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Original Article

Mathematical Modelling of Response Parameters During Ultrasonic Assisted Electro-Discharge Machining Process

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Abstract *- Choosing the optimum production conditions is one of the most important aspects of the Electric Discharge Machining operation because they affect critical variables such as roughness and rate of metal removal. Because this advanced material presents manufacturing issues if formed by standard methods, machining of Ni-Ti alloys is often attempted utilizing unconventional techniques for manufacturing, particularly EDM. In this work, shape memory alloy (NiTi) with ultrasonic vibration was used in the experiment. The work explains an effort to apply a low-frequency vibration on a shape memory alloy (NiTi) workpiece during the EDM process. Electrolytic copper tools on a die-sink discharge machine are utilized in the experiment to perform EDM on NiTi alloy. In the current work, a model for roughness and rate of metal removal during ultrasonic-aided electro-discharge machining (USA-EDM) of NiTi shape memory alloy using Buckingham's Pi-theorem has been attempted. The test finding shows that altering key dimensionless π parameters had a considerable impact on the values of roughness (SR) and rate of metal removal. Roughness (SR) and rate of metal removal (MRR) values predicted by the model created using Buckingham pi theorem and dimensions analysis are close to experimental findings.*

Keywords *- Ultrasonic Assisted Electro-Discharge Machine (USA-EDM), Roughness (SR), Rate of Metal Removal (MRR), Shape Memory Alloy (NiTi), Buckingham pi Theorem.*

1. Introduction

Electrically conductive materials, regardless of hardness, like metals, graphite, metallic alloys, and even some ceramic conductive materials, can be machined utilizing the widely used advanced manufacturing technology known as electrical discharge machining (EDM). It is commonly employed to manufacture surgical, automotive, aerospace, and mold and die components [1]. In this method, the workpiece and electrode repeatedly discharge electrically to remove material from the workpiece. In a gas or a dielectric liquid, this electric sparking process occurs. Small Viscosity, the strength of the dielectric high, efficient cooling, and flushing capacity are some of the desirable characteristics of an ideal dielectric [2]. E. Aliakbari et al. [4] discovered the optimal rotating process parameter setting and concluded from this study that current, on-time of pulse, the rotational speed of electrode, and electrode morphologies have the greatest impact on MRR, EWR, and SR as input parameters. They discovered the optimal rotating process parameter setting and concluded from this study that current, pulse on time, electrode rotational speed, and electrode morphologies have the greatest impact on MRR, EWR, and SR as input parameters. Cut width and depth are the factors that have the biggest impact on rough machining; according to Bala Murugan Gopalsamy et al. [6], cutting speed is the most significant element in final machining. Minhat et al. [7] provided the beginning, ignition, and discharge phases as the foundation for their mathematical model of EDM pulses. The model, however, was unable to identify the EDM profiles accurately, and the mathematical equations did not match the profiles in all stages. Bains et al. [9], and Ravindranath et. al.[10], used dimensional analysis and considered thermo-mechanical parameters to construct a mathematical model for Metal removal rate and surface roughness. Dimensional evaluation is a method where the most influential variables defining actual phenomena are chosen to formulate dimensionally correct equations. In dimensional analysis, mathematical models are created using algebraic equations [12]. The first and most crucial step in the dimensional analysis is to determine the variables that may have an impact on the outcome. The three types of variables are dependent, independent, and extraneous. It is possible to use response surface methodology (RSM) to build an empirical model that predicts the roughness and rate of metal removal. The RSM model was only constrained by the settings for the machine. As a result, a dimensional model is created that considers both thermos physical and machine setup characteristics [14.16]. The current study solves the Multi-Response Optimization issue by applying an ideal parametric collection of input variables like on Time, off Time, and Voltage [19]. This study examines the influence of Cu, the nanopowder, on electrical current-discharge machining (EDM) on the difficult-to-cut material Titanium matrix composite (TMCs). The final result demonstrated that Cu nanopowder influences both response parameters. MRR of the machining process improves with greater volume quantity, but TWR increases as well due to the inclusion of Cu nanopowder. The significance of the experiment is explained by the ANOVA result [20]. The appropriate specifications assure that the turned product has a high surface quality. According to a review of the literature, there is little information available on the effect of the copper electrode on NiTi material utilizing RSM. It was also discovered that the majority of research published was restricted to a certain range of process parameters that create responses in the finish, semi-finish, or roughing regions. In this paper, mathematical models for linking the SR and MRR were established. The Buckingham Pi theorem is employed in the current work to try to create a link between process variables, thermal-mechanical features, and performance indicators. The goal is to create a mathematical model that can estimate the rate of metal removal (MRR) during ultrasonic EDM while varying process parameters like gap current, on-time of the pulse, off-time of the pulse, voltage, electrical conductivity of workpiece, and electrical conductivity of tool electrode during the experiments, electric discharge machining of Ni-Ti alloy was conducted.

