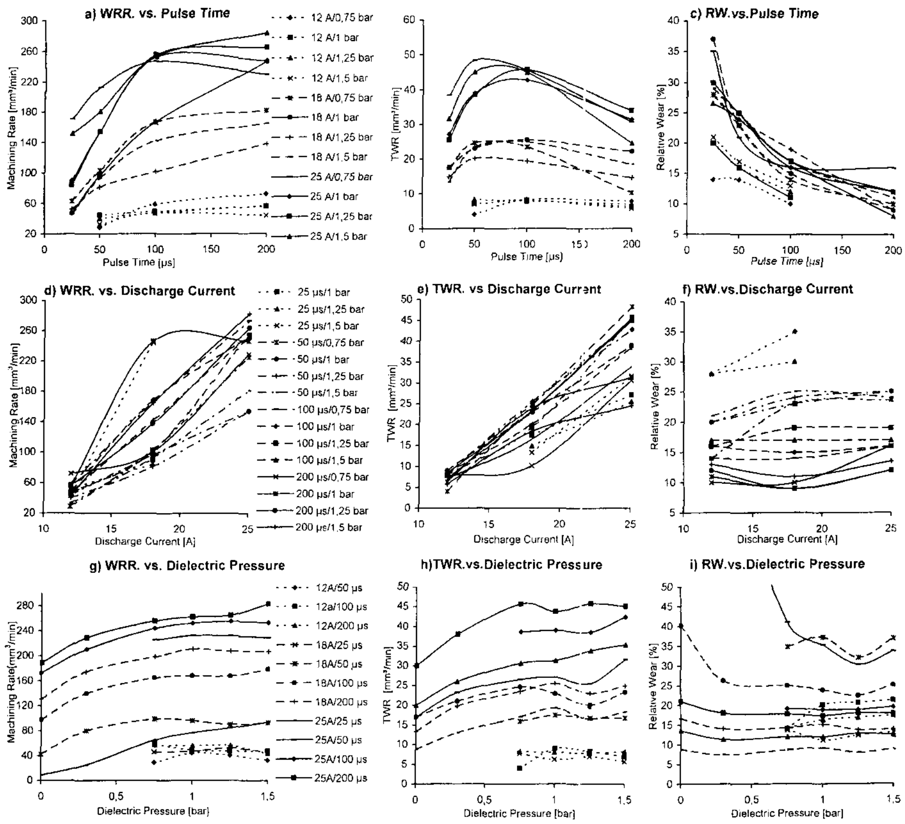

Fig. 3 Variation of WRR, TWR and RW with machining parameters

at low pressure values contributes to the WRR highly, but improvement in the WRR is very limited (above a certain value of pressure).

2.2.2 Variation of TWR with machining parameters

In Fig. 3(e), it is clear that the increasing discharge current increases the TWR. At low pulse time settings [Fig. 3(b)], the increasing pulse time increases the TWR. After 100μs pulse time, no significant variation or slight reduction in TWR with pulse time is observed for 12 A and 18 A current settings. At 25 A setting, the increasing pulse time above 100 μs causes significant reduction in TWR. This variation is attributed to the availibility of longer heat transfer time of the molten craters on the tool electrode surface resulting lower material removal amount from the molten craters (Zingerman, 1956; 1959; van Dijck, 1973). In Fig. 3(h), the tendencies observed for the variation of TWR with dielectric pressure are same as in the case of Fig. 3(g). It is clear that a small increase in pressure starting from static conditions highly increases the TWR, but further increase in pressure does not contribute significantly to the TWR. No significant variation in TWR with dielectric pressure is observed especially above 0.75 bar pressure.

The increase in TWR and WRR with discharge current and pulse time (especially at low pulse time values) is emphasized in other works and is attributed to the higher erosive effects of large energy discharge pulses in pulse trains (Crookall and Moncreff, 1973; Jeswani, 1979; Delpretti and Dauw, 1988).

2.2.3 Variation of relative wear (RW) with machining parameters

The decrease in RW with increasing pulse time is evident from Fig. 3(c). However, the poor surface quality caused by the long duration pulses restricts the use of the long pulse durations especially in finishing operations. A slight increase in RW is observed for almost all machining settings with increasing discharge current [Fig. 3(f)]. As evident from Fig. 3(d) and 3(e), both WRR and TWR increase with increasing discharge power. It is a well known fact that higher RW values cause rapid degeneration of the tool geometry. Due to this reason, high machining current settings should not be used for complex shape of tool electrodes which needs low tool shape degeneration and for the finishing applications requiring good surface quality. In Fig. 3(h), the RW decreases with increasing dielectric pressure starting from static dielectric condition. No significant variation of RW with dielectric pressure is observed after 0.3 bar pressure.

