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ANALYSIS OF PERFORMANCE CHARACTERISTICS OF WIRE ELECTRICAL DISCHARGE MACHINING

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ABSTRACT

Wire-cut Electro Discharge Machining (WEDM) is a commonly used process in the manufacturing sector to machine complex shapes of electrically conductive materials. WEDM is so complex in nature that the selection of appropriate input parameters is not possible by the trial-and-error method. The selection of machining parameters in any machining process significantly affects production rate, product quality and production cost of a finished component. In this work, the effects of machining parameters, viz., pulse-on time, pulse-off time, wire tension, wire feed and dielectric flow rate on surface roughness and metal removal rate are analyzed. It is based on the empirical models developed by response surface methodology.

Keywords: *Wire-cut Electro Discharge Machining, Modeling, Analysis, Performance characteristics.*

1. Introduction

Wire Electrical Discharge Machining (WEDM) belongs to the class of non-conventional machining to machine intricate shapes and profiles of any electrically conductive material. WEDM is a thermo-electrical process in which the thermal energy is released in the form of discrete sparks. A thin electrically conductive wire is used as the electrode. The wire feed is regulated by the numerical control and the work piece is immersed in a liquid dielectric medium. The thermal energy is released through wire electrode melts and vaporizes the minute amounts of work piece in order to obtain the required shape. The schematic diagram of WEDM process is presented in Fig. 1. Irrespective of the hardness of the electrically conductive material, WEDM is being applied extensively in various fields like tool and die manufacturing industries, space applications and automobile industries. This process involves a large number of control factors. Moreover, the process is stochastic in nature. These factors do not allow the operator to obtain the optimal performance just by the trial-and-error method.

2. Literature Review

Influences of WEDM parameters on surface roughness of newly developed DC53 die steel were investigated by Kanlayasiri and Boonmung [1], reported that the parameters, pulse-on time, pulse-peak current were significant on surface roughness. Fuzhu Han et al [2] conducted a thermal analysis to find the influence of discharge current on machined surfaces in finish cut of WEDM using finite element method and performed single discharge experiments under different pulse energies. They concluded that the short-duration pulses should be used to meet the requirements of surface roughness. A predictive reliability optimization based on the Gaussian process regression model approach and optimal decision making for high speed WEDM process optimization was proposed by Jin Yuan et al [3] and analyzed that the effective input parameters effecting the metal removal rate and surface roughness.

The effects of pulse duration, open circuit voltage, wire speed and dielectric flushing pressure on the dimensions of craters in the wire were experimentally investigated in WEDM by N. Tosun et al [4], found that increasing the pulse duration, open circuit voltage, wire speed increases the crater diameter and depth, whereas increasing the dielectric fluid pressure decreases these factors. The effects of spark cycle and pulse-on time on wire EDM for different engineering materials were investigated by Scott F. Miller et al [5]. Parametric analysis based on Taguchi methodology was carried out on γ-titanium aluminide alloy on wire EDM and modeled using additive model by Sarkar et al [6] and reported that surface roughness

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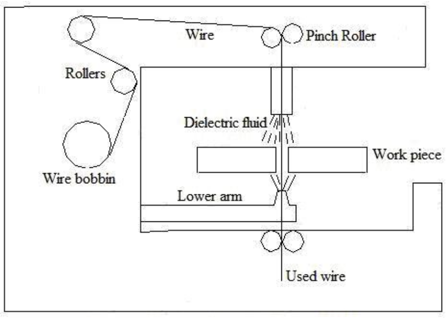


Fig. 1 Schematic Diagram of Wire-Cut EDM

and dimensional deviation are independent of the parameter pulse-off time.

The machining parameter, pulse-on time was varied to explore its effect on WEDM performance in machining alumina particle reinforced 6061 aluminum matrix composites by Biing Hwa Yan et al [7]. The effect of WEDM parameters such as open circuit voltage, pulse duration, wire speed and dielectric fluid pressure on machining characteristics of AISI D5 steel was investigated by Ahmet Hascalyk et al [8].

