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Investigation of cylindrical wire electrical discharge turning (CWEDT) of AISI D3 tool steel based on statistical analysis

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Abstract

In this work, a surface roughness (Ra), roundness and material removal rate (MRR) study on the cylindrical wire electrical discharge turning (CWEDT) has been carried out. The material chosen in this case was AISI D3 tool steel due to its growing range of applications in the field of manufacturing tools, dies and molds as punch, tapping, reaming and so on in cylindrical forms. This study was made only for the finishing stages and has been carried out on the influence of four design factors: power, voltage, pulse off time and spindle rotational speed, over the three previous mentioned response variables. This has been done by means of the technique of design of experiments (DOE), which allows us to carry out the above-mentioned analysis performing a relatively small number of experiments. In this case, a $2^2 \times 3^2$ mixed full factorial design, has been selected considering the number of factors used in the present study. The resolution of this factorial design allows us to estimate all the main effects, factor interactions and pure quadratic effects of the four design factors selected to perform this study. For MRR, Ra and roundness regression models have been developed by using the response surface methodology (RSM).

Keywords: Wire EDM; CWEDT; Ra; Roundness; MRR; DOE; RSM; AISI D3 tool steel

1. Introduction

Electrical discharge machining (EDM) is a thermoelectric process that erodes workpiece material by a series of discrete electrical sparks between the workpiece and electrode. Unlike traditional cutting and grinding processes which rely on a much harder tool or abrasive material to remove the softer work material, the EDM process utilizes electrical sparks or thermal energy to erode the unwanted work material and generate the desired shape. These sparks generate craters and the recast layer on the surface of the EDM workpiece. Wire electrical discharge machining (WEDM) is a widely accepted non-traditional material removal process used to manufacture components with intricate shapes and profiles. It is considered as a unique adaptation of the conventional EDM process, which uses an electrode to initialize the sparking process. However, WEDM utilizes a continuously traveling wire electrode made of thin copper, brass or tungsten of diameter 0.05–0.3 mm, which is capable of achieving very small corner radii. During the WEDM process the hardness and strength of the work materials are no longer the dominating factors that affect the tool wear and hinder the machining efficiency. This makes EDM particularly suitable for machining hard, difficult-to-machine materials, such as the metal–matrix composites (MMC). Without WEDM the fabrication of precision workpieces requires many hours of manual grinding and polishing.

The concept of cylindrical wire electrical discharge turning (CWEDT) is illustrated in Fig. 1. A rotary axis is added to a conventional five-axis wire EDM machine in order to produce cylindrical forms [1,2]. The initial shape of the part needs not to be a cylindrical form. The electrically charged wire is controlled by the X and Y slides to remove the work material and generation of the desired cylindrical form. Some turning wire EDM works have been reported for manufacturing small pins by Dr. Masuzawa's research group at the University of Tokyo [3–5]. The small-diameter pins can be used as tools for 3D micro EDM application. An example of the machined-parts using the CWEDT method is shown in [1,2]. Also the application of a water-cooled submerge-spindle extends the application of WEDM to WEDM turning with rotation speeds

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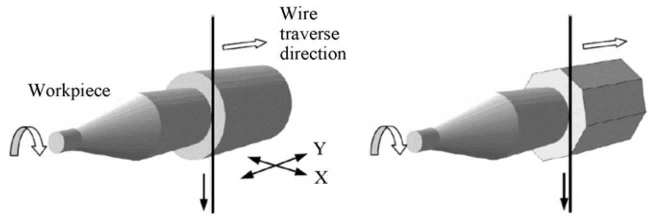

Fig. 1. The concept of turning with wire EDM [2].

up to 2800 rpm. This enables the production of gear wheels with integrated shafts for easy gear assembly [6]. The feasibility of using cylindrical WEDM for dressing a rotating metal bond diamond wheel used for the precision form grinding of ceramics has also been studied [7]. The results show that the WEDM process is capable of generating precise and intricate profiles with small corner radii. Qu et al. [8] investigated through a mathematical model the surface integrity of CWEDT parts. The same authors derived a mathematical model for the material removal rate (MRR) of a CWEDT process [2]. Mohammadi et al. [9] investigated turning by wire electrical discharge machining to evaluate the effects of machining parameters on Ra and roundness. Also, they investigated turning by wire electrical discharge machining to evaluate the effects of machining parameters on MRR by using the Taguchi approach in design of experiments (DOE) [1].

