MJSAT 3 (1) 17-23

MJSAT

Malaysian Journal of Science
and
Advanced Technology

journal homepage: https://mjsat.com.my/

Analysis and Modeling of Tool Wear Rate in Powder Mix EDM and Pure EDM Using Central Composite Design

Zakaria Mohd Zain[1], Mir Akmam Noor Rashid*[1], Ahsan Ali Khan[1]

[1]*Department of Manufacturing & Materials Engineering, International Islamic University Malaysia, Selangor, Gombak-53100, Malaysia*

KEYWORDS

Powder-mixed electrical
Discharge machining
Tantalum carbide powder
SUS 304 stainless steel
Tool wear rate

ARTICLE HISTORY

Received 9 January 2023
Received in revised form 3 February 2023
Accepted 26 February 2023
Available online 27 February 2023

ABSTRACT

The process of using dielectric fluid combined with different types of powders to improve the output of the machined surface is known as powder-mixed electrical discharge machining (PMEDM). In the electrical discharge machining (EDM) industry, this procedure is quickly gaining popularity. This investigation's goal is to ascertain whether tantalum carbide (TaC) powder-mixed dielectric fluid can reduce tool wear during the subsequent EDM machining of stainless-steel material. Two different EDM medium's tool wear rates and mathematical models were investigated during the machining. TaC powder at a concentration of 25.0 g/L in kerosene dielectric fluid was used for the machining process. The peak current, pulse on time, and pulse off time were the machining variables used. These variables' effects on the copper based EDMed electrode tools TWR were identified. The TWR for stainless steel (SUS 304) during electrical discharge machining was reduced by 37.9% when TaC powder additive was used, according to the results, demonstrating the effectiveness of this alternative method for reducing tool wear. The most influential factor, according to the tool wear ratio model for EDM with TaC powder additive (TWR_{PMEDM}), is current, followed by pulse on-time and pulse off-time.

1. INTRODUCTION

The tool and die industry make use of electrical discharge machining (EDM), which is one of the most popular alternative machining methods. When cutting out complicated shapes or materials with high strengths or hardnesses, this method is the one that is utilized most frequently [1]. It is almost becoming common practice to use this method for the production of prototypes as well as some manufactured products and parts, most commonly in applications involving low-volume production. Electrical sparks or discharges are produced during the process, and there is only a very narrow gap between the workpiece and the tool electrode. Extremely delicate materials and sections can be machined without the risk of deformation because they are not in direct physical contact with one another. One of the more recent innovations for improving the capabilities of the EDM process [2,3] is the addition of powder to the dielectric fluid used in the process. This process is also referred to as powder-mixed electrical discharge machining (PMEDM) and additive-mixed electrical discharge machining (AEDM), both of which can be found in [4].

PMEDM is a process that combines electrically conductive powder and dielectric fluid in order to increase the generation of sparks between the tool and the workpiece while simultaneously lowering the insulating strength of the dielectric fluid. This method results in an improvement to the breakdown properties of the dielectric fluid. The outputs of the EDM process, such as material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR), all improve as a result of the achievement of machining stability [5]. The wider discharge gap, which helps to keep the flushing of debris on a more even keel, is what makes stability possible. Research has been carried out in order to look into the ways in which different powders influence the performance of EDM. A few examples of these include aluminum, titanium carbide, silicon,

---

*Corresponding author:
E-mail address: Mir Akmam Noor Rashid < noorakmam@gmail.com >.