1.1. Experimental Setup

The die sinks EDM equipment was used for testing, as illustrated in Fig 1. The tool was chosen to be copper, which serves as the cathode, and the workpiece was chosen to be a shape memory alloy (NiTi), which acts as an anode. For machining, 20 x 20 x 15 mm shape memory alloy plates were chosen. The low-frequency vibration generator was linked to a workpiece controlling the frequency and amplitude. The component was vibrated with low-frequency and low-frequency fluctuations.

1.1.1. Duty cycle (τ)

It is a proportion of the overall cycle time to the on-time. The on-time is divided by the entire cycle duration to calculate this.

$$\tau = T_{on} / (T_{on} + T_{off}) \qquad (1)$$

1.2. Design of Experiments

Experiment planning was carried out in this study using the central composite rotatable design (CCRD) of the response surface method (RSM). To accomplish the desired objectives/goals, also known as responses, the influential parameters (also known as factors) were changed within a specific range. Some settings remained constant throughout the experiment.

Fig. 1 USA-EDM setup

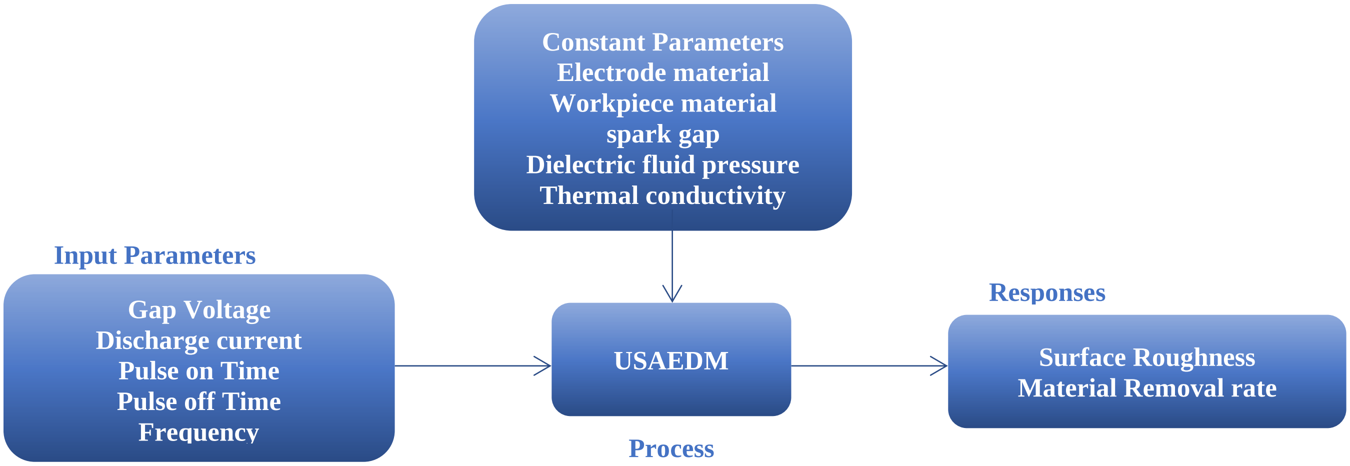

Fig. 2 Scheme adopted for USAEDM process

Fig. 2. shows the process parameters selected for USAEDM of shape memory alloy to achieve the desired response roughness of surface and rate of metal removal rate.

1.3. Factorial Design

Tests were created using the design of experiments. In this investigation, five input parameters with five levels each were used.

After conducting an experimental analysis, The findings were utilized to build a model using mathematics with various parametric combinations. Buckingham's theorem, a dimensional analysis, was applied to investigate the link between the SR, MRR, and machining variables. The projected SR and MRR determined with a model of mathematics were then compared to the experimental findings to test the design. [18].

Dimensional analysis is a strategy for formulating dimensionally correct equations by selecting the most relevant variables describing actual events. Algebraic equations are used to develop mathematical models in dimensional analysis. The first and most important stage in dimensional analysis is identifying the variables that may influence the outcome. Variables are classified into three types: dependent, independent, and superfluous. Response surface methodology (RSM) can be used to create an empirical model that predicts roughness and metal removal rate. The RSM model was only limited by the machine settings. As a result, a dimensional model is produced that takes into account both thermophysical and machine setup parameters.