The present work is an extension of previous work of the authors Schawn et al [9]. They used response surface methodology to model the surface roughness and the metal removal rate based on the second-order composite design matrix. The advantage of using RSM is that it significantly reduces the number of experimental observations needed for arriving at the desired level of accuracy. In their work, later on, the problem was formulated as a multi-objective optimization problem and solved using Non-dominated sorting genetic algorithm to obtain the Pareto-optimal front. The experiments were conducted on D3 tool steel because it is used very commonly in the manufacturing industries for tooling applications requiring a high degree of accuracy in hardening, such as draw dies, forming rolls, powder metal tooling and blanking and forming dies etc. In the present work, the analysis of performance measures of WEDM was carried out based on the models derived earlier by Schawn et al [9].

3. Analysis of Performance Characteristics

Metal removal rate (MRR) and surface roughness (R_a) are considered as the output responses. MRR was calculated as the ratio of volume of material removed from work piece to the machining time. R_a was measured in perpendicular to the cutting direction using MITUTOYO surface roughness tester at a 0.8 mm cutoff value. An average of six measurements taken at six different places along the cutting length was recorded as the response value. The following models of surface roughness (R_a) and metal removal rate (MRR) in terms of coded factors were secured from authors' previous work [9] for analysis:

$$R_a = 2.4468 + 0.3498x_1 - 0.1273x_2 + 0.0481x_3 + 0.0310x_4 - 0.0606x_5 - 0.0368x_1^2 - 0.0255x_4^2 + 0.0278x_1x_3 + 0.0209\,x_1\,x_4 - 0.0328\,x_1\,x_5 + 0.0247\,x_2\,x_3 \quad (1)$$

$$MRR = 0.3347 + 0.1290\,x_1 - 0.0626x_2 + 0.0087\,x_3 + 0.0082\,x_4 - 0.0124\,x_5 + 0.0055\,x_2^2 - 0.0042\,x_4^2 -0.0297\,x_1x_2 + 0.0069\,x_1\,x_4 - 0.0077\,x_1\,x_5 -0.0076\,x_3\,x_4 + 0.0066\,x_3\,x_5 +0.0083\,x_4\,x_5 \quad (2)$$

x_1, x_2, x_3, x_4 and x_5 represent the decoded values of pulse-on time, pulse-off time, wire tension, dielectric flow rate and wire feed respectively. These models were tested for their adequacy using the Analysis of Variance Test (ANOVA) and regression coefficients (R^2) [9]. However, another approach is used in the present work based on the plot of residuals versus predicted response [10]. The plots of the residuals versus the predicted response for R_a and MRR are shown in Figs. 2-3, respectively. A check on the plots in Figs. 2 and 3 reveal that the errors are distributed normally and they have no obvious pattern and unusual structure. This implies that the models proposed are adequate and there is no reason to suspect any violation of the independence or constant variance assumption.

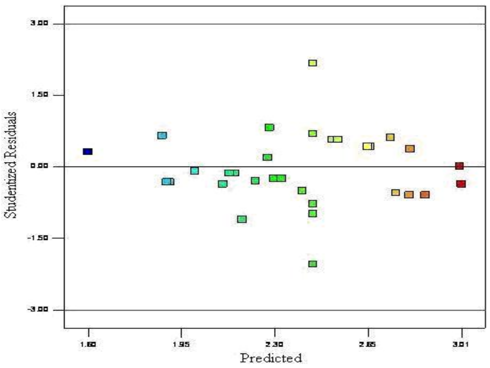


Fig. 2 Plot of Residual vs Predicted Response for R_a

In this work, the individual significant parameters have been found out by computing the 'P' values and Tables 1 and 2 summarize them for R_a and MRR respectively. If 'P' value for a factor is less than 0.05, then the factor is considered as statistically significant at 95% confidence level [11].

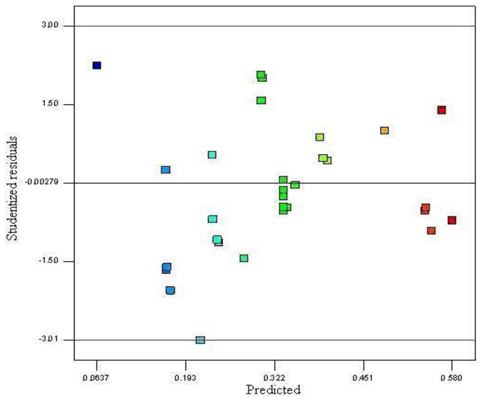


Fig. 3 Plot of Residual vs Predicted Response for MRR

From the Table 1, it is observed that the main effect of pulse-on time (X_1), pulse-off time (X_2), wire tension (X_3), dielectric flow rate (X_4) and wire feed (X_5) and the interaction of pulse-on time (X_1) and wire feed (X_5) are significant model terms as their P-values are less than the specified significance level of 0.05. The graphs are plotted for all the significant terms of R_a using statistical software, Design Expert, 7.1.3v [12].