There are also a number of published works that solely study the effects of the machining parameters on the WEDMed surface. Gökler and Ozanözgü [10] studied the selection of the most suitable cutting and offset parameter combination to get a desired Ra for a constant wire speed and dielectric flushing pressure. Tosun et al. [11] investigated the effect of the pulse duration, open circuit voltage, wire speed and dielectric flushing pressure on the WEDMed workpiece Ra. It was found that increasing the pulse duration, open circuit voltage and wire speed increases with the Ra, whereas increasing the dielectric fluid pressure decreases the Ra. Anand [12] used a fractional factorial experiment with an orthogonal array layout to obtain the most desirable process specification for improving the WEDM dimensional accuracy and Ra. Spedding and Wang [13] optimized the process parameter settings by using artificial neural network modeling to characterize the WEDMed workpiece surfaces, whilst Williams and Rajurkar [14] presented the results of the current investigations into the characteristics of WEDM generated surfaces.

This study investigates the roughness, roundness and MRR of turning parts via the CWEDT process and explores possible ways to adjust its parameters to achieve better roundness by statistical methods. The experiments are employed in this study to consider the effects of power, pulse off time, voltage and spindle rotational speed on MRR, Ra and roundness. This was done using the technique of design of experiments and techniques such as response surface methodology (RSM) for regression analysis. The combined use of these techniques has allowed us to create models, which make it possible to explain the variability associated with each of the technological variables studied in this work.

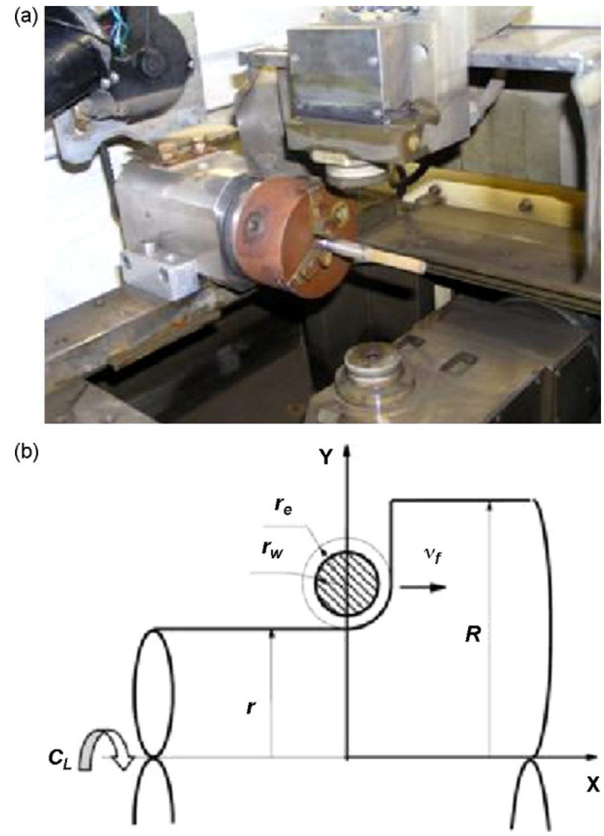

Fig. 2. Experimental setup: (a) spindle in five-axis WEDM machine; (b) turning profile.

2. Instruments and experimental design

2.1. Experimental setup

In this research, all experiments are conducted on ONA R250 wire EDM machine. The wire EDM machine was equipped with a rotary axis in order to produce cylindrical forms (Fig. 2(a)). The surface finish was measured using a mobile roughness measurement (Mahr Perthometer M2) with a 0.8 mm cut off length (according to DIN EN ISO 3274:1998). The roundness of machined parts was measured using a Coordinate Measuring Machine (ZEISS Prismo 5 CMM). The straight turning configuration as shown in Fig. 2(b) is used for this study. Theoretical Eq. (1) can be derived to describe the calculation for MRR:

$$\mathrm{MRR} = \pi(R^2 - r^2)v_{\mathrm{f}} \quad (1)$$

where R is the original radius of the workpiece, r the final radius of the workpiece after machining, and v_{f} is the machining cutting speed or feed rate [2].

