A Mathematical Model to Assess the Material Removal Rate during Gas-Assisted Electrical Discharge Drilling Process

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Abstract
This research work investigates the use of Gas-Assisted Electrical Discharge Drilling (GAEDD) of high carbon-chromium die steel. The poor material removal rate (MRR) is one of the profound drawbacks of the traditional Electrical Discharge Drilling (EDD) process. Hence, over the years researchers have been feeling the requisite to develop an advanced strategy that can enhance the MRR. This study has examined the utilization of compressed gas in conventional EDM under the constraint state to assess MRR. The impact of procedure parameters likedischarge current, pulse on time, duty cycle, electrode speed, and discharge gas pressure, on MRR, has been explored too. In addition, Variance Analysis (ANOVA) was performed to determine the significant parameters affecting the MRR. During the examination, a mathematical model was established MRR employing Buckingham π-theorem while the GAEDD was being applied. The experiment and anticipated values of the model show a noteworthy impact of the coefficient of thermal expansion in GAEDD of high carbon-chromium steel. In addition, the Response Surface Method (RSM) model has also been evolved. The comparative analysis of the models developed shows considerable agreement in anticipation. Moreover, the semi-empirical model appears to be even more adaptable especially in comparison to the RSM-based model. In fact, the conclusion of this work is that the dimensional analysis model is an effective and reliable strategy to precise EDD response prediction.

Keywords- Electrical discharge maching, Drilling, Responses, Material removal rate, Response surface methodology.

Nomenclature
I_p Discharge Current
T_{on} Pulse-on Time
DC   Duty Cycle
RPM   Tool Rotation
GP   Gas Pressure
K   Thermal conductivity
σ Electrical conductivity
ρ Density
C_p Sp. Heat
θ Melting point
MRR   Material removal rate

1. Introduction

Electrical discharge drilling (EDD) is a commonly adopted non-traditional method of machining that absorbs heat from a spark and excretes material from a rigid and stiff object, something that cannot be machined by a traditional technique. The technique is generally related to the production of die molds and aeronautical components (Ho and Newman, 2003). One of the real perplexities involved during EDD is the effective removal of eroded materials from electrodes gap. The phenomena of short circuit occurred when eroded material is collected between the electrodes gap. This leads to a reduced rate of material removal (MRR) and poor surface integrity (Singh et al., 2016, 2017).

So as to enhance the effectiveness of the EDM procedure, scientists look into different techniques regarding a few customary, innovative algorithm and creative frameworks. Due to the uncertainty and arbitrary nature of the different procedures and multiple methodological variables, the ideal approach has yet to be developed by researchers. Tsai and Wang (2001) applied Buckingham's pi-hypothesis to measures the SR during the EDM operation. In addition to the machining parameters, the electrical and non-electrical parameters used to create the model are also taken into account. The anticipated value of SR through model has a good agreement with the value obtained through the experiment. Yahya and Manning (2004) analyzed the significant factors affecting the EDM operation. They notable parameters were ascertained by using the ANOVA and these parameters were considered to evolve a model to predict the MRR during the EDM process. Kumar and Khamba (2009) proposed μ-model to measure the MRR using the dimensional technique during the ultrasonic-assisted EDM of titanium alloys specimens. Patil and Brahmankar (2010) developed a mathematical model based on Buckingham's π-theorem to assess the MRR during the wire-EDM (WEDM) process. The average error between actual and predicted values was found to be less than 5%. Yahya et al. (2012) performed comparative studies of finding obtained through the predictive model based on Buckingham's π-theorem and Artificial Neural Network (ANN) for the EDM operation. Dave et al. (2013) proposed the model using the dimensional analysis method to anticipate the MRR during the orbital-assisted EDM. The root means square error between actual and predicted values was found to be 3% (approx). Kumar et al. (2014) applied statistical techniques to analyze the impacts of process factors during WEDM on notable process output such as MRR and over-cut. In the course of the investigation, they created a predictive model centered on π-theorem of Buckingham to assess the process output. Bobbili et al. (2015) performed experimental analysis and proposed mathematical model to measures the WEDM responses like MRR and SR. Finding suggested the there is a good accord between measures and predicted values by developed model. In the course of an investigation, Bhaumik et al. (2018) developed a semi-empirical technique to assess MRR and radial overcut (ROC) during EDM with tungsten carbide electrode. Apart from the machining parameters, work material properties are also considered for the development of a predictive model using Buckingham's π-theorem. Kumar et al. (2015) proposed a mathematical model for the assessment of tool wear during powder mixed EDM using Buckingham's π-theorem. Estimated results from the mathematical model were verified and observed to be in agreement with the experimental outcome. Phate and Toney (2019) studied WEDM process responses by applying dimensional analysis and artificial neural network (ANN) techniques. It was evident from the coefficient of determination that both dimensional analysis and ANN techniques are qualified to estimate SR and MRR. In addition, the models developed using the ANN methodology have been discovered to be somewhat more accurate than the dimensional analysis techniques. Recently, Singh et al. (2016, 2017) proposed a semi-empirical model to measure the surface roughness during the argon-based EDM operation. Finding, reveal that the average error between experimental and predicted values are less than 3%. Further, they discover