Fig. 4 depicts the effect of wire tension on surface roughness. It is obvious from the Fig. 4 that the surface roughness increases with the increase in wire tension. The better surface finish can be obtained at moderate values of wire tension but at the same time, low wire tension leads to wire lagging or wire breakage.

The effect of water pressure on surface roughness is plotted in Fig. 5. It is observed that the increase in water pressure results in the poor surface quality. This can be attributed primarily to more chances of formation of craters on the work surface with the increased water pressure.

From Fig. 6, it is observed that the surface roughness increases with the increase in pulse-on time. This indicates that the discharge energy becomes more intense with increasing pulse-on time. The higher discharge energy causes more powerful explosion and deeper craters created on the machined surface. This results in rougher surface or poorer surface finish. Hence to obtain good surface finish the pulse-on time should be as low as possible. However, at the same time, if pulse-on time is very low, it leads to longer machining time.

Table 1: ANOVA [Partial Sum of Squares] for R_a

Source	Sum of Squares	dof	Mean Square	F Value	P-value Prob > F
X_1	2.94	1	2.94	1099.5	0.0001
X_2	0.39	1		145.9	0.0001
X_3	0.056	1	0.056	20.97	0.0008
X_4	0.023	1	0.023	8.53	0.0139
X_5	0.089	1	0.089	33.22	0.0001
X_1X_2	4.23E-03	1	4.23E-03	1.58	0.2348
X_1X_3	0.012	1	0.012	4.53	0.0568
X_1X_4	7.23E-03	1	7.23E-03	2.7	0.1285
X_1X_5	0.017	1	0.017	6.32	0.0288
X_2X_3	0.01	1	0.01	3.74	0.0793
X_2X_4	3.03E-03	1	3.03E-03	1.13	0.3103
X_2X_5	4.90E-03	1	4.90E-03	1.83	0.203
X_3X_4	2.50E-03	1	2.50E-03	0.94	0.3543
X_3X_5	2.25E-04	1	2.25E-04	0.084	0.7771
X_4X_5	4.90E-03	1	4.90E-03	1.83	0.203
X_1^2	0.04	1	0.04	14.87	0.0027
X_2^2	2.61E-03	1	2.61E-03	0.98	0.3444
X_3^2	9.10E-04	1	9.10E-04	0.34	0.5715
X_4^2	0.019	1	0.019	7.17	0.0215
X_5^2	1.36E-03	1	1.36E-03	0.51	0.49

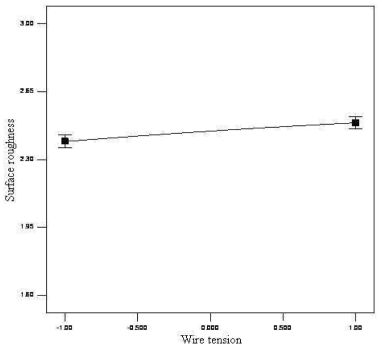


Fig. 4 Effect of Wire Tension on Roughness

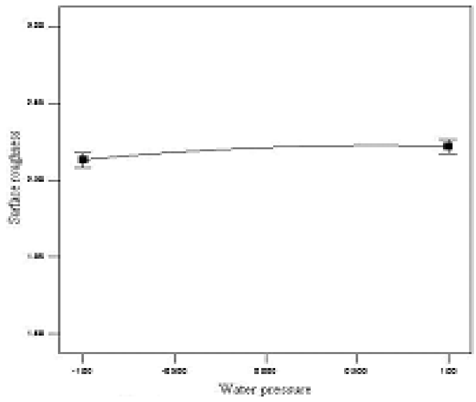


Fig. 5 Effect of Water Pressure on Roughness

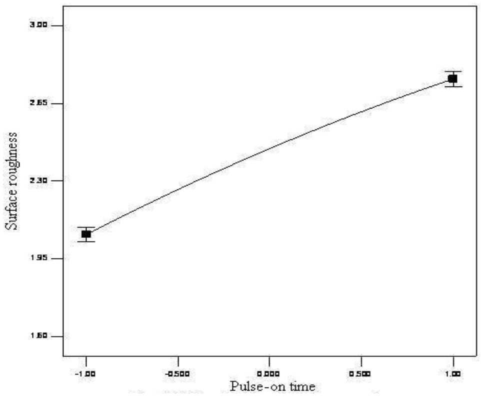


Fig. 6 Effect of Pulse on Time on Roughness

The individual effect of pulse-off time on surface roughness is shown in Fig. 7. It is noted that the roughness decreases with the increase in pulse-off time, as discharge energy decreases and deep craters are not formed and hence it leads to good surface finish. However, on the other hand, high pulse-off time leads to very low metal removal rate and hence results in long machining time.