2.2.4 Variation of edge radius with machining parameters

Sample outer and inner edge radii measurements are given in Table 1 and some edge radius profiles plotted on the experimental profiles are shown in Fig. 4. In this study, the outer and the inner edge profiles of the 52 tools are investigated. The minimum and maximum values of the outer edge radii are 0.43 mm and 1.55 mm, respectively. These values are 0.58 mm and 1.7 mm for the inner edge profiles. The measured inner edge radii are 10% to 50% higher than outer radii. This is due to the variation of dielectric flow characteristics at the inlet and outlet of the front gap (Schumacher, 1990; Wong et al., 1995; Enache, 1993) and the variation of strength of the dielectric field in the gap, which significantly affects dielectric breakdown characteristics. Wells and Willey (1975; 1976) stated that the dielectric flow velocity is inversely proportional to the distance from the central hole, being maximum at the centre and a minimum at the outside edge of the cylindrical tool. The formation of bubles in the high velocity dielectric causing a turbulent nature of flow is also a known fact. The high velocity and turbulent nature of the dielectric fluid flow at the inlet locations to the front side increases the probability of the occurrence of the next discharge at the same location causing higher discharge occurrence density at these locations (Zerweck and Müller, 1983; Wells and Willey, 1976). Wong et al (1995) used the similar shape and material of the tool and workpiece and investigated the effect of dielectric flushing on cracks formed on workpiece surface. The large amount of surface cracks observed at the inlet sections of the dielectric fluid is attributed to the thermal effects caused by successive erosive discharges occurred at these sections. Their findings about surface cracks confirm the experimental results obtained in this study.

The results attained from experiments conducted at static dielectric conditions are supporting the above findings. The inner and outer edge radii obtained under static dielectric are always smaller than those under dielectric flushing cases [Fig. 5(a) and 5(b)]. In static dielectric conditions, outer edge radii are 15% to 30% less than outer radii of the through hole flushing case. Similarly, in static conditions, inner edge radii are 15% to 35% less than inner radii of the through hole flushing cases. In static dielectric cases, the inner radii are 10% to 22% larger than the outer radii. Larger inner edge radii in the static dielectric case can be explained by higher discharge density at around the flushing hole due to stronger electric field which creates a highly preferable medium for the start of discharges. The experimental findings under static and flushing dielectric conditions indicate the strong influence of dielectric flushing in increasing both the inner and outer edge radii of the tool electrode. The experiments at static dielectric conditions also verify the importance of the strong electric field generated at around the flushing hole in the gap giving larger inner edge radii.

From Fig. 5(a) and 5(b), it is clear that the outer and inner edge radius values are increasing with dielectric pressure. At static conditions, the minimum inner and outer edge radii are observed. Starting from static conditions to 1 bar dielectric pressure, the rate of increase in radii is low and is in lineer form. At higher pressure settings, the sudden increase in edge radii (both for the inner and outer edge) is evident. Very high dielectric

Table 1 Sample edge radii of the wear profiles and the correlation constants of the fit of the exponential and power functions to the profiles ((i): inner edge, (o): outer edge), (s): static dielectric (no flushing))

