Investigating the Impact of EDM Parameters on Surface Roughness and Electrode Wear Rate in 7024 Aluminum Alloy

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ABSTRACT

Electrical Discharge Machining (EDM) is a significant process in the industry for machining hard metals. It is a time-consuming and costly method that requires a high level of expertise to operate effectively. EDM is considered one of the unconventional operating processes due to its unique characteristics and the challenges associated with its implementation. One of the challenges facing researchers is determining the optimal parameters for achieving high surface quality while minimizing equipment consumption and associated costs. In addition to being classified as one of the operating processes, EDM processes are also classified as electro-thermal processes that affect surface quality. In this study, the influence of EDM parameters on surface roughness and electrode wear rate when machining aluminum alloy type 7024 was investigated. A total of 27 experiments were conducted to evaluate the impact of three parameters at three levels. The parameters under investigation include current, pulse on time, and pulse off time. Subsequent analysis of the results by variance analysis revealed that the most influential parameter for both surface roughness and electrode wear rate is electric current, with a rate of influence of 74%. The results were then subjected to further analysis using variable effect graphs to identify the optimal variables for achieving the best results. Finally, neural networks were employed to predict the results, with an accuracy of up to 99%.

Keywords-EDM; surface roughness; electrode wear rate; artificial neural networks

I. INTRODUCTION

The durability of traditional machining tools exceeds that of the workpieces with which they are used. Some materials possess a hardness that exceeds the capabilities of conventional machining processes. The aviation engine, food, dairy, paper, die, and molding sectors require hard materials, which has led to the development of non-conventional machining techniques. These metal removal methods employ a variety of techniques, including electrochemical, thermal, and mechanical procedures. In certain instances, non-conventional techniques may prove to be more cost-effective [1]. In the 1770s, English scientist Joseph Priestly discovered EDM. In his investigations, Priestly discovered that electrical discharges were effective for removing electrode material. Priestly discovered EDM, but the process was found to be inaccurate and flawed [2]. EDM is applicable to a number of manufacturing sectors, including automotive and aerospace, as well as to the machining of a wide range of conductive materials. Due to the superior capabilities of EDM in the machining of high-strength and temperature-resistant materials, conductive materials, and conductive engineered ceramics with intricate geometries, it is often the preferred method of production [3]. Researchers have focused their efforts on improving machining performance, ensuring dimensional accuracy, and enhancing surface integrity. A review of the literature was conducted to gain insight into the EDM procedure and sinking EDM operation documents. Authors in [4] analyzed the influence of electrode shape on the EDM of mild steel, with a particular focus on the effects on Material Removal Rate (MRR) and Electrode Wear Rate (EWR). The highest MRR was observed for round electrodes, followed by those of square, triangular, and diamond shapes. Nevertheless, the diamond electrode exhibited the highest EWR.

