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Modeling and Validation of Parametric Combinations in PEDM of Superfer 800 Using Copper Electrode

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Abstract
In this study, the modeling and validation of optimal parametric combinations during powder mixed electrical discharge machining of Superfer 800 have been carried out by regression and artificial neural network. The experiments were conducted by varying polarity, peak current, pulse on-time, pulse off-time, discharge voltage and flushing pressure for evaluating performance characteristics i.e. tool wear rate. To establish the significant relationship between input parameters and output performance measure, the mathematical models have been developed using regression analysis. These developed models have been verified for predictions by conducting confirmation experiments and tested for goodness. It is observed from the experimental results that the developed model, when confirmed, specifies the acceptable degree of error. The use of artificial neural networks offers an environment, which is free from bulky mathematics as compared to regression analysis.

Keywords
Powder Mixed Electrical Discharge Machining (PEDM), Tool Wear Rate (TWR), Regression Analysis, Artificial Neural Network, Superalloy

I. Introduction

Electric Discharge Machining (EDM) is one of the most effective modern non-conventional machining processes and is capable of machining the newly developed high strength alloys precisely and economically. The application of the process in the industry, for the production of geometrically complex cavities moulds and dies, automotive, aerospace, and surgical components [1] shows its range of use in the research field. The improvement in machining performance has been noticed when conductive powder is mixed in a dielectric medium. The conductive powder mixed EDM process is more stable due to powder particle getting charged in between the electrodes, thereby producing uniform spacing, which results in a higher material removal rate (MRR) and lower Tool Wear Rate (TWR), as brought out by researchers.

Jeswani [2] investigated the effect of adding fine graphite powder in the dielectric of EDM and reported that addition of about 4g of fine graphite powder (10 μm in average size) per liter of kerosene increasing MRR by 60% and TWR by 15%. The wear ratio TWR/MRR was reduced by about 28%. This effect was attributed to the reduction in the breakdown voltage of the kerosene dielectric fluid caused by the addition of the graphite powder. P. Pecas and E. Henriques [3] have investigated the effect of the electrode area in the surface roughness and topography while using simple and powder-mixed dielectric in EDM process. A as [4] carried out the performance of two graphite electrodes for a seal slot in a jet engine turbine vane of nickel-based alloys and showed that the quality of the electrode have a significant effect on MRR and relative electrode wear. Bharti et al. [5] investigated the machining characteristics of Inconel 718 during die-sinking electrical discharge machining process with copper as tool electrode. Discharge current and pulse on-time were identified as common influencing parameters for MRR, SR and TWR. Kristian [6] in his study on IN 100mod Ni-base alloy, used two different qualities of electrode Poco AF5 and Poco EDM3 were tested in a 23 factorial test. Two levels of discharge current and pulse duration were tested. The results show that EDM3 graphite performs very well, giving significantly higher MRR than AF5, but still with acceptable relative electrode wears. The AF5 gives significantly lower wear, but also lower MRR. The AF5 has even finer grains than EDM3.

Caydas and Hascalik [7] in their study selected Ti alloy as work material while carrying out die-sinking EDM, pulse current was found the most important factor affecting both the electrode wear and white layer thickness, while pulse off-time has no significant effect on both responses. Hascalik and Caydas [8] investigated the influence of sinking EDM parameters on machining of Ti-6Al-4V using graphite, copper and aluminium electrodes. Bhattacharyya et al. [9] carried out modeling and analysis of EDMed job surface integrity. In addition, due to intense heat generated in the EDM process, white layer is formed on the machined surface. Abdulkareem et al. [10] studied the cooling effect of copper electrode on the die-sinking of electrical discharge machining of titanium alloy (Ti-6Al-4V). Analysis of the influence of cooling on the responses has been carried out and presented. It was possible to reduce the electrode wear ratio up to 27% by electrode cooling. Surface roughness were also reduced while machining with electrode cooling. Ho et al. [11] studied the use of powder metallurgy (PM) compacted electrodes for electrical discharge surface alloying/modification of Ti-6Al-4V alloy. The PM electrodes produced greater alloying than the solid electrode. Gu et al. [12] studied the feasibility of machining Ti-6Al-4V with a bundled electrode and its effect on EDM performance was compared experimentally using a solid die-sinking electrode. The results explain the high performance of the EDM process with a bundled electrode by through the use of multi-hole inner flushing to efficiently remove molten material from the inter-electrode gap and through the improved ability to apply a higher peak current. Sanchez et al. [13] conducted a study on gap variations due to different electrode materials in multi-stage planetary electric discharge machining. It was reported that copper electrode produces large gap variations than graphite electrode.