1.4. Buckingham's 'π' Theorem

A mathematical strategy called the Buckingham Pi Theorem enables the development of a relationship for a quantity of interest between the model and the actual scenario [20]. The operational connection between the process variables and roughness and metal removal rate is determined in this work utilizing the dimensional analysis Buckingham Pi theorem. Selecting repeating and non-repeating variables is necessary before building the model using the Pi theorem.

Table 1. Machine parameters and their related variation levels

EDM Parameter	Unit	Level1	Level2	Level3	Level4	Level5
Gap Voltage	V	25	45	65	85	105
Discharge current	A	10	15	20	25	30
Pulse On Time	us	30	45	60	75	90
Pulse Off Time	us	6	8	10	12	14
Frequency	Hz	200	250	300	350	400

Fundamental dimensions and repeating variables both have an equal number of instances. Therefore, the following criteria were used to identify six recurring parameters.

1. Because SR and MRR are dependent variables, it could not be the recurring responses.
2. The recurring variable must have geometric, flow, or fluid qualities.
3. A dimensionless group should not be formed by each repeating variable.
4. The essential dimensions of a recurring parameter should be the same.
5. The dimensions of two recurring variables must not be the same. The suggested model may express the mass rate of material removal (MRR) and roughness of the surface rate in terms of the other parameters given in Eqs. (2) and (3). 'f' reflects the relationship between input variables and empirically determined response parameters.

Table 2. Parameters with associated dimensions, symbols, and measurement systems

Sr. No	Parameters	Symbol	Unit	Dimension
1	Material removal Rate	MRR	g/min	$M\ T^{-1}$
2	Roughness of Surface	Ra	µm	L
3	On-Time pulse	Ton	µs	T
4	Off-Time pulse	Toff	µs	T
5	Electrical resistivity	R	µ Ω-m	$ML^{3}T^{-3}I^{-2}$
6	Frequency	F	Hz	T^{-1}
7	Material Density	ρ	g/cm3	$M\ L^{-3}$
8	on time Ultrasonic	UT_{on}	µs	T
9	off time Ultrasonic	UT_{off}	µs	T
10	Specific heat	CP	J/goC	$L^{2}\ T^{-2}\ \Theta^{-1}$
11	Duty Cycle	DC		1
12	Voltage	V	V	$ML^{2}T^{-3}I^{-1}$
13	Current	I	A	I
14	The amplitude of Ultrasonic Vibration	A	µm	L
15	Material Conductivity	Mc	S/m	$M^{-1}L^{-3}\ T\ Q^{2}$
16	conductivity of Thermal	K	W/m-K	$M\ L\ T^{-3}\ \Theta^{-1}$
17	Flushing pressure	F_p	Kg/cm^{2}	$M\ L^{-2}$

$$MRR = f\,(\,Ton, Toff, R, F, \rho, T_{on}, UT_{off}, CP, DC, V, I, A, Mc, K, F_p) \tag{2}$$

$$Ra = f\,(\,Ton, Toff, R, F, \rho, Ton, UToff, CP, DC, V, I, A, Mc, K, Fp) \tag{3}$$

A Dimensional model for MRR and Ra is developed using a total of 17 variables, as shown in

The fundamental variables in the present instance are mass (M), length (L), time (T), temperature (θ) and, current (I), charge (Q). As a result, the total number of factors is seventeen, and the basic dimensions are six, seventeen, and six. n =17 and r = 6; thus, the, Π = n – r = 11. The current investigation, Π Terms

$\Pi_{R1} = MRR\,[V]^a[A]^b[M_c]^c\,[F_p]^d\,[k]^e\,[I]^f$
$\Pi_{R1} = [M\,T^{-1}]\,[ML^2T^{-3}I^{-1}]^a\,[L]^b\,[M^{-1}L^{-3}\,TQ^2]^c\,[\,M\,L^{-2}]^d[M\,L\,T^{-3}\,\Theta^{-1}]^e[I]^f$
$\Pi_{R1}= \frac{MRR_g}{V^{1/3}A^{2/3}Fp^{2/3}I^{1/3}}$

