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Thermal-structural Analysis of Electrical Discharge Machining Process

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Abstract

In the present work, a thermal-structural model is presented to analyze the process parameters and their effect on three important responses such as material removal rate, tool wear rate and residual stresses on work piece in electrical discharge machining (EDM) process. The numerical model is validated conducting experiments on a die-sinking EDM machine. The numerical method provides an inexpensive and time saving alternative to study the performance of machining before actual cutting operation. A Box-Behnkin design of response surface methodology is adopted to collect data for analysis. Regression analysis is conducted to develop equations relating responses with process parameters. Finally, non-dominated sorting genetic algorithm is used to obtain pareto optimal solution for multi objective optimization.

Keywords: Numrical Analysis; Electrical Discharge Machining; Response Suface Methodology; Non-dominated Sorted Genetic Algorithm

1. Introduction

Electrical discharge machining (EDM) process is one of most popular amongst the non-traditional material removal techniques with applications in a broad variety of industries such as die and mould making, aerospace, automotive, medical and other industrial applications. The machining process involves controlled erosion of electrically conductive materials by the initiation of repetitive electrical spark discharge between the tool and the work piece separated by dielectric fluid. A spark gap is maintained in between the tool and the work piece to cause the spark discharge. The high temperature gradient generated by the spark causes evaporation and melting of the material from both work piece and tool material.

The complex nature of the process involving behavior of the EDM spark makes it even tougher to analyze the process experimentally and quantify the process responses. In the present scenario, researchers are concentrating their attention on the EDM process model for the better performance of the process parameters. Joshi and Pande [1] have proposed a numeral model for EDM for accurate prediction of process responses using Finite element method. The process responses were tested, trained and tuned for improved efficiency and finishing capabilities using neural network based techniques [2]. Yadav et al. [3] in their numerical modeling have found that compressive and tensile stresses develop around the spark location where the thermal stress is exceeding the maximum stress of the work piece. Singh and Ghosh [4] have concluded that electrostatic forces are major factor for material removal for short pulses and long pulses are dominant factor for melting of material. Das et al. [5] have suggested an EDM simulation model using finite element analysis for prediction of distortion, microstructure and residual stresses. The process parameters such as voltage, current, pulse-on-time are used to calculate the transient temperature distribution, liquid- and solid-state material transformation, and residual stresses that are induced in the work piece by virtue of a single-pulse discharge. The proposed model has been authenticated using experimental data. Schulze et al. [6] have measured and simulated crater morphology of EDM using ANSYS and the model is compared for single discharge and a sequence of discharges. The thermal channel based parameters are calculated

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measuring the current and voltage curves. In 2010, Joshi and Pande [2] established a two-dimensional axisymmetric model using ANSYS to study the effect of process parameter such as discharge current, discharge duration, discharge voltage and duty cycle on the process performance. Experimental investigations were conducted to study the MRR and crater shapes created during actual machining. When compared with the reported numerical models, ANSYS model was found to predict results closer to the experimental results. Chen and Allen [7] have proposed a thermo-numerical model which simulates a single spark discharge for the process. The numerical model was compared with experimental single spark crater sizes by using scanning electron microscopy (SEM) and optical evaluation method. The model was found to determine the result closer to the experimental set up. They have also presented residual stress distribution on the molybdenum work piece with a tungsten tool. In most of the literature, the above numerical models have been validated experimentally or optimized with one or two responses. In this paper, a multi objective optimization technique is proposed to optimize the performance of three responses in the EDM process simultaneously by identifying important process parameters. The data used for the proposed approach is generated using a numerical approach and solved by ANSYS.

2. Numerical modeling of the EDM process

2.1 Thermal analysis of the EDM process

Assumptions

- The combination of tool and work piece is homogeneous and isotropic in nature.
- The material properties of the tool and work piece are temperature dependent.
- The mode of heat transfer is purely by conduction. Other heat loses are neglected.
- The spark radius is assumed to be a function of discharge current and time.
- The analysis is done for a single spark.
- There is no accumulation of recast layers on the machined surfaces. Flushing abundance is considered to be 100%.
- The ambient temp is room temperature i.e. 298K.

2.2. Governing equation

For thermal analysis of the EDM process, Fourier heat conduction equation is considered as governing equation. ANSYS solves the differential equation for the heat transfer of the two dimensional axisymmetric work piece. The equation is given by

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \quad (1)$$

where r and z are the coordinates of cylindrical work piece, T is temperature, k is thermal conductivity, ρ is density, t is time and c is specific heat of the work piece.