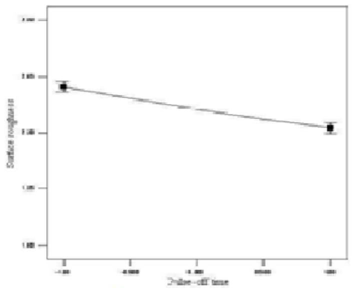


Fig.7 Effect of Pulse-off Time on Roughness

Fig. 8 exhibits the effect of wire feed on surface quality. It is noted that the surface roughness is decreased when the wire feed is increased. Fig. 9 shows the interaction effect of pulse-on time and wire feed on surface roughness in a 3D plot. It can be observed from the Fig. 9, the curvilinear profile is in accordance to the quadratic model fitted.

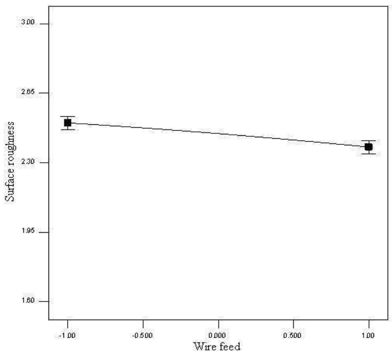


Fig. 8 Effect of Wire Feed on Roughness

Fig. 9 shows that the large values of wire feed affect the surface roughness at high values of pulse-on time than the low values of pulse-on time. But, it can be observed from the figures of individual effects that the low values of pulse-on time and high values of wire feed. In comparison, pulse-on time has larger effect on the surface roughness than the wire feed.

Similar analysis has been carried out for the other output response MRR and is given in Table 2. It is noted from the table 2 that the main effects of pulse-on time (x_1), pulse-off time (x_2), wire feed (x_5), and the interaction of pulse-on time (x_1) and pulse-off time (x_2) are significant model terms for MRR.

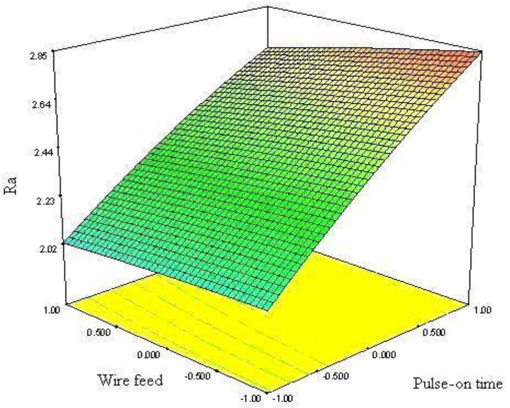
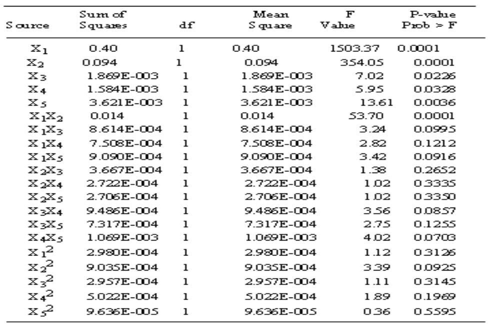


Fig. 9 3D Surface Graph for Surface Roughness

As seen the Fig. 10, the increase in the pulse-on time increases the discharge energy and the higher discharge energy causes the powerful explosion and result in the more metal removal from the work piece. To obtain a good rate of metal removal, pulse-on time should be large but large pulse-on time leads to poor surface finish.

On the contrary, Fig. 11 shows that MRR decreases with the increase in pulse-off time. This happens as the discharge current decreases and less amounts of material is removed. It is desirable to use low values of pulse-off time to obtain higher rates of metal removal.