	Machining Parameters			Edge radius	Ratio of Radius(i) to Radius(o)	Fit of Power Function		Fit of Exponential Function	
Sample No	I[A]	tp[μs]	P[bar]	(mm)		r	$\hat{r}2$	r	$\hat{r}2$
006 (o)	12	50	1	0,43	1,67	0,934	0,872	0,978	0,956
006 (i)				0,72		0,906	0,821	0,990	0,981
008 (o)	12	50	1,5	0,43	1,74	0,910	0,828	0,989	0,978
008 (i)				0,75		0,905	0,819	0,994	0,987
018 (o)	18	25	1	0,64	1,31	0,930	0,865	0,982	0,964
018 (i)				0,84		0,949	0,901	0,964	0,930
019 (o)	18	25	1,25	0,8	1,04	0,860	0,740	0,998	0,997
019 (i)				0,83		0,842	0,710	0,982	0,964
020 (o)	18	25	1,5	0,95	1,29	0,889	0,790	0,991	0,982
020 (i)				1,23		0,839	0,703	0,983	0,967
021(s) (o)	18	50	0	0,49	1,18	0,866	0,789	0,979	0,971
021(s) (i)				0,58		0,940	0,877	0,936	0,870
024 (o)	18	50	1,5	1,1	1,18	0,886	0,785	0,993	0,985
024 (i)				1,30		0,806	0,650	0,976	0,953
025(s) (o)	18	100	0	0,52	1,21	0,860	0,751	0,989	0,988
025(s) (i)				0,63		0,892	0,806	0,990	0,981
025 (o)	18	100	0,75	0,6	1,53	0,875	0,765	0,996	0,991
025 (i)				0,92		0,907	0,822	0,995	0,990
029(s) (o)	18	200	0	0,66	1,11	0,873	0,761	0,987	0,974
029(s) (i)				0,73		0,899	0,808	0,991	0,982
029 (o)	18	200	0,75	0,87	1,20	0,873	0,761	0,987	0,974
029 (i)				1,05		0,899	0,808	0,991	0,982
030 (o)	18	200	1	0,8	1,27	0,857	0,735	0,986	0,972
030 (i)				1,02		0,887	0,786	0,996	0,991
033(s) (o)	25	25	0	0,68	1,15	0,861	0,760	0,989	0,987
033(s) (i)				0,78		0,766	0,601	0,979	0,959
033 (o)	25	25	0,75	0,9	1,12	0,877	0,770	0,998	0,996
033 (i)				1,01		0,778	0,605	0,983	0,967
034 (o)	25	25	1	0,7·	1,45	0,889	0,791	0,994	0,988
034 (i)				1,02		0,876	0,767	0,994	0,988
040 (o)	25	50	1,5	1,15	0,98	0,905	0,819	0,991	0,981
040 (i)				1,13		0,855	0,732	0,988	0,977
041(s) (o)	25	100	0	0,52	1,22	0,906	0,820	0,989	0,979
041(s) (i)				0,63		0,852	0,730	0,991	0,980
041 (o)	25	100	0,75	0,65	1,55	0,915	0,838	0,991	0,983
041 (i)				1,01		0,866	0,750	0,994	0,989
045 (o)	25	200	0,75	0,92	1,25	0,874	0,765	0,996	0,991
045 (i)				1,15		0,875	0,765	0,995	0,990
047(s) (o)	25	200	0	0,89	1,17	0,886	0,779	0,989	0,980
047(s) (i)				1,04		0,836	0,720	0,990	0,981

