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Effect of Maghemite (γ-Fe_2O_3) Nano-Powder Mixed Dielectric Medium on Tool Wear Rate (TWR) During Micro-EDM of Co-Cr-Mo

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ABSTRACT

Micro Electro Discharge Machining (micro-EDM) is widely used for producing different types of micro features and micro components. Tool wear rate (TWR) is an important factor that affects the accuracy of machining as well as the productivity of micro-EDM process. This study examines the effects of process parameters and the use of Maghemite (γ-Fe_2O_3) nano-powder mixed dielectric medium on tool wear rate when micro-EDM Co-Cr-Mo. A Copper electrode with 300 µm diameter and positive polarity was used to evaluate the machining process by focusing on TWR. Two different concentrations of nano-powder (i.e., 2 g/l and 4 g/l) were added to the dielectric. Results showed that increasing the discharge current and voltage leads to a corresponding increase in TWR, while the presence of γ-Fe_2O_3 nano-powder in the dielectric liquid decreases TWR. Mixed micro-EDM with 2 g/l of nano-powder achieved a lower TWR.

Keywords: Cobalt Chromium Molybdenum (Co-Cr-Mo), Maghemite (γ-Fe_2O_3) nano-powder, powder-mixed-EDM, tool wear rate (TWR)

INTRODUCTION

Electrical discharge machining (EDM) is a process currently applied to the production of various tools and moulding used in industries for machining electrically-conductive parts. This method is capable of generating complex shapes with no limitation in the material hardness (Baseri & Sadeghian, 2016). One of the most proficient modern machining processes regarding the size and the precision of products is the micro-EDM process, which outperforms other fabrication processes such as laser, LIGA and ultrasonic ion beam, among others. The

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advantage of this process is its low cost, though it is slow (Jahan, Rahman, & Wong, 2011). Micro-EDM is broadly applied in the field of micro-mould making and the generation of dies, cavities, and complex 3D structures (Alting, Kimura, Hansen, & Bissacco, 2003). One of the latest developments in the technology of EDM is powder-mixed electric discharge machining (PMEDM) that works with the addition of powder particles to the dielectric for improving machining rate, surface quality, and precision. Suspended particles cause a reduction in the dielectric overall electrical resistivity, allowing sparking from a distance. Flushing conditions and the improved spark frequency together with multiple sparks lead to the simultaneous improvement of both surface quality and material removal rate (Talla, Gangopadhyay, & Biswas, 2016). In recent years, alloys that are based on cobalt have been used considerably in the metallurgical and biomedical fields as they are tough and their strength is retained at high temperatures. Additionally, they are biocompatible and resistant to wear and corrosion (Agarwal & Ocken, 1990). The alloys are also used in aerospace and nuclear industries (Rees, 2011). In numerous studies, the effects of powder materials on the characteristics of PMEDM have been investigated, taking into account the reduction in tool wear rate (TWR). Jeswani (1981) examined the impact of adding 4 g of Gr powder to each liter of kerosene oil for EDM of steel. Findings showed that the material removal rate (MRR) and TWR are enhanced by 60% and 15% respectively, whereas the wear ratio (i.e., TWR/MRR) decreased by about 28%. Han-Ming Chow et al. (2000) studied the effects of powder that was added to kerosene for the micro-slit machining of titanium alloy by means of EDM. Findings showed that kerosene with either Al or SiC powder added in EDM could result in fine surface finish, enhance the material removal depth, and reduce TWR. Kung, Horng and Chiang, (2009) examined MRR and TWR during conventional PMEDM of cobalt bonded tungsten carbide (WC–Co) by means of Al powder of 1.5–2 μm and 10–20 g/L. Results showed an increase in MRR when aluminium powder concentration is increased and the EWR value tended to reduce with the aluminium powder concentration down to a minimum value after which it tended to increase. Tiwary, Pradhan and Bhattacharyya, (2015) investigated the impact of a variety of process parameters into TWR, MRR, overcut (OC), and taper of micro-hole during EDM process of Ti-6Al-4V. The Cental Composite Design (CCD) technique was used to design the experiment, and Response Surface Methodology (RSM) was applied for mapping the relationships between the input and out process parameters. Jahan et al. (2011) investigated the improvement and enhancing the carbide surface characteristics in sinking and milling micro-EDM by using Gr nano-powder-mixed dielectric. Results showed both Ra and Rmax reduced with an increase in the powder concentration up to certain values; then they increased again. The EWR was decreased at certain concentrations; but at higher concentration, it tended to increase. According to Tzeng and Lee (2001), amongst SiC, Al, and chromium (Cr) powders, the use of Cr provides the highest MRR while the SiC powder produces the lowest MRR; and the SiC powder had the most significant effect on the tool wear followed by Al and Cr respectively. Figure 1 shows very few studies have been conducted on nano-powder-mixed EDM y while there is no published work on effects of γ-Fe_2O_3 nano-powder-mixed EDM. Thus, the present paper examines and discusses the feasibility of obtaining low TWR when micro- EDM of CoCrMo through the addition of γ-Fe_2O_3 nano-powder to the dielectric medium. The TWR was observed with and without powder-mixed micro-EDM.