Source	Sum of Squares	df	Mean Square	F Value	P-value Prob > F
X_1	0.40	1	0.40	1503.37	0.0001
X_2	0.094	1	0.094	354.05	0.0001
X_3	1.869E-003	1	1.869E-003	7.02	0.0226
X_4	1.584E-003	1	1.584E-003	5.95	0.0328
X_5	3.621E-003	1	3.621E-003	13.61	0.0036
X_1X_2	0.014	1	0.014	53.70	0.0001
X_1X_3	8.614E-004	1	8.614E-004	3.24	0.0995
X_1X_4	7.508E-004	1	7.508E-004	2.82	0.1212
X_1X_5	9.090E-004	1	9.090E-004	3.42	0.0916
X_2X_3	3.667E-004	1	3.667E-004	1.38	0.2652
X_2X_4	2.722E-004	1	2.722E-004	1.02	0.3335
X_2X_5	2.706E-004	1	2.706E-004	1.02	0.3350
X_3X_4	9.486E-004	1	9.486E-004	3.56	0.0857
X_3X_5	7.317E-004	1	7.317E-004	2.75	0.1255
X_4X_5	1.069E-003	1	1.069E-003	4.02	0.0703
X_1^2	2.980E-004	1	2.980E-004	1.12	0.3126
X_2^2	9.035E-004	1	9.035E-004	3.39	0.0925
X_3^2	2.957E-004	1	2.957E-004	1.11	0.3145
X_4^2	5.022E-004	1	5.022E-004	1.89	0.1969
X_5^2	9.636E-005	1	9.636E-005	0.36	0.5595

Fig. 10 Effect of Pulse- on Time on MRR

Similarly, MRR is increased with the increase in wire tension as seen in the Fig. 12 and the higher rates of metal removal at larger values of wire tension. As seen in the Fig. 13, the MRR increases with the increase in the water pressure. By increasing the water pressure, effective flushing of the debris can be attained which increases the machining performance and it in turn increases the MRR.

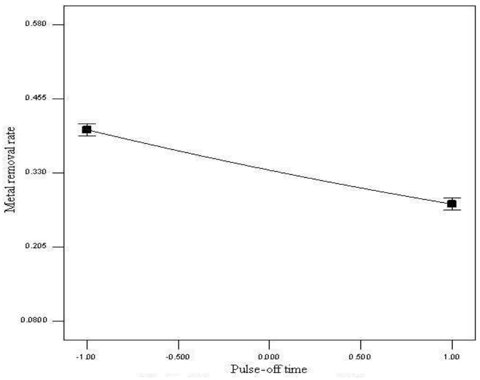


Fig. 11 Effect of Pulse-off Time on MRR

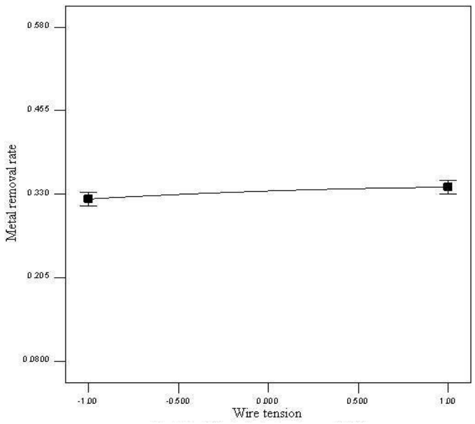
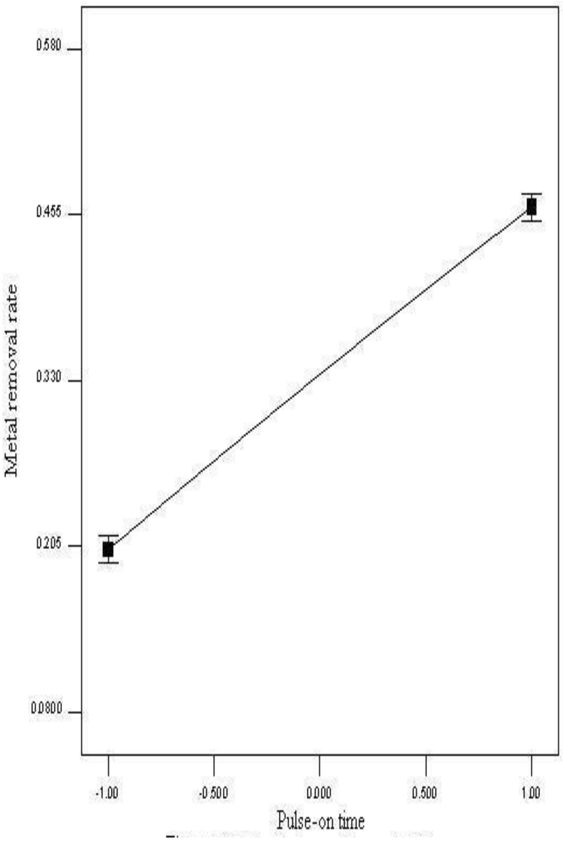