Authors in [5] investigated the impact of tool polarity on EDM, MRR, and EWR. The study demonstrates that direct polarity yields the greatest MRR while simultaneously minimizing Wear Rate (WR). The direct polarity method has been demonstrated to result in a fourfold increase in MRR and a fivefold reduction in WR in comparison to the reverse polarity method. Authors in [6] employed the Taguchi method to investigate the influence of machining factors on MRR in EDM operations. The studies employed a variety of pulse on time (T_{on}), pulse off time (T_{off}), and peak current (I_p) parameters. An orthogonal array with L27, S/N ratio, and ANOVA was employed to evaluate the performance of EDM on 202 SS. The findings indicate that the highest MRR is achieved when the I_p and T_{off} are at their highest levels and T_{on} is at its lowest. The interaction data indicates that there are significant effects associated with the variables I_p and T_{off}. Authors in [7] examined the impact of combining aluminum and copper fine metal particles with dielectric fluid on MRR during the machining of AISI D3 and EN-31 steel. The process inputs included the workpiece material, the peak current (I_p), the pulse on time (T_{on}), the duty factor, the gap voltage (V), and the mixing of fine metal powder in the dielectric fluid. The output parameters used to assess the performance of the process were the MRR. The experimental results demonstrate that the presence of metal particles in a dielectric fluid leads to an enhancement in the MRR. Authors in [8] presented a novel method for enhancing the precision of silver-tungsten electrodes machined by micro-EDM. This method involves combining powder (suspended nanographite) with dielectric (kerosene). The microcrack density and the surface roughness (R_a) of the machined surface were observed to decrease by 85% and 22%, respectively. Authors in [9] investigated the impact of I_p, T_{on}, and T_{off} on R_a in EDM operations, employing the Taguchi approach to achieve a superior surface finish. The combination of low T_{on}, I_p, and high T_{off} resulted in the optimal R_a. The anticipated range for R_a was between 2.14 and 3.36. Authors in [10] presented a detailed explanation of the impact of I_p, T_{on}, and T_{off} (three-level parameters) on R_a. The Taguchi method was employed in the course of these studies. An EDM was employed to assess the performance of a titanium alloy when subjected to the action of copper, brass, and aluminum electrodes. The influence of I_p on R_a is significant, and the use of Al electrode alloys has been shown to result in lower R_a values. Authors in [11] developed a model to predict the variables of volume V, T_{on}, I_p, T_{off}, and reaction surface finish in AISI D2 steel EDM using Response Surface Methodology (RSM). The face Central Composite Design (CCD) was employed for the purpose of determining the experimental plan. The surface quality was superior when low I_p, T_{on}, V, and high T_{off} were employed. The researchers found that model-based RSM is an effective method for manufacturing AISI D2 tool steel. Authors in [12] developed a technique for high-finish EDM machining. A series of tests were conducted to measure R_a under varied voltage and T_{on} cutting conditions. The findings of the modeling and optimization demonstrate that the roughness for voltage and T_{on} is significantly lower than that of all experimental runs. In this study, the impact of EDM parameters, specifically current (A), pulse on time (µsec), and pulse off time (µsec), was investigated to ascertain their effect on R_a and EWR values. This was achieved through the use of analysis of variance and ANN techniques.

II. ELECTRICAL DISCHARGE MACHINING MECHANISM

The principal mechanism of material erosion in EDM is the conversion of electrical energy into thermal energy through discrete electrical discharges between the tool (the electrode) and the workpiece immersed in a dielectric fluid. The creation of a plasma channel between the tool electrode and the workpiece results in the breakdown of the dielectric [13], as shown in Figure 1. The breakdown typically occurs between the electrode and the workpiece at the closest point of contact. Spark breakdown causes a rapid decline in voltage and an increase in current, which results in the ignition of multiple monodes.

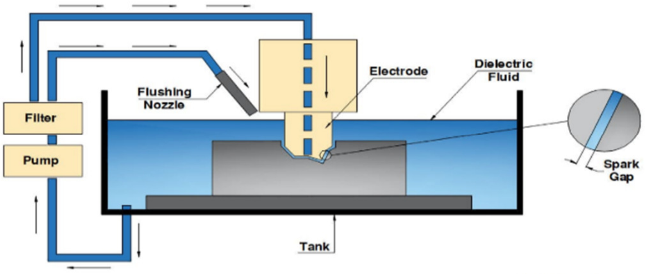

Fig. 1. Principle of EDM.

III. EXPERIMENTAL WORK

The requisite specifications for machine tools, workpiece materials, and electrode tools, in addition to their corresponding response characteristics, are used to assess surface roughness and electrode wear rate.

A. *Machine Tool*

As presented in Figure 2, all experiments were conducted on an EDM CNC machine.

Fig. 2. EDM machine tool.

B. Workpiece Material

The workpiece was composed of aluminum alloy type 7024. Prior to EDM processing, the workpiece was manufactured in 50×40 mm square specimens with a surface roughness of 2 μm. Table I shows the chemical composition of the aforementioned specimens.

TABLE I. CHEMICAL COMPOSITION OF AL ALLOY TYPE 7024 WORKPIECE

Si (%)	**0.163**	**Zn (%)**	**4.93**
Fe (%)	0.422	Ti (%)	0.038
Cu (%)	2.14	Ga (%)	0.010
Mn (%)	0.216	V (%)	0.007
Mg (%)	1.55	Pb (%)	0.071
Cr (%)	0.090	Other (%)	0.132
Ni (%)	0.012	AL (%)	90.219

C. Tool Electrode

The experiments employed a 50-mm-long, 15-mm-diameter copper cylindrical solid electrode.