that the semi-empirical model projected the EDM output quite accurately in comparison of regression model.

On the basis of the study of literature available, it tends to be seen that the greater part of the exploration work concentrated on either conventional or wire-EDM. Singh et al. (2016, 2017) earlier trial examinations have discovered the benefits of gas-assisted EDM when contrasted with rotational EDM regarding MRR and EWR. From a review of previous literature, no investigation of a statistical model could be identified, in perspective on thermal as well as mechanical properties, which would make certain improvement in MRR during gas based EDM. The model based on a dimensional analysis, previously developed, was largely dependent on the parameters of the machining operation and various properties of the workpiece. The advancement of the model taking into account dielectric characteristics, including compressed gas supply and electrode revolution speed for additional studies, has not been documented to the author 's information. From a review of past research work, it was additionally seen that no work is accounted for on parts of material removal mechanism in inert gas-based EDM operation.

In light of the above mentioned problems, the purpose of the contemporary investigation is to explore and establish a mathematical model for predicting MRR by introducing high-pressure argon gas via perforated electrode in conventional EDD.

2. Materials and Methods
2.1 Workpiece and Electrode Material
The experiments have been performed on carbon-chromium steel samples, employing rounded copper as tool. The sample utilized has a rectangular dimension (15 x10x10 mm) and having wear resistance of 55HRC. Table 1 reveals the specified specimen's chemical composition.
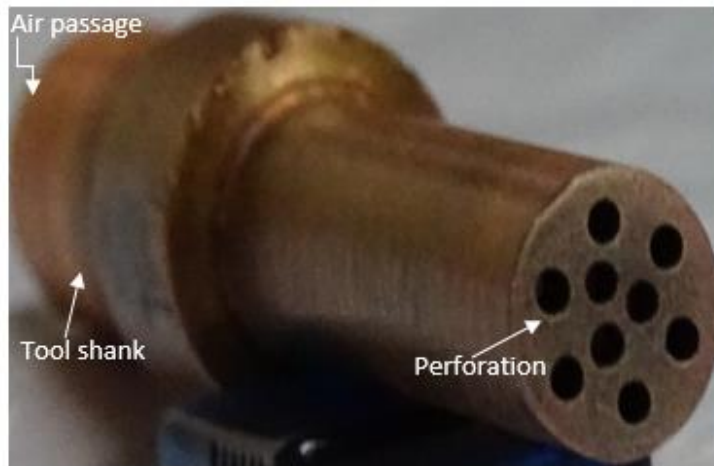

Figure 1. Image of the tool

Table 1. Chemical composition of the workpiece

Cr	C	Si	Mn	P	S	Fe
11.05	2.25	0.50	0.25	0.09	0.05	Rest.