aluminum oxide, titanium dioxide, molybdenum disulfide, nickel, and many other powders that are also used in micro or nano forms [6,7]. The increased peak current and Al2O3 powder reduced tool wear, according to Khan et al. [7]. TiC had lower layer thickness, greater hardness, and carbon depositions than Al2O3 powder. PMEDM uses Al powder extensively. Singh et al. [9] studied the effects of electric parameters on hastelloy machining performance. It has also been used with kerosene to machine cobalt-tungsten carbide. Surfactant and conductive Al powders were used [8,10] in kerosene dielectric during SKD steel machining. Adding powder to dielectric fluids increased MRR, decreased TWR, and increased SR. Powder concentrations and sizes affected machining outputs [11]. Graphite powder was used in the dielectric to improve Inconel 718 and WC-Co machining [12]. The cold-treated copper electrode powder reduced TWR and improved Ra and MRR at the nano level. Chatha et al. [13] raised the workpiece's MRR with TiO2 powder in dielectric fluid. It is also noticed that powder-derived elements migrated to the machined surface. Mixing silicon powder with dielectric fluid produces mirror-like EDM surfaces [14]. Kansal et al. [15] found it had the best machining performance. The above studies on EDM output parameters show how PMEDM was used to improve MRR, surface finish, and TWR. Furutani et al. [16] studied how dielectric fluid powders behaved when machined. They also coated the workpiece with dielectric oil-dissolved powders [17,18]. During EDM of stainless steel, they used MOS2 in the dielectric fluid to lubricate space-exposed sliding parts. From these writings, it's clear that various powders have been used to improve machining and EDMed surfaces. Tantalum carbide (TaC) powder in the dielectric fluid may reduce stainless steel tool wear, but more research is needed. This study uses SUS 304 stainless steel. This adaptable and widely used steel grade is used in kitchen benches and utensils, food processing equipment, and chemical environments requiring low machining wear. Formability and weldability make it versatile.

The authors have studied the viability of making EDM electrodes from TaC powder [19,20] and the impact of TaC powder concentration on MRR and SR outputs. 20 In a later study, MRR was 0.38 g/min at an Ip of 2.5 A. It is needed to study how dielectric fluid powder affects electrode tool wear. In light of this, the purpose of the current research is to investigate the TWR and the performance of its mathematical modeling using PMEDM with TaC powder in dielectric fluid in order to select the PMEDM input parameter that is the most efficient.

2. MATERIALS AND METHODS

2.1 Workpiece: Stainless Steel

Stainless steel is well known because of its corrosion and oxidation resistance due to the chromium-rich oxide layer on the surface layer of alloyed steel. Besides that, it is also tougher and has higher ductility besides having higher hot strength which means, it can operate at high temperatures and retain its strength. Figure 1 shows the stainless steel workpiece used in the experiment and the EDM machine used for the experiment. Copper was utilized as the electrode material and tool in this study. Copper's high thermal and electrical conductivity make it a desirable material. It is an excellent thermal conductor, electrical conductor, building material, and alloying component [11].

Fig.1. Stainless-steel workpiece

Figure 2 illustrates the copper workpiece used in the experiment. It has a dimension of 50mm x 30mm x 10mm. As we required a parallel and less distorted contact surface of 10mm x 10mm, the electrode was cut by wire EDM. They were also ground to ensure that the adjacent surfaces are parallel. A total of 6 electrodes are prepared.

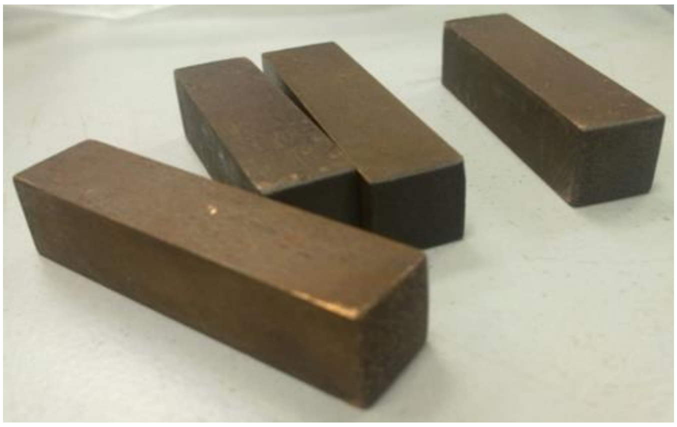


Fig. 2: Copper electrode

2.2 Powder: Tantalum Carbide (TaC)

Extremely hard, with a Mohs scale hardness of 9–10, as stated by Blanc et al. [11]. Only diamond is harder than this material. It is sometimes added to tungsten carbide alloys as a fine-crystalline additive. Its status as the stoichiometric binary compound with the highest measured melting point of 3880 °C. The melting point of the sub-stoichiometric compound TaC is higher, hovering around 4000 degrees Celsius. As a result, it produces a spectacular flash when exposed to air and is only marginally soluble in acids.