2.2. Design of experiments

Factors and their levels are shown in Table 1. Power, pulse off time, voltage and spindle rotational speed are adopted as factors (independent variables) which vary during the experiments. Fixed factors are in Table 2. These factors are set apart from the experiment, and they are neither presumed to have effect on the process, nor can vary because of the equipment setup. A proper design of experiments is conducted to perform more accurate, less costly and more efficient experiments. Full factorial technique is used widely in DOE lately and is employed to perform the experimental design [15,16]. In this case a mixed full factorial design, $2^2 \times 3^2$ design, has been selected due to the number of factors and factor levels considered in the study. Thus, 36 experiments were conducted at parameter levels shown in Table 1. Each run is replicated two times so that the total number of runs is 72. The resolution of this full factorial design allows

Table 1
Factors, factor levels, and factor designation

Factors	Factor levels		
	1	2	3
Power (level of current); for each power level there is a corresponding average current between wire and workpiece	10	11	–
Pulse off time (μs); time interval between one discharge and the next	6	8	10
Voltage (V); indicated potential difference during ionization of the gap	100	110	120
Spindle rotational speed (rpm)	16	45	–

Table 2
Non-variable parameters in this experimentation

Factors	Factor levels
Max. feed rate (mm/min)	1
Depth of cut (mm)	2
Diameter of specimens (mm)	10
Workpiece hardness (HRC)	62 ± 2
Material	AISI D3
Machining length (mm)	10
Servo (V)	50
Wire tension (kg)	16
Wire speed (mm/s)	8
Dielectric	31
Inverse, finish	Off

us to estimate all the main effects, factor interactions in this study. Note that run orders are used randomly during the experiment.

3. Data analysis

3.1. Analysis of surface roughness

Eq. (2) presents the linear relationship between factors, factors effects and surface roughness (response) which is the result of response surface regression analysis.

$$\mathrm{Ra}\,(\mu\mathrm{m}) = -6.04139 + 1.06098 \times \text{power} + 0.02664 \times \text{voltage} - 0.14981 \times \text{pulse off time} - 0.01182 \times \text{spindle rotational speed} \quad (2)$$

Table 3 indicates that the regression model is the best one in comparison with the others that can be used with these factors and factor levels by R^2_{adj} test (The R-Sq (R^2) value indicates that the predictors explain 70.9% of the variance in Ra). The R-Sq (adj) (R^2_{adj}) is 69.2%, which accounts for the number of predictors in the model. Both values indicate that the model fits the data well. Table 4 shows the coefficients of factors and factor effects in regression model. Table 5 shows the ANOVA table for regression analysis. This table indicates that the model estimated by regression procedure is significant at an α-level of 0.05. This implies that at least one coefficient is different from zero. Table 6 shows verification of the test results. The predicted machining parameters performance was compared with the actual machining performance and a good agreement was obtained between these performances. The above mathematical model for surface roughness of CWEDT is of great importance to the proper selection of machining parameters during the machining of the cylindrical parts.

Fig. 3 shows that power, voltage, pulse off time and spindle rotational speed have the most significant effect on Ra. In addition, power has direct proportion to the Ra; that is, by increasing power, Ra increases significantly. Also it is indicated from this figure that voltage has a significant effect on Ra, because at lower voltage Ra increases strongly with increasing voltage, but at higher voltage the rate of increase is much less. As indicated in Fig. 3 pulse off time and spindle rotational speed have reverse effects on Ra.

Fig. 4 shows the estimated response surface for the Ra parameter, according to the design parameters of voltage and pulse off time, whilst the other factors remain constant in their central values. It is indicated that by increasing the pulse off time values and decreasing the voltage values, the amount of Ra is

Table 3
Table of R^2 and R^2_{adj} test for regression model for Ra analysis

Degree	R-Sq (%)	R-Sq (adj) (%)
Linear	70.9	69.2
Linear + squares	71	68.4
Linear + interaction	72.6	68.1
Full quadratic	72.2	67.2

Table 4
Table of regression model for Ra analysis

Term	Coef.	S.E. coef.	*T*	*P*
Constant	−6.04139	1.29149	−4.678	0
Power	1.06098	0.10116	10.488	0
Voltage	0.02664	0.00619	4.301	0
Pulse off time	−0.14981	0.03097	−4.837	0
Spindle rotational speed	−0.01182	0.00349	−3.389	0.001
S = 0.4292	R-Sq = 70.9%		R-Sq (adj) = 69.2%	

Table 5
ANOVA table for regression model for Ra analysis

Source	d.f.	Seq SS	Adj SS	Adj MS	*F*	*P*
Regression	4	30.094	30.094	7.5235	40.84	0
Linear	4	30.094	30.094	7.5235	40.84	0
Residual error	67	12.342	12.342	0.1842		
Lack-of-fit	31	6.263	6.263	0.202	1.2	0.3
Pure error	36	6.079	6.079	0.1689		
Total	71	42.436				

