The Effect of the Cutting Parameters on Performance of WEDM

Nihat Tosun*
Mechanical Engineering Department, Firat University, 23119 Elazig, Turkey

In this study, variations of cutting performance with pulse time, open circuit voltage, wire speed and dielectric fluid pressure were experimentally investigated in Wire Electrical Discharge Machining (WEDM) process. Brass wire with 0.25 mm diameter and AISI 4140 steel with 10 mm thickness were used as tool and work materials in the experiments. The cutting performance outputs considered in this study were surface roughness and cutting speed. It is found experimentally that increasing pulse time, open circuit voltage, wire speed and dielectric fluid pressure increase the surface roughness and cutting speed. The variation of cutting speed and surface roughness with cutting parameters is modeled by using a regression analysis method. Then, for WEDM with multi-cutting performance outputs, an optimization work is performed using this mathematical models. In addition, the importance of the cutting parameters on the cutting performance outputs is determined by using the variance analysis (ANOVA).

Key Words : Wire EDM, Cutting Performance, ANOVA, Regression Analysis

1. Introduction

Wire Electrical Discharge Machining (WEDM) involves a complex erosion effect from electric sparks generated by a pulsating current power supply. The sparks are generated between the workpiece and a wire electrode flushed or immersed in the dielectric fluid. The most important performance measures for a WEDM process, which have been considered by others, include metal removal rate/cutting speed, surface finish and cutting kerf. Discharge current, discharge capacitance, pulse time, pulse frequency, wire speed, wire tension, servo voltage and dielectric flushing pressure are parameters that influence the performance of the process. Surface roughness and cutting speed were considered as performance measures in this study.

Scott et al. (1991) have presented a formulation and solution of a multi-objective optimization problem for the selection of the best control settings for a WEDM machine. The measures of performance for the model are taken to be metal removal rate and surface finish quality. In their study, a factorial design model has been used to predict the measures of performances as a function of a variety of control settings. Rajurkar and Wang (1993) analyzed the wire rupture phenomena with a thermal model. An extensive experimental investigation has been carried out to determine the process performances such as machining rate and surface finish with overall control parameters of an ED machine in the study. The relationship between the machining rate and surface finish under optimal machine settings has been determined by means of a multi-objective model. Kozak et al. (1994) presented the results of experimental and theoretical investigations of the effect of grain size of PCD, discharge frequency and discharge energy of WEDM on the machining feed rate and the quality of machined surfaces of PCD blanks. Tarng et al. (1995) used a feed forward neural network to determine the optimal cutting parameters (pulse on time, pulse off time, peak current setting, no-load voltage, servo reference voltage, capacitor setting, servo speed setting and workpiece thickness) for impro-

* **E-mail** : ntosun@firat.edu.tr
Mechanical Engineering Department, Firat University, 23119 Elazig, Turkey. (Manuscript **Received** August 16, 2002; **Revised** February 15, 2002)

ving the cutting performance (machining speed and surface finish). Liao et al.(1997) proposed an optimization for a suitable selection of machining parameters in the WEDM process. In the study, based on the Taguchi quality design method and the analysis of variance, the significant factors affecting the machining performance have been determined. Spedding and Wang(1997) presented an attempt at optimization of the process parametric combination by using artificial neural networks and characterization of the machined surface. Lok and Lee(1997) compared the machining performance in terms of material removal rate and surface finish by the processing of two advanced ceramics under different cutting conditions using WEDM. Rozenek et al.(2001) investigated experimentally the effect of machining parameters on the machining feed rate and surface roughness during WEDM of a metal matrix composite. Wire speed and dielectric flushing pressure was constant for all the experiments in this study. Kim and Kruth(2001) investigated the electrical conductivity of dielectric and cobalt percentage on the output parameters such as metal removal rate and surface roughness value of sintered carbides cut by WEDM. Cogun and Akaslan (2002) studied the effect of machining parameters on tool electrode edge wear and machining performance in EDM.

The aim of this study was to perform experiments under different cutting settings of pulse time, open circuit voltage, wire speed and dielectric flushing pressure to determine the cutting performance outputs (the cutting speed and the surface roughness) in WEDM. In this study, mathematical relation ship between the cutting performance outputs and the cutting parameters were established by a regression analysis method. Then, for WEDM with multi-cutting performance outputs, an optimization work was performed using this mathematical model. In addition, the effect of the cutting parameters on the cutting performance outputs was statistically evaluated and the significant factors affecting the cutting performance outputs were determined based on the analysis of variance.

