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Experimental Investigation of the Pulse and Plasma Flushing Efficiency in Electrical Discharge Machining

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ABSTRACT

This paper presents a study of the relationship between Electrical Discharge Machining (EDM) parameters on the EDM efficiency factors using a full factorial design, based on pulse on-time, duty cycle and tool polarity parameters in EDM machining of AISI H13 tool steel. The results show that, in positive polarity, the plasma flushing efficiency and pulse efficiency increase according to the pulse-on time, but plasma flushing efficiency decreases over 15(μs) pulse duration only under negative polarity of electrode. Based on the experimental results, the plasma flushing efficiency and pulse efficiency increases when the duty cycle increases in positive tool polarity.

Keywords: Pulse-on time; Duty cycle; Polarity; Pulse efficiency; Plasma efficiency

1 INTRODUCTION

ELECTRO-DISCHARGE machining (EDM) is a fundamental manufacturing process, which has been extensively used in the tool and die industry[1]. This process is known by a perfect reproduction of the shape of the tool on the workpiece. It uses thermal energy to generate heat that melts and vaporizes the workpiece by ionization within the dielectric medium. The electrical discharges generate impulsive pressure by dielectric explosion to remove the melted material [2]. Fig. 1 shows created plasma channel and discharge crater for each spark respectively. According to previous researches, only 15% of the molten workpiece material is flushed away by the dielectric. The remaining material re-solidifies on the EDM surface due to the fast cooling rate generated by the dielectric. This recast layer is referred to as the white layer since it is very difficult to etch and because its appearance when, observed through an optical microscope, is white [1].

(a) (b)

Fig. 1
Discharge crater for each spark [3], a: created plasma channel, b: discharge crater after each spark.

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Hot-worked H13 tool steel was used in this study in precision molds of manufacturing tools for processing or die casting since it has advantages of high resistance to thermal shock and thermal fatigue, high abrasion resistance and heat resistance. Due to the nature of electric current and voltage at EDM process, according to the type, shape and number of generated plusses the process can be controlled, its status can be interpreted and instructions can be sent online to control unit. Among available pulses, four different types (open pulse, short circuit, normal pulse and arc pulse) are quite distinct and important. In open pulse current was zero and voltage was equal to open voltage. Neither spark nor thermal heat is produced in this pulse. During machining, if collision or contact directly or by locating debris is occurred between the workpiece and electrode, short circuit is generated. Also in machining operations, if the distance between the electrode and the work piece is infected and no new dielectric fluid is located in, the generated pulse is arc. The normal pulse, leads to erosion and effective pulse [4].

Gostimirovic et.al [5] studied the influence of effective parameters on the spark energy in machining manganese-vanadium tool steel with copper electrode. Based on survey results, spark energy directly depends on the pulse-on time and current, by increasing these parameters material removal rate and surface roughness increase as well. The study also determined that by assuming R_{max} as radius of discharge crater on the work piece surface, acceptable result can be achieved. Descoeudres [6] studied the characteristics of created plasma channel during electrical discharge machining. The results, indicated the temperature difference between anode and cathode in electrical discharge machining process, thus the cathode surface temperature is reported much hotter than anode one. This phenomenon wastes the heat, generated by copper electrode, in negative polarity. Eubank et. al [7], by modeling the cathode and anode during electrical discharge machining process, concluded that, during electrical discharge, plasma channel formation starts on anode then, first anode is melted then plasma channel length reaches to cathode. This phenomenon makes positive pole plasma channel radius larger than the negative one, this alters erosion of the positive and negative poles in different circumstances. Kokubo et al. [8], studied the effect of two types of dielectric (kerosene and De- ionized Water), tool polarity and pulse-on time on the volume of removed material and discharge crater depth during electrical discharge machining process of AISI 1049 steel survey and reported that increasing pulse-on time in both tool polarities, increases the discharge crater depth and volume of removed material. Pandey & Singh [9], introduced pulse-on time, pulse-off time, gap between electrode and work piece, duty cycle and tool polarity as essential electrical input parameters and rotation of tool electrode, type of flushing, tool geometry and tool material as non- electrical input parameters. Based on this research, by decreasing the pulse-off time (T_{off}) to the extent that process keeps its stability and simultaneously increasing the pulse-on time, material removal rate can be increased.