IV. DESIGN OF EXPERIMENT

The number of experiments required is contingent upon the experimental design. It is therefore essential to conduct well-designed cutting experiments. In order to measure R_a for AL-alloy 7024 specimens, a three-level full factorial design was employed, resulting in the execution of 27 cutting experiments. The current I_p, pulse on time T_{on}, and pulse off time T_{off} are the variables under consideration. The levels of the cutting parameters are presented in Table II.

TABLE II. THE LEVELS OF CUTTING PARAMETERS

Levels	**Current (A)**	**Pulse on time (μsec)**	**Pulse off time (μsec)**
1	24	50	25
2	30	100	50
3	36	150	75

V. MEASUREMENT OF RESPONSE CHARACTERISTICS

A. Surface Roughness (R_a)

A standard parameter, R_a in μm, is employed to assess surface roughness by comparing the maximum peaks and minimum troughs of specific locations. This approach relies on the device's cut-off length and mean line.

B. Electrode Wear Rate (EWR)

In a manner analogous to the material removal rate procedure, the workpiece was substituted with the electrode. The formula for EWR is given [14]:

$$\mathrm{EWR} = \frac{\mathrm{W}_{ie}-\mathrm{W}_{fe}}{\rho_{\mathrm{e}}\mathrm{t}} \quad (1)$$

where W_{ie} is the initial electrode weight (gm), W_{fe} is the final electrode weight (gm), ρ_e is the density of electrode (gm/mm^3).
The calculation is built on the basis that the density of the electrode is (8.9 gm/cm^3) [15].

VI. ARTIFICIAL NEURAL NETWORK MODELING

The objective is to develop a mathematical model that expresses the minimization of surface roughness and electrode wear rate in cutting parameters. This study employs ANN to create the aforementioned model. ANNs comprise one or more hidden layers situated between the input and output layers. Each neuron in the network receives input from all preceding layer neurons [16]:

$$net_j = \sum_{j=0}^{N} w_{ij} x_i \quad (2)$$

where the j_{th} hidden layer neuron receives N inputs, collectively denoted as net_j, w_{ij} represents the weight of the connection from the i_{th} forward layer neuron to the j_{th} hidden layer neuron and, x_i denotes the input from the preceding layer neuron. A neuron in the network processes the net input through an activation (transfer) function, such as the tangent hyperbolic function employed in this study [17]. The objective of this study is to identify the optimal combination of parameters that minimizes a combination of squared errors, thereby producing a well-generalized network. A single hidden layer with three inputs and one output was employed to model the process, as shown in Figure 3. The three most significant input variables are current, pulse on time, and pulse off time, while the output variables are R_a and EWR. The distribution of experimental data, comprising 27 groups, was conducted in a manner whereby the training subset encompasses 21 groups, or 75% of the data, while the testing subset comprises 6 groups, or 25% of the data. In order to identify an appropriate network architecture, a number of different architectures have been considered. The model with a 3-5-1 architecture was determined to be the optimal choice for the task.

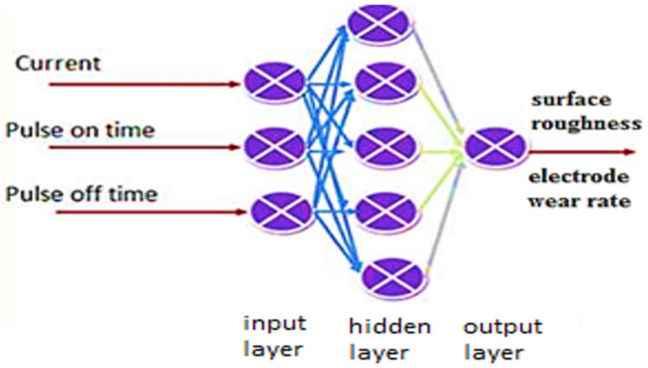

Fig. 3. Neural network architecture designed.