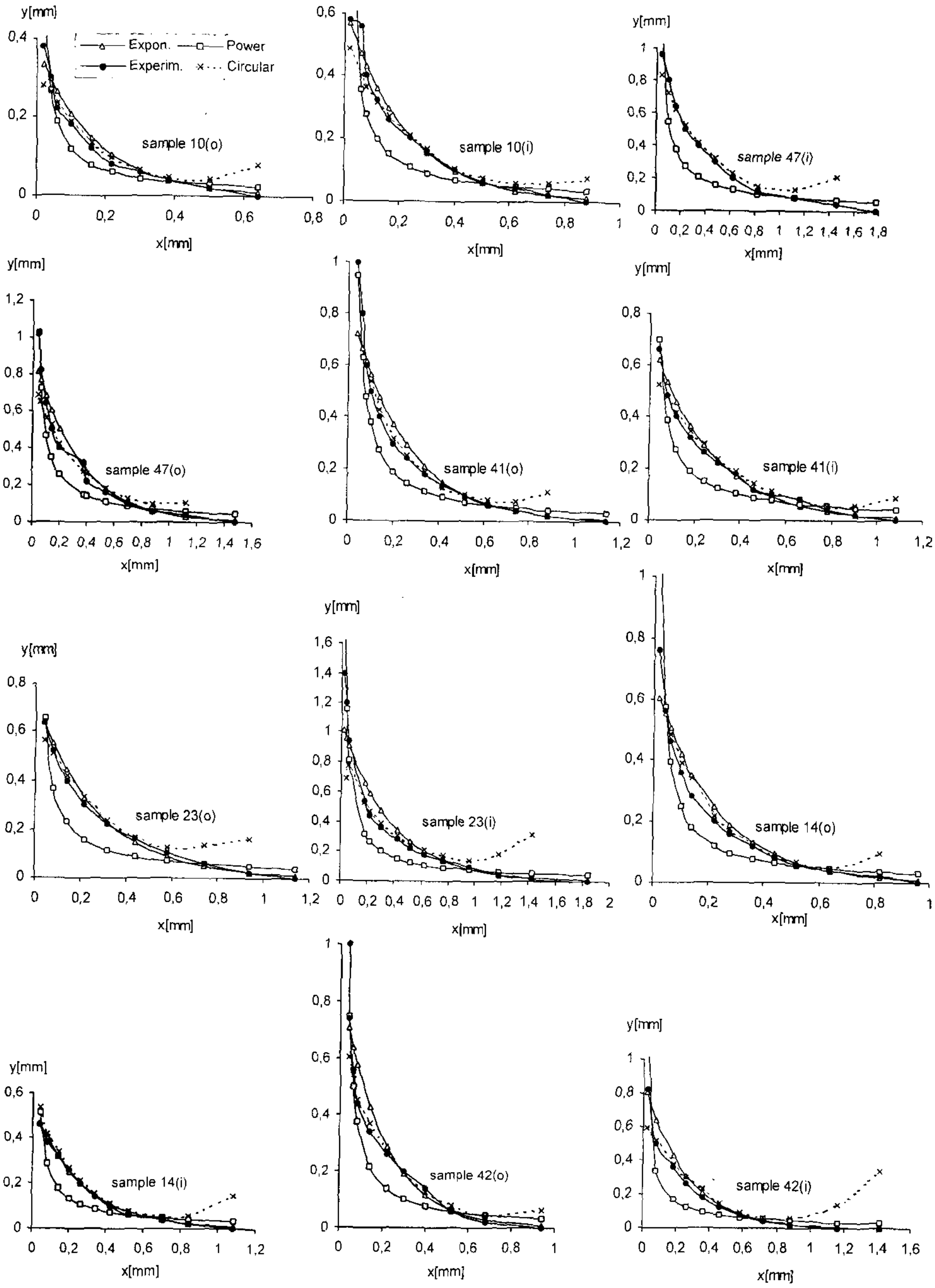

Fig. 4 The fit of the circular arcs, exponential and power functions to the experimentally obtained outer and inner edge profiles

flushing pressure values should thus be avoided not to increase the edge radii of the tool electrodes. Figure 5(c) and 5(d) indicate that increasing pulse time increases the inner and outer edge radii. It is also shown that the increasing discharge current increases the inner and outer radii of the edges [Fig. 5(e) and 5(f)]. The results are consistent with those obtained in Zerweck and Muller's work (1983), in which the edge rounding with machining duration was