Due to the complexity of analyzing created pulses and theoretical modeling of machining operations for investigating plasma flushing efficiency (%PFE) and efficiency pulse, the purpose of this study is experimentally to investigate the effect of input parameters (pulse-on time, (T_{on}), duty cycle (T_{on} / (T_{on} + T_{off})) and tool polarity) on plasma flushing efficiency and pulse efficiency in the machining AISI H13 tool steel.

2 EXPERIMENTAL PROCEDURES

For steel samples preparation, first cutting and turning operations were performed and 20 cylindrical steel samples were prepared. Then, in order to achieve the desired hardness (52-45 HRC) heat treatment process for H13 steel was carried out precisely. In EDM process tool properties including electrical and thermal conductivity, melting point and specific heat are important. Because of high electrical conductivity and convenient machining capabilities, copper is used widely [10]. Thus, copper tools were used for testing and preparing electrodes for machining operations.

To study the effect of different levels of input parameters on the plasma flushing efficiency and efficiency pulse, the tests are designed by full factorial design (pulse-on time at five levels, duty cycle and tool polarity at two levels). They were tested at positive polarity (2×5=10) and at negative polarity (2×5=10). All the samples were machined by die sinking EDM machine (Tehran-Ekram-CNC) at Iso pulse mood for 20 minutes. To calculate the total volume of material removed, the sample before and after machining operations were weighed by (CP2245-Surtorius) digital balance. To measure the surface roughness of machined work pieces, maximum surface roughness (R_{max}) parameter was used and its values were measured by Maher-perthometerM2.

Table 1
Material and input parameters levels at full factorial design.

Generator type	Iso pulse
Work piece	H13 steel Ø 20×20 mm
Tool	Copper Ø 18 × 20 mm
Tool polarity	Positive and negative
Dielectric	Kerosene oil
Flashing type	Normal submerged
Gap	0.01
Duty cycle	20%,30%
Power (A)	16
Pulse-on time (μs)	6 , 10 , 15,25,50
Voltage (V)	200

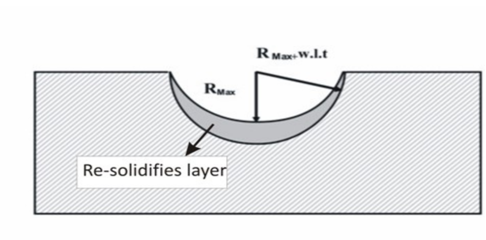


Fig. 2
Schematic view of discharge crater.

In order to measure the thickness of re-solidified layer thickness, first machined samples were cut by Wire Cutting EDM with 0.01(mm) resolution. After sample preparation, microscopic images prepare from the layers near the machined surface by an Olympus PMG3 optical microscope. Table 1 shows input parameters used in the test.

3 RESULTS AND DISCUSSION

To calculate the metal removed volume per discharge, the radius of discharge craters, supposed to be hemispherical, after machining operations on the surface of work piece, can be assumed equal to R_{max} Fig. 2. In this case, the volume of created crater on the surface of work piece is equal to the volume of removal metal which is calculated according to Eq. (1):

$$V_e = \frac{2}{3}\pi R_{\max}^3 \quad (1)$$

where V_e is the volume of removal material per one spark (mm^3) and R_{max} is the maximum roughness (μm) [5-11]. Also according to the Fig. 2 and Eq. (1) the total volume of discharge crater (V_t) includes the collection of white layer volume and volume of removal metal of the work piece surface per discharge (V_t) that can be stated by Eq. (2):

$$V_t = \frac{2}{3}\pi (R_{\max} + t_{wlt})^3 \quad (2)$$

where t_{wlt} is the average white layer thickness (w.l.t) on the work piece (μm). PFE (%) is used to estimate the fraction of each discharge molten material that is removed from discharge crater in each spark and evaluate the efficiency of the EDM process which is defined Eq. (3):

$$\text{PFE (\%)} = \frac{V_e}{V_t} \times 100 \quad (3)$$

Using Eq. (1) and Eq. (2), PFE (%) described as Eq. (4):

$$\text{PFE}\ (\%) = \left(\frac{R_{\max}}{R_{\max} + t_{wlt}}\right)^3 \times 100 \tag{4}$$