Table 6
Results of confirmation tests for Ra analysis

Run	Power	Voltage	Pulse off time	Spindle rotational speed	Results of model (Ra)	Results of experiments (Ra)	Regression error (%)
1	11	120	6	16	7.74	7.48	3.4
2	10	100	10	45	5.2	5.2	0
3	11	110	8	45	6.83	6.872	−0.6
4	12	105	12	90	6.63	6.78	−2.2

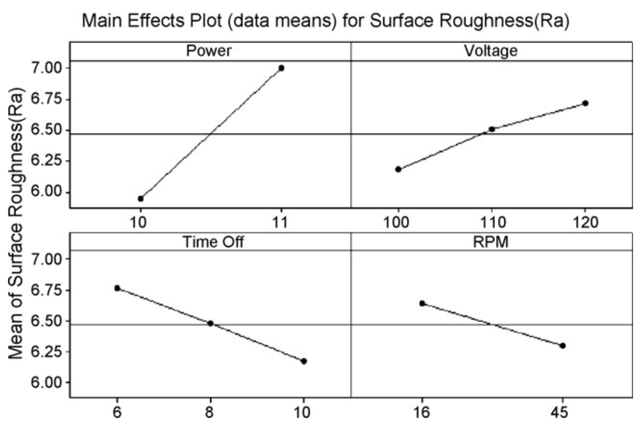

Fig. 3. Effects of factors on Ra.

minimized. Whilst, in the higher values of voltage by increasing the pulse off time values, Ra decreases. Also, in the lower values of pulse off time by decreasing the voltage values, Ra decreases.

3.2. Analysis of roundness

Eq. (3) presents the relationship between factors and roundness (response) which is the result of response surface full quadratic regression analysis.

$$\begin{aligned}\text{Roundness}\,(\mu\text{m}) = {} & 0.046354 + 0.002631 \times \text{power} - 0.00027 \\ & \times \text{voltage} - 0.00079 \times \text{pulse off time} \\ & - 0.00208 \times \text{spindle rotational speed} \\ & + 0.000017 \times \text{voltage} \\ & \times \text{spindle rotational speed} \end{aligned} \tag{3}$$

Table 7 indicates that the regression model is the best one in comparison whit the others that can be used with these factors

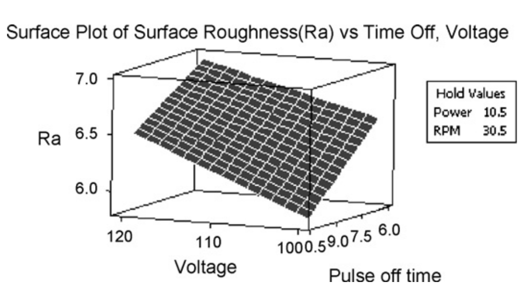

Fig. 4. Estimated response surface of Ra vs. voltage and pulse off time.

Table 7
Table of regression model for roundness analysis

Term	Coef.	S.E. coef.	*T*	*P*
Constant	0.046354	0.022612	2.05	0.044
Power	0.002631	0.001186	2.219	0.03
Voltage	−0.00027	0.000169	−1.587	0.117
Pulse off time	−0.00079	0.000363	−2.18	0.033
Spindle rotational speed	−0.00208	0.000552	−3.757	0
Voltage × spindle rotational speed	0.000017	0.000005	3.439	0.001
S = 0.005030	R-Sq = 44.8%		R-Sq (adj) = 40.6%	

and factor levels by R^2_{adj} test. The R-Sq (R^2) value indicates that the predictors explain 44.8% of the variance in MRR. The R^2_{adj} value is 40.6%, which accounts for the number of predictors in the model. Both values indicate that the model fits the data well. Also this table shows the coefficients of factors and factor effects in regression model. Table 8 shows the ANOVA table for regression analysis. This table indicates that all terms of the model estimated by regression procedure are significant at an α-level of 0.05. Table 9 shows verification of the test results. The predicted machining parameters performance was compared with the actual machining performance and a good agreement was obtained between these performances.

Fig. 5 shows the graph of the main effects for each of the factors which have been considered in this study. As can be seen in Fig. 5, the most influential factor over roundness is spindle rotational speed, in such a way that the value of the roundness decreases greatly when spindle rotational speed is increased. With regard to the power and voltage factors, as it is shown in Fig. 5, the value of roundness tends to increase when these factors are increased, but the effect of voltage on the roundness is much higher. The effect of pulse off time on the roundness is lower than others. Fig. 5 shows that with increasing pulse off time value, roundness decreases, especially in the higher values of pulse off time.