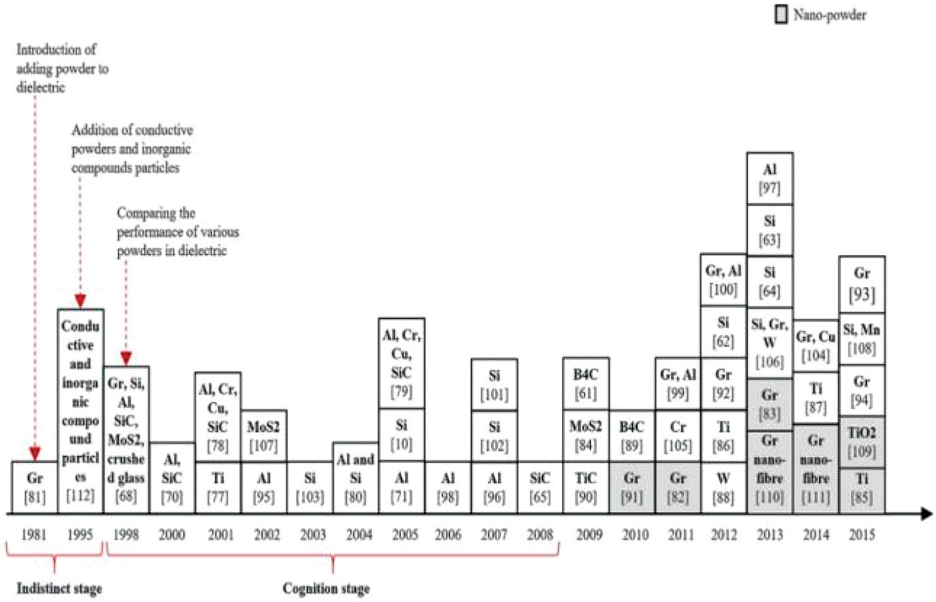

Figure 1. Studies conducted on PMEDM between 1981 and 2015 (Marashi, Jafarlou, Sarhan, & Hamdi, 2016)

METHODS: EXPERIMENTAL SETUP

The experiments in the current research were performed using an AG40L Sinker EDM (Figure 2), and the samples were the CoCrMo alloy; the latter was cut into slides with dimensions of 50 mm x 90 mm x 1mm, and the electrode was from copper with 6 mm length and 300 µm diameter. The electrode had positive polarity, and oil-based dielectric fluid mixed with two percentages of γ-Fe_2O_3 nano-powder, which were 2g/l and 4g/l respectively were utilised. In the first group, the EDM dielectric was utilised, and in the second group, γ-Fe_2O_3 nano-powder with size less than 10 nm was mixed with the dielectric medium. The PMEDM experiments were carried out in working tank with dimensions of 46 cm × 35 cm × 24 cm made up of 1.5 mm thick stainless steel sheets. During the tests, a stirrer was employed to maintain a consistent suspension of Fe_2O_3 nano-powder in the tank,. The working tank is depicted in Figure 3. The input variables of the study were current, voltage, and pulse on time. The experiments were designed using a 2-level factorial design that comprised 11 runs including 8 points (2^3) and 3 centre points. In order to calculate TWR for all experimental runs, equation 1 was used. A precision electronic balance was used to measure the electrode weights.

