A simulation-based approach for modelling of fraction of energy transfer to workpiece in electrical discharge machining

C.R. Sanghani*

School of Engineering,
R.K. University,
Rajkot-360020, Gujarat, India
Email: scr1385@yahoo.com
*Corresponding author

G.D. Acharya

Institute of Technology and Science,
Atmiya University,
Rajkot-360005, Gujarat, India

K.D. Kothari

Mechanical Engineering Department,
School of Engineering,
R.K. University,
Rajkot – 360020, Gujarat, India

Abstract: For any process, modelling is the best way to investigate the effect of various parameters on its performance measures. The numerical modelling has been the subject of interest for researchers for a long time as compared to other techniques and hence more work has been recorded in the field of EDM using this technique. In numerical analysis, a fraction of energy transfer is a critical parameter and it depends on the workpiece-tool combination. Researchers have assumed constant value or given range for this parameter but no exact value has been reported in any literature. This paper presents a novel approach to estimate the fraction of energy transfer to the workpiece during the EDM process using a combination of experimental results and finite element analysis (FEA). To validate the model, confirmation experiments were carried out which showed good agreement between simulation and experimental results.

[Submitted 17 November 2018; Accepted 27 January 2019]

Keywords: electrical discharge machining; fraction of energy transfer; modelling; finite element analysis; FEA; material removal rate; MRR.

Reference to this paper should be made as follows: Sanghani, C.R., Acharya, G.D. and Kothari, K.D. (2020) 'A simulation-based approach for modelling of fraction of energy transfer to workpiece in electrical discharge machining', *Int. J. Manufacturing Research*, Vol. 15, No. 3, pp.285–296.

Biographical notes: C.R. Sanghani is a PhD scholar at School of Engineering, R.K. University, Rajkot and working as a Lecturer in Mechanical Engineering Department at S.T.B.S. College of Diploma Engineering, Surat. He has more than eight years of academic experience. He has published several research papers in various journals and presented three research papers in international conferences.

G.D. Acharya is working as a Principal at Atmiya Institute of Technology and Science, Rajkot. His specialisation and interest are in the field of manufacturing and design, production, fabrication technology, advanced machining process, and statistical analysis. He has vast industrial as well as academic experience in this field. He has also published several research papers in this field.

K.D. Kothari is working as an Associate Professor and Head, Mechanical Engineering Department at RK University, Rajkot. His specialisation and interest are in the field of advanced machining processes, production, integrated manufacturing system, and product data management.

1 Introduction

In electrical discharge machining process, material removal takes place by thermal erosion between workpiece and tool. During electric discharge, each pulse generates thermal energy. The total energy generated during discharging gets distributed into the workpiece, tool, dielectric and some portion of the total energy gets lost in form of radiation, light, and sound. The material removal rate (MRR) and tool wear rate (TWR) depends on the fraction of energy transfer to workpiece and tool respectively. During their investigations, several researchers have found or assumed the different value of the fraction of energy transfer to cathode and anode in the thermal analysis of EDM. In cathode erosion modelling of EDM, Dibitonto et al. (1989) used point heat source and assumed a constant fraction of energy transfer to the cathode as 0.183. Patel et al. (1989) developed the anode model with the assumption of 8% of the total energy transfer to the anode. Shao and Rajurkar (2013) found the average energy distribution to the anode and cathode as 9.4% and 3.6% respectively during experimentation with discharge energy from 0.09 μJ to 1.02 μJ. A comparison made by Yeo et al. (2008) for five different electro-thermal models of EDM showed that an assumption of an improper fraction of energy transfer overestimates the MRR. Joshi and Pande (2010) suggested applying a higher fraction of energy transfer for higher energy input in thermal modelling of EDM. For any discharge durations, Okada et al. (2000) suggested the energy distribution into tool and workpiece from 24 to 29% and 10 to 13% respectively. Experimental analysis conducted by Singh (2012) showed that the energy transferred to the workpiece varies with the discharge current and pulse duration from 6.1% to 26.82%. Yeo et al. (2007) proposed a fraction of energy transfer to the anode and cathode as 14% and 39% respectively during micro-EDM of AISI 4140 alloy steel with pure tungsten as the electrode. In their study, Shabgard et al. (2013) demonstrated that the fraction of energy transferred to the electrodes is not constant but a function of input process parameters. In their process parameter setting, the fraction changed from 4.13% to 8.9%, and 4.13% to 36.4% for the cathode and anode respectively. Salonitis et al. (2009) reported that the fraction of energy entering the workpiece or tool and the actual material removal energy depends on various parameters like melting point, specific heat, thermal conductivity, flushing pressure, discharge current, pulse on time, etc. So, prediction of a generally accepted fraction of energy for thermo-physical models is difficult. This paper proposed a new method of determining the fraction of energy transferred to the workpiece during EDM of AISI D2 tool steel with the copper electrode by varying the machining parameters.