2. Experiments

2.1 Materials and test conditions

Experimental studies were performed on a Sodick A320D WEDM machine tool. Different settings of pulse duration, open circuit voltage, wire speed and dielectric flushing pressure were used in the experiments (Table 1). Pulse interval time (16 μs), table feed rate (7.6 mm/min) and wire tension (1800 g) were kept constant throughout the experiments. In selecting the range of variable machining parameters settings during experimentation, the upper and lower limits of the parameter values, which were recommended by the machine tool manufacturer, were considered in order to search the largest possible machining range. The average values of the ranges recommended by the machine tool manufacturer were taken for the variables which were set to be constant through out the experiments. A factorial experimental design model was used to predict the measures of performance as a function of a variety of control parameters. 108 ($4\times3\times3\times3$) different combinations of cutting parameters were determined by using the full factorial experimental design method. Table 1 shows the level of machining parameters used throughout this study. For a given machining setting two experiments were conducted. The results obtained were compared and the mathematical average of the two measurements was used in the study. If the two

Table 1 Experimental design

Symbol	Control factor	Unit	Level 1	Level 2	Level 3	Level 4
A	Pulse duration, t_d	ns	300	500	700	900
B	Open circuit voltage, u_i	V	80	100	270	—
C	Wire speed, v_w	m/min	5	8	12.5	—
D	Flushing pressure, p	kg/cm^2	6	12	18	—

measurements were not consistent, then a third experiment was conducted to eliminate one of the three measurements. The experimental work showed that two experiments were sufficient to obtain consistent measurements for the applied machining parameter settings.

CuZn37 master brass wire with 0.25 mm diameter and 900 N/mm^2 tensile strength was used in the experiments. AISI 4140 steel (DIN 42CrMo4) with 10 mm thickness was used as workpiece materials.

2.2 Performance measurements

Cutting speed (FR) is expressed as

$$FR=\frac{L}{T} \tag{1}$$

where, T is the cutting time and L is the length of workpiece. T was determined by using a stopwatch for 15 mm cutting length of workpiece.

Mitutoyo Surftest SJ-201 was used for the average surface roughness (R_a) measurements of the workpiece. The cut-off length, λ_c, and the sampling number, l, were chosen as 0.8 mm and 5, respectively. The surface roughness measurements were made in the direction parallel to the wire cutting direction. Fight independent readings were taken and the average of the values were used.

3. Experimental Results and Discussion

Figure 1 shows that the increasing pulse duration increases the cutting speed and the workpiece surface roughness. The volume of the material eroded from the workpiece material increases proportionally with pulse energy (Doyle et al. 1987, Fuller 1989, Tosun et al. 2002). The cutting speed and the workpiece surface roughness increase due to larger energy discharge with increasing pulse duration. The pulse energy (W_e) can be expressed as

$$W_e=u_e.i_e.t_d \tag{2}$$

where u_e is the discharge voltage, i_e is the discharge current and t_d is the discharge duration

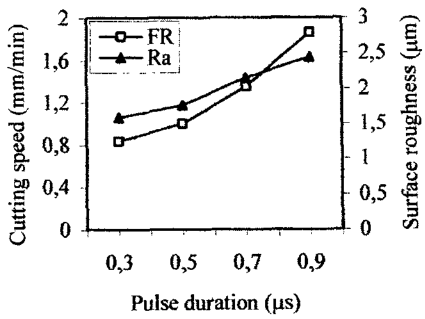

Fig. 1 Effect of pulse duration on cutting speed and surface roughness (v_w=8 m/min, p=12 kg/cm^2, u_i=100 V)

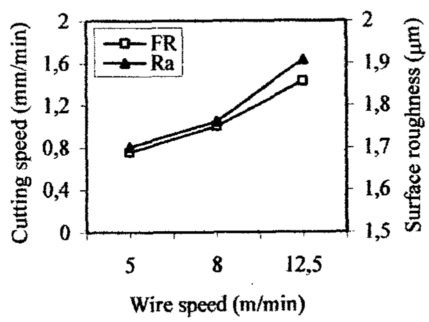

Fig. 2 Effect of wire speed on cutting speed and surface roughness (t_d=0.5 μs, p=12 kg/cm^2, u_i=100 V)

for a discharge (spark) pulse. Pulse duration and discharge duration are equal for the isopulse generator used in this study.

Figure 2 clearly shows that the increasing wire speed increases the cutting speed and the workpiece surface roughness. It can be seen that the increasing wire speed increases the workpiece surface roughness.