2.2 Experimental Procedure

The machining execution period for argon-assisted EDM with a perforated tool has been set to 15 minutes for each and every experiment. The EDM oil-gas mixed dielectric was used in GAEDD process. During machining, the electrode was immersed in the dielectric fluid. The argon gas was provided directly through the perforated electrode in to the electrodes gap. The gas pressure was modified to prevent the formation of a completely dry or wet state. Five variable factors, like those of discharge current, pulse duration, duty cycle, electrode rpm, and gas pressure, were utilized to conduct the experiment. The range of selected control factors was decided on the grounds of preliminaries experiments and machine limit. For conventional EDM, high-pressure argon gas was being used to avoid oxidation reactions, the risk of flame and hazards throughout machining operations. Table 2 displays the variety of machining factors used for the current study. Schematic of tool electrode is depicted in Figure 1. The proposed work plans experiments with Central Composite Rotatable Design (CCRD) way to assess effects of various process variables on output. A total of 32 experiments with independent variables at 5 different levels were performed using CCRD approach. Each experiment was conducted thrice to minimize experimental errors, and its mean value was taken as the response to the process. For each experiment in the GAEDD method the evaluated MRR values were summarized in Table 3.

Table 2. Control factors with their levels

Factors	Levels				
	-2	-1	0	1	2
Discharge Current (I_p) (A)	3	4	5	6	7
Pulse-on Time (T_{on}) (µs)	100	200	300	400	500
Duty Cycle (DC)	0.52	0.58	0.64	0.70	0.76
Tool Rotation (rpm)	100	300	500	700	900
Gas Pressure (GP)(mm Hg)	3	6	9	12	15

The MRR was determined as an extent of wear volume of a workpiece to the machining time (Srivastava and Pandey, 2013).

$$\text{MRR (mm}^3/\text{min)} = \frac{Wear\ volume\ of\ the\ specimen}{Machining\ time} \tag{1}$$

Machined workpiece have been cleaned in acetone. The electronic gauging balance was used for the calculation of weight. Electronic clock (precision of 0.1 seconds) was used to ensure precise machining time figuring.

Table 3. Measured responses corresponding to each trial of GAEDD process

Run Order	Discharge Current	Pulse-on Time	Duty Cycle	Tool Speed	Gas Pressure	MRR
	(A)	(µs)		(rpm)	(mm Hg)	(mg/min)
1	4	200	0.58	300	12	8.70
2	6	200	0.58	300	6	13.19
3	4	400	0.58	300	6	7.25
4	6	400	0.58	300	12	13.37
5	4	200	0.7	300	6	9.94
6	6	200	0.7	300	12	17.75

Table 3 continuied...

7	4	400	0.7	300	12	8.65
8	6	400	0.7	300	6	12.65
9	4	200	0.58	700	6	6.98
10	6	200	0.58	700	12	16.15
11	4	400	0.58	700	12	9.42
12	6	400	0.58	700	6	10.35
13	4	200	0.7	700	12	10.69
14	6	200	0.7	700	6	15.93
15	4	400	0.7	700	6	7.65
16	6	400	0.7	700	12	11.85
17	3	300	0.64	500	9	5.54
18	7	300	0.64	500	9	21.42
19	5	100	0.64	500	9	15.21
20	5	500	0.64	500	9	6.43
21	5	300	0.52	500	9	8.25
22	5	300	0.76	500	9	12.35
23	5	300	0.64	100	9	9.13
24	5	300	0.64	900	9	7.67
25	5	300	0.64	500	3	7.78
26	5	300	0.64	500	15	10.95
27	5	300	0.64	500	9	10.78
28	5	300	0.64	500	9	10.98
29	5	300	0.64	500	9	10.69
30	5	300	0.64	500	9	10.67
31	5	300	0.64	500	9	10.63
32	5	300	0.64	500	9	10.77