2 Experimentation

The workpiece and tool materials used in the present study are AISI D2 tool steel and electrolytic copper, respectively. The thermal-physical properties of such materials are given in Table 1. The experiments have been performed on a die sinking EDM machine (TOOLCRAFT G30 (i)). During the EDM experiments, the workpiece and the tool were submerged in commercial grade EDM oil (Spark Spo-A) which acted as the dielectric fluid. Each machining test was carried out for 15 min. The machining settings and the other test conditions are summarised in Table 2. To calculate MRR, the diameter and depth of tool impressions on work surface are measured by portable articulated arm coordinate measuring machine (6-axes space 2.5 plus arm) having a measuring range of 2,500 mm and point repeatability 0.016 mm.

Table 1 Thermal-physical properties of work material

Property	*Values*			
Density (kg/m^3)	7,700			
Young's modulus (GN/m^2)	208			
Poisson's ratio	0.3			
Melting temperature (K)	1,984			
Boiling temperature (K)	2,773			
Latent heat of melting (kJ/kg)	307			
Latent heat of vaporisation (kJ/kg)	2,746			
Temperature (K)	298	673	1,100	1,990
Thermal conductivity (W/m °C)	29	29.5	30.7	32.3
Thermal expansion coefficient (/°C)	5.71×10^{-6}	6.9×10^{-6}	10.2×10^{-6}	12×10^{-6}
Specific heat (J/kg K)	412.21	418.36	421.83	431

Table 2 Experimental test conditions

Workpiece material	AISI D2 Tool steel
Tool material	Electrolytic Copper
Dielectric fluid	Commercial grade EDM oil
Polarity	Negative
Discharge voltage (V)	18
Flushing pressure (kgf/cm^2)	0.4
Discharge current (A)	6, 9, 15
Pulse on time (μs)	100, 200, 500
Pulse off time (μs)	20, 50, 100

3 A thermal model of the EDM process

During the EDM process, sparks occur between the workpiece and tool at the minimum gap and it is considered that all the sparks are same. Hence, the analysis for a single spark is carried out and results are extended for multi-spark operation. In the present analysis, small cylindrical portions of the workpiece and tool around the spark are selected for analysis.

3.1 Assumptions

As the EDM process is highly complex and uncertain in nature; the following assumptions are made to solve the proposed model mathematically:

- a single spark model is considered (Ming et al., 2014)
- the material of the workpiece is homogeneous and temperature-based thermophysical properties are used
- thermal analysis is considered to be of a transient type
- plasma channel is considered as a uniform cylindrical column and the spark radius is considered to be a function of discharge current and pulse on time (Ikai and Hashiguchi, 1995)
- the heat source is assumed to have a Gaussian distribution of heat flux on the surface of the workpiece (Patel et al., 1989)
- the mode of heat transfer to the workpiece is by conduction
- heat loss due to radiation is neglected
- the material flushing efficiency is assumed to be 100% (Joshi and Pande, 2010).

3.2 Governing equation and boundary conditions

In the EDM process, heat generated by plasma increases the temperature of workpiece higher than its melting point and hence conduction is considered as the primary mode of heat transfer. For the transient thermal analysis of EDM process, Fourier heat conduction equation with necessary boundary conditions is taken as the governing equation.

$$\frac{1}{r\partial r}\left(Kr\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right)=\rho C_p\frac{\partial T}{\partial t} \tag{1}$$

where T is the temperature (K), t is the time (s), ρ is the density (kg/m^3), K is the thermal conductivity (W/m-K), C_p is the specific heat capacity of workpiece material in solid state (J/kg-K), as well as r and z, is the radial and axial coordinates.

