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Comparison of Experimental and Theoretical Results of Tool Wear Rate in Electrical Discharge Machining

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Abstract

Though electrical discharge machining (EDM) process is capable for complex and precise machining of materials irrespective of their hardness, it has certain limitations like low material removal rate (MRR), high tool wear rate (TWR), etc. which restrict its application areas. In EDM, material removal from workpiece and tool takes place by means of sparking between them which is a quite complex process. So, it is difficult to predict material removal rate and tool wear rate for various process parameters. In this paper, the experimental data available in existing literature are used to derive empirical formulas for heat distribution factor, crater radius and depth. The tool wear rate is calculated based on these formulas and validated with experimental results. For the selection of optimum process parameters, the proposed theoretical model can be used in EDM process.

Keywords: *EDM, TWR, experiment, empirical formula*

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INTRODUCTION

At the present time, electrical discharge machining (EDM) is the widespread technique used in industry for high-precision machining of electrically conductive materials irrespective of the hardness and it is widely used for the manufacture of mould, die, automotive, aerospace and surgical components [1]. In this process, material removal takes place as a result of the generation of extremely high temperatures due to the high-intensity discharges between tool and workpiece that melt and evaporate the material.

In EDM, the tool wear is a critical problem as the change in tool shape directly affects the final shape of the product. The contribution of the tool cost is more than 70% to the total operation cost in most of EDM operations. So, during planning and designing of EDM operations, the tool wear should be carefully taken into consideration [2]. The amount of electrode wear depends on various parameters like tool-workpiece material, dielectric fluid, flushing method, electrical parameters (pulse on time, pulse off time, frequency of spark) etc. [3]. Abdulkareem showed that electrode wear can be reduced up to 27% by cooling of electrode using liquid nitrogen [4]. Khan found that wear along the cross-section of the tool electrode is more compared to the same along its length due to easier heat transfer along the length [5].

Over last four decades, researchers are trying to develop different models for MRR and TWR using various techniques. Due to the uncertainty and complexity of EDM process in nature, so far, the material removal process in EDM machining is still not very clear, and hence, nobody has established a complete mathematical model to expose the laws governing tool wear in EDM machining. Marafona and Chousal developed a thermal-electrical model for sparks generated by electrical discharge based on the Joule heating effect [6]. Using electro-thermal concept, Yeo *et al*. developed the theoretical models for the anode and cathode in micro-EDM process [7].

Thermal analysis of workpiece was carried out by Saedodin *et al*. using hyperbolic heat conduction model [8]. Kalajahi *et al*.

investigated MRR using response surface methodology and analyzed EDM process using finite element method [9]. Liu *et al*. simulated tool wear in small hole EDM on titanium alloy [10]. In this paper, tool wear rate is calculated using different empirical and regression equations and then, the theoretical predictions are compared with the experimental results.

THEORETICAL MODEL OF TWR

Energy Distribution in Workpiece

During single discharge, the energy released can be estimated by Eq. (1):

$$E=VIT_{on} \tag{1}$$

Tool wear rate depends on energy transmitted to tool during machining. When the discharge takes place between two electrodes, a large amount of energy is released, but only a fraction of this energy is absorbed by tool. So, exact amount of energy transmitted to tool is required to calculate the tool wear rate. Various researchers have proposed value of energy distribution factor for their models in literature.

Dibitonto *et al*. and Patel *et al*. assumed fraction of energy transferred to workpiece as 18% and tool as 8% [11, 12]. Okada *et al*. showed that the energy distribution ratios into tool and workpiece are from 24 to 29% and 10 to 13% respectively under any discharge duration [13].

Yeo *et al*. compared five different electro-thermal models of EDM and found that four models overestimated the material removal rate due to consideration of improper energy distribution factor while DiBitonto's model predicted accurate erosion rate [14].

Joshi and Pande showed that it is essential to apply higher energy distribution factor for higher energy zones [15]. Singh and Shukla demonstrated that the amount of energy absorbed by the workpiece during the EDM process depends on the process parameters [16].