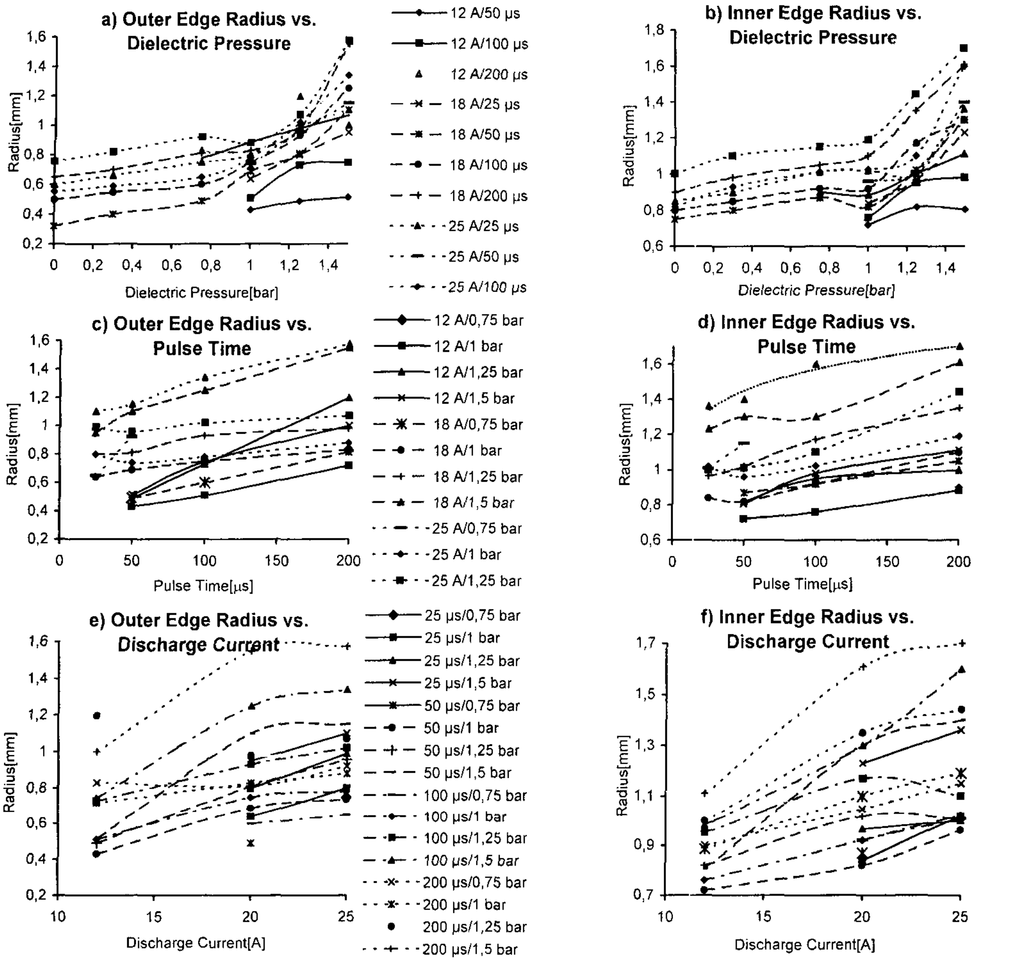

Fig. 5 Variation of edge radius with machining parameters

investigated for 20 A and 40 A settings for electroformed copper electrodes. For 40 A setting, the edge radii are found about twice to triple that of the 20 A setting with increasing depth of erosion.

2.2.5 The relation between tool edge rounding and machining outputs (WRR, TWR and RW)

When Fig. 3 and Fig. 5 are considered together, it is clear that the adjustment of the machining parameters, like discharge current, pulse time and dielectric pressure, in the direction of increasing TWR, also increases the tool edge wear radius. The increase in dielectric pressure does not cause a significant variation in TWR for high dielectric pressure settings used in this study, but it still increases the tool edge radius. Similarly, the high pulse time settings reduce the TWR though the edge radii increase. The large proportion of the TWR is due to the front wear of the tool. The loss of material due to edge wear is the small proportion of the total volumetric removal from the tool. Therefore, the edge radii of the tool can not be easily predicted from the TWR values, and some of the variations of machining parameters which cause an increase in edge wear cannot be considered equally effective in increasing TWR.

2.2.6 Modeling of the wear profiles and variation of exponential model parameters with machining parameters

In this work, it is found that circular arcs can only represent a limited portion of the profiles [i.e. the arc 'bc' in Fig. 1(c)]. The circular arc does not fit to the arc segment 'ad' completely (especially 'ab' and 'cd' segments) (Fig. 4). In order to represent the profile segment 'ad' with a single function, several models (functions) are considered. After the preliminary tests, the exponential function and power function are found to be the candidate statistical functions. The higher correlation constants (r and r^2) indicate the better fit of the tested model. The investigation indicates that 99 profiles out of 104 give better correlation constants (r and r^2) of the regression analysis for exponential model (Table 1). Better fit of the exponential function is also clear from the visual examination of the plotted functions with experimental edge profiles (Fig. 4). It is also tested and validated that the four edge wear profiles given by Mohri et al. (1995) can be represented perfectly by the exponential function instead of the circular arcs.

Further analysis is conducted to observe the variation of the model parameters of the exponential model a and b, with machining parameters. For the examined edge profiles, the model parameter a vary between 0.3 and 1.2 and b between 2 and 6. For the described range of a and b values, the shape variation of the exponential distribution is given in Fig. 6. The higher value of the a reflects more seperation of the curves from the horizontal line. The larger amount of edge wear should be represented by the higher values of a. The b value of the exponential model reflects the curvature characteristics of the profiles. For the increasing value of b, the radius of the curvature of the exponential curve gets smaller (Fig. 6).

In Figs. 7 and 8, the variations of a and b values for edge profiles with varying machining parameters are presented. The a value increases with dielectric pressure [Fig. 7(a) and 8(a)]. The increasing trend is very uniform especially for low pressure settings. Figures 7(c), 7(e), 8(c) and 8(e) show the increasing value of a with pulse time and discharge current. From Figs. 7(b), 7(d), 7(f), 8(b), 8(d) and 8(f), it is clear that the