The governing partial differential equations for initial and boundary conditions are

Initial Condition: $T = T_o, \quad t = 0$

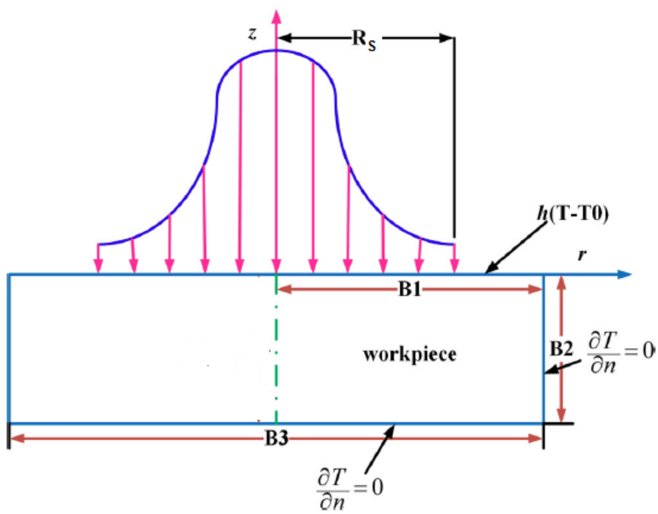
Boundary Condition: $K\dfrac{\partial T}{\partial z} = Q(r), \quad 0 \le r \le R_S \quad (\text{For } B_1)$

$K\,\partial T/\partial z = h_f\,(T - T_o), \quad r > R_S \quad (\text{For } B_1)$

$\dfrac{\partial T}{\partial n} = 0, \quad (\text{For } B_2 \text{ and } B_3)$

In the present analysis, the workpiece domain is considered as a rectangle and symmetric about Z-axis. Figure 1 shows the schematic diagram of a thermal model of the workpiece with the applied boundary conditions.

Figure 1 A thermal model of the workpiece in the EDM process (see online version for colours)



Source: Ming et al. (2014)

3.3 Heat input to the workpiece

For accurate prediction of MRR in the EDM model, some factors like the thermo-physical properties of the material, the amount of heat input and radius of plasma channel are important. When plasma channel incidents on the workpiece surface, it causes the temperature rise in the workpiece. Due to over-simplicity of point and uniform disk heat source, prediction of MRR could not be accurate (Joshi and Pande, 2010). In actual practice, maximum heat intensity is found at the centre of the spark and decreases in the radial direction. It means workpiece is subjected to the Gaussian distribution type heat load. Hence, the Gaussian distribution of heat flux is used in the present work. If it is assumed that total power of each pulse is to be used, heat flux at the radius of r for single spark can be written as follows (Patel et al., 1989):

$$Q(r) = \frac{4.45 F_W V I}{\pi R_s^2} \exp\left\{-4.5\left(\frac{r}{R_S}\right)^2\right\} \tag{2}$$

where F_W is the fraction of heat input to the workpiece, V is the voltage between anode and cathode during discharge occur, I is the Discharge current, R_s is the spark radius and r is the distance from the centre of arc plasma.

The fraction of energy transfer is also an important factor in the thermal analysis of EDM as it governs the amount of energy going to the workpiece. Different values of this factor were considered by researchers in literature as discussed in the introduction section. The literature shows a lack of information for the exact amount of energy transfer to the workpiece at any set of process parameters. To derive the correlation between the fraction of energy transfer and input parameters, simulations are carried out.

3.4 Spark radius

Spark radius plays an important role in the thermal modelling of the EDM process. It is very difficult to measure spark radius experimentally due to the occurrence of a spark in a very short period of time. Ikai and Hashiguchi (1995) proposed a semi-empirical equation of spark radius (μm) which is a function of discharge current and pulse on time. In this work, that equation is used due to more accurate results as compared with the other approaches.

$$R_S = 2.04 \times I^{0.43} \times T_{ON}^{0.44} \tag{3}$$

where I is discharge current (A) and T_{ON} is pulse on time (μs).