$$TWR=[(W1-W2)\times1000]/(T\times\rho) \quad [1]$$

Where W2 and W1 stand for the weights of the tool after and before machining respectively (in grams) while ρ denotes the density of workpiece in gm/cc, and T signifies the experiment time in minutes.

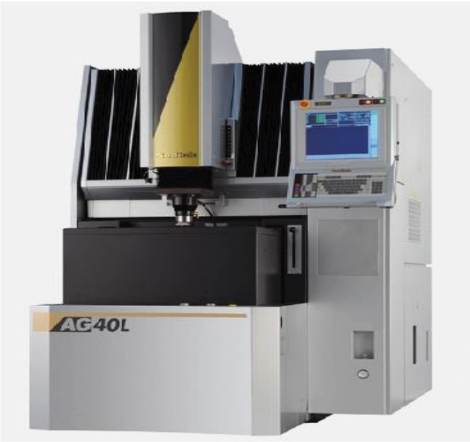

Figure 2. AG40L Sinker EDM

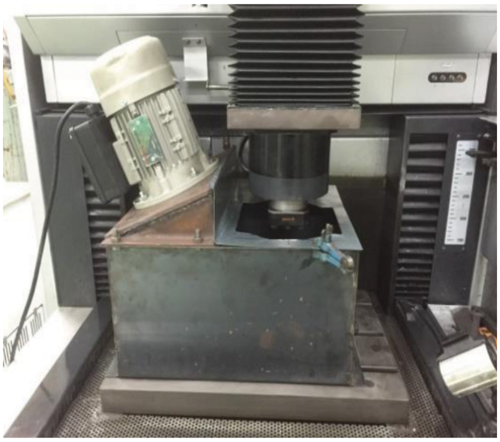

Figure 3. Working tank

Table 1
Machining Parameters

Description	Input Factors	Unit	Value		
			Low	**Centre**	**High**
A	Current	A	1.5	2.25	3
B	Voltage	V	60	90	120
C	Pulse On	μs	10	105	200

Table 2
Experimental Results

Exp No	TWR1 Without nano-powder (mm^3/min)	TWR2 2g/l- nano-powder (mm^3/min)	TWR3 4g/l- nano-powder (mm^3/min)
1	0.000617	0.000322	0.00032
2	0.003713	0.00041	0.004998
3	0.007163	0.001821	0.029149
4	0.054019	0.011946	0.033762
5	0.006726	0.000252	0.000198
6	0.000676	0.000661	0.002478
7	0.025621	0.000539	0.000229
8	0.026912	0.015995	0.017812
9	0.009497	0.000868	0.00997
10	0.009586	0.0009	0.00646
11	0.007062	0.002563	0.006719