VII. ANALYSIS OF VARIANCE

The experimental results are subjected to ANOVA in order to ascertain the impact of cutting parameters on R_a and EWR, with the latter serving as the dependent variable. The independent variables in this analysis are current, pulse on time, and pulse off time. This analysis was conducted with a significance level of 0.05, which corresponds to a confidence level of 95%.

VIII. RESULTS

Following the completion of the practical component and the subsequent measurement of the outcomes for both R_a, as determined by the surface roughness tester (MarSurf SP1), and EWR, calculated in accordance with (1) and Table III, a detailed discussion was undertaken on the following:

A. *Analysis of Mean for Surface Roughness*

The EDM current and other process parameters influence the R_a of the components. The current has an impact on the R_a of EDM. Figure 4 demonstrates that higher EDM currents result in an increase in material removal rates. An increase in energy input and more aggressive material removal can result in the formation of a coarser surface finish, but the process will be completed more rapidly. The objective is to optimize the process for distinct materials. The EDM current interacts with the pulse duration, voltage, and electrode material. In order to achieve the desired surface finish, it is necessary to optimize these parameters and current. The pulse-on time in EDM has a significant impact on R_a. The following section will examine the impact of pulse-on time on EDM surface roughness [18]. The formation of a melt pool is dependent upon a number of factors, including the timing of the pulse that controls the duration of the electrical discharge. A longer pulse-on period results in an increase in the size of the melt pool. An increase in heat generation resulting from extended pulse-on durations can lead to the melting of the material and the formation of recast layers, ultimately resulting in a surface quality that is more irregular. The wear of the electrode is also a factor to consider. The prolonged electrical discharge resulting from extended pulse-on periods has the potential to cause wear on the electrodes. The presence of EDM imperfections resulting from excessive electrode wear may lead to a deterioration in the surface finish of the workpiece. The impact of the pulse-off time in EDM on the R_a value, whereby the separation of discharges is influenced by this parameter. The influence of the pulse-off time on the surface roughness of the EDM process has been the subject of considerable research. The characteristics of the process, including the duration of the pulse-on time, the level of current, the voltage, and the composition of the electrode material, have an impact on the duration of the pulse-off time. In order to achieve the requisite surface finish in EDM, it is necessary to optimize the aforementioned parameters and pulse-off time.

TABLE III. READINGS OF EXPERIMENTAL WORK

No.	**Current (A)**	**Pulse on time (μsec)**	**Pulse off time (μsec)**	**Surface Roughness R_a (μm)**		**Electrode Wear Rate (EWR) (mm3/min)**	
				Measured	Predicted	Measured	Predicted
1	24	50	25	4.64	4.60333	0.88	0.71630
2	24	50	50	4.15	4.23222	0.89	0.79852
3	24	50	75	3.88	3.96778	0.70	0.87630
4	24	100	25	4.70	4.69222	0.89	0.89185
5	24	100	50	4.30	4.32111	0.99	0.97407
6	24	100	75	4.00	4.05667	1.13	1.05185
7	24	150	25	4.87	4.81111	1.12	1.20296
8	24	150	50	4.56	4.44000	1.50	1.28519
9	24	150	75	4.20	4.17556	1.06	1.36296
10	30	50	25	5.60	5.58667	0.98	1.22630
11	30	50	50	5.32	5.21556	1.22	1.30852
12	30	50	75	4.94	4.95111	1.23	1.38630
13	30	100	25	5.50	5.67556	1.45	1.40185
14	30	100	50	5.30	5.30444	1.62	1.48407
15	30	100	75	4.91	5.04000	1.46	1.56185
16	30	150	25	5.80	5.79444	1.80	1.71296
17	30	150	50	5.48	5.42333	1.89	1.79519
18	30	150	75	5.30	5.15889	2.10	1.87296
19	36	50	25	5.80	5.80667	2.11	1.86185
20	36	50	50	5.54	5.43556	2.05	1.94407
21	36	50	75	5.10	5.17111	2.08	2.02185
22	36	100	25	5.96	5.89556	1.99	2.03741
23	36	100	50	5.80	5.52444	1.89	2.11963
24	36	100	75	5.30	5.26000	2.30	2.19741
25	36	150	25	6.01	6.01444	2.18	2.34852
26	36	150	50	5.09	5.64333	2.09	2.43074
27	36	150	75	5.53	5.37889	2.78	2.50852