3.5 Latent heat of melting and evaporation

Due to repeatedly heating and cooling of workpiece surface in EDM, phase change of material takes place which consumes a significant amount of heat generated from plasma during melting of material equivalent to the latent heat (Shankar et al., 1997). Hence, to increase the simulation accuracy, it is required to include the latent heat of fusion and vaporisation. In the present work, to make the model more realistic, the latent heat of fusion and vaporisation are incorporated by modifying the specific heat of workpiece material as below (Varghese at al., 2014).

$$C_{p_{eff}} = C_p + \frac{L_m}{\Delta T_m} + \frac{L_v}{\Delta T_v} \tag{4}$$

where C_P is the specific heat, L_m is the latent heat of melting, L_v is the latent heat of vaporisation, ΔT_m is the temperature difference between melting temperature and room temperature, ΔT_v is the temperature difference between vaporisation temperature and melting temperature.

3.6 Solution methodology

For prediction of temperature distribution in the workpiece, transient thermal analyses were carried out using FEA software ANSYS 14.5 with respect to different parameter settings. The size of the rectangular domain for the analyses was dependent on the input parameters as the spark radius varied with the machining settings. The domain was discretised using four-noded, axi-symmetric, thermal solid element (PLANE 55). The temperature dependent material properties as shown in Table 1 were employed. The transient thermal analyses were carried by applying the heat flux at the spark location, heat transfer coefficient beyond spark radius and using the pulse on time as the time step for the analysis. Figure 2 shows the temperature contour plot for the machining conditions: discharge current 9 A, discharge voltage 18 V and pulse on time of 500 µs. The elements showing temperature more than the melting point of workpiece material were selected and eliminated from the meshed domain. A crater cavity generated by this analysis is shown in Figure 3.

Figure 2 Temperature contour plot (see online version for colours)

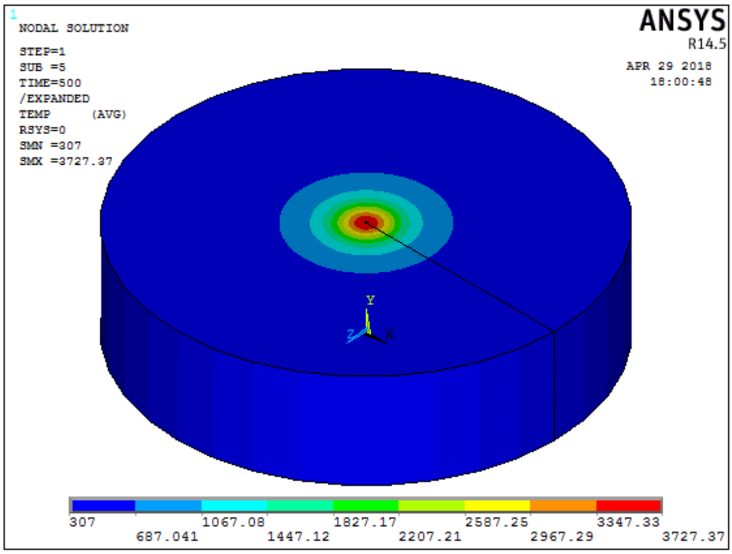
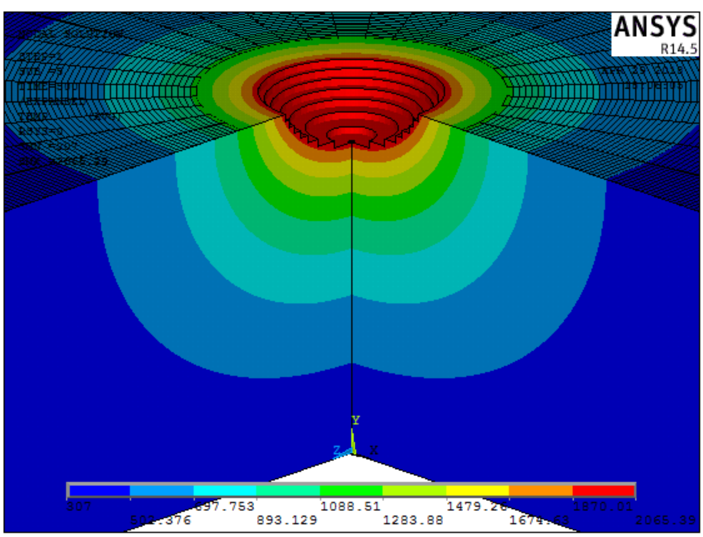


Figure 3 Crater cavity formation (see online version for colours)



To calculate MRR, it is necessary to find out the cavity volume at the end of discharge. The crater geometry is assumed to be the circular parabolic shape. The equation for the parabolic geometry of crater is described by the following:

$$V_C = \frac{1}{2}\pi R_c^2 H \tag{5}$$

where R_c is the radius of the crater and H is the depth of the crater.