2.3 Dielectric Fluid

Kerosene is commonly used as a dielectric fluid in die-sinking EDM due to the benefits it provides in terms of decreased tool wear, improved precision, and enhanced surface quality. The eroded particles between the workpiece and the electrode can be cooled by passing a current through a dielectric fluid, which also acts as a dielectric barrier for the spark. Due to these qualities, kerosene has been selected as the dielectric fluid to be used in the experiments.

2.4 Design of Experiment (DOE)

The analysis of experimental data, as opposed to theoretical models, is at the heart of experimental design, which is a strategy for acquiring empirical knowledge. It can be used whenever more information is needed about a phenomenon, or when existing information needs to be upgraded. The first steps in designing an experiment are to establish its goal and to decide on the process variables and study outcomes.

This study uses DOE's factorial design and response surface methodology (RSM). RSM models input/output relationships empirically using polynomials as local approximations.

2.5 Process Parameters

In any DOE, determining the process parameter is the key. Table 1 discloses the process parameters that have been used for the experimentation. From Table 1, it can be seen that there are four factors which are concentrations, peak current, on-time, and off-time. Table 2 shows the 5 levels of input parameters.

Table 1. Parameters and level values were selected for the experiments.

Parameter/Factors	Low value	High value
Concentration (TaC), C_t	5g/L	45g/L
Peak Current, I_p	2A	8A
On-Time, T_{on}	5.5µs	7.1µs
Off-Time, T_{off}	6.0 µs	8.0µs

Table 2. Values of machining variable and levels

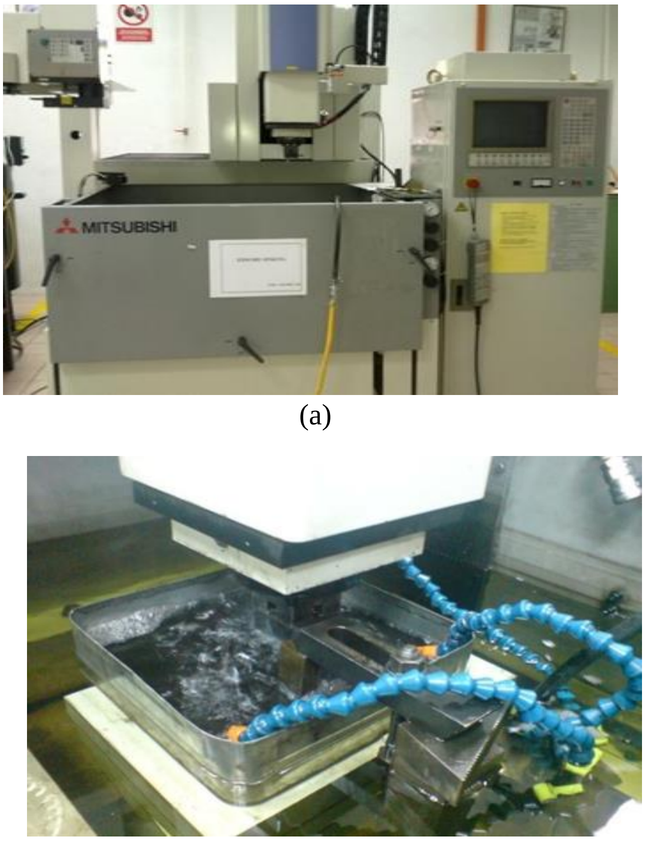
Variables	Levels				
	-2	-1	0	1	2
Concentration (TaC), C_t	5	15	25	35	45
Peak Current, I_p	2	3.5	5	6.5	8
On-Time, T_{on}	5.5	5.9	6.3	6.7	7.1
Off-Time, T_{off}	6	6.5	7	7.5	8

2.6 TWR

As far as TWR is concerned, there are several ways used to indicate the rate of tool wear. One method which is widely used is the Center Line Average Method. TWR is the average wear value of the profile that depicts the profile points' average absolute deviation from a mean line. Nikon Measurement machine (Fig.3) was used to measure the tool wear rate.