2.3 Analysis of Variance (ANOVA)

ANOVA was performed to know the notable factors influencing MRR during the GAEDD. The ANOVA model of MRR was depicted in Table 4. The measurements of 'Prob > F' were found to be less than 0.05 (95 percent confidence) for the ANOVA model. Therefore, the conclusion may be drawn that the variables in the model had a major impact on the EDD output. The statistical model for MRR in the form of equations 2 had shown as below.

$$MRR = 5.30 - (3.73 \times I_p) - (0.0216 \times T_{on}) + (10.9 \times DC) + (0.0131 \times RPM) + (0.032 \times GP) + (0.712 \times I^2{}_p) - (0.000015 \times RPM^2) \tag{2}$$

Table 4. ANOVA table for MRR

Source	DF	SS	MS	F	P	R^2	
Regression	8	432.15	54.01	62.74	0	0.95	$F^{standard}_{(0.05,8,23);} = 2.80$ $F^{regression} > F^{standard}_{(0.05,8,23)}$
Linear	5	405.35					$F^{standard}_{(0.05,8,23);} = 1.76$
Square	2	20.72					
Interaction	1	6.07					$F^{lack-of-fit} < F^{standard}_{(0.05,18,23)}$ The method is suitable and
Residual error	23	19.80	0.86				the lack of fit is negligible.
Lack-of-Fit	18	16.77		1.54	0.335		

2.4 Dimensional Analysis for Assessing MRR During GAEDD

The dimensional investigation is a strategy applied to acquire a specific arrangement of data about a considered occurrence. Absolute preparation of dimensionless variables can be obtained through dimensional analysis. The methodology of dimensional technique is primarily always had to mitigate the uncertain intricacies of physical problems by minimizing the number of variables that don't have a fundamental effect on the particular problem (Sonin, 2001). In the event that the problem is assumed to have 'n' variables and in the situation that 'k' implies elemental dimensions, then the dimensional perusal minimizes the difficulty to just π-dimensionless terms. For the most part, 'n-k' refers to the total dimensionless terms that manage the issue. The attributes of physical quantities are shown in Table 5.

Table 5. Various attributes of physical quantities

	Parameters	value	Dimensions
Process Factors	Current		QT^{-1}
	Pulse-duration		T
	Tool speed		T^{-1}
	Gas pressure		$ML^{-1}T^{-2}$
	Duty cycle		1
Material Properties	Thermal conductivity	50 *W/m-K*	$MLT^{-3}\theta^{-1}$
	Electrical conductivity	0.01824 *S/m*	$M^{-1}L^{-3}TQ^2$
	Density	7700 *Kg/m³*	ML^{-3}
	Sp. Heat	0.46*Cal/S mole °C*	$L^2T^{-2}\theta^{-1}$
	Melting point	1421 0^C	θ
Response	Material removal rate		L^3T^{-1}

Function:

$$MRR = f(I_p, T_{on,} RPM, GP, DC, K, \sigma, \rho, C_p, \theta) \tag{3}$$

In this scenario, the matrix is five, so there are 11 factors. Consequently, as per Buckingham postulate, there are six π--terms and there is an equation for the for the given problem is:

$$[L^3T^{-1}]^{k_1}[QT^{-1}]^{k_2}[T]^{k_3}[T^{-1}]^{k_4}[ML^{-1}T^{-2}]^{k_5}[MLT^{-3}\theta^{-1}]^{k_7}$$

$$[M^{-1}L^{-3}TQ^2]^{k_8}[ML^{-3}]^{k_9}[L^2T^2\theta^{-1}]^{k_{10}}[\theta]^{k_{11}} = [M^0L^0T^0Q^0\theta^0] \tag{4}$$