Table 8
ANOVA table for regression model for roundness analysis

Source	d.f.	Seq SS	Adj SS	Adj MS	*F*	*P*
Regression	5	0.001356	0.001356	0.000271	10.72	0
Linear	4	0.001056	0.001035	0.000259	10.22	0
Interaction	1	0.000299	0.000299	0.000299	11.83	0.001
Residual error	66	0.00167	0.00167	0.000025		
Lack-of-fit	30	0.000666	0.000666	0.000022	0.8	0.737
Pure error	36	0.001004	0.001004	0.000028		
Total	71	0.003026				

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Table 9
Results of confirmation tests for roundness

Run	Power	Voltage	Pulse off time	Spindle rotational speed	Results of model	Results of experiments	Error (%)
1	11	120	6	16	0.0375	0.035	7.19
2	10	100	10	45	0.0207	0.022	−5.43
3	11	110	8	45	0.0298	0.031	−2.26

Fig. 6(a) shows the estimated response surface of roundness in function of the factors of voltage and spindle rotational speed, whilst the pulse off time and power remains constant in their central values. Fig. 6(a) shows that by increasing the spindle rotational speed and decreasing the voltage values, the roundness values minimizes. It is clearly seen that in the higher values of voltage, the influence of spindle rotational speed is limited, but in the lower values of voltage, by increasing the spindle rotational speed values, the roundness values decreases strongly. As can be clearly seen in Fig. 6(a), in the higher values of spindle rotational speed, by increasing the voltage values, the roundness values increases.

Fig. 6(b) shows the estimated response of roundness, varying the factors of voltage and pulse off time. As can be clearly seen in this figure, by increasing the voltage and decreasing the pulse off time values, the roundness maximizes. The higher values of pulse off time and lower values of voltage, contributes significantly to the lowest values of roundness. Furthermore, in the lower values of pulse off time, by decreasing the voltage values, the roundness decreases. Also in the higher values of voltage, by increasing the pulse off time values, the roundness decreases.

Fig. 6(c) shows the estimated response surface of roundness in function of the factors of voltage and power, whilst the pulse off time and spindle rotational speed remain constant in their central values. Fig. 6(c) shows that by decreasing the power and voltage values, the roundness value minimizes. It indicates that in the higher values of voltage, by increasing the power value, the roundness decreasing. Also in the higher values of power, by decreasing the voltage value, roundness decreases.

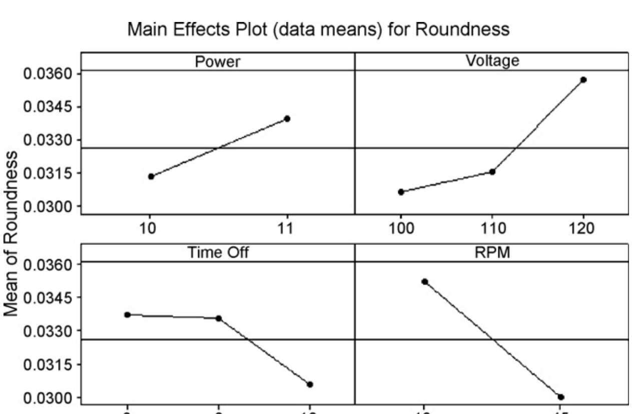

Fig. 5. Effects of factors on roundness.

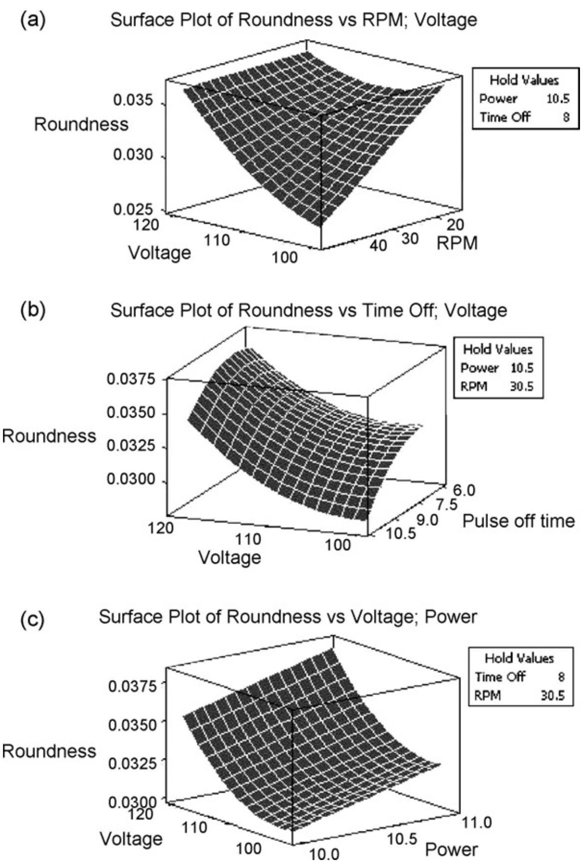

Fig. 6. Estimated response surface of roundness vs. (a) voltage and spindle rotational speed, (b) voltage and pulse off time, (c) voltage and power.

