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Optimization of Parameters in Wire-EDM for Powder Metallurgical Cold Worked Tool Steel

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ABSTRACT

Wire electric discharge machining is a non-traditional material removal process used to manufacture components with intricate shapes and profiles. In the present research, wire wear ratio of WEDM machine during machining of P/M cold worked tool steel is studied. Selection of optimum machining parameters for obtaining minimum wire wear is a challenging task in Wire electric discharge machining due to the presence of a large number of process variables and complicated mechanisms. In general, no perfect combination of parameters exists for getting the minimum wire wear. These requirements enable the manufacturing engineers to compute the optimal wire electric discharge machining process parameters for obtaining minimum wire wear. A series of experiments have been conducted with WEDM on P/M cold worked tool steel based on Taguchi L_{27} orthogonal array (OA). This methodology is capable of predicting the response parameter as a function of six different process parameters, i.e. pulse on time (ON), pulse off time (OFF), spark gap set voltage (SV), peak current (IP), wire tension (WT), water pressure (WP). The effect of process parameters on wire wear is evaluated by signal-to-noise (S/N) ratio. The optimum levels of process parameters are found to be at pulse on time (A1) = 108 µsec, pulse off time (B3) = 63 µsec, peak current (C1) = 11 amperes, spark gap set voltage (D1) = 18 volts.

Key words: Analysis of variance, Optimization, Taguchi design, Wire wear ratio, WEDM

I. INTRODUCTION

Wire electrical discharge machining (WEDM) has become an important non-traditional machining process which is being widely used in aerospace, nuclear, die and tooling, and automotive industries, for machining difficult-to-machine materials. This process is used to machine any electrically conductive material irrespective of their hardness. It is a thermo electrical process in which material is removed by generating a series of discrete sparks between electrode and work piece immersed in a liquid dielectric medium. The discrete spark discharges melt and vaporizes minute amounts of work piece. WEDM employs continuously moving electrode in the form of a wire. The wire moving on the spool, feeds through the work piece, and is taken up on a second spool. The movement of the wire is controlled by computer numerical control mechanism to get required shape and accuracy of work piece. The dielectric fluid is continuously injected to flush away minute amounts of removed material. The selection of machining parameters in a machining process significantly affects wire wear ratio. The selection of these parameters in WEDM is primarily dependent on the operator's experience and user manuals provided by the machine-tool manufacturers.

Han et al., [1] presented influence of machining parameters (including pulse duration, discharge current, sustained pulse time, pulse interval time, polarity effect and dielectric) on surface finish in the finish cutting of WEDM. Experiments proved that the surface roughness can be improved by decreasing both pulse duration and discharge current. It was observed that when the pulse energy per discharge is constant, shorter pulses and longer pulses resulted in the same surface roughness but different surface morphology and different material removal rates. The metal removal rate, when a shorter pulse was used much higher than when the pulse duration is long. Huang and Liao, [2] focused on the determination of the number of finish cutting operations and process parametric setting in wire electrical discharge machining utilizing the concept of Taguchi quality design. Six machining parameters were chosen as the control factors whereas the machining performances of the finish cutting process were gap width, surface roughness, white layer depth and finish cutting area ratio. It was shown that the pulse on time and the distance between the wire periphery and the work piece surface in finish cutting were the 2 factors influences the machining performance. Rozenek et al., [3] experimentally investigated effect of machining parameters (discharge current, pulse-on time, pulse-off time, voltage) on machining rate and surface roughness during WEDM of MMCs $AlSi_7Mg/SiC$ and $AlSi_7Mg/Al_2O_3$. It was observed that machining rate of WEDM cutting composites significantly depends on the kind of reinforcement. The maximum cutting speed of $AlSi_7Mg/SiC$ and $AlSi_7Mg/Al_2O_3$ metal matrix composites were approximately 3 times and 6.5 times lower than the cutting speed of aluminium alloy respectively. Current and pulse on time had considerable influence on cutting rate and surface finish. Lok and Lee, [4] analysed processing of advanced ceramics (Sialon and Al_2O_3-TiC) using the wire-cut EDM process. The volumetric material removal rate for processing these ceramic materials was found to be very low as compared with alloy steels and the surface roughness achieved was inferior to that obtained with the die sinking EDM process. The extent of sub surface damage resulted from this thermal process was evaluated further by flexural strength data obtained from three points and four-point quarter bend test methods. The results showed that WEDM process is a viable material processing method for machining of advanced ceramics, but work has to be carried out to further study the ways and means of improving the surface finish and surface integrity of the machined ceramics. Manna and Bhattacharyya, [5] carried out an experimental investigation to determine the machine parameter settings during WEDM of aluminium reinforced silicon carbide metal matrix composites. Taguchi's L18 orthogonal array was used to plan the experiments as well as to determine the signal to noise ratios. ANOVA and F- test values were used to indicate the significant machining parameters affecting the MRR, surface roughness and spark gap.