A number of pulses (*NOP*) occurring during the unit time are to be known for the estimation of MRR. The number of pulses can be determined from machining time:

$$NOP = \frac{t_{mach}}{T_{ON} + T_{OFF}} \tag{6}$$

where t_{mach} is machining time, T_{ON} is a pulse on time and T_{OFF} is pulse off time.

By knowing V_c and *NOP*, one can compute *MRR* (mm^3/min) by

$$MRR = \frac{V_c \times NOP}{t_{mach}} \tag{7}$$

3.7 Regression modelling

In a novel approach for the calculation of the fraction of energy transfer to the workpiece (F_w), a combined effect of energy dispersion into the workpiece and the volume of molten metal flushed from the workpiece at the end of discharge have been considered. The value of the energy distribution to the workpiece was calculated based on the results of finite element analysis (FEA) and the experiments at different parameter settings. At this stage, the trial and error method, by iterating the calculated results of FEA to agree with the experimental data with a known degree of reliability, were adapted to achieve the values of F_w at different parameter settings. The fraction of energy transfer to workpiece obtained at different parameter settings is shown in Table 3.

Table 3 Fraction of energy transfer to workpiece

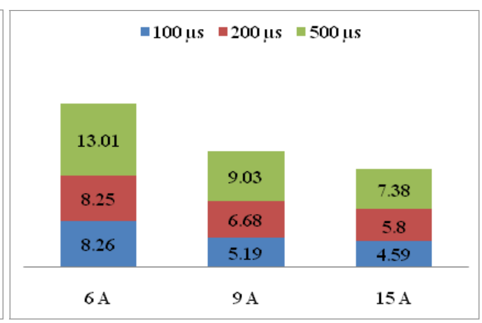
Ex. no.	*I (A)*	T_{ON} *(μs)*	T_{OFF} *(μs)*	*MRR (mm³/min)*	*Spark radius,* R_s *(μm)*	*Fraction of energy,* F_W *(%)*
1	9	500	100	10.12	80.82	9.52
2	15	100	100	23.97	49.58	5.03
3	6	500	100	4.17	67.89	10.55
4	9	500	50	10.80	80.82	9.03
5	6	500	20	4.94	67.89	12.53
6	6	200	20	5.92	45.36	7.87
7	9	200	50	11.55	54.00	6.68
8	9	100	20	13.94	39.81	5.99
9	6	100	100	4.77	33.44	7.24
10	15	100	20	34.23	49.58	4.72
11	9	200	20	12.21	54.00	7.22
12	15	500	50	23.31	100.67	7.38

Table 3 Fraction of energy transfer to workpiece (continued)

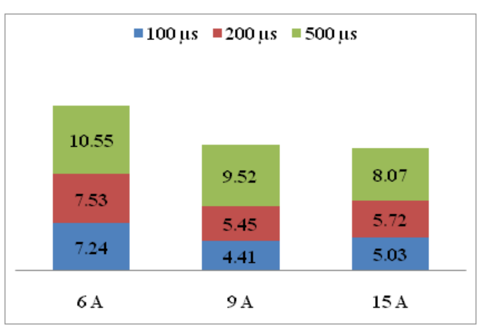
Ex. no.	*I (A)*	T_{ON} *(μs)*	T_{OFF} *(μs)*	*MRR* (mm^3*/min)*	*Spark radius,* R_s *(μm)*	*Fraction of energy,* F_W *(%)*
13	6	100	50	5.31	33.44	8.26
14	6	100	20	6.56	33.44	8.17
15	15	200	50	27.02	67.27	5.80
16	9	100	50	12.38	39.81	5.19
17	6	200	100	4.52	45.36	7.53
18	15	100	50	26.88	49.58	4.59
19	9	500	20	10.91	80.82	9.58
20	6	200	50	6.14	45.36	8.25
21	15	500	100	24.79	100.67	8.07
22	6	500	50	4.53	67.89	13.01
23	9	100	100	9.28	39.81	4.41
24	15	200	20	29.96	67.27	5.60
25	15	200	100	26.16	67.27	5.72
26	9	200	100	10.65	54.00	5.45
27	15	500	20	24.78	100.67	7.59