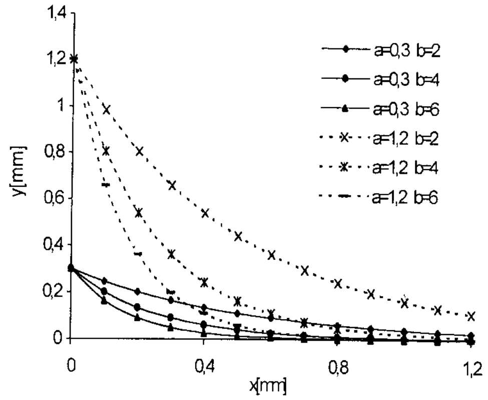

Fig. 6 Various shapes of the exponential model

increasing dielectric pressure, pulse time and discharge current reduce the b value for both inner and outer edges. As explained before, the increasing dielectric pressure, pulse time and discharge current increase the outer and inner edge profile radii. Therefore, it can be concluded that the machining parameters which increase the edge radius increase the a value and decrease the b value of the exponential model. This trend is common in almost all results. The variation of a and b with machining parameters formulated mathematically by using power functions in the following forms ;

$$a = A(I)^{C1} (t_p)^{C2} (P)^{C3} \quad (1)$$

$$b = B(I)^{D1} (t_p)^{D2} (P)^{D3} \quad (2)$$

Here, A, B, C1, C2, C3, D1, D2 and D3 are the constants. In Table 2, the constants of the power function and the correlation coefficients solved using a software, which is linked to MATLAB software package, are given. The correlation coefficients of least-square analysis, which indicate the goodness of fit of the power function to the experimental results, indicate that the power function is a suitable expression to represent the variations of a and b with the varying machining conditions. Chi-square goodness of fit is also used to check the validity of the power function and its constants. An excellent fit with significance level (α) of 0.999, verifies the correctness of the selected function (Table 2).

Eight experiments are conducted at 40μs and 150μs pulse time, 0.5 bar and 1 bar dielectric

Table 2 The power function constants and correlation coefficients

	A	C1	C2	C3	χ^2(calculated) (α=0,999)	χ^2(critical) (α=0,999)	Correlation Coefficient (r)
Outer edge	0,0445	0,836	0,0794	0,0608	0,60	24,7	0,878
Inner edge	0,0484	0,837	0,0958	0,1858	1,32	24,7	0,828
	B	D1	D2	D3	χ^2(calculated) (α=0,999)	χ^2(critical) (α=0,999)	Correlation Coefficient (r)
Outer edge	14,363	−0,356	−0,0517	−0,135	2,19	24,7	0,805
Inner edge	46,670	−0,739	−0,0903	−0,223	6,97	24,7	0,787