Mathematical models relating input process parameters and output responses were established using Gauss elimination method for effective machining of Al/SiC metal matrix composites. Open gap voltage and pulse on period were the most significant and influencing parameters for controlling the metal removal rates whereas wire tension and wire feed rate emerged as the most significant parameters for surface roughness. Spark gap was dominantly dictated by wire tension and spark gap voltage. Liao et al. [6] proposed a parameter setting for WEDM process based on Taguchi quality design method and the analysis of variance by relating the machining performance measures and the machining parameters of table feed, pulse-on time, pulse-off time, wire speed, wire tension and dielectric flow. An analysis was carried out to find the influencing parameters on performance measures. Mahapatra and Patnaik [7] used the Taguchi experimental design for setting suitable machining parameters in order to maximize metal removal rate and surface finish.

Ramakrishnan and Karunamoorthy [8] presented a multi response optimization method using Taguchi's approach in order to predict the performance measures of the WEDM. The responses, metal removal rate, surface roughness and wire wear ratio have been transformed into multi response S/N ratio and optimized using S/N ratio analysis. Huang and Liao [9] applied the grey relational analysis to determine the optimal selection of machining parameters for WEDM. The significant influencing parameters on metal removal rate and surface roughness are found using grey theory. The drawback of grey relational analysis is that uncertainty always exists in the system because part of information is known and part of information is unknown. It reduces the responses into a single grey relational grade and it does not attempt to find the best solution but it helps to determine a good solution. Scott et al., [10] used a factorial-design method to determine the optimal combination of control parameters in WEDM, with measures of machining performance being the metal removal rate and the surface finish. Based on the analysis of variance (ANOVA), it was found that discharge current pulse duration and pulse frequency were significant control factors for both the metal removal rate and the surface roughness. A total number of 729 experiments were conducted. Thirty-two machining settings which resulted in a better metal removal rate and surface roughness were determined by two distinct techniques namely, explicit enumeration of all possible combinations and the dynamic programming approach. Gokler and Ozano¨zgu¨ [11] studied the selection of the most suitable cutting and offset parameter combination to get a desired surface roughness for a constant wire speed and dielectric flushing pressure. Tosun and Cogun, [12] investigated the effect of cutting parameters on wire wear ratio, material removal rate and mean surface roughness in WEDM of AISI 4140 steel with brass wire using regression analysis technique. It was observed that, wire wear ratio increased with increase in pulse duration and open circuit voltage. It gets decreased with increase in wire speed due to the reducing number of craters on wire per unit length of wire. The minimum value of wire wear ratio was observed at open circuit voltage of 80V, pulse duration of 300 ns, wire speed of 12.5 m/min and dielectric flushing pressure equal to 1.2 Pa. A very low value of experimental error was observed indicating the high accuracy in results. Anand [13] used a fractional factorial experiment with an orthogonal array layout to obtain the most desirable process specification for improving the WEDM dimensional accuracy and surface roughness.

The literature review above indicates that most of the studies have been concentrated on other different types of steels, in recent years, along with other types of steels powder metallurgical cold worked tool steel has also emerged as an important material for industrial applications. So that there is a need to provide a standard set (manual) of operating conditions, to machine powder metallurgical cold worked tool steel to the operators to run the machine optimally without relies on the operator experience, skill and trail-and-error methods. So, the aim of present research is to identify optimum machining conditions for WEDM of powder metallurgical cold worked tool steel, for minimum wire wear ratio using Taguchi technique. The experiments carried out to study various WEDM process parameters such as pulse on time (ON), pulse off time (OFF), spark gap set voltage (SV), peak current (IP), wire tension (WT) and water pressure (WP). Experiments conducted based on the L_{27} orthogonal array. For minimizing WWR "smaller-the-better" performance characteristic was applied in order to identify the optimal cutting condition. ANOVA was applied with 95% confidence level in order to determine the significance of the variables on wire wear ratio. The optimized process parameters leading to minimum wire wear ratio are then verified through a confirmation experiment. The details of the procedures are addressed in the following sections.