The effect of open circuit voltage on cutting speed and surface roughness is shown in Fig. 3. It is seen that increasing open circuit voltage increases the cutting speed and the surface roughness. Higher open circuit voltage produces higher spark energy in WEDM (Eq (1)). The cutting speed and the surface roughness increase with increasing open circuit voltage since the higher spark energy produces a bigger crater on the work surface resulting in higher material removal from the workpiece.

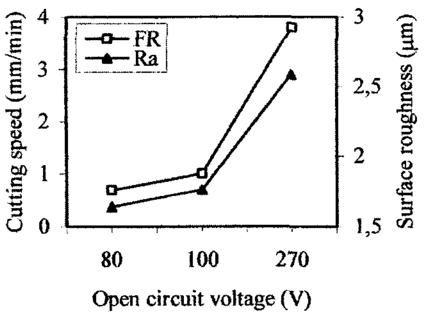

Fig. 3 Effect of open circuit voltage on cutting speed and surface roughness (t_d=0.5 μs, v_w=8 m/min, p=12 kg/cm^2)

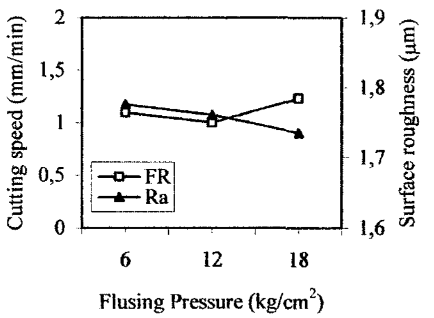

Fig. 4 Effect of flushing pressure on cutting speed and surface roughness (t_d=0.5 μs, v_w=8 m/min, u_i=100 V)

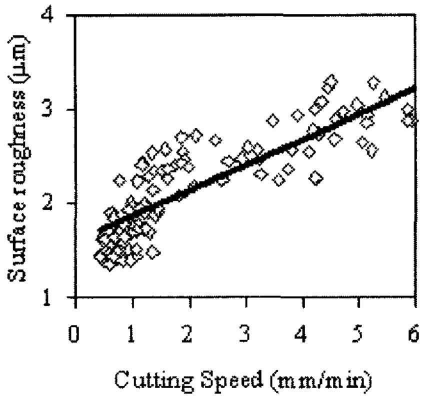

Fig. 5 Cutting speed vs. surface roughness

Increasing dielectric flushing pressure decreases the workpiece surface roughness (Fig. 4). The decreasing surface roughness is due to the rapid cooling effect of dielectric flushing on the workpiece surface which results in the formation of smaller molten craters. The cutting speed decreases for dielectric pressures up to 12 kg/cm^2 whereas the cutting speed increases for dielectric pressures above 12 kg/cm^2.

Higher cutting speed and smoother surface are preferred in WEDM. However, the goals of high cutting speed and good surface finish quality are conflicting. Figure 5 shows that the surface roughness increases as the cutting speed increases. Consequently, no particular combination of cutting parameters can be proposed to give the best cutting speed and the best surface roughness simultaneously.

3.1 Mathematical models

For predicting the cutting performance outputs for various settings of cutting parameters, mathematical relationships (models) between the performance outputs (cutting speed and work surface roughness) and cutting parameters were established. The mathematical model suggested was in the following form :

$$y=a_i\cdot t_d^{a2}\cdot u_i^{a3}\cdot v_w^{a4}\cdot p^{a5} \tag{3}$$

where y is the performance output (term) and a_i is the model constant. Here, the constants were calculated by using a non-linear regression analysis method. The calculated coefficients were substituted in Eq (3) and the following relations can be obtained.

$$FR=0.000114\cdot t_d^{0.424}\cdot u_i^{1.221}\cdot v_w^{0.238}\cdot p^{0.223}\ (r=0.98) \tag{4}$$

$$R_a=0.048\cdot t_d^{0.361}\cdot u_i^{0.321}\cdot v_w^{0.076}\cdot p^{-0.056}\ (r=0.97) \tag{5}$$

The high correlation coefficients (r) indicate the suitability of the model used and the correctness of the calculated constants.