$$MRR = (0.0007138) \times Z \left(\frac{I_p \, \rho \, C_p^{1.5}}{K^{1.5}\sigma^{0.5}} \right)^\alpha \times \left(\frac{T_{on} \, \rho \, C_p^2 \, \theta}{K} \right)^\beta \times$$

$$\left(\frac{RPM \, K}{\rho \, C_p^2 \theta} \right)^\gamma \times \left(\frac{GP}{\rho C_p \, \theta} \right)^\delta \times (DC)^\lambda \tag{5}$$

where, the constant is Z and the undefined exponents are $\alpha, \beta, \gamma, \delta$ and λ. The non-linear method is applied to evaluate the constant and unidentified exponents. Estimates of $Z, \alpha, \beta, \gamma, \delta$ and λ are shown to be *281,729169.70, 1.0913,-0.4182,-0.0125, 0.2907* and *0.9505* separately.

The point by point procedure is altogether clarified in Appendix A. Condition (5) can be written in the accompanying structure:

$$MRR = (212.12) \times \left(\frac{I_p \, \rho \, C_p^{1.5}}{K^{1.5} \sigma^{0.5}} \right)^{1.0913} \times \left(\frac{T_{on} \, \rho \, C_p^2 \, \theta}{K} \right)^{-0.4182} \times$$

$$\left(\frac{RPM \, K}{\rho \, C_p^2 \theta} \right)^{-0.0125} \times \left(\frac{GP}{\rho C_p \, \theta} \right)^{0.2907} \times (DC)^{0.9505} \tag{6}$$

The competency of the created model has been verified by the mean error (ME), root means square error (RMSE) and average percentage error (ΔE%) (Singh et al., 2019). The accompanying conditions were utilized for these investigations:

$$ME = \frac{1}{N} \sum_{i=1}^{N} (A_i - A) \tag{7}$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (A_i - A)^2} \tag{8}$$

$$\Delta E(\%) = \frac{1}{N} \sum_{i=1}^{N} (A_i - A) \tag{9}$$

Here, N is the entire collection of data, A_i is the computation of the expected information, and A is the measure anticipated by the model on the basis of the dimensional analysis. The reliability of the perception model was evaluated utilizing the ME, RMSE, (ΔE %) and is recorded in Table 6. From such attributes, it appears to be presumed that the model produced succesively empowers to correct and realistic expectations.

Table 6. Accuracy of predictive model

Process output	ME	RMSE	(ΔE%)
MRR	0.028	0.752	2.80

Table 7. Affirmation of the MRR prediction through the proposed model

Exp. No.	Machining parameters					MRR (mm^3/min)	
	I_p	T_{on}	DC	rpm	GP	Predict.	Exp.
1	7	300	0.58	500	15	20.03	19.66
2	4	100	0.64	300	9	10.81	10.76
3	5	200	0.76	100	6	10.75	10.55

Examinations were led under various parametric combinations to approve the developed model. The forecasting capability of any model can be resolved uniquely with an altogether new

arrangement of data. Consequently, the created model was tried utilizing data, not recently utilized during the experimentation procedure. Subtleties are displayed in Table 7. It very well may be gathered from Table 7 that the developed model can foresee MRR during the GAEDD procedure with great precision.

3. Results and Discussion
The experiment and the anticipated measures taken through the semi-empirical model were discussed in the following subsections.

3.1 Process Factors Effect on MRR During GAEDD
The comparison of regression, semiempirical and observational outcomes is shown in Figure 2(a), Figure 2(b), Figure 2(c) and Figure 2(d). The outcomes demonstrate a decent understanding between test esteems and anticipated qualities in the semi-experimental model. It concludes from these figures that the semi-empirical approach actually results in valid and accurate results in the regression model correlation. Semi-empirical models, which had developed earlier, were largely dependent on the machining operation variables, electrical, physical and thermal attributes of the workpiece. Besides the above-mentioned properties, the dielectric attributes, the discharge gas pressure and the electrode revolution were also taken into account in the current analysis. In addition, this model can be related to look at MRR just as specific procedure responses (Table 8).