II. EXPERIMENTAL SET UP AND PREPARATION OF SPECIMENS

The chemical composition, mechanical and thermal properties of powder metallurgical cold worked tool steel used in experiments is given in Table 1 and

Table 2. The experiments were performed on an Electronica Ultima 1F WEDM machine as shown in Figure 1.

Table 1. Chemical composition of powder metallurgical cold worked tool steel

Composition	**Wt. (%)**
C	1.36
Si	0.4
Mn	0.35
Cr	4.54
Mo	3.44
V	3.58
P	0.019
S	0.016
W	0.07
Cu	0.08

Table 2. Mechanical and thermal properties of powder metallurgical cold worked tool steel

Density	7610 kg / m³
Modulus of elasticity	30.4 X 106 psi
Coefficient of thermal expansion	11.2 X 10-6 °C
Specific heat	22 W/m °C

Experiments were conducted on powder metallurgical cold worked tool steel plate material and mounted on the WEDM machine tool as shown in Figure 1. Figure 2 shows that specimen pieces of work materials with cutting area of 7mm × 7mm × 24mm.

Figure 1. Work piece Mounted on WEDM

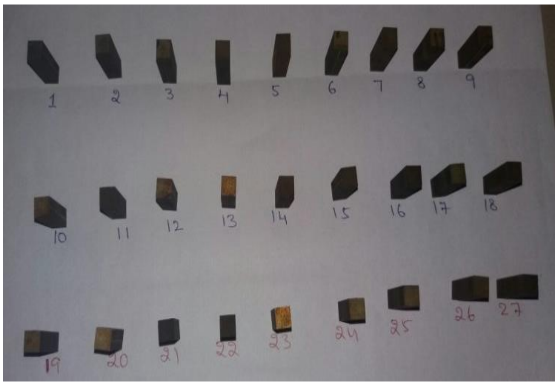

Figure 2. Specimens placed in vertical

Table 3. Process parameters along with the levels

S. No.	Process Parameters	Symbols	Units	Coded Factors	Levels		
					1	2	3
1	Pulse on time	ON	μsec	A	108	118	128
2	Pulse off time	OFF	μsec	B	47	55	63
3	Peak current	IP	Amperes	C	11	13	15
4	Spark gap set voltage	SV	Volts	D	18	43	68
5	Wire tension	WT	Grams	E	2	5	8
6	Water pressure	WP	Kg/cm²	F	8	11	14

In order to find the process parameters which is influencing on the process responses and also for selection of levels of process parameters, first sample experiments were conducted on the same material. Then it is found that pulse on time (ON), pulse off time (OFF), spark gap set voltage (SV), peak current (IP), wire tension (WT) and water pressure (WP) are more influencing the process responses. Levels of the process parameters are selected by conducting pilot experiments using one factor at a time approach. The selected process parameters and their machining levels with coded factors are given in Table 3. In this research Taguchi's L_{27} orthogonal array was selected for performing experiments. Servo feed (2150 m/min), wire feed (8 m/min) and table feed rate (7.6 mm/min) were fixed. Coated brass wire of 0.25 mm diameter was used as an electrode in experiments. De-ionized water was used as the dielectric fluid. The wire wear ratio value is obtained using by using Eq. (1).

$$\omega_R = \frac{W_L}{W_i} \qquad \text{------ } \textit{Equ. (1)}$$

Where ωL is the weight loss of wire after machining and ωi is the initial wire weight. To measure the weight an electronic balance with 0.001 gm accuracy was applied. In order to minimize the measurement error, the average value of three-weight measurements was used. The Taguchi's L_{27} orthogonal array and experimental results of wire wear ratio is presented in Table 4.