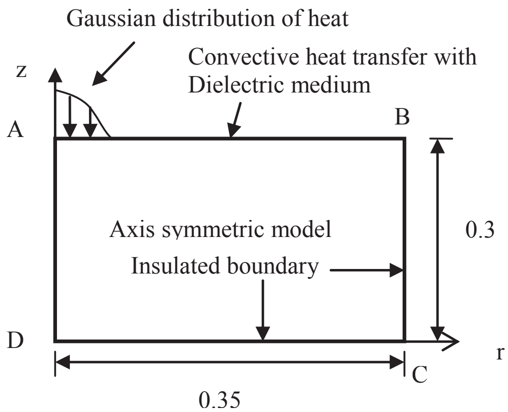

Fig. 1. An axi-symmetric two dimensional model for the EDM process analysis

2.3 Desired Boundary Conditions, heat input and spark radius

The boundary conditions allied with the EDM process are shown in Fig. 1. The work piece is submerged in dielectric medium. Insulated boundary condition is assumed for the boundaries away from the spark radius as boundary AD is an axi-symmetric boundary and heat flux is applied to the top surface of the boundary AB. In this model, Gaussian distribution of heat flux is assumed with quantity of heat entering into the work piece is given by relation

$$q_w(r) = \frac{4.45PVI}{\pi R_s^2} exp\left\{-4.5\left(\frac{r}{R_s}\right)^2\right\} \quad (2)$$

where q_w is the heat entering into the work piece, P is fraction of heat going to work piece, V discharge voltage (V), I discharge current (A), R_s is spark radius in μm, and R_s is given by equation

$$R_s = (2.04exp - 3)I^{0.43}T_{on}^{0.44} \quad (3)$$

where T_{on} is the pulse-on-time.

2.4. Energy distribution

Joshi and Pande [1] have suggested an energy distribution of 1-8% for work piece and 18.3% for tool material using AISI W1 tool steel and graphite as the work and tool material respectively. In the present model, an energy distribution of 2-5% for work piece and 4-8% for tool material has been recommended by employing D2 steel and brass as the work and tool material respectively comparing the experimental and numerical analysis.

2.5. Solution methodology of thermal analysis in ANSYS software

ANSYS™ 10.0 has been used to solve the governing equation (Eq. 1) with boundary conditions as shown in Fig. 1 by Finite Element Method to compute the temperature distribution. The 2-Dimentional, axisymmetric, thermal solid element (PLANE 55), continuum of size 0.35×0.3 mm has been considered for the thermal analysis. Isometric material properties and thermal conductivity are given as inputs to the numerical model and crater and temperature distribution are obtained from the model. Model geometry is created and meshing is done with element size of 1μm. Material property such as density, specific heat and thermal conductivity is employed along with initial bulk temperature is set to at 298 K. The heat flux location equation is introduced Eq. 2 and applied to the spark location on the center of the 2d continuum. Temperature distribution is obtained. The node having temperature more than melting point temperature is identified and killed to eliminate from mesh. The MRR and TWR are calculated using coordinate data of the craters of work and tool material respectively.

2.6. Solution methodology of the coupled thermal structural analysis for the EDM process in ANSYS software

The high temperature gradient developed on the work material due to repetitive spark discharges causes residual stresses to develop on work surface leading to structural disorder affecting the surface integrity and reducing the fatigue life of the machined surfaces. Therefore, it is essential to determine the induced residual stress on the machined parts so that it can be minimized. To determine the residual stresses in the work piece, a sequentially coupled thermal-structural analysis has been employed to predict the residual stresses with ANSYS™ 10.0 as the FEM solver. An axisymmetric model is shaped with element type (PLANE 55) for thermal analysis and (PLANE 42) for structural analysis. For analysis, the EDM geometry size is taken as 0.35×0.3 mm with an element size of 1 μm. The thermal environment has been created with thermal material property. Desired boundary conditions are set along with initial bulk temperature set at 298K. The load step has been solved to get the result. Elements above the melting temperature of the work piece were killed. The residual stress distribution was estimated by solving the previously obtained temperature profiles in structural environment applying structural boundary conditions.

2.7. Model Validation through experimental set up

The architecture related to the design of the process parameters for the numerical analysis of the EDM is based on response surface method (RSM). Response surface method (RSM) is an assembly of statistical and mathematical method beneficial for developing, refining and optimizing process. Generally, a second-order model as specified in Eq. 4 is employed in response surface methodology.

$$Y = \beta_0 + \sum_{i=1}^{k}\beta_i X_i + \sum_{i=1}^{k}\beta_{ii} X_i^2 + \sum_{kj}\sum \beta_{ij} X_i X_j + \varepsilon \quad (4)$$

where Y is the corresponding response of input variables X_i, X_i^2 and X_iX_j are the square and interaction terms of parameters respectively. β_0, β_i, β_{ii} and β_{ij} are the unknown regression coefficients and ε is the error. For the purpose of numerical analysis, Box-Behnken design is suitable as it assist to fit the second order model to the response with the use of a least number of runs. Three input parameters such as discharge current, pulse-on-time, and duty factor each at three levels have been considered for numerical analysis. The total number of numerical experiments is fifteen. Table 1 shows the levels for each parameter. The numerical and experimental results are shown in Table 2 for responses material removal rate (MRR), tool wear rate (TWR), and residual stresses.