2.7 Machine Setup

A Mitsubishi EX22 die-sinking EDM machine is used in the experiment. Jet flushing was adequate for our experiment. The setup that was used in all the experiments is shown in Figure 3 (a) and (b) represent the photo of the Mitsubishi EX22 die-sinking EDM machine and the physical setup of the EDM machine. The following section comprises the setup procedure (preparation of experimentation) of the EDM machine.



(a)

(b)

Fig.3: (a) MITSUBISHI EX22 die-sinking EDM (b) Experimental setup for Die Sinking EDM

Firstly, the experimental setup is prepared as shown in Figure 3. To limit the excess use of powder and as well as dielectric fluid (kerosene), instead of using the whole tank, a comparatively smaller (250 × 250× 100 mm) container is used where the machining takes place. To avoid sedimentation of powder particles at the bottom, a stirring system is provided in terms of air flushing. Then, both the workpiece and tool are weighed using a single pan electric balance and their weights are recorded. A corresponding weight of TaC powder is measured using the same electric balance to get the required concentration. Next, the workpiece is a fixture within the container where a suitable concentration of powder-mixed kerosene dielectric has been added based on the DOE. Meanwhile, the tool is mounted on the tool holder of the Mitsubishi EX22 die-sinking EDM machine. The input parameters are entered and the EDM process started. After each experiment/run the machining time is recorded. After each experiment/run is complete, both the workpiece and tool are weighed. The difference in weight is used to calculate MRR and TWR.

3. RESULTS AND DISCUSSION

3.1 Analysis of Variance for TWR Models

Lack-of-fit tests for the proposed model using analysis of variance (ANOVA) are carried out to improve the quadratic model which is selected for the TWR_{PMEDM}, the insignificant model terms of A, B, C, and A^2 were accepted only from the model. The resulting ANOVA table is shown in Table 3. In the same manner, insignificant model terms in the quadratic model for TWR_{EDM} (Table 3) were removed. The p-value (Prob>F) column of Table 3 shows p-values of 0.0001 for the model which is less than 0.05. The significant model terms A, B, C, and A^2 all have p-values (Prob>F) of less than 0.05. Similarly, in Table 3 the model and model terms: A, B, and A^2 are all significant with a value of (Prob>F) less than 0.05. $P > 0.05$ is the probability that the null hypothesis is true. 1 minus the P value is the probability that the alternative hypothesis is true. A statistically significant test result ($P \leq 0.05$) means that the test hypothesis is false or should be rejected. A P value greater than 0.05 means that no effect was observed.

Table 3. Analysis of variance for TWR_{PMEDM} (reduced model)

Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	117.33	4	29.33	106.46	< 0.0001	significant
A-Current	108.59	1	108.59	394.11	< 0.0001	
B-On-Time	1.22	1	1.22	4.44	0.0452	
C-Off-Time	1.55	1	1.55	5.62	0.0257	
A^2	5.97	1	5.97	21.66	< 0.0001	
Residual	6.89	25	0.28			
Lack of Fit	6.88	20	0.34	223.79	0.153	not significant
Pure Error	7.686 E-003	5	1.537 E-003			
Cor Total	124.22	29				

3.2 Developed Model for the TWR

The developed models for TWR with and without TaC after removing the insignificant factors are shown in Eq. 1 and 2 respectively.