3.2 Optimization for multi cutting performance outputs

There are two different objectives in the present work ; namely, the surface roughness and the cutting speed (Eqs. (4) and (5)). In this part of the study an effort has been made to find the machining settings to obtain the minimum surface roughness and the maximum cutting speed. This represents the case of an optimal search for cutting parameters for a multi-objective optimization problem (MOP) with multi performance characteristics. Through the mathematical model determined above (Eqs. (4) and (5)), the optimization problem for the minimum surface roughness and the maximum cutting speed can be formulated as a multi-objective, multi-variable, nonlinear optimization problem with multi-constraints.

In this study, a weighting method is used for the optimization of a WEDM process with multi cutting performance outputs. Since the surface roughness and the cutting speed are two different objectives, in the order to overcome the large differences in numerical values between the sub-objectives, the function corresponding to every cutting performance output is normalized first to solve the MOPs (Davim and Antonio 2001). For example, the normalized surface roughness is defined by

$$R_a^* = \frac{R_a}{R_{a_{max}}},\ R_{a_{max}} = \max(R_{a_i},\ i=1,\ \cdots,\ k) \quad (6)$$

where k is the total number of experimental values. A weighting method is then adopted to transform the normalized surface roughness R_a^* and normalized cutting speed FR^* into a single objective format (Eq. (7)). The resulting weighted objective function to be minimized here is:

$$U = \omega_1 \cdot R_a^* - \omega_2 \cdot FR^* \quad (7)$$

subject to:

$$t_{d_{min}}^* \leq t_d^* \leq t_{d_{max}}^* \quad (8)$$

$$u_{i_{min}}^* \leq u_i^* \leq u_{i_{max}}^* \quad (9)$$

$$v_{w_{min}}^* \leq v_w^* \leq v_{w_{max}}^* \quad (10)$$

$$p_{min}^* \leq p^* \leq p_{max}^* \quad (11)$$

where ω_1 and ω_2 are the weights of the normalized surface roughness and normalized cutting speed, respectively in optimization. Here, $\omega_{1,2} \geq 0$ and $\omega_1 + \omega_2 = 1$. Symbol (*) denotes the normalized values.

Several methods have been developed for solving a MOP. Matlab optimization toolbox was used to obtain the optimum cutting parameters in WEDM with multi performance outputs. Through the simulated annealing search, the optimal process parameters with several weighting combinations are obtained. The value of weighting factor is dependent upon engineering judgment. The larger the weighting factor, the greater the improvement in cutting performance outputs. The process parameters with a higher cutting speed can be obtained by increasing the weight of ω_2, whereas the process parameters with a lower surface roughness can be obtained by increasing the weight of ω_1. Table 2 shows the optimum conditions of the cutting parameters for multi performance outputs with different combinations of the weighting factors. For Case 1, the order of the performance outputs are the surface roughness ($\omega_1=0.7$) and the cutting speed ($\omega_2=0.3$) and for Case 2, they are the surface roughness ($\omega_1=0.5$) and the cutting speed ($\omega_2=0.5$). Finally, the order of the performance outputs for Case 3 is changed, namely, the surface roughness ($\omega_1=0.3$) and the cutting speed ($\omega_2=0.7$). As shown clearly in Table 2, the cutting conditions for lower surface roughness and cutting speed were obtained in Case 1. This was due to the largest weighting factor of surface roughness for the multi-performance outputs in Case 1. The cutting conditions for medium surface roughness and cutting speed were obtained in Case 2 in which the surface roughness and the cutting speed had equal weighting factors. The cutting conditions for higher surface roughness and cutting speed were obtained in Case 3 where the cutting speed had the largest weighting factor.

Table 2 Optimum cutting conditions for multi performance with different weighting factor

Control factor	Optimum cutting conditions		
	Case 1 $\omega_1=0.7$ $\omega_2=0.3$	Case 2 $\omega_1=0.5$ $\omega_2=0.5$	Case 3 $\omega_1=0.3$ $\omega_2=0.7$
Pulse duration	300	300	900
Open circuit voltage	80	270	270
Wire speed	5	12.5	12.5
Flushing pressure	18	18	18

4. Data Analysis

In this study, analysis of variance (ANOVA) and statistical F-test were used for the analysis of experimental results. ANOVA and F-test were

Table 3 S/N ratios for the cutting speed and the surface roughness

Control factor	Mean S/N ratio (dB)							
	Level 1		Level 2		Level 3		Level 4	
	FR	Ra	FR	Ra	FR	Ra	FR	Ra
Pulse duration	1.87	−4.82*	3.34	−5.83	5.49	−7.22	6.93*	−8.44
Open circuit voltage	1.47	−5.09*	2.07	−5.87	12.62*	−8.77	−	−
Wire speed	2.25	−6.23*	4.96	−6.60	6.01*	−6.90	−	−
Flushing pressure	3.83	−6.86	3.64	−6.59	5.75*	−6.29*	−	−

Total mean S/N ratios : −6.58 dB for Ra, 4.41 for FR
*Optimum level

used to investigate the statistically significant cutting parameters and to determine the percent contribution of cutting parameters on the performance outputs (surface roughness and cutting speed). The optimal cutting parameters were also investigated for the performance outputs in WEDM.