B. *Analysis of Mean for Electrode Wear Rate*

As presented in Figure 5, the current has a significant impact on the EWR in EDM. The current has an impact on the wear rate of electrodes used in EDM. There is a direct correlation between the two variables. The intensity of the EDM current has a direct impact on electrode wear. An increase in current levels results in enhanced material removal, which in turn leads to electrode deterioration. The interdependence between electrode wear and material removal in EDM are described, with both processes being contingent upon the pulse-on time. The rate of material removal is dependent upon the duration of the pulse-on phase in EDM and has an impact on the rate of material removal. As a consequence of the increased duration of contact and the greater energy input, longer pulse-on periods result in enhanced rates of material removal and electrode wear. A trade-off exists between electrode wear and workpiece surface polish, whereby adjusting the pulse-on time affects one or the other. In order to achieve optimal results in an EDM operation, it is necessary to strike a balance between electrode wear and surface finish. The EDM pulse-off time has a significant impact on the EWR and other process parameters. The impact of pulse-off time on the wear rate of electrodes used in EDM is a topic worthy of further investigation. The removal of heat and debris is facilitated by the cooling effect of the EDM process. The pulse-off time facilitates the cooling of the electrode and the removal of debris and gases from the machining gap. The removal of heat and debris through efficient cooling mitigates the thermal effects and wear on the electrode. Prolonged pulse-off periods facilitate enhanced heat dissipation from the electrode, thereby reducing the temperature at the tool-electrode interface. The surface finish is a significant factor. In order to achieve the optimal reduction in electrode wear, it is essential to consider the surface quality of the workpiece. The objective of optimal machining outcomes is to achieve a balance between wear rates and surface finish.

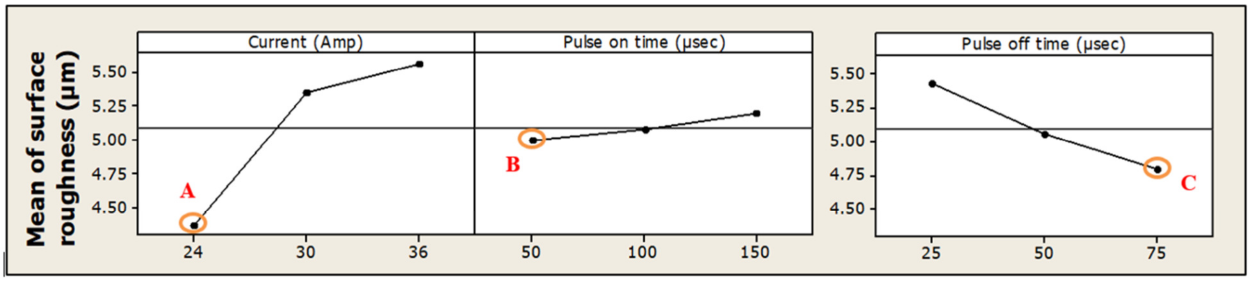

Fig. 4. Mean effect plot for surface.

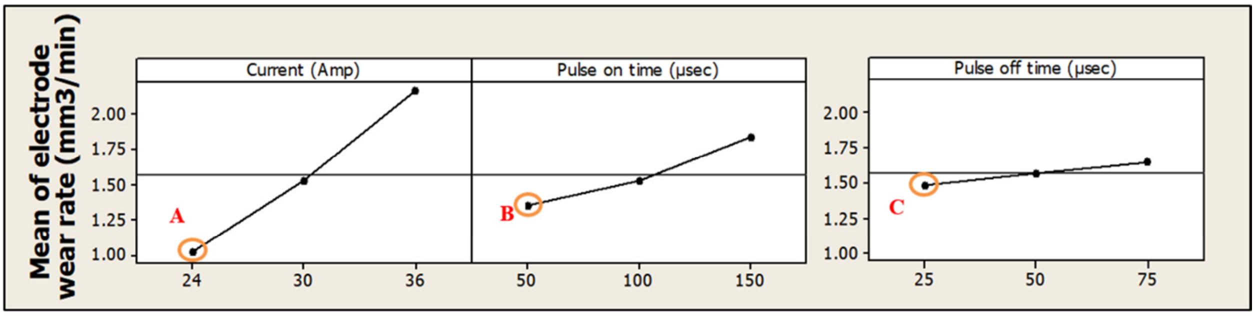

Fig. 5. Mean effect plot for electrode wear rate.