Fig. 12 Effect of Wire Tension on MRR

Table 2: ANOVA [Partial Sum of Squares] for MRR



It can be observed from the Fig. 14, MRR is decreased with the increase in wire feed. This is due to the effect of the time between two pulses and the pulse width on the discharge of spark. At low wire feed, the time between two pulses is shorter and longer pulse width prevails which result in the greater discharge power. The greater power produces larger diameter of crater and hence high MRR.

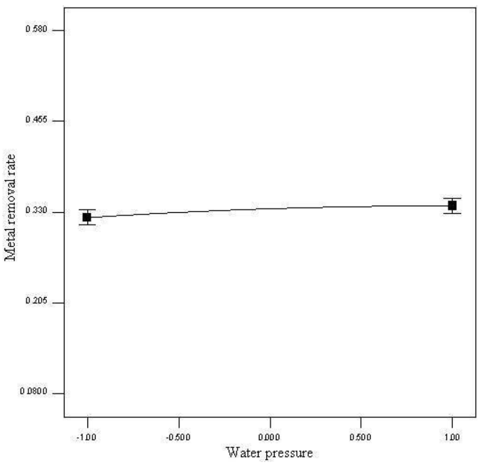


Fig. 13 Effect of Water Pressure on MRR

The 3D surface graph for metal removal rate is shown in Fig. 15. It can be observed from the graphs that the effect of pulse-off time on material removal rate is larger at high pulse-on time than at low pulse-on time.

Eventually, it is obvious from the tables that the control factors, namely, pulse-on time, pulse-off time and wire feed were the most significant factors on both the responses. The factor, wire tension was not so significant on the two responses.

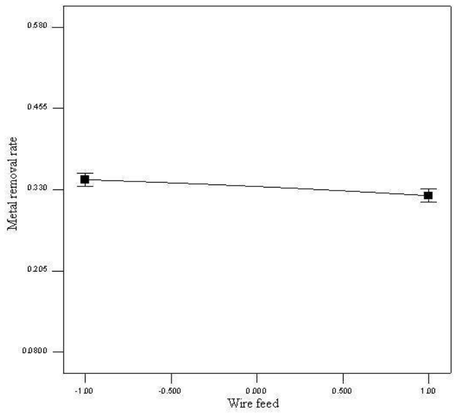


Fig. 14 Effect of Wire Feed on MRR

However, low values of pulse-on time along with the moderate values of wire tension and water pressure should be used to obtain the good surface finish. To obtain higher rates of metal removal, large values of pulse-on time, wire tension and dielectric flow pressure should be used.

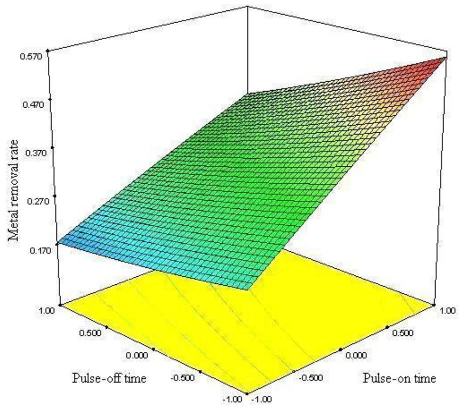


Fig. 15
3D Surface Graph for MRR

4. Conclusion

The analysis of performance characteristics for wire EDM process was carried out. The effects of input parameters pulse-on time, pulse-off time, wire tension, wire feed and dielectric flow pressure on surface roughness, metal removal rate while machining the D3 material were analyzed. Graphs were plotted for all the significant terms. The input parameters pulse-on time, wire tension, dielectric flow pressure were found to be significant on responses surface roughness and metal removal rate. The output responses decrease with the increase in pulse-off time and wire feed. The results obtained out of this analysis vary from material to material as the properties of all the materials are not same. Similarly, the results vary from machine to machine.

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