Equation for TWR_{PMEDM}

$$\text{Ln (TWR)PMEDM} = + 0.45 + 2.13\ A - 0.23\ B - 0.25\ C - 0.46\ A^2 \quad (1)$$

$$\text{Ln (TWR)PMEDM} = - 4.58472 + 3.44111\ \text{Current} - 0.56462\ \text{On-Time} - 0.50816\ \text{Off-Time} - 0.20230\ \text{Current}^2 \quad (2)$$

The equation developed for TWR_{EDM}

$$\text{Ln } (TWR)_{EDM} = + 0.49 + 1.61\ A - 0.3\ B - 0.54\ A^2 \quad (3)$$

$$\text{Ln (TWR)} = - 4.99050 + 3.45160\ \text{Current} - 0.92502\ \text{On-time} - 0.23789\ \text{Current}^2 \quad (4)$$

3.3 Adequacy Test for the Developed TWR Model

Lack-of-fit, R-squared, adjusted R-squared, predicted R-squared, and adequate precision statistics are used to check model adequacy. Table 4 shows no "lack-of-fit." The TWR quadratic models fit response data well. The adjusted R-squared (Adj R^2 is greater than 0.7 and the difference between the adjusted and predicted R-squared is less than 0.2. Table 4 shows that significant model terms explain 93.57% of $TWR_{PMEDM's}$ observed variability (A, B, C, and A2). For TWR_{EDM}, A, B, and A2 explain 91.0% of model variability.

Table 4. Summary Statistic for *TWR*

Condition	TWR_{EDM}	TWR_{PMEDM}
R^2	0.9242	0.9445
Adj R^2	0.9100	0.9357
Pred R^2	0.8353	0.9193
Adeq Precision	27.489	39.704
Lack-of-fit	0	0

Further confirming the model's adequacy is that the adequate precision of the two models is more than 4 (Table 4). Model adequacy check for normally distributed residuals is shown on a normal probability plot, where points follow a straight line. Figures 4a and 4b show this by scattering residuals along a straight line. The residuals are normally distributed.

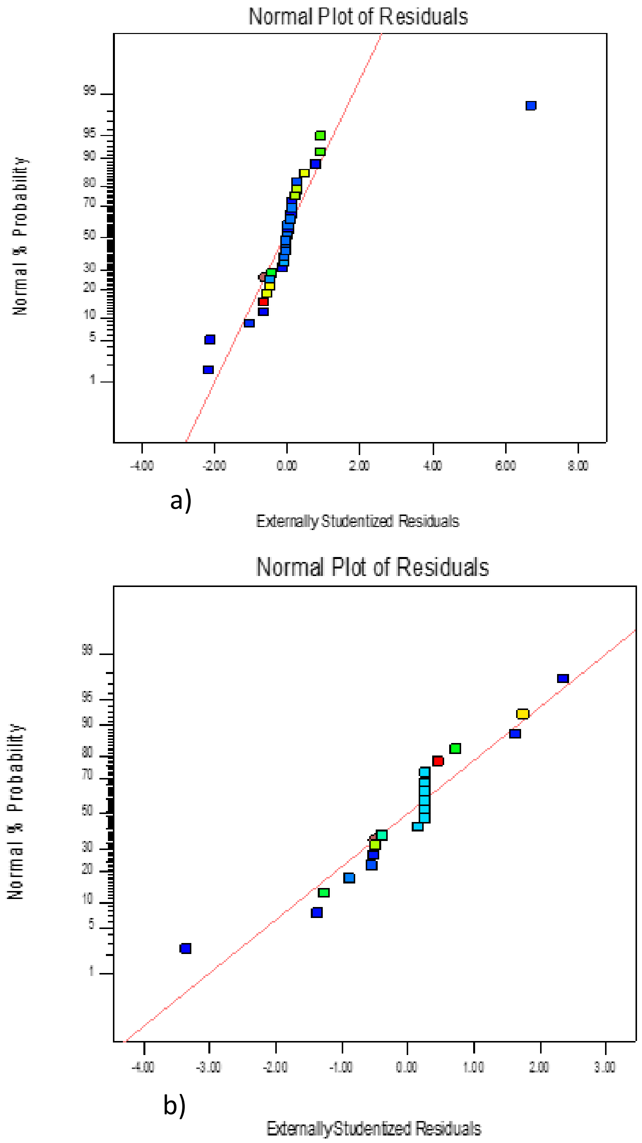
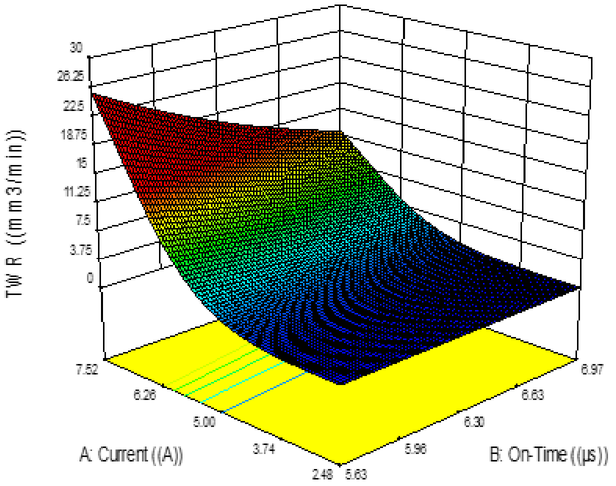