Table 4. Experimental Results for wire wear ratio with cutting conditions and S/N ratio values

Run No.	ON (µsec)	OFF (µsec)	IP (Amps)	SV (Volts)	WT (Grams)	WP (kg/cm^2)	Wire Wear Ratio			S/N Ratio
							R1	R2	R3	
1	108	47	11	18	2	8	0.039	0.038	0.040	28.177
2	108	47	13	43	5	11	0.164	0.163	0.165	15.703
3	108	47	15	68	8	14	0.136	0.135	0.137	17.329
4	108	55	11	43	5	14	0.035	0.034	0.036	29.116
5	108	55	13	68	8	8	0.065	0.064	0.066	23.741
6	108	55	15	18	2	11	0.050	0.049	0.051	26.019
7	108	63	11	68	8	11	0.082	0.081	0.083	21.723
8	108	63	13	18	2	14	0.037	0.038	0.036	28.634
9	108	63	15	43	5	8	0.131	0.132	0.130	17.654
10	118	47	11	43	8	11	0.104	0.105	0.103	19.659
11	118	47	13	68	2	14	0.206	0.207	0.205	13.723
12	118	47	15	18	5	8	0.122	0.123	0.121	18.273
13	118	55	11	68	2	8	0.077	0.078	0.076	22.270
14	118	55	13	18	5	11	0.051	0.052	0.050	25.847
15	118	55	15	43	8	14	0.155	0.156	0.154	16.193
16	118	63	11	18	5	14	0.034	0.035	0.033	29.368
17	118	63	13	43	8	8	0.130	0.131	0.129	17.721
18	118	63	15	68	2	11	0.174	0.173	0.173	15.222
19	128	47	11	68	5	14	0.248	0.247	0.247	12.134
20	128	47	13	18	8	8	0.233	0.232	0.234	12.653
21	128	47	15	43	2	11	0.408	0.407	0.409	7.787
22	128	55	11	18	8	11	0.104	0.103	0.105	19.659
23	128	55	13	43	2	14	0.338	0.337	0.339	9.422
24	128	55	15	68	5	8	0.348	0.347	0.349	9.168
25	128	63	11	43	2	8	0.120	0.119	0.121	18.416
26	128	63	13	68	5	11	0.274	0.273	0.275	11.245
27	128	63	15	18	8	14	0.200	0.199	0.201	13.979

The average response values of wire wear ratio for each parameter at level 1, 2 and 3 for S/N data and raw data are given in Table 7 and Table 8 respectively.

III. RESULTS AND DISCUSSIONS

A. Effect on wire wear ratio

The Figures 3 and 4 reveals that the wire wear ratio increases with increase in pulse on time and this is due to the discharge energy increases while increasing pulse on time, and these higher energy causes a powerful explosion and results in high wire wear ratio, as seen in Figure 3 the wire wear ratio increases with increase in peak current, this is due to increment in peak current results in a corresponding increase in wire wear ratio due to intense thermal effect on the wire electrode, which causes severe wear of the wire surface. Figure 3 and Figure 4 exhibits that wire wear ratio decreases with increase of pulse off time this happens as the discharge current decreases and the less amounts of material is removed which result in low wire wear ratio. Wire wear ratio is decreases while increasing spar gap set voltage.

Table 5. Pooled Analysis of Variance for (S/N ratios)

Source	DOF	Seq. SS	Adj. MS	F	P
ON	2	513.78	256.888	67.64	0.000
OFF	2	78.18	39.089	10.29	0.001
IP	2	215.57	107.785	28.38	0.000
SV	2	206.16	103.078	27.14	0.000
Residual	18	68.36	3.798		
Total	26	1082.04			

Table 6. Pooled Analysis of Variance for Means (Raw data)

Source	DOF	Seq. SS	Adj. MS	F	P
ON	2	0.1464	0.073194	47.30	0.000
OFF	2	0.0154	0.007686	4.97	0.019
IP	2	0.0466	0.023291	15.05	0.000
SV	2	0.0392	0.019606	12.67	0.000
Residual	18	0.0279	0.001547		
Total	26	0.2754			

Table 7. Response Table For Signal To Noise Ratios

Smaller is better				
Level	**ON**	**OFF**	**IP**	**SV**
1	23.19	16.21	22.32	22.55
2	19.81	20.17	17.64	16.85
3	12.72	19.33	15.75	16.31
Delta	10.47	3.96	6.57	6.25
Rank	1	4	2	3