To validate the numerical model, experiments are carried out on a die sinking EDM machine (ELECTRONICA-

ELECTRAPULS PS 50ZNC) shown in Fig. 2 with servo-head (constant gap). The dielectric fluid used was EDM oil (specific gravity= 0.763, freezing point= 94°C).

Table 1. Process parameters and their codes.

Process Parameters	Symbols	Codes		
		-1	0	1
Discharge current in Amp	Ip	3	5	7
Pulse-on- time in µs	Ton	100	200	300
Duty Factor in %	τ	80	85	90

Table 2. Comparision of numerical analysis with experimental results.

No.	Current in Amp.	Pulse on time (Ton) in µs	Duty Factor (τ) in %	Numerical MRR (mm^3/min.)	Experimental MRR (mm^3/min.)	Numerical TWR (mm^3/min.)	Experimental TWR (mm^3/min.)	Residual Stress of work piece in (M Pa)
1	-1	-1	0	1.64	1.57	1.85	1.84	12.7
2	1	-1	0	3.43	3.37	3.53	3.48	15.5
3	-1	1	0	1.75	1.61	1.29	1.24	13.8
4	1	1	0	7.30	7.03	3.28	3.26	16.5
5	-1	0	-1	1.58	1.56	1.34	1.30	14.1
6	1	0	-1	5.41	5.29	2.89	2.81	16.3
7	-1	0	1	2.14	2.07	1.94	1.90	13.9
8	1	0	1	6.57	6.22	4.55	4.54	16.35
9	0	-1	-1	2.06	2.01	2.02	2.01	13.9
10	0	1	-1	3.25	3.06	1.74	1.7	15.3
11	0	-1	1	2.62	2.62	3.19	3.15	15.0
12	0	1	1	4.39	4.24	2.71	2.69	15.6
13	0	0	0	3.69	3.64	2.82	2.7	15.7
14	0	0	0	3.69	3.58	2.82	2.81	15.7
15	0	0	0	3.69	3.54	2.82	2.75	15.7

Work material -D2 steel, discharge voltage = 45V(Constant), thermal conductivity (K) = 20W/mK, heat capacity (C) = 460J/kgK, density (ρ) = 7,710kg/m^3 , melting point temperature (Tm) = 1657K, Tool material-Brass, thermal conductivity (K) =115 W/mK, heat capacity (C) = 377J/kgK, density (ρ) = 8565kg/m^3, melting point temperature (Tm) = 1203K.

3. Results and discussions

From Table 2, it clear that the values of the responces predicted by numerical model are closer to the experimental results. Thus, it can be concluded that the numerical model would give better prediction of process responses compared to the earlier reported models. Figures 3, 4, and 5 show the predicted crater, temperature distribution and residual stress on work piece respectively. Figure 6 shows the surface plot of MRR with discharge current and pulse-on-time. It is obseved that MRR increses rapidly with increse in current for a particular value of pulse-on-time. However, increse of MRR with increse of current is more pronounced at high level of pulse-on-time. At low level of curent, MRR increses with spark-on-time, attains maximum value, and then shows constant trend. For high level of current, MRR increses with pulse-on-time. A similar trend has been also shown in the numerical results of Joshi and pande [1]. However, contribution of duty factor on MRR is not significant as compared to current and pulse-on-time. Figure 7 shows the surface plot of TWR with discharge current and pulse-on-time. TWR increases with increase in discharge current irrespective of level of pulse-on-time. For a prticular level of current, TWR decreases with increase in puse-on-time. Tool wear shows an increasing trend with increase in duty factor. Therefore, higher values of duty factor can be suggested for roughing application at the expense of more tool wear. Figure 8 shows the surface plot of residual stress with discharge current and pulse-on-time. Resudual stress increases briskly with increase in discharge current and pulse-on-time. Residual stress increases slowly with increase in duty factor.