3.3. Analysis of material removal rate

Regression analysis is performed to find out the relationship between factors and MRR. Table 10 indicates that full quadratic model is the best one in comparison with the others that can be used with this factors and factor levels by R^2_{adj} test. The R-Sq (R^2) value indicates that the predictors explain 82.1% of the variance in MRR. The R-Sq (adj) (R^2_{adj}) is 78.4%, which accounts

Table 10
Table of R^2 and R^2_{adj} test for regression model

Degree	R-Sq (%)	R-Sq (adj) (%)
Linear	76.4	75
Linear + squares	78.2	76.2
Linear + interaction	80.2	77
Full quadratic	82.1	78.4

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Table 11
Table of first regression model for MRR analysis

Term	Coef.	S.E. coef.	T	P
Constant	18.1541	0.16804	67.558	0
Power	2.2902	0.07515	9.839	0
Voltage	−0.7931	0.09204	−11.167	0
Pulse off time	2.4353	0.09204	4.832	0
Spindle rotational speed	0.1788	0.07515	2.554	0.013
Voltage × voltage	0.0038	0.15942	2.354	0.022
Pulse off time × pulse off time	−0.0301	0.15942	−0.755	0.453
Power × voltage	0.0105	0.09204	0.573	0.569
Power × pulse off time	−0.22	0.09204	−2.39	0.02
Power × spindle rotational speed	−0.0069	0.07515	−0.668	0.507
Voltage × pulse off time	0.0001	0.11273	0.026	0.979
Voltage × spindle rotational speed	−0.0014	0.09204	−2.152	0.036
Pulse off time × spindle rotational speed	0.0039	0.09204	1.218	0.228
S = 0.6377	R-Sq = 82.1%		R-Sq (adj) = 78.4%	

for the number of predictors in the model. Table 11 shows the coefficients of factors and factor effects in regression model. It can be seen from Table 11 that some interaction effects have no significant effect in regression model, because their p-value is higher than 0.05, accepting that there is statistical evidence of curvature in the first-order model, for a confidence level of 95%. Thus, since the proposed first-order model is suitable for a significance level α of 0.05 is rejected and so, the second-order model is selected. Table 12 shows the regression table for the case of the proposed second-order model, where now, the total number of degrees of freedom is equal to 71. As can be seen in Table 12, all effects have a p-value less than 0.05, which means that they are significant for a confidence level of 95%. On the other hand, a value of 0.812 was obtained for the R^2-statistic, which signifies that the model explains 81.2% of the variability of MRR, whereas the adjusted R^2-statistic (R^2_{adj}) is 0.792. The ANOVA table for the MRR using the fitted model with linear, square and interaction terms is shown in Table 13. This table

Table 12
Table of second regression model for MRR analysis

Term	Coef.	S.E. coef.	T	P
Constant	8.96796	20.5238	0.437	0.664
Power	3.23882	0.7387	4.385	0
Voltage	−0.68118	0.3454	−1.972	0.053
Pulse off time	2.08759	0.951	2.195	0.032
Spindle rotational speed	0.13699	0.0688	1.991	0.051
Voltage × voltage	0.00375	0.0016	2.395	0.02
Power × pulse off time	−0.21999	0.0905	−2.432	0.018
Voltage × spindle rotational speed	−0.00137	0.0006	−2.189	0.032
S = 0.6268	R-Sq = 81.2%		R-Sq (adj) = 79.2%	

Table 13
ANOVA table for second regression model for MRR analysis

Source	d.f.	Seq SS	Adj SS	Adj MS	F	P
Regression	7	108.682	108.682	15.526	39.52	0
Linear	4	102.223	51.744	12.936	32.93	0
Square	1	2.253	2.253	2.2534	5.74	0.02
Interaction	2	4.205	4.205	2.1027	5.35	0.007
Residual error	64	25.143	25.143	0.3929		
Lack-of-fit	28	12.768	12.768	0.456	1.33	0.21
Pure error	36	12.375	12.375	0.3437		
Total	71	133.825				

indicates that all terms of the regression model are significant at the confidence level of 95%. In this way, the simplified model which presents the highest value for the adjusted R^2-statistic by using response surface methodology, is that shown in Eq. (4):

$$\begin{aligned}\text{MRR (mm}^3\text{/min)} = {} & 8.96796 + 3.23882 \times \text{power} - 0.68118 \\ & \times \text{voltage} + 2.08759 \times \text{pulse off time} \\ & + 0.13699 \times \text{spindle rotational speed} \\ & + 0.00375 \times \text{voltage} \times \text{voltage} - 0.21999 \\ & \times \text{power} \times \text{pulse off time} - 0.00137 \\ & \times \text{voltage} \times \text{spindle rotational speed}\end{aligned} \tag{4}$$