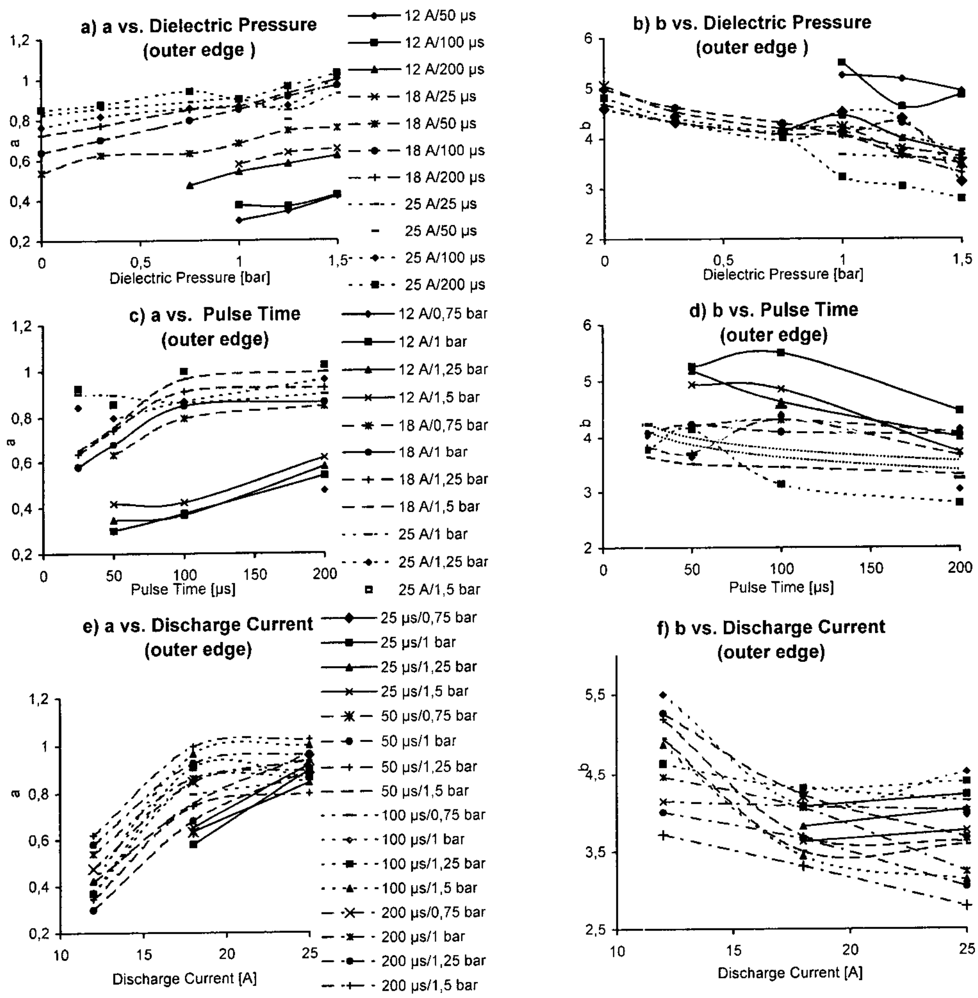

Fig. 7 Variation of exponential model parameters a and b with machining parameters for outer edge profiles

pressure and 16 A and 22 A discharge current settings by using the same type of tool electrode and workpiece. The experimental edge profiles are compared with the profiles obtained from exponential model with a and b values solved from Eqs. (1) and (2). The correlation coefficients (r) obtained from the least-square analysis are in the range of 0.825–0.915 (indicates a very good fit). The experimentally obtained values and predicted values from Eqs. (1) and

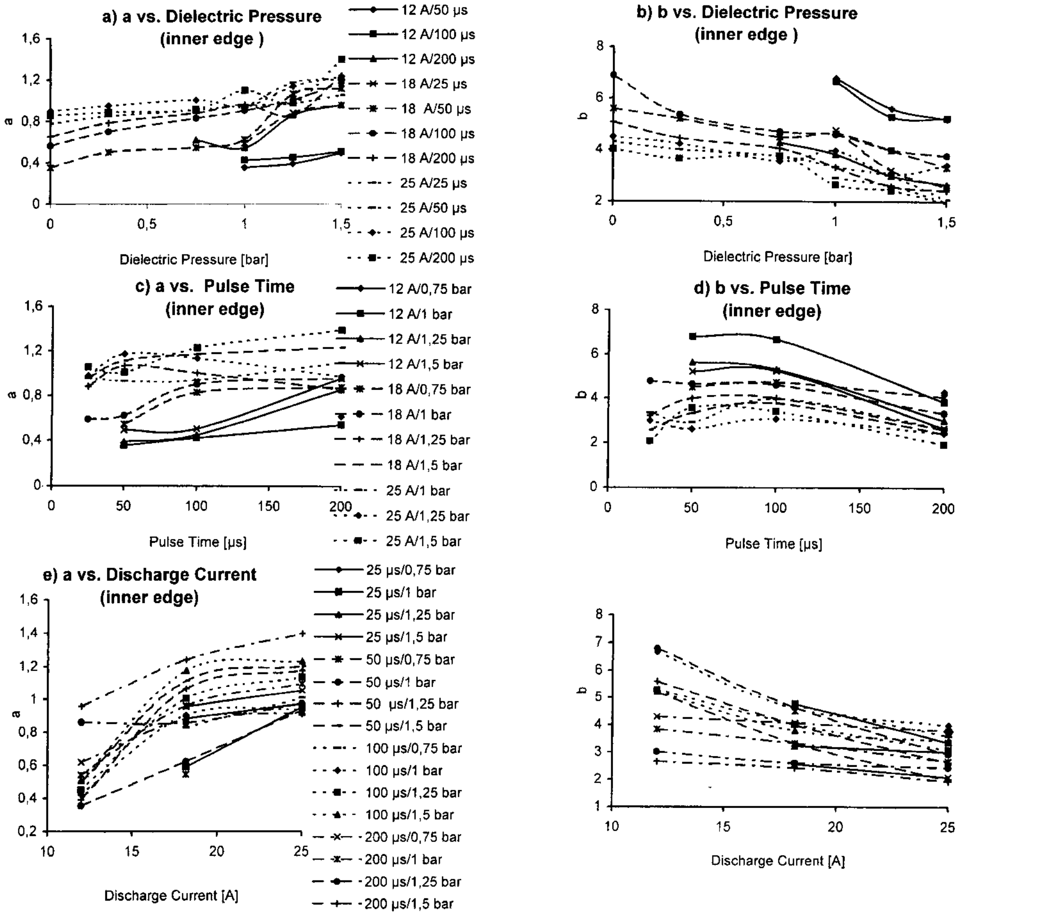

Fig. 8 Variation of exponential model parameters a and b with machining parameters for inner edge profiles

(2) verify the validity of the proposed exponential model, and its parameters formulated in Eqs. (1) and (2) in modeling the edge wear profiles. It can be concluded that the prediction of the edge wear profile for the performed pilot experiments are possible by using the exponential model and its parameters.