RESULTS AND DISCUSSIONS

Tables 1 and 2 respectively show the experimental parameters results obtained for TWR. Calculation was done for TWR1 (without nano-powder), TWR2 (adding 2 g of γ-Fe_2O_3 nano-powder to each liter of oil), and TWR3 (adding 4 g of γ-Fe_2O_3 nano-powder to each liter of oil). Design-Expert Software Ver. 7 was used to analyse the dependent variables. ANOVA (Analysis of variance) was carried out in order to examine the significance of the micro-EDM and PME-micro-EDM of Co-Cr-Mo model, individual model terms, and the lack of fit. The ANOVA results of TWR1, 2 and 3 are presented in tables 3, 4, and 5 respectively. Table 3 and Figure 4 show TWR1 increased with an increase in the peak current and gap voltage, whereas the effects of the pulse on time on TWR1 were insignificant. When current settings were high, more electric current (energy) passing through the gap resulted in a large amount of workpiece and electrode material removal through evaporation and melting. This is why the increased current led to higher TWR (Unses & Cogun, 2015). In addition, low TWR1 was obtained once the pulse on was 10 µs and the current was 1.5 A. Based on Table 4 and Figure 5, (A, B, AB) factors had a significant effect on TWR2. The TWR2 value increased with an increase in the peak current and spark gap voltage. Higher heat energy is subjected to both electrodes when machining is done with higher values of the discharge current. It increases the volume of the molten and ejected metal from both electrodes (Habib, 2009). Table 5 and Figure 6 show the factors of A, B, C, and BC were significant. The TWR3 was increased with an increase in the current and gap voltage, whereas it was reduced once the pulse on time was increased. Increasing the pulse on time values decreases the TWR3 values. When values of pulse duration are small, more negatively charged particles in motion strike the positive tool electrode, which leads to an increase in the rate of melting of the electrode material (Habib, 2009). R-squared values for TWR1, TWR2 and TWR3 (0.9873, 0.9124, 0.9409 respectively) that are near to 1 which is desirable. There is a small difference between Pred R-squared and Adj R-squared (less than 0.2), which means there is an acceptable transaction between the input and output parameters. An Adeq precision greater than 4 is desired. Regression models regarding the actual factors for TWR1, TWR2 and TWR3 predictions are displayed as below:

Sqrt(TWR1) =-0.0215-0.0204* Current-0.00028*Voltage+0.00096*Pulse On+0.00095 * Current * Voltage 0.000413* Current * Pulse On

Ln(TWR2) =-7.981-0.95266 * Current-0.013101 * Voltage+0.022584* Current* Voltage

TWR3 =-0.038112+0.0048* Current+0.00049* Voltage+0.000104* Pulse On-0.00000181* Voltage * Pulse On

Table 3
Analysis of Variance (ANOVA) Test for TWR1

Response: TWR1							
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**		
A (Current)	0.002173	1	0.002173	17.85	0.0134		
B(Voltage)	0.025	1	0.025	205.46	0.0001		
C(Pulse On)	0.0001073	1	0.0001073	0.88	0.4009		
AB	0.003685	1	0.003685	30.26	0.0053		
AC	0.006957	1	0.006957	57.13	0.0016		
Residual	0.000487	4	0.0001218				
Lack of Fit	0.000362	2	0.0001814	2.92	0.2551	not significant	
R-Squared	0.9873	Adj R-Squared	0.9715	Pred R-Squared	0.8428	Adeq Precision	23.45

Table 4
Analysis of Variance (ANOVA) Test for TWR2

Response: TWR2							
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**		
Model	17.55	3	5.85	20.84	0.0014	significant	
A (Current)	5.25	1	5.25	18.69	0.005		
B (Voltage)	10.24	1	10.24	36.47	0.0009		
AB	2.07	1	2.07	7.36	0.035		
Residual	1.68	6	0.28				
Lack of Fit	0.93	4	0.24	0.61	0.6964	not significant	
R-Squared	0.9124	Adj R-Squared	0.8687	Pred R-Squared	0.7186	Adeq Precision	10.868

Table 5
Analysis of Variance (ANOVA) Test for TWR3

Response: TWR3							
Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob > F**		
A (Current)	0.0001062	1	0.0001062	6.63	0.0498		
B (Pulse On)	0.0006653	1	0.0006653	41.50	0.0013		
C-Voltage	0.0002822	1	0.0002822	17.6	0.0085		
BC	0.0002229	1	0.0002229	13.9	0.0136		
Residual	0.000080	5	0.00001603				
Lack of Fit	0.000072	3	0.00002417	6.32	0.1397	not significant	
R-Squared	0.9409	Adj R-Squared	0.8936	Pred R-Squared	0.6144	Adeq Precision	12.649