C. *ANOVA for Surface Roughness*

Following an analysis of the results, it was determined that the electric current exerts the greatest influence on the Ra values, with the pulse off time as the second most influential parameter. In contrast, the pulse on time was identified as the least influential parameter, as presented in Table IV.

TABLE IV. ANOVA PRESENTS WORK FOR SURFACE ROUGHNESS

Source of variance	Degree	Sum of squares	Variance	*P* (%)
Current (A)	2	7.390	3.695	74.14
Pulse on time (µm)	2	0.196	0.098	1.96
Pulse off time (µm)	2	1.835	0.917	18.41
Error ,e	20	0.545	0.0166	5.47
Total	26	9.967		100

D. *ANOVA for Electrode Wear Rate*

Following an analysis of the results, it was determined that the electric current exerts the greatest influence on the EWR values, with the pulse on time as the second most influential parameter. In contrast, the pulse off time was identified as the least influential parameter, as shown in Table V.

E. *Regression and Comparison for Surface Roughness by an ANN*

A regression graph is a visual representation that demonstrates the relationship between network targets and outputs. Figure 6 shows the validation, learning, testing, and all data regression plots. The solid line should be in accordance with the dotted line.

TABLE V. ANOVA PRESENTS WORK FOR ELECTRODE WEAR RATE

Source of variance	Degree	Sum of squares	Variance	*P* (%)
Current (A)	2	5.9290	2.9645	74.98
Pulse on time (µm)	2	1.093	0.547	13.83
Pulse off time (µm)	2	0.115	0.058	1.46
Error ,e	20	0.774		9.8
Total	26	7.9071		100

A comparison is made between a measured and a predicted result in order to validate the ANN model. As shown in Figure 7, the neural network model demonstrates a high degree of accuracy, with a close alignment between the actual calculated R_a and the predicted output. The ANN model was trained using 21 Ra values, while the remaining six were employed as a test set within the MATLAB toolbox. The experimental results demonstrated that the ANN can be effectively utilized for the prediction of R_a in the machining of 7024 aluminum alloy, as it offers enhanced accuracy and reduces the time required. Figure 8 presents the regression coefficients for the model based on the data, which were found to be (1) for training, (0.997) for validation, (1) for testing, and (0.99958) for all data sets. These results indicate that the network is learning and predicting Ra properly. The chart demonstrates that the regression coefficient for the training set is 1, indicating a linear relationship between the objectives and outputs.

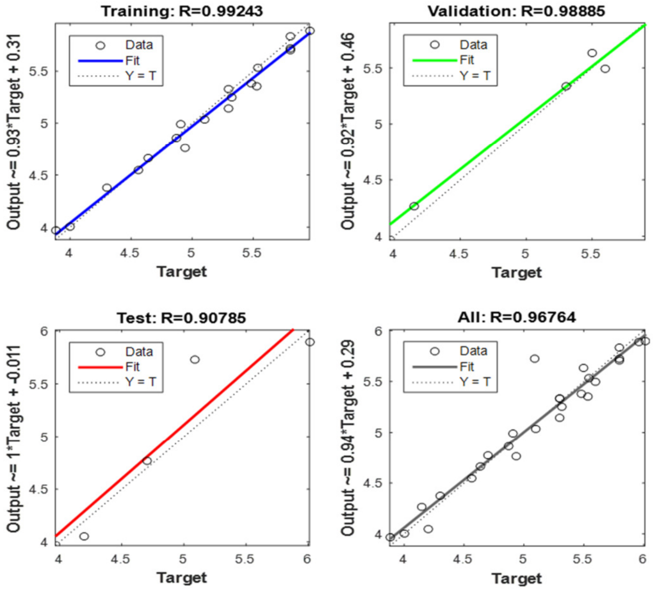

Fig. 6. Regression graphs for model.