Little research work has been stated on effect of machining parameters on machining characteristics of Superalloys, these alloys are extremely useful in high temperature applications gas turbine, space vehicles, aeronautics, nuclear reactors, petrochemical equipment's. In this paper a systematic and simplified approach is used for development of mathematical model and analysis of TWR with Polarity (PL), Peak current (I), Pulse-on-time (T-on), Pulse-off-time (T-off), Discharge Voltage (V) and Flushing Pressure (FP) as input parameters using regression analysis and artificial neural network.

II. Experimental Procedure

EDM of Superfer 800 workpiece with a cylindrical copper rod as the tool electrode was carried out using dielectric fluid mixed with graphite powder. The chemical composition of workpiece and detailed description of the experiment is shown in Table 1 & 2 respectively.The selected process parameters and their levels are listed in Table 3. The experimental trials were performed as per L18 ($2^1 \times 3^7$) orthogonal array, containing 18 runs at different combinations. The measurements of TWR werecarried out using an electronic balance DENVER (SI-234).

Table 1: Composition of Superfer 800

Element percentages	
Carbon	0.08
Sulfur	0.003
Manganese	1.0
Silicon	0.7
Titanium	0.46
Aluminum	0.28
Copper	0.06
Nickel	33.8
Chromium	20.4
Iron	Bal.

Table 2: Experimental Details

Description		
EDM machine	:	Electra EMS 5535 (Electronica make)
Workpiece	:	200 × 50 × 7 mm plate
Tool electrode	:	Copper rod (16 mm diameter)
Dielectric fluid	:	EDM oil
Powder used	:	Graphite (10 gm/l)
Machining time	:	10 minutes

Table 3: Factors With Their Levels

Process parameters		Level		
		1	2	3
Electrode polarity, A		+	-	
Peak current, B (amp)		3	6	9
Pulse on-time, C (μ-sec)		20	50	100
Pulse off-time, D (μ-sec)		20	40	60
Discharge voltage, E (V)		25	30	35
Flushing pressure, F (Kg/cm²)		1	0.8	1

III. Results and Discussion

A. Development of Mathematical model for TWR using Regression Analysis

Multi-variable linear regression (MVLR) analysis is used and an empirical expression of the EDM process is developed to evaluate the relationship between the input parameters and the TWR. The average output values of TWR are presented in Table 4.

Table 4: Average Value of TWR

Exp. No.	A Polarity	B Peak Current (A)	C Pulse on-time (μs)	Average TWR (mm³/min)
1	+	3	20	0.0149
2	+	6	50	0.1266
3	+	9	100	0.4267
4	+	3	20	0.0131
5	+	6	50	0.1158
6	+	9	100	0.4188
7	+	3	50	0.0292
8	+	6	100	0.1677
9	+	9	20	0.3068
10	-	3	100	0.0010
11	-	6	20	0.0016
12	-	9	50	0.0056
13	-	3	50	0.0006
14	-	6	100	0.0024
15	-	9	20	0.0060
16	-	3	100	0.0009
17	-	6	20	0.0017
18	-	9	50	0.0059

SPSS standard version software (SPSS 17.0 for windows) has been used to estimate the parameters.The Table 5 presents the empirical expression developed by 1st order model for three variables.

Table 5: Empirical Expressions Developed by 1st Order Model for TWR

Predictor	Coefficient of TWR
b_0	-5.071
X_1	1.671
X_2	2.263
X_3	0.432

The developed empirical model by 1st order modelfor TWR is expressed as:

$$Y = -5.071 + 1.671X_1 + 2.263X_2 + 0.432X_3 \quad \text{Eq. (1)}$$

With the help of the experimental data of Table 4 and the above mentioned equation the relative error between observed output values and predicted output values of TWR are calculated and presented in the Table 6.

Table 6. Comparison between predicted and observed values of TWR (1st order model)

Exp. No.	Predicted values (mm³/min)	Observed values (mm³/min)	Percentage error
1	0.0174	0.0149	14.61
2	0.1244	0.1266	-1.75
3	0.4202	0.4267	-1.55
4	0.0174	0.0131	24.92

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5	0.1244	0.1158	6.93
6	0.4202	0.4188	0.33
7	0.0259	0.0292	-12.64
8	0.1679	0.1677	0.10
9	0.2097	0.3068	-46.34
10	0.0007	0.0010	-34.05
11	0.0018	0.0016	10.44
12	0.0066	0.0056	15.71
13	0.0006	0.0006	-8.51
14	0.0036	0.0024	32.97
15	0.0045	0.0060	-34.17
16	0.0007	0.0009	-20.65
17	0.0018	0.0017	4.84
18	0.0066	0.0059	11.19

The developed 1st order empirical model for TWR revealed a lack of fitness due to high prediction error for TWR, as shown in Table 6. As a result, the 2nd order model has been developed. The empirical equation for TWR is formulated using regression results as shown in Table 7.