At EDM process the spark frequency is usually between 500-500000 spark in a second, material removing is done by calculating their effect during machining [12]. Since all pulses created by pulse producer, do not result in spark pulse and material removal, estimating pulse spark percentage is important for getting optimal statues for machining. Eq. (5) is the relation between the number of effective frequency (spark pulse) and total volume of removed material during machining.

$$V_w = V_e \cdot f_f \tag{5}$$

where V_w is material removal rate (mm^3/s), f_f is the number of pulse per second which cause erosion ($^1/s$) and V_e is the volume of removed material per one sparks (mm^3). Therefore, by using Eq. (5) the numbers of spark pulses are calculated. Pulse efficiency in EDM is resulted from the division of spark pulse number to total number of sparks, which is described as following:

$$\text{Pulse efficiency}\ (\%) = \frac{f_f}{f_p} \times 100 \tag{6}$$

where f_f is the number of spark pulse and f_p is the total created pulse by control unit per second. f_p values are obtained from Eq. (7):

$$f_p = \left(\frac{10^6}{T_{on} + T_{off}}\right) \tag{7}$$

where T_{on} and T_{off} are in microseconds. Table 2 shows the amount of measured technological parameters after machining operation for calculating pulse efficiency and plasma flushing efficiency. Also, Fig. 3 shows the process and steps of the calculation.

Table 2
Input and output technological parameters

Machining conditions		Technological performances of EDM					
		Polarity (-)			Polarity (+)		
Duty cycle	T_{on} (μs)	V_t (mm^3/s)	$w.l.t$ (μm)	R_{max} (μm)	V_t (mm^3/s)	$w.l.t$ (μm)	R_{max} (μm)
20%	6	1.3×10^{-3}	38.52	10.12	6.516×10^{-3}	26.5	17.01
	10	2×10^{-3}	53.52	16.22	0.014	28.9	24.29
	15	2.1×10^{-3}	54.2	16.8	0.0285	36.1	25.58
	25	1.6×10^{-3}	67.07	15.61	0.0818	40.1	31.52
	50	1.5×10^{-3}	76.38	12.41	0.286	43.3	35.29
30%	6	2.06×10^{-3}	38.44	12.12	0.029	25.32	20.41
	10	3.48×10^{-3}	45.28	19.52	0.052	28	28.5
	15	3.8×10^{-3}	45.52	20.1	0.085	35.38	29.32
	25	2.88×10^{-3}	58.72	19.13	0.174	38.1	32.89
	50	2.4×10^{-3}	77.2	14.28	0.455	41.18	35.45

3.1 *Effect of pulse-on time and duty cycle on pulse efficiency*

Fig. 4 and 5 show the effect of pulse-on time on pulse efficiency on pulse efficiency at positive and negative polarity. As it can be seen, by increasing the pulse-on time at both tool polarities, pulse efficiency increases as well. Since sparks energy is subordinate to pulse-on time, by increasing pulse-on time, more energetic sparks are created and plasma channel temperature is increased. Since the inside plasma pressure is subordinate to plasma channel temperature, by increasing the temperature, plasma channel pressure is increased as well and at pulse-off time, due to the high temperature difference at bulk boiling, created debris is slung to the far distance of discharge crater and the amount of pollution between electrode and work pieces decreases. Pollution reduction reduces the possibility of creating the short circuit, consequently, the pulse efficiency will increase as well due to increased in the number of normal pulse. Comparing Fig. 4 and 5 show the effect of duty cycle on pulse efficiency. According to Fig. 4, in the positive polarity, by increasing duty cycle, pulse efficiency increases as well. The reason can be justified in this way,