Fig. 4: Normal probability of residuals for (a) TWR_{PMEDM} and (b) TWR_{EDM}

3.4 3-Dimensional Surface plots for TWR_{PMEDM}

The 3- Dimensional surface plots are used to check the interactions between two factors in the model. It can be seen that for TWR_{PMEDM} (Eq. 1 & 2) significant interactions exist between current and on-time (AB) and off-time (AC). Figure 5 shows the 3-Dimensional and the corresponding surface plots for the model developed for *TWR*. The curved shapes of the plots are a result of the quadratic effects and the interactions between the factors. Figure 5 also shows the surface and contour graphs model suggest the best TWR_{EPMEDM} 4mm^3/min achieved at current 5 A, on-time 6.30 μs *and* off-time 7.00 μs with powder TaC powder concentration 25g/L. This means that the effect of on-time and off-time is equal versus current in TWR_{PMEDM}, because of existing of TaC powder in dielectric medium.

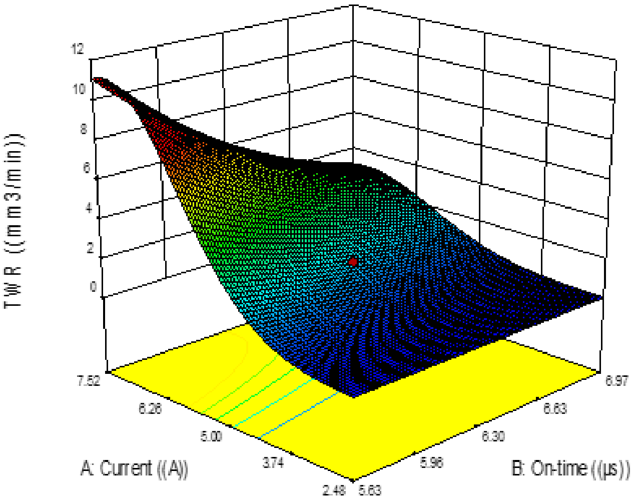


(a)

Fig. 5: 3-D surface plots of TWR_{PMEDM} with current and on time

3.5 3-Dimensional Surface and Contour Graphs for TWR_{EDM}

The significant interaction of the 3-Dimensional surface plot for the model developed for TWR_{EDM} (Eq. 3 & 4) is shown in Figure 6. As explained for the TWR_{PMEDM} model, Fig. 6 shows that there is an interaction between current and pulse on-time (AB) for TWR_{EDM} model. This shows that the effect of pulse on-time on TWR_{EDM} depends on the level of current. The corresponding contour plot for the 3-Dimensional surface shows that the interaction and the quadratic terms in the model produced the curve shape in Figure 6. It also shows contour graphs model suggests the best TWR_{EDM} 1.8mm^3/min achieved at current 5 A, on-time 6.30 μs *and* off-time 7.00 μs.