A loss function was used to calculate the deviation between the experimental value and the desired value. The loss function is further transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristics, namely, lower is better (LB), nominal is best (NB), or higher is better (HB). Each performance characteristic may belong to a different category in the analysis of the S/N ratio. Lower surface roughness and higher cutting speed apparently give better cutting performance. Therefore, the "lower is better (LB)" for surface roughness and "higher is better (HB)" for cutting speed were selected in this study. For HB and LB criteria, the definitions of the loss function (L) for cutting performance results y_i of n repeated number are :

$$S/N_{HB}=-10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (12)$$

$$S/N_{LB}=-10\log\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \quad (13)$$

The S/N ratios of the cutting speed and the surface roughness were calculated for each level of the cutting parameters given in Table 1. The results of S/N ratio are shown in Table 3. Figure 6 shows the S/N response graph of each level of the cutting parameters for the cutting speed and the surface roughness. A larger S/N ratio indicates a more stable response for both HB and LB criteria. Therefore, the optimal level of the cutting parameters is the level with the largest S/N ratio. Based on the analysis of S/N ratio, the minimum surface roughness was obtained at 80 V open circuit voltage, 300 ns pulse duration, 5 m/min wire speed and 18 kg/cm^2 dielectric flushing pressure setting, while the maximum cutting speed was obtained at 270 V

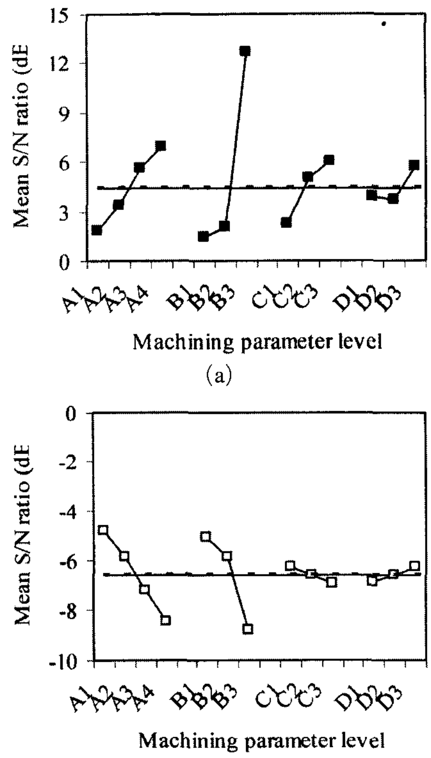

Fig. 6 The influence of cutting parameters on the cutting speed (a) and the surface roughness (b)

Table 4 Result of ANOVA for the cutting speed

Cutting parameter	Degree of freedom (df)	Sum of square (SSA)	Variance (VA)	FA0	Contribution %
Pulse duration	3	407.63	135.87	135.87	8.59
Open circuit voltage	2	3871.84	1935.92	1935.92	81.58
Wire speed	2	269.86	134.93	134.93	5.69
Flushing pressure	2	98.47	49.23	49.23	2.07
Error	98	98.28	1.00	—	2.07
Total	107	4746.09	—	—	100

Table 5 Result of ANOVA for the surface roughness Cutting parameter

Cutting parameter	Degree of freedom (df)	Sum of square (SSA)	Variance (VA)	FA0	Contribution %
Pulse duration	3	204.22	68.07	309.40	40.11
Open circuit voltage	2	269.87	134.93	613.31	53.01
Wire speed	2	8.01	4.00	18.18	1.57
Flushing pressure	2	5.75	2.87	13.04	1.13
Error	98	21.26	0.22	—	4.18
Total	107	509.12	—	—	100

open circuit voltage, 900 ns pulse duration, 12.5 m/min wire speed and 18 kg/cm^2 dielectric flushing pressure setting (Table 3). These findings are consistent with the experimental results.