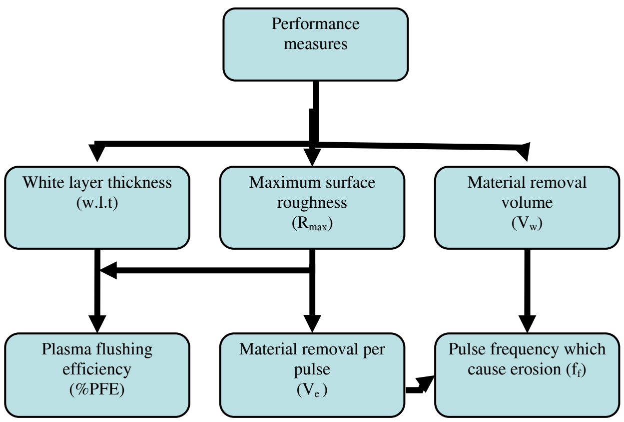


Fig. 3
Process of calculating the pulse efficiency and (%) PFE.

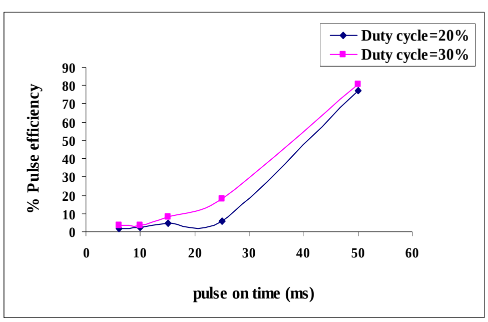


Fig. 4
The influence of the pulse-on time and duty cycle on the pulse efficiency in positive polarity.

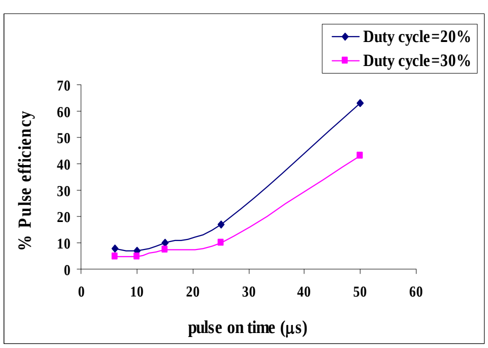


Fig. 5
The influence of the pulse-on time and duty cycle on the pulse efficiency in negative polarity.

with increasing duty cycle due to reduction pulse-off time, the number of sparks increases during machining and creates more sparks during machining time so this will result an in increase in spark efficiency. According to the Fig. 5, in the negative polarity, spark pulse is created in less duty cycle and in a less duty cycle, greater percentage of the sparks cause erosion. The reason relies on the fact that in negative polarity, due to the deformation of debris from spherical in positive polarity to the non-spherical in negative polarity [8], the pollution between machining gap increases, on the other hand, increases of the duty cycle due to reduced pulse-off time and less flushing, debris accumulation increases between electrode and work piece and the possibility of occurring arc spark and short pulse increases and this consequently decreases pulse efficiency.

3.2 Effect of pulse-on time and duty cycle on plasma flushing efficiency

Fig. 6 shows the effect of pulse-on time on plasma flushing efficiency in positive polarity. According to Fig. 6, by increasing the pulse-on time, (%) PFE increases as well. The reason is that by increasing the pulse-on time, current density, spark energy and size of discharge crater on work piece surface as well as discharge crater volume are increased. Also, increasing the pulse-on time to an optimal level, pressure increases inside the plasma channel. Therefore, when the plasma channel is destroyed and the thermal runaway phenomenon occurs, a greater amount of molten metal is slung from discharge crater into the dielectric liquid and plasma flushing efficiency is increased. But the drop in plasma flushing efficiency after T_{on}=15(μs), can be described, that because of expanding plasma channel radius along with increasing pulse-on time, plasma channel compression in higher pulse-on times declines and plasma flushing efficiency lowers but along with the increase in pulse-on time to an optimal level plasma flushing efficiency will have an ascending trend. Fig. 7 shows the effect of pulse-on time on plasma flushing efficiency in negative polarity. According to Fig.7, by increasing the pulse-on time, (%)PFE like positive polarity case increases as well, but after pulse one time T_{on}=15(μs) , along with increasing in pulse-on time, plasma flushing efficiency decreases. Considering the point that the plasma channel radius in the work piece surface in the negative polarity was larger than the positive polarity and work piece surface temperature is lower than the one in negative polarity, Due to the large expansion of plasma channel on the surface after T_{on}=15(μs) and reduction of heat input flux to the workpiece surface [6-7], because of decrease in plasma channel pressure and heat input flux to surface, the possibility of slung molten material into the dielectric liquid decreases and greater percentage of molten material at work piece surface is re-solidified.