Figure 4 Fraction of energy transfer to workpiece (%), (a) T_{OFF} = 20 μs (b) T_{OFF} = 50 μs (c) T_{OFF} = 100 μs (see online version for colours)

(a)



(b)



(c)

Based on these results, a power regression equation for F_w is developed using statistical software MINITAB 16 in order to establish the relationship between the energy transfer to workpiece and the discharge current as well as pulse on-time, accounting for the fact that the amount of energy transfer to the workpiece differs with process parameters of EDM. The following equation represents the procedure of calculating the F_w

$$F_W = 3.6599 \times I^{-0.4830} \times T_{ON}^{0.3253} \tag{8}$$

where I is discharge current (A) and T_{ON} is pulse on time (μs).

The equation developed in this study can be further used in the existing thermo-physical models, to predict the results more accurately. It will also be helpful for investigating the effect of process parameters on MRR and deriving the optimum parameters by FEA. The percentage of energy transfer to the workpiece is shown in graphical form in Figure 4.

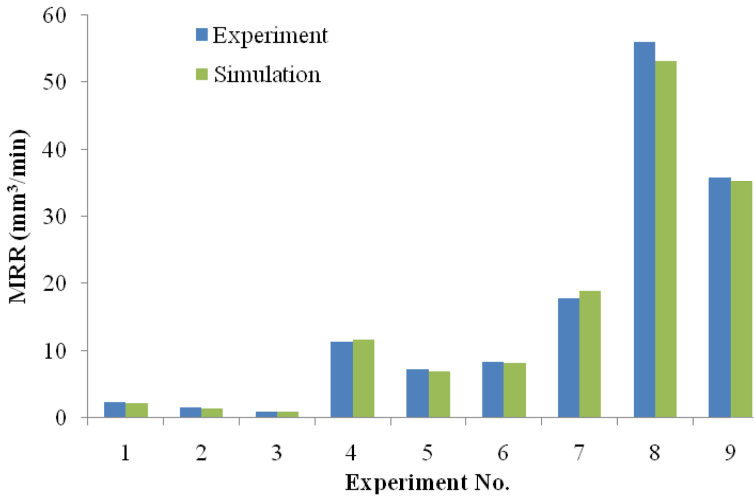
4 Validation of the model

The confirmation experiments were carried out to validate the regression equation for fraction of energy transfer to the workpiece, derived from simulation results. These experiments were designed based on Taguchi's L9 orthogonal array using different values of input parameters. The simulations were carried out for confirmation experiments by using values of a fraction of energy transfer obtained from the developed regression equation. The experimental and simulation results for MRR are shown in Table 4 while Figure 5 shows a bar chart for the comparison of experimental and simulation results for MRR. It shows that there is no significant difference between experimental and simulation results.

Table 4 Results of MRR for confirmation experiments

Exp. no.	*I (A)*	*T_{ON} (μs)*	*T_{OFF} (μs)*	*MRR (mm^3/min)*		*Prediction error (%)*
				Experiment	*Simulation*	
1	3	50	10	2.36	2.22	5.93
2	3	200	50	1.53	1.41	7.84
3	3	1,000	200	1.02	0.94	7.84
4	9	50	50	11.35	11.72	3.25
5	9	200	200	7.31	6.95	4.92
6	9	1,000	10	8.33	8.14	2.28
7	21	50	200	17.84	19	6.5
8	21	200	10	55.99	53.14	5.09
9	21	1,000	50	35.89	35.26	1.75

Figure 5 Comparison of experimental and simulation results for MRR (see online version for colours)