The exploratory and anticipated measures of MRR during the GAEDD procedure are displayed in Figure 3. The results of the tests and model anticipation measures of the MRR during the GAEDD procedure can be considered as per agreement.

The normal error between the anticipated and observation values is around 5%. The commitment level of each parameter and the response error, determined by the calculation of the error variance (Ve) and the sum of the regression squares as acquired from the ANOVA table. (Srivastava and Pandey, 2013), can be defined as pursues:

$$\Delta Y = t_{\alpha/2}, DF\sqrt{V_e} \tag{10}$$

where ΔY represents the error accordingly, the dimension of certainty interim is meant by α and is considered as 0.05. The difference of error of expected procedure response is indicated by Ve. The determined fallacy can be in Figure 3 by the use of error bars.
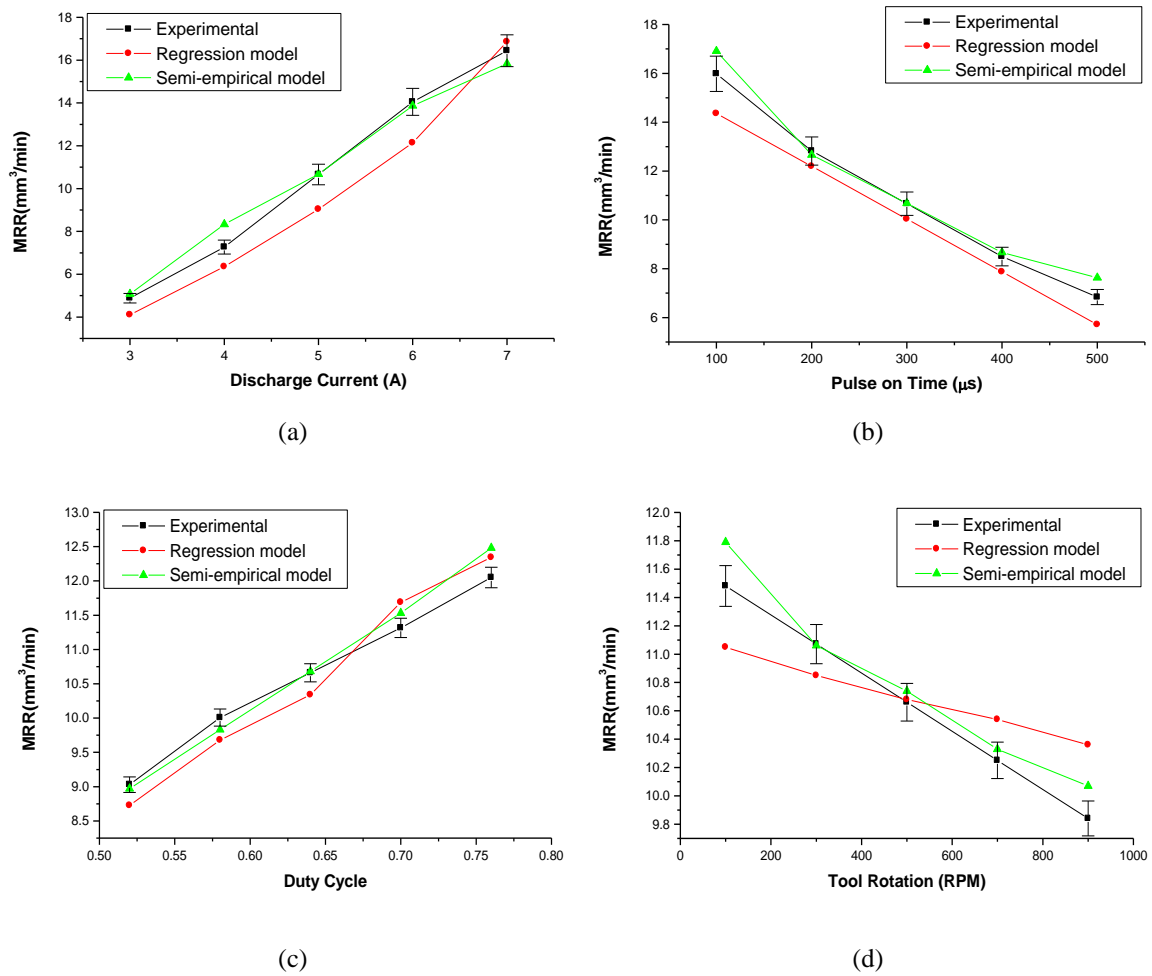
Figure 2. The comparative study of MRR between the experimental, regression and semi-empirical models
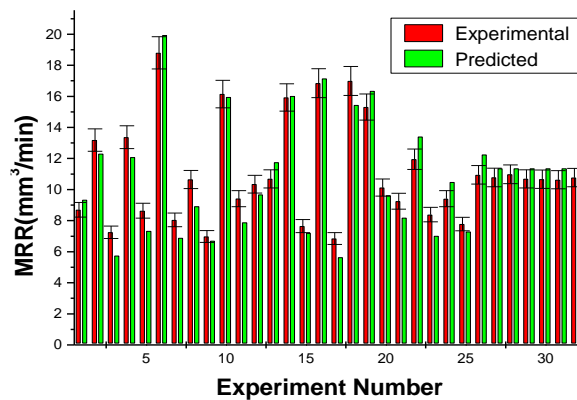for (a) current (b) pulse duration (c) duty cycle (d) tool rotation