The effects of machining time (erosion depth), polarity and geometrical properties (size and shape) of the tool electrode on modeling of edge wear are not introduced in this study. The increasing edge radius with machining time is introduced and investigated before (Zerweck and Müller, 1983). The wear model suggested in this study would not be changed since there is no observed geometrical deviation from circular form except its increasing radius with machining time. The increasing radius with time can be easily simulated by decreasing b and increasing a value in the suggested model. Since there is no further rounding in the edge after 10mm depth of sinking (Zerweck and Müller, 1983), the a and b values would remain unchanged after certain depth of tool sinking. In this study, the normal polarity is used in all experiments. The reverse polarity is mostly used for carbon tool electrodes. Nowadays, the copper and its alloys (containing tungsten) are very popular in EDM technology (about 90% of EDM applications) due to their reasonable cost, easy shaping/machining and good WRR and RW performance. Therefore, the effect of reverse polarity on the edge wear modeling is not considered. The shape change of the tool electrode would bring the problem of nonuniform dielectric flow in the gap, which naturally results in nonuniform wear on the working surface of the tool. In such a case, the machining surface of the tool should probably seperated into different geometric regions according to their distance from the flushing point(s). Then, the edge wear at these regions should be considered seperately and different a and b values should be assigned to the edge profiles in every region. The cylindrical electrode with center hole flushing gives symmetrical and predictable velocity and flow behaviour of the dielectric, which makes the modeling possible. The use of the exponential model in modeling of the edge wear for different shape of the tool electrodes would be an interesting future research work, which needs extensive experimental and theoretical efforts.

3. Conclusions

It is found that the WRR and TWR are increased with the increasing discharge current. The increase in TWR with pulse time is evident at low pulse time settings. At high pulse time settings, a slight reduction in TWR is observed. The WRR is increased by increasing pulse time. The increasing dielectric pressure slightly improves the WRR, especially at high current settings. The results are attributed to the increasing removal effect (energy) of discharge pulses from both tool electrode and workpiece with increasing pulse time, discharge power and dielectric pressure. The RW is reduced with increasing pulse time. A slight increase in RW is observed with increasing current. The variation of TWR and RW with the dielectric flushing pressure is insignificant for the high pressure (above 1 bar) values.

The outer and inner edge wear profiles of the cylindrical copper tool electrodes are represented by circular arcs and their radii are found. The inner edge radii are higher than outer radii of the tool electrode in all machining conditions. The inner and outer edge radii are found to be increasing with the pulse time, discharge current and dielectric flushing pressure. The experiments conducted under static dielectric (no flushing) conditions indicate that the inner and outer edge radii are always smaller than that of flushing case. In static dielectric flushing conditions, the inner edge radius is still slightly larger than outer radius. This is attributed to the high electric field generated at around the flushing hole in the gap causing higher density of discharges. The authors believe that the higher electric field density at around the flushing hole and irregular (turbulent) nature of the higher velocity dielectric flow at the inlet of the workpiece-tool frontal gap are the two basic reasons resulting in occurrence of larger number of discharges causing larger edge radius. It is also found that very high dielectric flushing pressure values (above 1 bar) increase both inner and outer edge radii (wear) causing rapid tool edge profile degeneration.

It is found that the fitted circular arcs to the edge profiles can only represent the limited portion of the profiles. The exponential model with model parameters a and b can perfectly be used to model the edge wear profiles. The a value reflects the separation of the edge wear profile from the horizontal line, and the b value reflects the curvature characteristics. The increasing dielectric pressure, pulse time and discharge current can be presented by the increase in a and the decrease in b values. It is also shown that a and b values of the model can be represented in terms of the machining parameters by using the power function. The proposed exponential model and its parameters expressed by power functions are tested by the experiments and successful results are obtained. It is possible to predict the edge wear profiles by using the model and its parameters determined by the conducted pilot experiments.

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