5 Conclusions

The main objective of present work is to develop an equation for fraction of energy transfer to the workpiece (F_W) during machining of AISI D2 tool steel with the copper electrode. Hence, a novel method based on the crater profile has been presented by carrying out simulations in ANSYS APDL 14.5. By comparing simulation and experimental results, the exact value of the fraction of energy transfer responsible for MRR were obtained for different set of process parameters. This study shows that the value of F_W varies from 4.41% to 20.37% for the different combination of process parameters. From those results, a regression equation of a fraction of energy transfer to workpiece is developed. The confirmation experiments based on Taguchi's L9 orthogonal array were conducted to validate the regression equation for fraction of energy transfer to the workpiece. When the simulation results were compared with confirmation experiment results, it was found that the average error between experimental and simulation results is 5.04%. The researchers can use the equation of a fraction of energy transfer to the workpiece in process modelling of EDM to investigate the effect of process parameters on MRR as well as to find out optimal process parameters without experimentation.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

DiBitonto, D.D., Eubank, P.T., Patel, M.R. and Barrufet, M.A. (1989) 'Theoretical models of the electrical discharge machining process-I: a simple cathode erosion model', *Journal of Applied Physics*, Vol. 66, No. 9, pp.4095–4103.

Ikai, T. and Hashiguchi, K. (1995) 'Heat input for crater formation in EDM', *Proceedings of International Symposium for Electro-Machining-ISEM XI*, Lausanne, Switzerland, 17–21 April, pp.163–170.

Joshi, S.N. and Pande S.S. (2010) 'Thermo-physical modeling of die-sinking EDM process', *Journal of Manufacturing Processes*, Vol. 12, No. 1, pp.45–56.

Ming, W., Zhang, G., Li, H., Guo, J., Zhang, Z., Huang, Y. and Chen, Z. (2014) 'A hybrid process model for EDM based on finite-element method and Gaussian process regression', *International Journal of Advanced Manufacturing Technology*, Vol. 74, Nos. 9–12, pp.1197–1211.

Okada, A., Uno, Y. and Okajima, I. (2000) 'Energy distribution in electrical discharge machining with graphite electrode', *Memoirs of the Faculty of Engineering*, Vol. 34, Nos. 1–2, pp.19–26, Okayama University.

Patel, M.R., Barrufet, M.A., Eubank, P.T. and DiBitonto, D.D. (1989) 'Theoretical models of the electrical discharge machining process-II: the anode erosion model', *Journal of Applied Physics*, Vol. 66, No. 9, pp.4104–4111.

Salonitis, K., Stournaras, A., Stavropoulos, P. and Chryssolouris, G. (2009) 'Thermal modelling of the material removal rate and surface roughness for die-sinking EDM', *International Journal of Advanced Manufacturing Technology*, Vol. 40, Nos. 3–4, pp.316–323.

Shabgard, M., Ahmadi, R., Seyedzavvar, M. and Oliaei, S.N.B. (2013) 'Mathematical and numerical modeling of the effect of input-parameters on the flushing efficiency of plasma channel in EDM process', *International Journal of Machine Tools & Manufacture*, Vol. 65, pp.79–87.

Shankar, P., Jain, V.K. and Sundarajan, T. (1997) 'Analysis of spark profiles during EDM process', *Machining Science & Technology*, Vol. 1, No. 2, pp.195–217.

Shao, B. and Rajurkar, K.P. (2013) 'Micro-EDM pulse energy distribution ratio determination', *Proceedings of the 8th International Conference on Micro Manufacturing*, University of Victoria, Victoria, BC, Canada, 25–28 March.

Singh, H. (2012) 'Experimental study of distribution of energy during EDM process for utilization in thermal models', *International Journal of Heat and Mass Transfer*, Vol. 55, No. 19, pp.5053–5064.

Varghese, A., Kuriachen, B., Panda, S. and Mathew, J. (2014) 'Experiments and simulation of three-dimensional micro EDM with single and multiple discharges', *5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014)*, IIT Guwahati, Assam, India, 12–14 December.

Yeo, S.H., Kurnia, W. and Tan, P.C. (2007) 'Electro-thermal modelling of anode and cathode in micro-EDM', *Journal of Physics D: Applied Physics*, Vol. 40, No. 8, pp.2513–2521.

Yeo, S.H., Kurnia, W. and Tan, P.C. (2008) 'Critical assessment and numerical comparison of electro-thermal models in EDM', *Journal of Materials Processing Technology*, Vol. 203, Nos. 1–3, pp.241–251.