Table 14 shows verification of the test results. The predicted machining parameters performance was compared with the actual machining performance and a good agreement was obtained between these performances. The above mathematical model for MRR of CWEDT AISI D3 tool steel is of great importance to the proper selection of machining parameters during the machining of the cylindrical parts.

Fig. 7 shows the graph of the main effects for each of the design factors. As can be clearly seen in the graph, the factors of power, voltage, pulse off time and spindle rotational speed have the most significant effect on MRR. Also it can be seen from Fig. 7 that pulse off time respectively is reciprocally proportional to MRR. Also, Fig. 7 shows that increasing power causes MRR to increase significantly. Spindle rotational speed has little effect

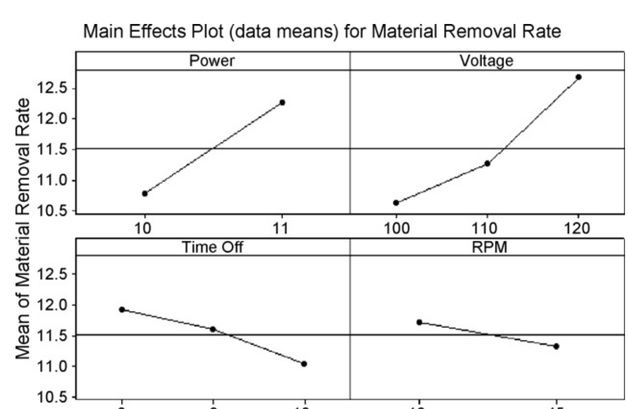

Fig. 7. Effects of factors on MRR.

Table 14
Results of confirmation tests for MRR analysis

Run	Power	Voltage	Pulse off time	Spindle rotational speed	Results of full factorial model	Results of experiments	Error of the model (%)
1	11	120	6	16	14.42	14.916	−3.34
2	10	100	10	45	9.62	9.475	1.5
3	11	110	8	45	11.76	11.948	−1.6
4	12	105	12	90	10.41	10.453	−0.38

on MRR. Voltage, like power, has significant direct effect on MRR, but in high values of voltage, MRR increases strongly.

Fig. 8(a) shows the estimated response of MRR, varying the factors of pulse off time and spindle rotational speed. As can be clearly seen in Fig. 8(a), the MRR value tends to increase with the higher pulse off time and rotational speed values. On the other hand, by decrease in rotational values in the higher values of pulse off time, the MRR values increase. Also in the higher values of spindle rotational speed by decreasing the pulse off time values, the MRR values increases.

Fig. 8(b) shows the estimated response surface of MRR in function of the factors of voltage and spindle rotational speed, whilst the pulse off time and power remain constant in their central values. Fig. 8(b) shows the limited influence that spindle rotational speed possesses over MRR for lower values of voltage, but in the higher values of voltage by decreasing the spindle rotational speed values, the MRR values increases. In the higher values of spindle rotational speed by increasing the voltage values, the MRR values increases, respectively.

Fig. 8(c) shows the estimated response surface for the MRR parameter, according to the design parameters of power and pulse off time, whilst the other factors remain constant in their central values. As has been previously pointed out, Fig. 8(c) shows the important influence that the design factor of power possesses over the MRR parameter, so that when power is increased, the MRR parameter also tends to increase appreciably at least up to a maximum value, after which it tends to decrease, for high values of the pulse off time factor and within the considered work interval. Furthermore, it can also be observed that the MRR parameter tends to increase when the pulse off time factor is decreased, especially for high values of power. The previous tendency of growth for this factor becomes less intense as we move towards lower values of power, with the MRR parameter actually decreasing slightly, after reaching a peak, for values close to the low level of power.