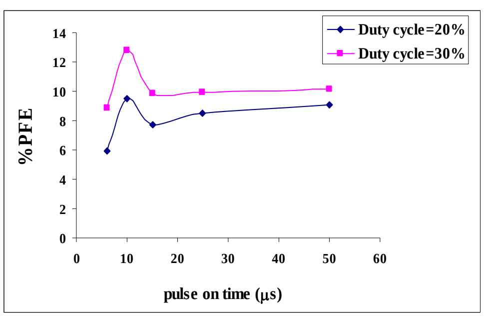


Fig. 6
The influence of the pulse-on time and duty cycle on the (%)PFE in positive polarity.

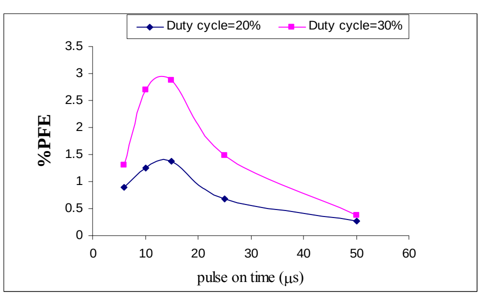
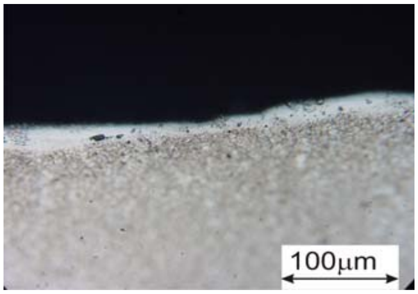
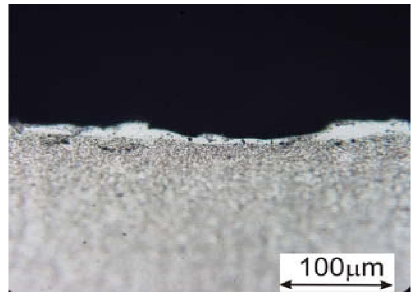


Fig. 7
The Influence of the pulse-on time and duty cycle on the (%)PFE in negative polarity.



(a)



(b)

Fig. 8
Influence of the tool polarity on the re-solidified layer (w.l.t) thickness an optical microscope(X500). a: negative polarity , b: positive polarity (T_{on}=25 (μs), duty cycle=30%).

This increases the volume of re-solidified layer at work piece surface, thus result in a drastic reduction in plasma flushing efficiency at negative polarity. Fig. 8 shows the increase in the average thickness of re-solidified layer on the work piece surface at negative polarity.

4 CONCLUSIONS

The experimental study of the EDM of AISI H13 workpiece steel provided important quantitative results for obtaining possible high plasma flushing efficiency. The leading conclusions are as follows:

1. Increasing pulse-on time at both tool polarity, the pulse efficiency is increased.
2. In case of positive polarity, most of spark pulse occurs at a higher duty cycle while in negative polarity the highest percentage of spark pulse occurs in less duty cycle.
3. While increasing the pulse-on time in positive polarity, the plasma flushing efficiency is increased
4. In case of negative polarity, plasma flushing efficiency is initially increased but at higher pulse-on times with increasing pulse-on time, is declined.
5. Increasing duty cycle, plasma flushing efficiency at both tool polarities is increased.

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