Figure 3. A comparative studies of experimental data and MRR model estimates during the GAEDD process

Table 8. The error between the anticipated and the exploratory outcomes

Run order	Experimental (MRR)	Predicted (MRR)	Error
1	8.70	9.34	-0.64
2	13.19	12.31	0.88
3	7.25	5.75	1.5
4	13.37	12.08	1.29
5	8.64	7.33	1.31
6	18.80	19.95	-1.15
7	8.05	6.89	1.16
8	10.65	8.72	1.93
9	6.98	6.71	0.27
10	16.15	15.96	0.19
11	9.42	7.78	1.64
12	10.35	9.69	0.66
13	10.69	11.76	-1.07
14	15.93	16.02	-0.09
15	7.65	7.21	0.44
16	16.85	17.15	-0.3
17	6.85	5.64	1.21
18	16.99	15.45	1.54
19	15.31	16.35	-1.04
20	10.13	9.63	0.5
21	9.25	8.19	1.06
22	11.95	13.91	-1.96
23	8.39	6.91	1.48
24	9.41	10.68	-1.27
25	7.78	7.30	0.48
26	10.95	12.66	-1.71
27	10.78	11.36	-0.58
28	10.98	11.36	-0.38
29	10.69	11.36	-0.67
30	10.67	11.36	-0.69
31	10.63	11.36	-0.73
32	10.77	11.36	-0.59

4. Conclusions

EDD of high carbon-chromium steel was successfully performed in this work by a gas-assisted perforated electrode.

- ANOVA was carried out in order to learn the influence of different control factors on MRR. The far more influential parameter controlling the MRR, supplemented by pulse time and gas pressure, was observed to be the discharge current.
- A dimensional analysis based MRR model was developed based on the predominant machining parameters and thermo-physical attributes of the workpiece. The exploratory and expected outcomes of the MRR during the GAEDD method were ascertained to be as per the agreement. The relative deviation between the expected and exploratory outputs was less than 3%.
- Corroborative assessments have been carried out in order to reaffirm the established model.This appears to benefit from the finding that the develop model can measure MRR with great accuracy during the GAEDD process.
- A correlation has been formed between the regression and dimensional analysis based models to differentiate the most reliable between them. The dimensional analysis model was shown to anticipate process output most precisely when compared with the regression model.