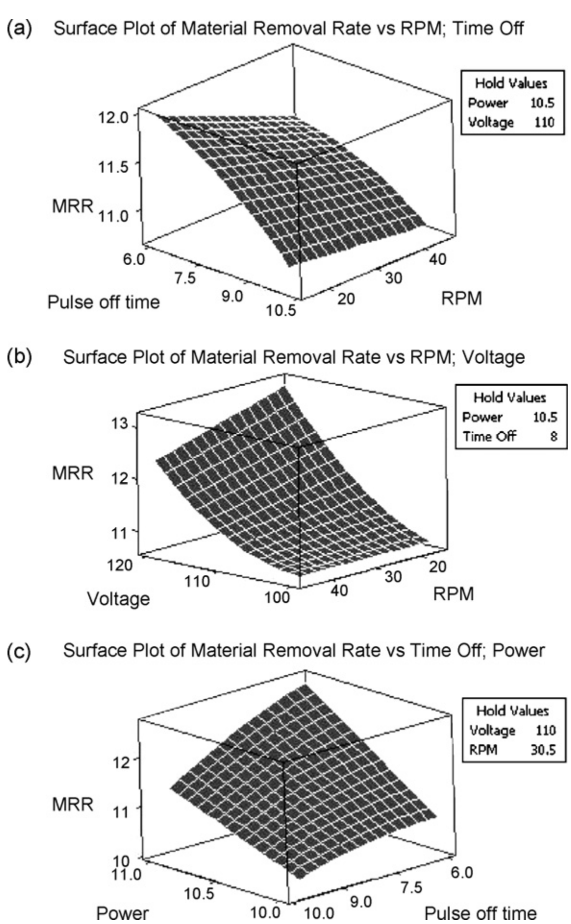

Fig. 8. Estimated response surface of MRR vs. (a) pulse off time and spindle rotational speed, (b) voltage and spindle rotational speed, (c) pulse off time and power.

4. Discussion

In this present work, modeling procedures of some of the most important parameters within the process of CWEDT were carried out. The material chosen in this study was an AISI D3 tool steel due to its growing range of applications in the field of tools, dies and molds as a punch, deep drawing, tapping, reaming and so on in cylindrical forms. With this work, it has been confirmed that the technique of design of factorial experiments, combined with techniques of response surface methodology, can be successfully applied to modeling the functions which depend on various variables. In order to carry out this study, some technological variables such as: surface roughness (evaluated by means of the Ra parameter), roundness and material removal rate (evaluated by means of the MRR parameter) were selected. These technological variables were studied in relation to design factors such as: the level of power supplied by the WEDM machine generator (level of current), voltage, pulse off time and spindle rotational speed. In all the response variables used in this work, the mathematical model was derived. In the case of the Ra parameter the most influential factors were power, voltage, pulse off time, spindle rotational speed followed by the interaction effects between voltage and spindle rotational speed. When either power or voltage was increased, the roughness value also increased. Therefore, in order to obtain a good surface finish in the case of CWEDT, low values should be used for both power and voltage. Another way of obtaining low roughness values, although higher than in the previous cases, is to combine the use of high values of voltage and high values of pulse off time, within the considered work interval. In the case of roundness, it was also seen that the spindle rotational speed was the most influential, followed by the interaction effect of voltage and spindle rotational speed. In order to be able to obtain low values of roundness, values of the voltage factor close to its central value or slightly higher should be used along with high values for spindle rotational speed, within the considered work interval. Finally, in the case of MRR, it was observed that the most influential factors were power, voltage, pulse off time and spindle rotational speed, followed by the interaction effects of the power and pulse off time, voltage and spindle rotational speed. The value of MRR increased, as would logically be expected, when power and voltage were increased, whilst an increase in pulse off time and spindle rotational speed brought about a decrease in MRR. Therefore, in order to obtain high values of MRR for the case of CWEDT, within the work interval considered in this study, one should use, above all, high values for power and voltage. Furthermore, although to a lesser extent, low values of the pulse off time factor should also be used.

5. Conclusion

The effect of power, voltage, pulse off time and spindle rotational speed were experimentally investigated on Ra, roundness and MRR in CWEDT process. Response surface regression equations were found and presented as Eqs. (2)–(4). The developed mathematical models for the different machining performance characteristics of the CWEDT process are proposed for proper selection of machining parameters for evaluation of Ra, roundness and MRR under various machining combination during the machining of the cylindrical parts by CWEDT process. The confirmation tests indicated that it is possible to optimize Ra, roundness and MRR significantly by using the proposed statistical technique. It can be seen from the results that the important strength of factorial design of experiment is the potential to build models and to gradually increase the complexity of the models if this is needed. In order to determine prediction model in EDM and WEDM processes, one can first use full factorial design in DOE technique to determine a working space with high robustness, and then use regression analysis to generate a model of high stability.

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