Table 8. Response Table For Means

Response Table for Means				
Level	**ON**	**OFF**	**IP**	**SV**
1	0.08167	0.18400	0.09341	0.09648
2	0.11693	0.13581	0.16637	0.17611
3	0.25248	0.13126	0.19130	0.17848
Delta	0.17081	0.05274	0.09789	0.08200
Rank	1	4	2	3

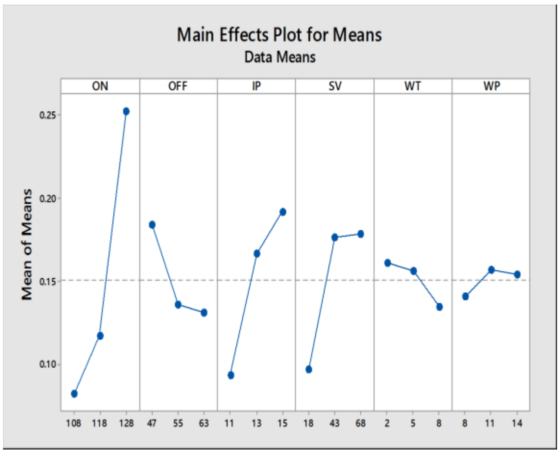

Figure 3. Effects of process parameters on wire wear ratio (Raw Data)

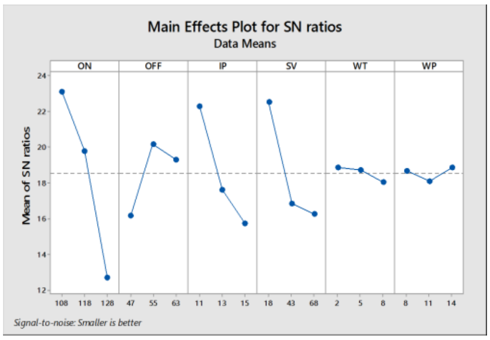

Figure 4. Effects of process parameters on wire wear ratio (S/N Data)

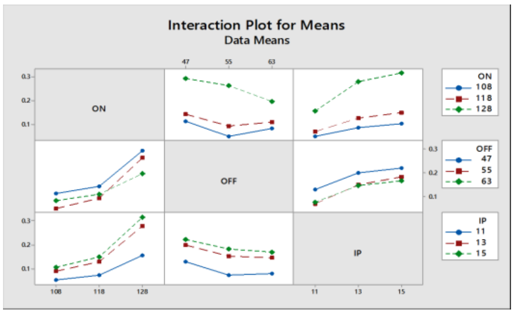

Figure 5. Effects of process parameters Interactions on wire wear ratio (Raw Data)

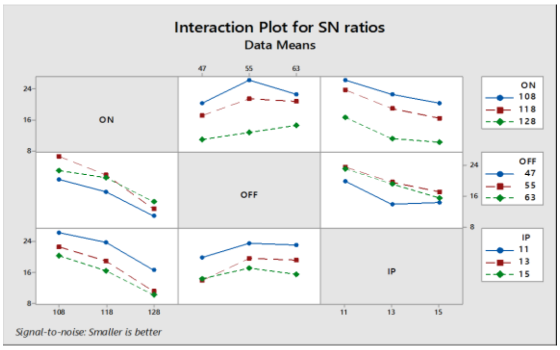

Figure 6. Effects of process parameters Interactions on wire wear ratio (S/N Data)

From the Figure 5 and Figure 6 It also clear from the interaction plots for means and interaction plots for S/N Ratio that there is no interaction between pulse on time and peak current, pulse on time and pulse off time in effecting the wire wear ratio because the interaction lines are almost parallel. There is moderate interaction between pulse on time and pulse off time.

B. Analysis of variance:

In order to study the significance of the process parameters towards wire wear ratio, Analysis of variance (ANOVA) was performed. From ANOVA, it was found that wire tension and water pressure are insignificant process parameter on wire wear ratio. Insignificant parameters were pooled and the pooled versions of ANOVA of the S/N data and raw data for wire wear ratio are given in Table 5 and Table 6 respectively. From Table 5 and Table 6, it is observed based on P value and F-value, the pulse on time, pulse off time, peak current, and spar gap set voltage has strongly affecting the both raw data and S/N data on the wire wear ratio values.