- This study can be extended to the development of semi-empirical models for electrode wear rate, surface finish and surface crack length employing Buckingham's π-theorem. Empirical model can be employed using a RSM together with a multiple regression method.

References

Bhaumik, S., Maggirwar, R., Datta, S., & Pathak, S.D. (2018). Analyses of anti-wear and extreme pressure properties of castor oil with zinc oxide nano friction modifiers. *Applied Surface Science, 449*, 277-286.

Bobbili, R., Madhu, V., & Gogia, A.K. (2015). Modelling and analysis of material removal rate and surface roughness in wire-cut EDM of armour materials. *Engineering Science and Technology, an International Journal, 18*(4), 664-668.

Dave, H.K., Desai, K.P., & Raval, H.K. (2013). Development of semi empirical model for predicting material removal rate during orbital electro discharge machining of Inconel 718. *International Journal of Machining and Machinability of Materials, 13*(2-3), 215-230.

Ho, K.H., & Newman, S.T. (2003). State of the art electrical discharge machining (EDM). *International Journal of Machine Tools and Manufacture*, *43*(13), 1287-1300.

Kumar, A., Kumar, V., & Kumar, J. (2014). Semi-empirical model on MRR and overcut in WEDM process of pure titanium using multi-objective desirability approach. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 37*(2), 689-721.

Kumar, J., & Khamba, J.S. (2009). Modeling the material removal rate in ultrasonic machining of titanium using dimensional analysis. *The International Journal of Advanced Manufacturing Technology, 48*(1-4), 103-119.

Kumar, S., Singh, R., Batish, A., & Singh, T.P. (2015). Modeling the tool wear rate in powder mixed electro-discharge machining of titanium alloys using dimensional analysis of cryogenically treated electrodes and workpiece. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 231*(2), 271-282.

Patil, N.G., & Brahmankar, P.K. (2010). Determination of material removal rate in wire electro-discharge machining of metal matrix composites using dimensional analysis. *The International Journal of Advanced Manufacturing Technology, 51*(5-8), 599-610.

Phate, M.R., & Toney, S.B. (2019). Modeling and prediction of WEDM performance parameters for Al/SiCp MMC using dimensional analysis and artificial neural network. *Engineering Science and Technology, an International Journal, 22*(2), 468-476.

Singh, N.K., Pandey, P. M., & Singh, K.K. (2017). Experimental investigations into the performance of EDM using argon gas-assisted perforated electrodes. *Materials and Manufacturing Processes, 32*(9), 940-951.

Singh, N.K., Pandey, P.M., & Singh, K.K. (2016). EDM with an air-assisted multi-hole rotating tool. *Materials and Manufacturing Processes, 31*(14), 1872-1878.

Singh, N.K., Pandey, P.M., Singh, K.K., & Sharma, M.K. (2016). Steps towards green manufacturing through EDM process: a review. *Cogent Engineering*, *3*(1), 1272662.

Sonin, A.A. (2001). Dimensional analysis: Technical report, Massachusetts Institute of Technology.

Srivastava, V., & Pandey, P.M. (2013). Experimental investigation on electrical discharge machining process with ultrasonic-assisted cryogenically cooled electrode. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 227*(2), 301-314.

Tsai, K.M., & Wang, P.J. (2001). Semi-empirical model of surface finish on electrical discharge machining. *International Journal of Machine Tools and Manufacture, 41*(10), 1455-1477.

Yahya, A., & Manning, C.D. (2004). Determination of material removal rate of an electro-discharge machine using dimensional analysis. *Journal of Physics D: Applied Physics, 37*(10), 1467.

Yahya, A., Trias, A., Erawan, M.A., Nor Hisham, K., Khalil, K., & Rahim, M.A.A. (2012). Comparison studies of electrical discharge machining (EDM) process model for low gap current. *Advanced Materials Research, 433-440*, 650-654.