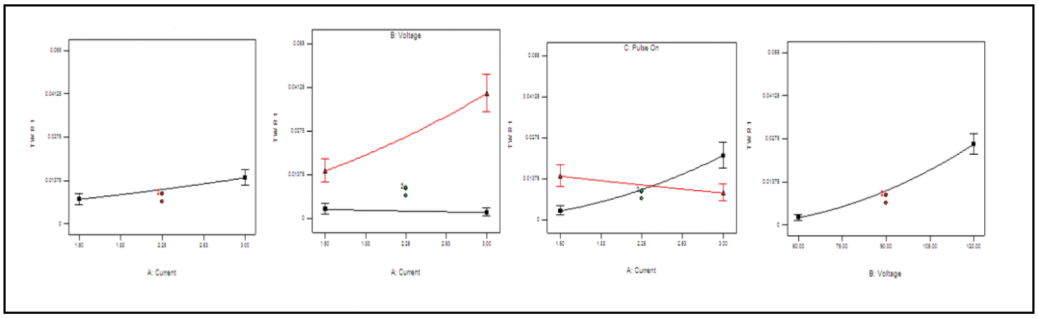

Figure 4. Effect plot showing variation of TWR1 with process parameters

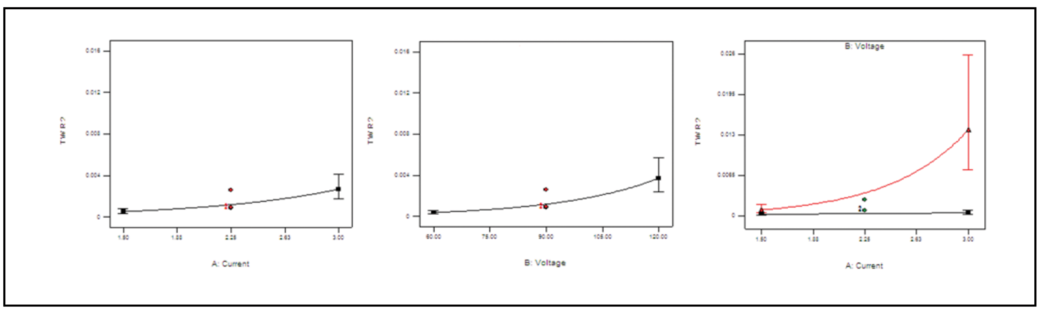

Figure 5. Effect plot showing variation of TWR2 with process parameters

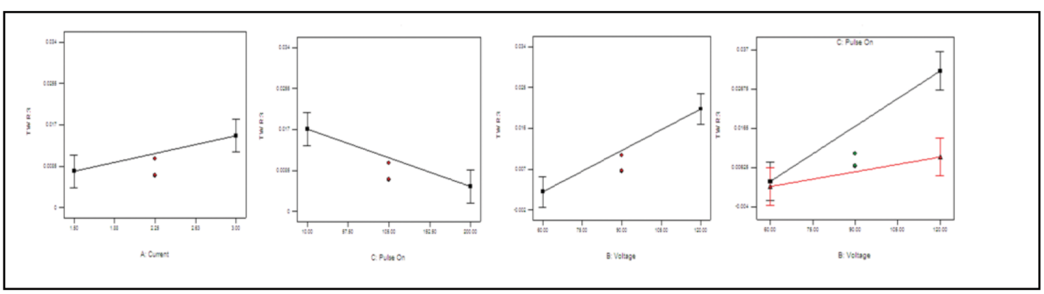

Figure 6. Effect plot showing variation of TWR3 with process parameters

Figure 7 shows that the residuals follow a roughly straight line in the normal probability plot, which indicates they are distributed in a normal way. The residuals have a constant variance since they are randomly scattered around zero in residuals versus predicted values. Therefore, there is no error due to the time or data collection order.