Table 7. Value of coefficient of TWR by 2nd order model

Predictor	Coefficient of TWR
b_0	-5.597
X_2	2.125
X_3	1.176
PX_2	0.214
PX_3	0.208
X_2X_3	-1.390
P^2	1.248
X_2^2	1.607
X_3^2	0.042

The developed 2nd order empirical model by regression analysis for TWR is given by equation (2), where P refers to polarity transformed from X_1.

$$\hat{Y} = -5.597 + 2.125X_2 + 1.176X_3 + 0.214PX_2 + 0.208PX_3 - 1.390X2X_3 + 1.248P_2 + 1.607X_2^2 + 0.042X_3^2 \quad \text{Eq. (2)}$$

The predicted output values for TWR are calculated with the help of equation (2). The relative error between predicted and measured output value for TWR is calculated and presented in Table 8.

Table 8: Observed and predicted values of TWR by 2nd order model

Exp. No.	Predicted values (mm^3/min)	Observed values (mm^3/min)	Percentage error
1	0.0139	0.0149	-7.52
2	0.1200	0.1266	-5.52
3	0.4261	0.4267	-0.15
4	0.0139	0.0131	5.47
5	0.1200	0.1158	3.49
6	0.4261	0.4188	1.71
7	0.0301	0.0292	3.01
8	0.1648	0.1677	-1.77
9	0.3107	0.3068	1.25
10	0.0009	0.0010	-5.61
11	0.0017	0.0016	4.37
12	0.0058	0.0056	2.63
13	0.0006	0.0006	-0.69
14	0.0024	0.0024	1.41
15	0.0059	0.0060	-2.02
16	0.0009	0.0009	4.95
17	0.0017	0.0017	-1.61
18	0.0058	0.0059	-2.58

It is seen that the relative error of TWR is well within a close of the 10 % limit. The maximum and minimum error percentage is 5.47% and -7.52%, respectively. The developed model for TWR using regression modeling, are highly adequate as their R^2 value is 0.992 and R^2 adjusted value is 0.990, which are very close to 1.

B. Validation of MVLR model and Observed TWR by using ANN

The confirmations experiments are performed to validate the earlier developed empirical expressions for TWR, according to the orthogonal array as shown in Table 9.

Table 9.Observed values of TWR for validation

Exp. No.	A	B	C	D	E	F	Average TWR (mm^3/min)
	Polarity	Peak Current (A)	Pulse on-time (µs)	Pulse off-time (µs)	Discharge Voltage (V)	Flushing Pressure **(Kg/cm^2)**	
1	+	3	20	20	25	0.5	0.0175
2	+	6	20	40	30	0.75	0.1213
3	+	9	20	60	35	1	0.4254
4	+	3	20	40	30	1	0.0176
5	+	6	20	60	35	0.5	0.1150
6	+	9	20	20	25	0.75	0.4166
7	+	3	20	20	35	0.75	0.0203
8	+	6	20	40	25	1	0.1232
9	+	9	20	60	30	0.5	0.3865
10	-	3	20	60	30	0.75	0.0008

11	-	6	20	20	35	1	0.0021
12	-	9	20	40	25	0.5	0.0054
13	-	3	20	60	25	1	0.0007
14	-	6	20	20	30	0.5	0.0023
15	-	9	20	40	35	0.75	0.0055
16	-	3	20	40	35	0.5	0.0008
17	-	6	20	60	25	0.75	0.0021
18	-	9	20	20	30	1	0.0054

The predicted and observed values of the TWR are presented in Table 10, which also shows the percentage error of output parameters. The maximum and minimum error percentage for TWR is 8.06% and -8.44%, respectively, which is very much satisfactory to validate the goodness of predictive models.

Table 10.Validation between predicted and observed values of TWR by MVLR

Exp. No.	Predicted values (mm^3/min)	Observed values (mm^3/min)	Percentage error
1	0.0187	0.0175	6.52
2	0.1159	0.1213	-4.70
3	0.4204	0.4254	-1.19
4	0.0187	0.0176	5.98
5	0.1159	0.1150	0.74
6	0.4204	0.4166	0.90
7	0.0187	0.0203	-8.44
8	0.1159	0.1232	-6.34
9	0.4204	0.3865	8.06
10	0.0008	0.0008	-5.83
11	0.0022	0.0021	6.67
12	0.0053	0.0054	-1.49
13	0.0008	0.0007	7.40
14	0.0022	0.0023	-2.22
15	0.0053	0.0055	-3.37
16	0.0008	0.0008	-5.83
17	0.0022	0.0021	6.67
18	0.0053	0.0054	-1.49

Data taken from Table 9 is divided randomly i.e. for training, 70%, for validation, 15% and for testing, 15%. The best validation performance in terms of least mean square error (mse) is achieved at epoch 2 by the network for TWR as shown in fig. 1.