(a)

Fig. 6: 3-D surface plots of TWR_{EDM} with current and on time

3.6 Model Predictability for TWR

Figures 7 (a) and (b) show the plots of predicted against actual response values for *TWR*. The scattered along a straight-line nature of the plot confirms the model adequacy. It shows a close variation between the actual and predicted values of *TWR* for the two conditions of with and without TaC

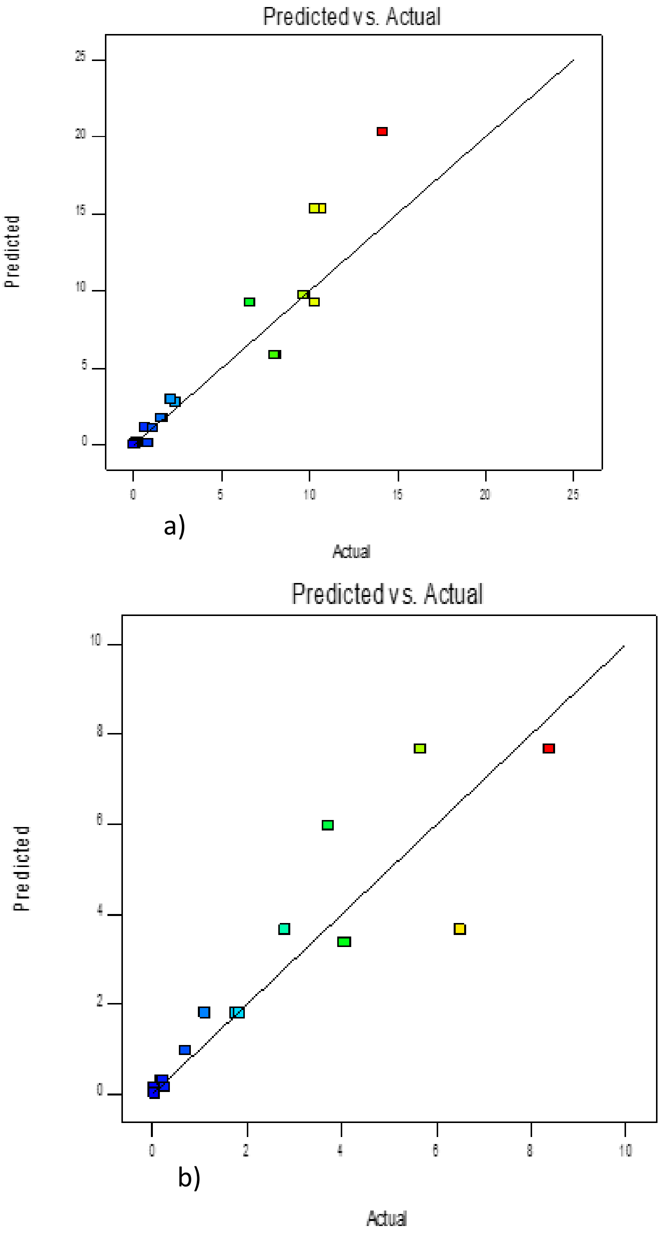


Figure 7. Scattered plots of predicted against the measured values for (a) TWR_{PMEDM} and (b) TWR_{EDM}.

4. CONCLUSION

Following are some of the conclusions that can be drawn based on the results and the discussion:

The tool wear ratio model for EDM with TaC powder additive (TWR_{PMEDM}) suggests that current is the most influencing parameter, followed by pulse on-time and pulse off- time. Concentration is found to be insignificant but has influence indirectly. In the case of tool wear ratio without TaC powder additive (TWR_{EDM}), the current is the most significant factor affecting tool wear, followed by pulse off-time and pulse on-time. According to the model, concentration is also an insignificant parameter to TWR_{EDM} conditions. TaC powder additive has been proven to be an alternative method in reducing tool wear during the electrical discharge machining of stainless steel (SUS 304). There is a reduction of 37.9 % in *TWR* during the EDM of stainless steel. TaC powder additive during EDM of stainless steel improves the EDM technological responses, which includes the less tool wear rate (TWR).

ACKNOWLEDGMENT

The International Islamic University Malaysia's tool and die lab, workshop, and metrology lab were used for the research. The author is appreciative of the contemporary lab setting as well as the lab assistant's assistance.

REFERENCES

[1] Abu Qudeiri, J. E., Mourad, A. H. I., Ziout, A., Abidi, M. H., & Elkaseer, A. (2018). Electric discharge machining of titanium and its alloys. The international journal of advanced manufacturing technology, 96, 1319-1339.