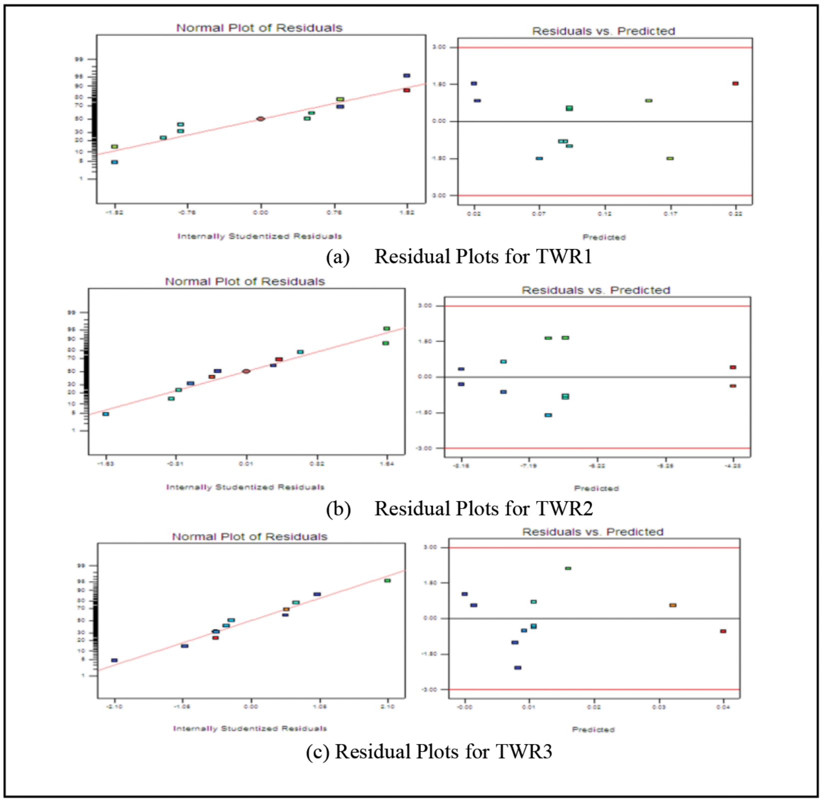

Figure 7. Normal plots of Residual for TWR

Figure 8 compares the amounts of TWR generated with the addition of various concentrations of Fe_2O_3 nano-powder to dielectric. Findings indicate that the addition of 2 g/l of Fe_2O_3 nano-powder to dielectric fluid causes lower TWR, whereas if 4g/l is added to the dielectric, the TWR values are increased, as shown in Figure 9. During micro-EDM, if conductive or semi-conductive powders exist in the working gap, the breakdown strength of dielectric can be reduced, resulting eventually in a higher spark gap. The decrease in TWR due to adding powder is because of the decrease of ineffective pulses at higher spark gap and the improved flushing, while the increased trend of TWR at higher concentration is because of the settlement of powder in the spark gap (Jahan et al., 2011; Yih-fong & Fu-chen, 2005)