$\Pi_{R2} = SR\,[V]^a[A]^b[M_c]^c\,[F_p]^d\,[k]^e\,[I]^f$

$\Pi_{R2} = \frac{S_R}{A}$

$\Pi_3 = T_{on}[V]^a[A]^b[M_c]^c\,[F_p]^d\,[k]^e\,[I]^f$

$\Pi_3 = \frac{T_{on}I^{1/3}V^{1/3}A^{4/3}}{F_p^{1/3}}$

$\Pi_4 = T_{off}\,[V]^a[A]^b[M_c]^c\,[F_p]^d\,[k]^e\,[I]^f$

$\Pi_4 = \frac{T_{off}I^{1/3}V^{1/3}A^{4/3}}{F_p^{1/3}}$

$\Pi_5 = R\,[V]^a[A]^b[M_c]^c\,[F_p]^d\,[k]^e\,[I]^f$

$\Pi_5 = \frac{R\,I}{V\,A}$

$\Pi_6 = F[V]^a[A]^b\,[M_c]^c\,[F_p]^d\,[k]^e\,[I]^f$

$\Pi_6 =\frac{F\,A^{4/3}Fp^{1/3}}{V^{1/3}I^{1/3}}$

$\Pi_7 = \rho\,[V]^a[A]^b\,[M_c]^c\,[F_p]^d\,[k]^e\,[I]^f$

$\Pi_7 = \frac{\rho\,A}{Fp}$

$\Pi_8 = UT_{off}\,[V]^a[A]^b\,[M_c]^c\,[F_p]^d\,[k]^e\,[I]^f$

$\Pi_8 = \frac{UT_{off}V^{1/3}I^{1/3}}{A^{4/3}Fp^{1/3}}$

$\Pi_9 = UT_{on}\,[V]^a[A]^b\,[M_c]^c\,[F_p]^d\,[k]^e\,[I]^f$

$\Pi_9 = \frac{UT_{on}\,V^{1/3}I^{1/3}}{A^{4/3}Fp^{1/3}}$

$\Pi_{10} = Cp[V]^a[A]^b\,[M_c]^c\,[F_p]^d\,[k]^e\,[I]^f$

$\Pi_{10} = \frac{C_pV^{1/3}Fp^{2/3}A^{-1/3}}{A^2\,k}$

$\Pi_{11} = DC$

Derived π terms can be expressed as

$$\pi_R=f(\pi_1\pi_2\pi_3\pi_4\pi_5\pi_6\pi_7\pi_8\pi_9\pi_{10}\pi_{11}) \tag{4}$$

Then equation becomes,

$$\frac{MRR_g}{V^{\frac{1}{3}}A^{\frac{2}{3}}Fp^{\frac{2}{3}}I^{\frac{1}{3}}} = f\left(\begin{array}{c}\frac{T_{on}I^{\frac{1}{3}}V^{\frac{1}{3}}A^{\frac{4}{3}}}{F_p^{\frac{1}{3}}},,\frac{T_{off}I^{\frac{1}{3}}V^{\frac{1}{3}}A^{\frac{4}{3}}}{F_p^{\frac{1}{3}}},\frac{R\,I}{V\,A},\frac{F\;A^{\frac{4}{3}}Fp^{\frac{1}{3}}}{V^{\frac{1}{3}}I^{\frac{1}{3}}}\frac{\rho\,A}{Fp},\frac{UT_{off}\,V^{\frac{1}{3}}I^{\frac{1}{3}}}{A^{\frac{4}{3}}Fp^{\frac{1}{3}}},\\ \frac{UT_{on}\,V^{\frac{1}{3}}I^{\frac{1}{3}}}{A^{\frac{4}{3}}Fp^{\frac{1}{3}}},\frac{C_pV^{1/3}Fp^{2/3}A^{1/3}}{I^{1/3}\,k},Dc\end{array}\right) \tag{5}$$

$$\frac{S_R}{A} = f\left(\begin{array}{c}\frac{T_{on}I^{\frac{1}{3}}V^{\frac{1}{3}}A^{\frac{4}{3}}}{F_p^{\frac{1}{3}}},,\frac{T_{off}I^{\frac{1}{3}}V^{\frac{1}{3}}A^{\frac{4}{3}}}{F_p^{\frac{1}{3}}},\frac{R\,I}{V\,A},\frac{F\;A^{\frac{4}{3}}Fp^{\frac{1}{3}}}{V^{\frac{1}{3}}I^{\frac{1}{3}}}\frac{\rho\,A}{Fp},\frac{UT_{off}\,V^{\frac{1}{3}}I^{\frac{1}{3}}}{A^{\frac{4}{3}}Fp^{\frac{1}{3}}},\\ \frac{UT_{on}\,V^{\frac{1}{3}}I^{\frac{1}{3}}}{A^{\frac{4}{3}}Fp^{\frac{1}{3}}},\frac{C_pV^{1/3}Fp^{2/3}A^{1/3}}{I^{1/3}\,k},Dc\end{array}\right) \tag{6}$$

Above equations depict a mathematical model for defining the rate of metal removal and roughness.