Experiments conducted by Singh concluded that the energy transferred to the workpiece varies with the discharge current and pulse duration from 6.1 to 26.82% [17]. The literature shows lack of information for exact amount of energy transferred to tool or workpiece at any set of process parameters.

In this present work, the experimental results obtained by Singh are used to model the correlation between fraction of energy transferred to workpiece (F_c), discharge current (I) and pulse duration (T_{on}) [17]. Considering the difference of machining conditions, and work-tool materials combination, especially the thermal conductivity of copper (K=401 W/mK) is higher than Tungsten-Carbide (K=84.02 W/mK) [17], the proportionality coefficient Kp which equal to 3.134 is assumed [18].

The power regression model is represented in Eq. (2):

$$F_c=0.0582\times I^{4.3243}T_{on}^{-2.7167} \tag{2}$$

Where, the unit of F_c is %.

TWR Calculation

To find out tool wear rate (TWR), it is necessary to calculate the cavity volume for each discharge. The volume of material removed by a single discharge varies linearly with applied energy while the diameters of the craters are proportional to the cube-root of applied energy [19]. The applied energy is:

$$E_a=F_c\times E \tag{3}$$

The regression equation for crater radius from experimental data is:

$$R_c=2.67E_a^{0.333} \tag{4}$$

To find out depth of crater, a relation between crater depth and radius using power regression is derived from experimental results obtained by Mathew *et al*. and it is given by [20]:

$$h=0.753R_c^{1.052} \tag{5}$$

Dibitonto *et al*. and Yeo *et al*. predicted hemispherical shaped crater cavity in their work [11, 14]. Joshi and Pande predicted shallow bowl shaped crater cavity [15]. A hemispherical-cap shaped crater profile was estimated by Tan and Yeo in their analysis [21], while Sahu and Sahu also assumed the same shaped crater morphology [22]. In this work, hemispherical cap shaped crater geometry is assumed and its volume is given by Eq. (6):

$$V_c = \frac{1}{6}\pi h(3{R_c}^2 + h^2) \qquad (6)$$

Tool wear rate (TWR) can be found out in mm^3/min using equation:

$$TWR = \frac{V_c \times 60 \times 10^{-3}}{T_{on} + T_{off}} \qquad (7)$$

MODEL VALIDATION

In this study, the experimental results of a published literature are used to check the validity of the developed model [12]. Table 1 shows experimental parameters, TWR from experiments and predicted TWR by Patel *et al.*, in which steel workpiece and copper tool are used [12]. The predicted TWR using theoretical model is shown in Table 2. Figure 1 shows the comparison of TWR predicted by theoretical model, Patel's model and the experimental data. It is seen that the values of TWR predicted by theoretical model are closer to the experimental results compared to those by Patel's model. Thus, it could be concluded that our theoretical model would give better prediction of TWR.

Table 1: *Experiment and Patel's Model Result for TWR [12].*

Exp. No.	V (V)	I (A)	Ton (μs)	Toff (μs)	Experiment TWR (mm^3/min)	Patel's Model TWR (mm^3/min)
E1	25	68	560	10	4.47	4.78
E2	25	58	420	7.5	4.84	6.70
E3	25	44	240	5.6	3.69	6.01
E4	25	36	180	4.2	6.78	8.54
E5	25	25	100	4.2	3.37	5.38
E6	25	20	56	3.2	3.59	5.69
E7	25	12.8	42	3.2	0.76	1.84
E8	25	10	32	2.4	0.62	1.07
E9	25	8.5	24	2.4	0.30	0.94
E10	25	5.3	18	2.4	0.07	0.16
E11	25	3.67	13	2.4	0.03	0.11
E12	25	2.85	7.5	1.3	0.02	0.07
E13	25	2.34	5.6	1	0.01	0.06