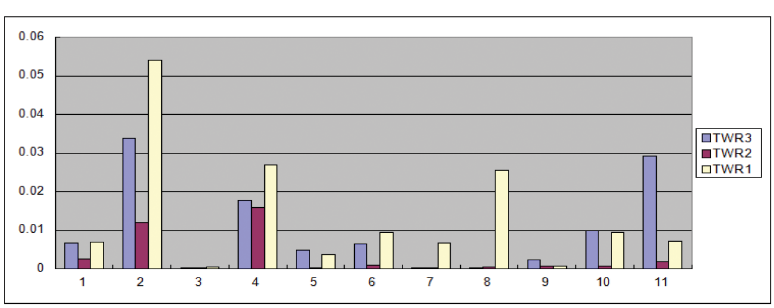

Figure 8. Comparison between TWR values

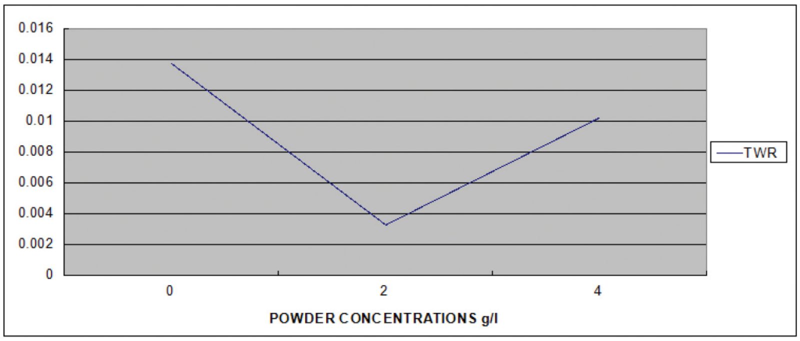

Figure 9. Effect of the powder concentration on TWR

Optimal Parameters and Confirmation Runs

Optimisation is aimed at exploring an appropriate set of conditions that can achieve all of the defined goals. The ANOVA results indicate that voltage, current, and pulse were significant. The input variables were adjusted to obtain desirable values of TWR in the optimisation process. The voltage and current were set as minimum values, while the pulse was set in range for TWR1 and TWR2; however, for TWR3, the pulse on time was set at maximum. When the desired value nears 1, the setting parameters provide the desirable responses. In Figure 10, the red area displays the best desirable values of parameters. For verification of the model's adequacy, two confirmation experiments were carried out on TWR1, TWR2, and TWR3, and data from the confirmation runs are listed in Table 6. The maximum deviation of the predicted results from the experimental results is -13.52%.

Table 6

Analysis of Confirmation Experiments for TWR

IP	V	Ton	Powder %	Response	Actual	Predict	%error
1.5	70	10	0	TWR1	0.0217	0.0215	2.52
1.88	60	10	0	TWR1	0.02161	0.0245	-13.52
1.5	70	10	2	TWR2	0.0025	0.0026	-7.32
1.88	60	10	2	TWR2	0.0039	0.0037	5.12
1.5	70	200	4	TWR3	0.02156	0.0207	3.98
1.88	60	200	4	TWR3	0.0297	0.0314	-5.91

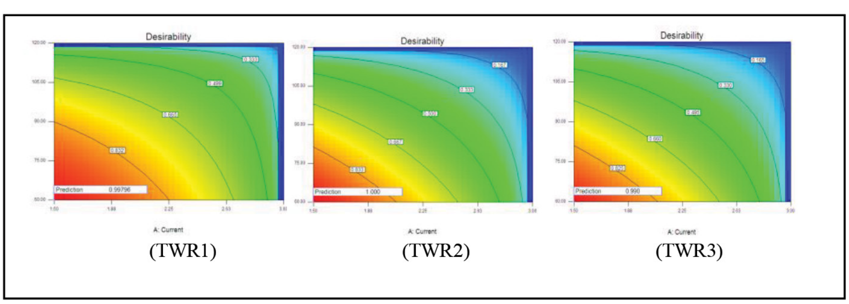

Figure 10. Desirability graphs for TWR1, TWR2 and TWR3

CONCLUSION

The present study shows that a decreasing tool wear rate (TWR) is achievable during the EDM process of CoCrMo using Fe_2O_3 nano-powder. It also examined the impacts of process parameters on TWR. Below is the summary of the findings of this study:

- As indicated by the ANOVA analysis for TWR responses, current and voltage were the significant factors. By setting the current at 3A and voltage at 120V, the highest value of TWR was obtained. With an increase in current, the TWR increased; this was because using higher values of current during machining process meant higher heat energy was subjected to both electrodes. As result, the material that is removed from both electrodes increased too.
- During the powder-mixed micro-EDM of Co-Cr-Mo, adding γ-Fe_2O_3 nano-powder to the dielectric liquid caused a reduction in TWR. 2 g of nano-powder reduced the TWR, whereas 4 g/l of γ-Fe_2O_3 nano-powder increased the TWR.

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