The relative importance of the cutting parameters on the cutting performance was investigated to determine the optimum combinations of the cutting parameters more accurately by using ANOVA. The results of ANOVA for the cutting performance are presented in Tables 4 and 5. Statistically, F-test provides a decision at some confidence level as to whether these estimates are significantly different. Larger F value indicates that the variation of the process parameter results in a significant change on the performance characteristics (Phadke 1989, Ross 1996, Lin 2000, Tosun et al. 2002). The F values of the cutting parameters are compared with the appropriate confidence table. When the F value of the cutting parameter is larger than $F_{\alpha,v1,v2}$ value of the confidence table, where α is risk, v_1 and v_2 are degrees of freedom associated with numerator and denominator, the cutting parameter has a significant effect on the cutting performance. Otherwise, it is insignificant. In addition, the percent contribution also indicates the relative power of a factor to reduce the variation. For a factor with a high percent contribution, a small variation will have a great on the overall performance.

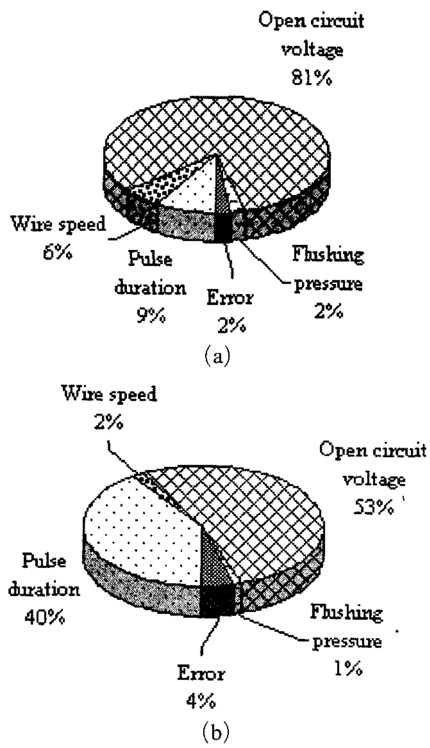

Fig. 7 Factors and their contributions (%) on cutting speed (a) and surface roughness (b)

According to the F-test analysis (Tables 4 and 5), the most effective parameters on both the cutting speed and the surface roughness are open circuit voltage, pulse duration, wire speed and dielectric flushing pressure because the degree of freedom of the error is high. However, when the degree of freedom of the error is low the percent contributions of the cutting parameters on the performance outputs is taken into consideration (Fig. 7). The most effective parameters on the cutting speed are open circuit voltage, pulse duration, wire speed whereas the effects of dielectric flushing pressure on the cutting speed are insignificant. The most effective parameters on the surface roughness are open circuit voltage and pulse duration whereas the effects of wire speed and dielectric flushing pressure on the surface ronshness are insignificant. Very low experimental errors for the ANOVA applied to the performance characteristics indicate the accuracy of the applied procedure.

If the insignificant cutting parameters are removed from Eqs. (4) and (5), the cutting speed and the surface roughness can be expressed as

$$FR=0.000114 \cdot t_d^{0.42} \cdot u_i^{1.221} \cdot v_w^{0.238} \quad (14)$$

$$Ra=0.048 \cdot t_d^{0.361} \cdot u_i^{0.321} \quad (15)$$

Different sets of experiments are conducted and very consistent cutting performance values are obtained from Eqs. (14) and (15) with experimental measurements (maximum 10% difference).

5. Conclusion

The experimental and statistical study of the cutting performance characteristics in WEDM at various pulse duration, open circuit voltage, wire speed and dielectric flushing pressure reveals the following results:

(1) It is found experimentally that increasing pulse duration, open circuit voltage, wire speed and dielectric fluid pressure increase the cutting speed. The surface quality of the workpiece increases with decreasing pulse duration, open circuit voltage and wire speed, and with increasing dielectric fluid pressure.

(2) The surface roughness increases as the cutting speed increases.

(3) Mathematical relations hips between the cutting parameters and the cutting performance characteristics are established by regression analysis method. Among the several functions tried, the power function is found to be the best-fit model. The established mathematical models are used in estimating the performance characteristics.

(4) For multi-performance outputs, the optimum cutting conditions depend on the importance order of the cutting performance outputs which are determined for three cases. The larger the weighting factor, the greater is the improvement in cutting performance outputs.

(5) Based on ANOVA method, the effective parameters on cutting speed are open circuit voltage, pulse duration and wire speed whereas the effects of dielectric flushing pressure are insignificant. The effective parameters on the surface roughness are open circuit voltage and pulse duration whereas the effects of wire speed and dielectric flushing pressure are insignificant.

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