Table 2: *TWR Using Theoretical Model.*

Exp. No.	F_c (%)	E_a (μJ)	R_c (μm)	h (μm)	V_c (μm^3)	TWR (mm^3/min)
E1	0.17	1591.75	31.10	28.00	53993.79	5.68
E2	0.18	1118.28	27.65	24.74	37617.79	5.28
E3	0.25	671.41	23.33	20.69	22315.80	5.45
E4	0.23	377.97	19.27	16.92	12394.51	4.04
E5	0.24	148.77	14.12	12.21	4773.63	2.75
E6	0.44	122.69	13.25	11.41	3919.36	3.97
E7	0.14	18.68	7.08	5.90	571.40	0.76
E8	0.10	8.00	5.34	4.38	240.15	0.42
E9	0.11	5.52	4.72	3.85	164.26	0.37
E10	0.03	0.73	2.41	1.90	20.80	0.06
E11	0.02	0.18	1.51	1.16	4.98	0.02
E12	0.02	0.12	1.32	1.01	3.30	0.02
E13	0.02	0.07	1.10	0.83	1.89	0.02

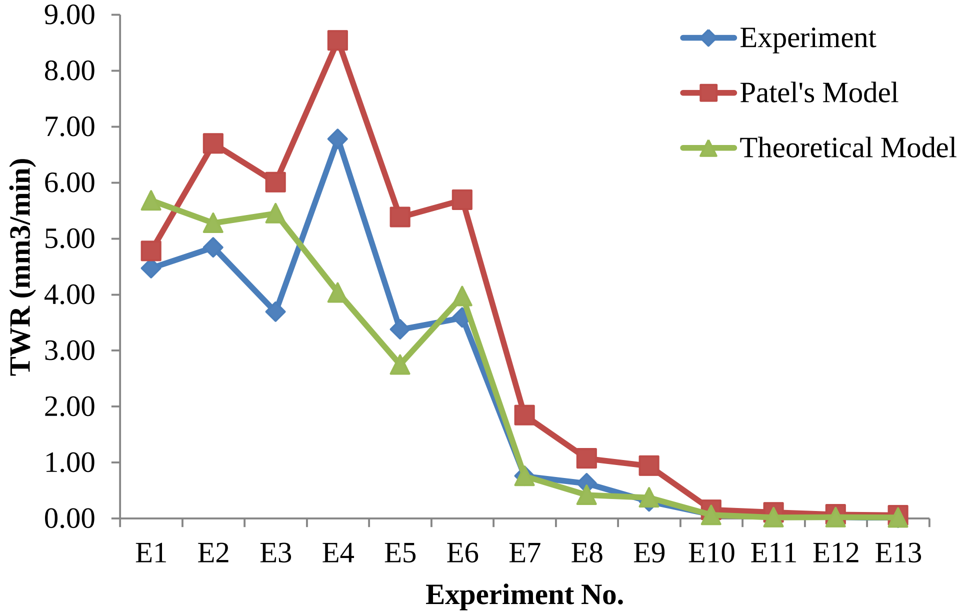

Fig. 1: *Comparison of the Experiment, Patel's Model and Theoretical Model for TWR.*

CONCLUSION

In this study, a theoretical model is developed to calculate the tool wear rate (TWR) in EDM process. The TWR values obtained from the developed model are compared with the experimental results taken from the literature. The developed model is in good agreement with the experimental results reported in the literature compared to Patel's model and capable of providing good estimation of tool wear rate in EDM [12]. Using this model, the TWR can be predicted for different machining conditions without performing the experiments.

NOMENCLATURE

E= Discharge energy (µJ)
V= Discharge voltage (V)
I= Discharge current (A)
T_{on}= Pulse on time (µs)
K= Thermal Conductivity (W/mK)
F_c=Fraction of energy transferred to tool (%)
E_a= Applied energy (µJ)
R_c= Crater radius (µm)
h= Depth of crater (µm)
V_c= Crater volume (µm^3)
T_{off}= Pulse off time (µs)

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