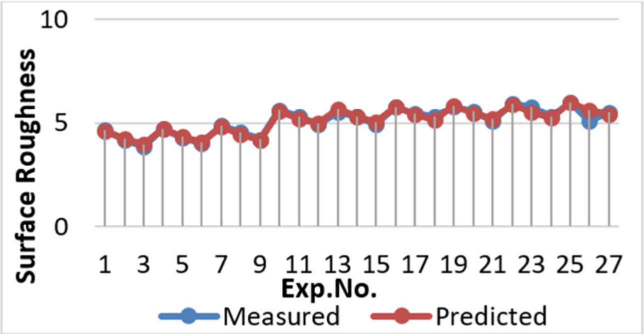

Fig. 7. The comparison between the measured and predicted values of Ra for the training set.

F. Regression and Comparison for Electrode Wear Rate by ANN

The number of tests has an impact on the 27 EWR value presented in Figure 9. A total of 21 EWR values were employed for the training of the ANN model, while six were used for its evaluation in MATLAB Toolbox. The correlation between the experimental EWR values and the ANN model predictions, is observed. The observed and projected EWR levels exhibit a high degree of similarity.

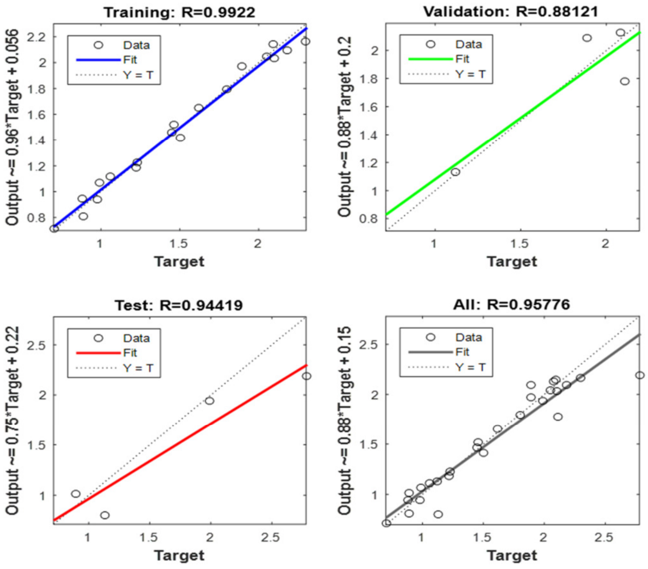

Fig. 8. Regression graphs for model.

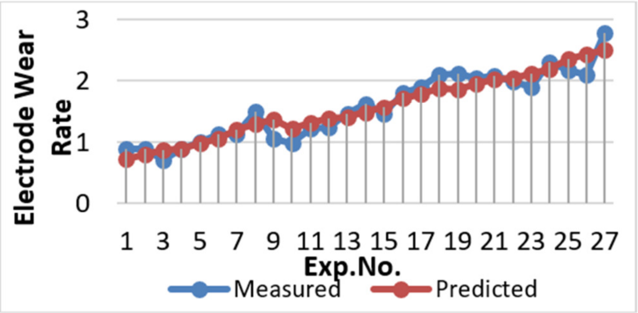

Fig. 9. The comparison between the measured and predicted values of EWR for the training set.

IX. CONCLUSIONS

The results of the experimental work indicated that the most influential factor on both the surface quality and the amount of metal removal (production speed) is the amount of electric current. It was observed that the lowest amount of electric current resulted in the best surface quality (less surface roughness), while the highest value of electric current resulted in the best production speed (the largest amount of metal removal). The lowest value of pulse on time and pulse off time yielded the optimal surface quality. A neural network with an accuracy of up to 99% was constructed. Considering the above results we can conclude:

- The Electrical Discharge Machining (EDM) current is a significant factor influencing surface roughness. Operators may optimize the EDM process to obtain the requisite surface finish for a given workpiece material and application by carefully managing the current level and evaluating its interaction with other process factors.

- The EDM pulse-on time has an impact on surface roughness. Operators may oversee the management of material removal processes, heat input, and surface finish quality for an EDM application.

- The EDM pulse-off time affects several processes, including heat dissipation, debris clearance, electrode wear, re-ignition, and surface texture management. These effects contribute to the overall surface roughness of the material being processed.

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