C. Selection of Optimum Levels

The response Tables (Tables 7 and 8) shows the average of each response characteristic (S/N data and raw data) for each level of process variables. Tables 7 and 8 also included ranks based on delta statistics, which compare the relative magnitude of effects. The delta statistic is the highest minus the lowest average for each factor. Minitab assigns ranks based on delta values; rank 1 to the highest delta value, rank 2 to the second highest, and so on. The ranks indicate the relative importance of each factor to the response. From the response Tables, it was concluded that pulse on time has the greatest effect on wire wear ratio and is followed by peak current, spark gap set voltage and pulse off time. WWR should be minimum for optimum manufacturing cost so, "smaller the better" performance characteristic was applied. From Fig. 3, it can be found that the first level of pulse on time (A1), third level of pulse off time (B3), first level of peak current (C1) and first level of spark gap set voltage (D1), results minimum value of wire wear ratio. The S/N ratio analysis (Fig. 4) also suggests the same levels of the variables (A1, B3, C1 and D1) as the best levels for obtaining minimum wire wear ratio in wire cut electric discharge machining process while machining of power metallurgical cold worked tool steel.

(VANADIS 4E).

D. Estimation of Optimum Response Characteristics

In this section, the optimum values of the wire wear ratio along with their respective confidence intervals have been predicted at optimal cutting condition. The optimal value of wire wear ratio characteristic is predicted by considering the effect of the significant parameters only. The results of confirmation experiments are also presented to validate the optimal results. The optimum value of wire wear ratio is predicted at the optimal levels of significant variables which have already been selected as pulse on time (A1), pulse off time (B3), peak current (C1) and spark gap set voltage (D1) (Table 8 and Figure 3). The estimated mean of the response characteristic (WWR) can be determined (Kumar, 1993 and Roy, 1990) as

$$Mean\ \mu_{WWR} = \overline{A1} + \overline{B3} + \overline{C1} + \overline{D1} - 3\,\overline{T}$$

$\overline{T}$ = overall mean of wire wear ratio = $(\Sigma R1+\Sigma R2+\Sigma R3)/81$ = 0.1205

$\overline{A1}$ = Average value of wire wear ratio at the first level of pulse on time = 0.0817

$\overline{B3}$ = Average value of wire wear ratio at the third level of pulse off time = 0.131

$\overline{C1}$ = Average value of wire wear ratio at the first level of peak current = 0.093

$\overline{D1}$ = Average value of wire wear ratio at the first level of peak spark gap set voltage = 0.0965

Substituting the values of various terms in the above equation,

$Mean\ \mu_{WWR}$ = 0.0817 + 0.131 + 0.093 + 0.0965 - 3(0.1505) = 0.0493

E. Confirmation Experiment

In order to validate the results obtained, three confirmation experiments were conducted for the response characteristics (wire wear ratio) at optimal levels of the process variables. The average values of the wire wear ratio were obtained and compared with the predicted values. The results are given in Table 9.

Table 9. Predicted Optimal Values, Confidence Intervals and Results of Confirmation Experiments

Performance Response	Wire wear ratio
Optimal condition	$A_1 B_3 C_1 D_1$
Predicted value	0.0493
Experimental value	0.0471
% of error	4.462

IV. CONCLUSIONS

This paper furnishes the effects of machining parameters on wire wear ratio in Wire electrical discharge machining (WEDM) while machining of powder metallurgical cold worked tool steel has been studied with the aim of minimization of wire wear ratio using Taguchi's design. The following conclusions are drawn from the result of present research work.

1. Ranges of WEDM process parameters have been established based on review of literature and by performing the pilot experiments using one factor at a time approach.
2. The significant parameter on the wire wear ratio is determined by using ANOVA. Based on ANOVA method, the highly effective parameter on wire wear ratio was found as pulse on time and wire tension, water pressure was found as insignificant parameter.
3. The optimal sets of process parameters were obtained for wire wear ratio using Taguchi's technique. The best possible optimum set of conditions of WEDM while machining of powder metallurgical cold worked tool steel is found to be at first level of pulse on time (A1): 108 machine units, third level of pulse off time (B3): 63 machine units, first level of peak current (C1): 11 amperes, first level of spark gap set voltage (D1): 18 volts
4. The wire wear ratio value is predicted at optimal set of conditions. The error between experimental and predicted values at the optimal combination of parameter settings for wire wear ratio was 4.462 %. Obviously, this confirms excellent reproducibility of the experimental conclusions.

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