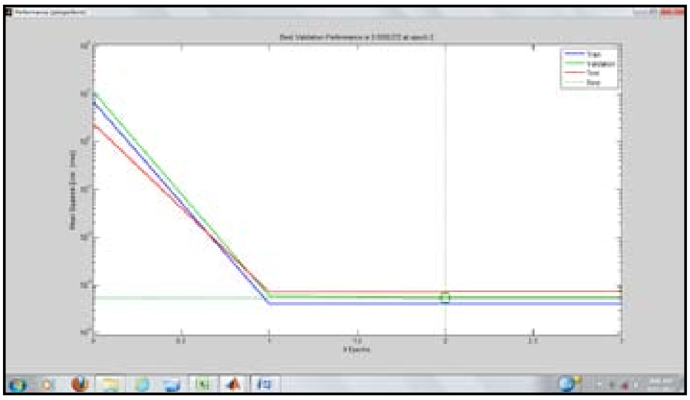

Fig. 1: Performance Plot for TWR

The range of deviation in error percentage is from 8.19% to -7.70% as shown in Table 11 which is within the acceptable limits. The comparison of observed and predicted values of TWR by MVLR and ANN is shown in Figure 2. The developed model is suitable for TWR, as verified by the predicted and observed results for having close relation to each other.

Table 11: Validation between predicted and observed values of TWR by ANN

Exp. No.	Predicted values (mm^3/min)	Observed values (mm^3/min)	Percentage error
1	0.0188	0.0175	7.15
2	0.1181	0.1213	-2.70
3	0.4210	0.4254	-1.05
4	0.0188	0.0176	6.62
5	0.1181	0.1150	2.63
6	0.4210	0.4166	1.04
7	0.0188	0.0203	-7.70
8	0.1181	0.1232	-4.31
9	0.4210	0.3865	8.19
10	0.0007	0.0008	-6.90
11	0.0022	0.0021	4.45
12	0.0054	0.0054	0.91
13	0.0007	0.0007	6.46
14	0.0022	0.0023	-4.65
15	0.0054	0.0055	-0.92
16	0.0007	0.0008	-6.90
17	0.0022	0.0021	4.45
18	0.0054	0.0054	0.91

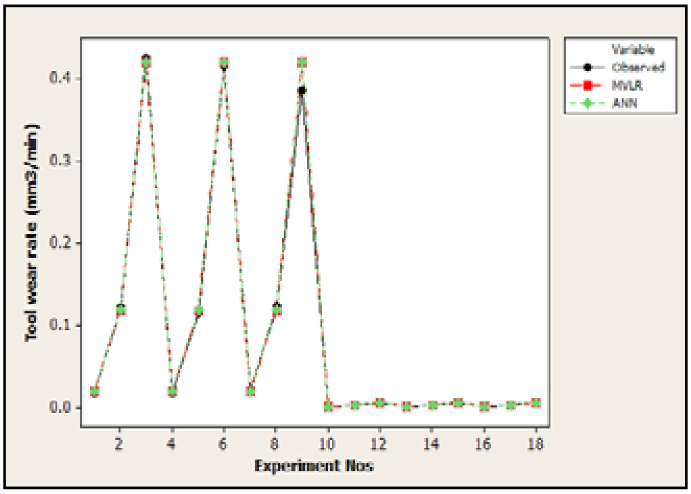

Fig. 2: Comparison Between Observed and Predicted Results of TWR Using MVLR and ANN

IV. Conclusion

In this investigation, modeling of TWR is proposed for the powder EDM of Superfer 800 with copper electrode. The 2nd order model was developed for prediction of TWR during the EDM process with logarithmic data transformation as a 1st order model showed lack of fitness. The proposed models have been successfully applied to estimate the values under various machining conditions.The following conclusions are summarized below:

1. The developed empirical formulae can be used to evaluate TWR produced by EDM machining with low prediction error.
2. The proposed model is validated to conclude as well fit for predictions of machining output with low prediction error.
3. The developed models for TWR using regression modeling, are highly adequate as their R^2 values are very close to 1.
4. Maximum and minimum error percentage for tool wear rate is 8.19% and -7.70%.

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