[2] Talla, G., Gangopadhayay, S., & Biswas, C. K. (2017). State of the art in powder-mixed electric discharge machining: a review. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 231(14), 2511-2526.

[3] Al-Amin, M., Abdul Rani, A. M., Abdu Aliyu, A. A., Abdul Razak, M. A. H., Hastuty, S., & Bryant, M. G. (2020). Powder mixed-EDM for potential biomedical applications: A critical review. Materials and Manufacturing Processes, 35(16), 1789-1811.

[4] Marashi, H., Jafarlou, D. M., Sarhan, A. A., & Hamdi, M. (2016). State of the art in powder mixed dielectric for EDM applications. Precision Engineering, 46, 11-33.

[5] Rashid, M. A. N., Saleh, T., Noor, W. I., & Ali, M. S. M. (2021). Effect of laser parameters on sequential laser beam micromachining and micro electro-discharge machining. The International Journal of Advanced Manufacturing Technology, 114, 709-723.

[6] Dual-stage artificial neural network (ANN) model for sequential LBMM-μEDM-based micro-drilling. The International Journal of Advanced Manufacturing Technology, 117(11-12), 3343-3365.

[7] Khan AA, Ndaliman MB, Zain ZM, et al. Surface modification using electric discharge machining (EDM) with powder addition. Appl Mech Mater 2012;110–116: 725–733.

[8] Kuang YK, Jenn TH and Ko TC. Material removal rate and electrode wear ratio study on the powder mixed electrical discharge machining of cobalt-bonded tungsten carbide. Int J Adv Manuf Technol 2009; 40:95–104.

[9] Singh P, Kumar P, Beri N, et al. Some experimental investigation of aluminium powder mixed EDM on machining performance of hastelloy steel. Int J Adv Eng Technol 2010; 1(2): 28–45

[10] Sharma S, Kumar A, Beri N, et al. Effect of aluminum powder addition in dielectric during EDM of hastelloy on machining performance using reverse polarity. Int J Adv Eng Technol 2010; 1(3): 13–24.

[11] Noor, W., Saleh, T., Rashid, M. A. N., & Ibrahim, A. M. (2022, June). Effect of process parameters on the laser microdrilling performance of stainless steel, aluminium and copper. In IOP Conference Series: Materials Science and Engineering (Vol. 1244, No. 1, p. 012020). IOP Publishing.

[12] Sharma S, Kumar A and Beri N. Study of tool wear rate during powder mixed electrical discharge machining of hastelloy steel. Int J Adv Eng Technol 2011; 2(2):133–139.

[13] Chatha SS, Bhatia R, Sidhu HS, et al. Impact of added titanium oxide in dielectric of EDM on surface characteristics and MRR. In: Proc. Nat. Conf. Advancements and Futuristics Trends in Mech. Mater. Eng., Talwandi Sabo, 19–20 February 2010

[14] Pecas P and Henriques E. Influence of silicon powder– mixed dielectric on conventional electrical machining. Int J Mach Tools Manuf 2003; 43: 1465–1471

[15] Kansal HK, Singh S and Kumar P. Performance parametersoptimization (multi characteristics) of powder mixed dielectric discharge machining (PMEDM) through Taguchi’s method and utility concept. Indian J Eng Mater Sci 2006; 13: 209–216

[16] Furutani K, Saneto A, Takezawa H, et al. Accretion of titanium carbide in electrical discharge machining with powder suspended in working fluid. Precis Eng 2001;25: 138–144.

[17] Furutani K and Shimizu Y. Experimental analysis of deposition process of lubricant surface by electrical discharge machining with molybdenum disulfide powder suspended in working oil. Int J Mach Tools Manuf 2002; 43: 1287–1300

[18] Ndaliman MB, Khan AA and Zain ZM. Performance of PM compacted Cu-TaC electrodes during EDM. In: Presented at the 2nd Int. Conf. Mech. Manuf. Eng. (ICME 2011), PICC, Putrajaya, Malaysia, 6–8 June 2011.