As the variety of undefined variables increases, then is necessary to reduce them into a single undefined group, which is generated by multiplying one of them by another. These are decreased through the use of the subsequent mathematical operations:

1.5. Simplification of Non-Dimensional Variables

To be able to obtain the rate of metal removal and roughness response, equations are solved using a multiple factorial regression model. Rewriting equations in power law form.

$$\Pi_R = \Psi\,X\,(\Pi_a)^{a_1}X\,(\Pi_b)^{a_2}\,X\,(\Pi_c)^{a_3}\,X\,(\Pi_d)^{a_4} \tag{7}$$

Table 3. Result of all 32 experiments using the semiempirical formula

Expt. No.	Exp SR	Dimensional model SR	Mean Error Eq.11	RMSE Eq.12	ΔEavg.% Eq.13	Exp. MRR	Dimensional model MRR	Mean Error Eq.11	RMSE Eq.12	ΔEavg.% Eq.13
1	1.24	1.314	0.0023	0.00	5.882	12.344	12.956	0.0191	0.012	4.958
2	1.54	1.678	0.0043	0.001	8.82	7.122	8.231	0.0347	0.038	15.571
3	1.86	2.141	0.0055	0.001	9.496	9.914	10.124	0.0066	0.001	2.118
4	1.06	1.154	0.0031	0.00	9.384	16.088	16.985	0.028	0.025	5.576
5	2.96	3.543	0.0049	0.001	5.297	8.222	9.342	0.035	0.039	13.622
6	1.53	2.234	0.0034	0.00	7.148	9.077	10.322	0.0389	0.048	13.716
7	2.33	2.988	0.0085	0.002	11.728	10.031	10.678	0.0202	0.013	6.45
8	1.99	2.211	0.0043	0.001	6.895	12.375	13.546	0.0366	0.043	9.463
9	5.52	4.997	0.0165	0.009	9.54	8.555	7.889	0.0208	0.014	7.785
10	3.92	4.212	0.009	0.003	7.367	8.291	9.665	0.0429	0.059	16.572
11	3.01	3.976	0.0082	0.002	8.765	10.531	10.988	0.0143	0.007	4.34
12	3.62	4.222	0.0125	0.005	11.068	11.425	11.989	0.0176	0.01	4.937
13	3.52	3.879	0.0111	0.004	10.074	12.666	13.765	0.0343	0.038	8.677
14	1.99	2.324	0.0074	0.002	11.928	11.674	12.657	0.0307	0.03	8.42
15	3.33	4.121	0.0186	0.011	17.925	11.375	10.765	0.0191	0.012	5.363
16	2.88	3.232	0.0109	0.004	12.105	10.375	11.675	0.0406	0.053	12.53
17	1.42	1.765	0.0018	0.00	4.076	9.375	9.876	0.0157	0.008	5.344
18	4.52	3.976	0.0171	0.009	12.074	11.764	12.234	0.0147	0.007	3.995
19	4.34	4.997	0.008	0.002	5.873	10.062	11.084	0.0319	0.033	10.157
20	3.22	4.854	0.0198	0.013	19.652	11.675	12.076	0.0125	0.005	3.435
21	2.88	3.654	0.0085	0.002	9.4	11.146	11.986	0.0263	0.022	7.536
22	2.87	3.785	0.0066	0.001	7.379	11.064	11.876	0.0254	0.021	7.339
23	4.65	4.987	0.0104	0.003	7.155	10.375	11.433	0.0331	0.035	10.198
24	3.12	3.878	0.0079	0.002	8.131	11.831	12.432	0.0188	0.011	5.08
25	2.01	2.547	0.0042	0.001	6.71	8.675	9.765	0.0341	0.037	12.565
26	5.24	5.789	0.017	0.009	10.393	10.395	11.222	0.0258	0.021	7.956
27	3.22	3.899	0.0055	0.001	5.461	11.375	12.223	0.0265	0.022	7.455
28	3.65	4.124	0.0116	0.004	10.126	9.375	10.221	0.0264	0.022	9.024
29	4.12	4.547	0.0132	0.006	10.257	12.831	13.543	0.0223	0.016	5.549
30	3.01	3.789	0.0087	0.002	9.233	15.965	16.776	0.0253	0.021	5.08
31	2.24	2.897	0.0014	0.00	2.051	9.831	10.432	0.0188	0.011	6.113
32	3.42	4.124	0.0093	0.003	8.735	9.777	10.786	0.0315	0.032	10.32

Where a_1, a_2, a_3, a_4, and a_5 are the unknowns that need to be evaluated after carrying out real experiments. Taking log on both sides of equation (7) can be written as,

$$\log \Pi_R = \log \Psi + a_1 \log \Pi_a + a_2 \log \Pi_b + a_3 \log \Pi_c + a_4 \log \Pi_d \quad (8)$$

$$Y = a_o + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 \quad (9)$$

As there are n (16) experiments to be performed to obtain these unknowns, then all the experimental results can be grouped as

$$\sum_{i=1}^{n} yi = n\, a_o + a_1\sum_{i=1}^{n} Xi1 + a_2\sum_{i=1}^{n} Xi2 + a_3\sum_{i=1}^{n} Xi3 + a_4\sum_{i=1}^{n} Xi4 \qquad (10)$$

Where i- represent the response of i^th^ experiment.

To obtain five unknowns in the equation, other equations are developed by multiplying Xi1, Xi2, Xi3, and Xi4 with the equation separately. The obtained equation is written in matrix form in the equation and solved using MATLAB code.

$$\begin{bmatrix} n & \sum_{i=1}^{n} Xi1 & \sum_{i=1}^{n} Xi2 & \sum_{i=1}^{n} Xi3 & \sum_{i=1}^{n} Xi4 \\ \sum_{i=1}^{n} Xi1 & \sum_{i=1}^{n} Xi1\ Xi1 & \sum_{i=1}^{n} Xi1\ Xi2 & \sum_{i=1}^{n} Xi1\ Xi3 & \sum_{i=1}^{n} Xi1\ Xi4 \\ \sum_{i=1}^{n} Xi2 & \sum_{i=1}^{n} Xi2\ Xi1 & \sum_{i=1}^{n} Xi2\ Xi2 & \sum_{i=1}^{n} Xi2\ Xi3 & \sum_{i=1}^{n} Xi2\ Xi4 \\ \sum_{i=1}^{n} Xi3 & \sum_{i=1}^{n} Xi3\ Xi1 & \sum_{i=1}^{n} Xi3\ Xi2 & \sum_{i=1}^{n} Xi3\ Xi3 & \sum_{i=1}^{n} Xi3\ Xi4 \\ \sum_{i=1}^{n} Xi4 & \sum_{i=1}^{n} Xi4\ Xi1 & \sum_{i=1}^{n} Xi4\ Xi2 & \sum_{i=1}^{n} Xi4\ Xi3 & \sum_{i=1}^{n} Xi4\ Xi4 \end{bmatrix} \begin{bmatrix} ao \\ a1 \\ a2 \\ a3 \\ a4 \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} yi \\ \sum_{i=1}^{n} Xi1\ yi \\ \sum_{i=1}^{n} Xi2\ yi \\ \sum_{i=1}^{n} Xi3\ yi \\ \sum_{i=1}^{n} Xi4\ yi \end{bmatrix}$$

After solving the equations using MATLAB code, five unknowns and the response SR and MRR were achieved. The median error (ME), error of root-mean-square, and amount of average error (Eavg.%) are used to assess the model's appropriateness. The subsequent models were used in this correlation investigation. Table 3 shows the outcomes of the MATLAB function.

$$ME = \frac{1}{n}\sum_{I=1}^{n}(y_i - y) = 0.0023 \qquad (11)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{I=1}^{n}(y_i - y)^2} = 0.00 \qquad (12)$$

$$\Delta E\% = \frac{1}{n}\sum_{i=1}^{n}\frac{(y_i - y)}{y_i * 100} = 5.882 \qquad (13)$$

2. Conclusion

The From this study, the optimum parameters related to the USA-EDM of Shape Memory Alloy are optimized to attain a low surface roughness. During these tests, thirty-two sets were conducted on the material alloy of shape memory using an electrode of copper. The input parameters are taken, such as Voltage, Discharge current, on-time Pulse, off-time Pulse, and frequency. The following findings were drawn from the experiment and its design:

The empirical model for surface roughness and mass material removal rate for USA EDM is derived using Buckingham Π theorem and validated accordingly.

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