Fig. 2. Die Sinker EDM Model: PS 50ZNC

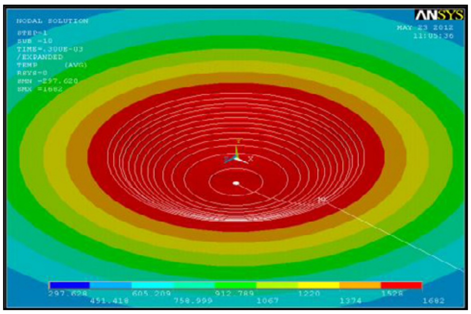

Fig. 3. Predicted crater (depth 13µm, maximum radius 43µm) at current 7A, spark-on-time 300µs, and voltage 45V

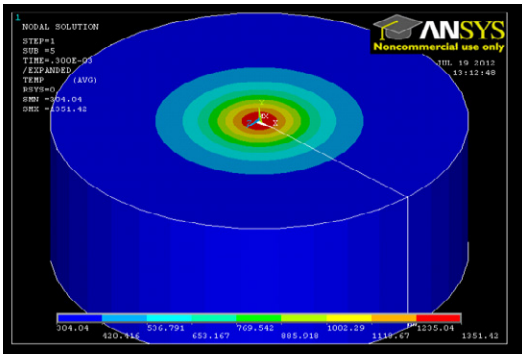

Fig. 4.Temperature distribution on tool at current 7A, spark-on-time 300 µs and voltage 45V

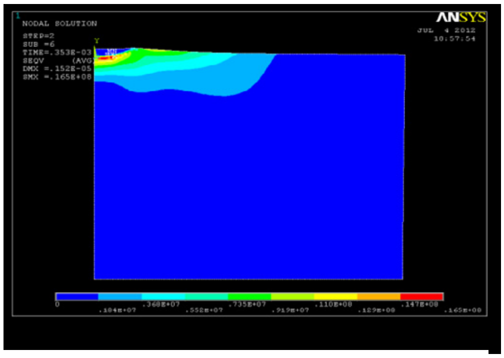

Fig. 5.Residual stress on work piece at current 7A, spark-on-time 300 µs, and voltage 45V

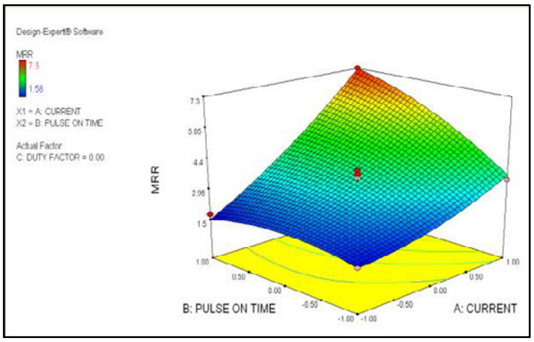

Fig. 6.Surface plot of MRR with current vs. pulse-on-time

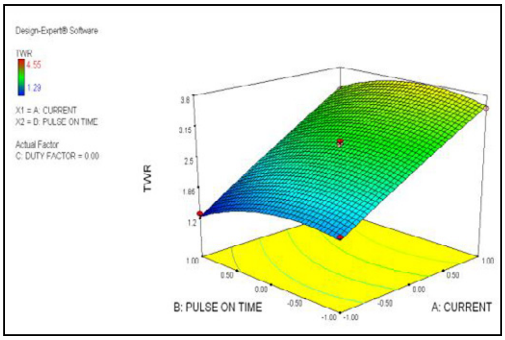

Fig. 7. Surface plot of TWR vs. current and pulse-on-time

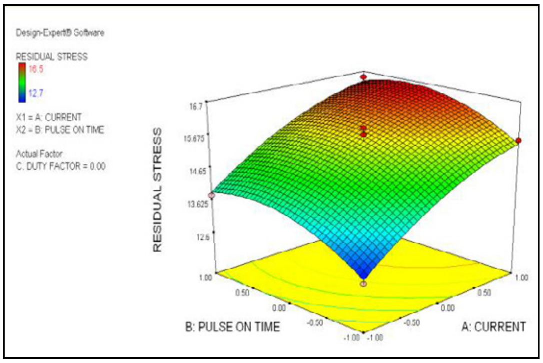

Fig. 8. Surface plot of residual stress vs. current and pulse-on-time

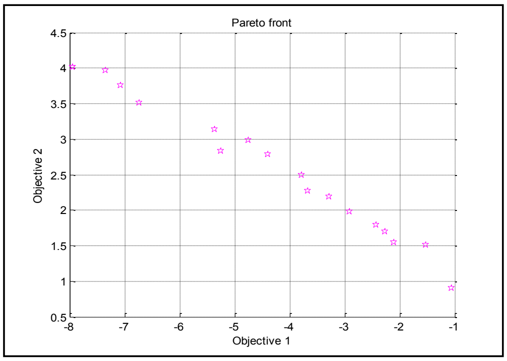

Fig. 9. Pareto-optimal front for objectives MRR and TWR

The process models for three responses are obtained by regression analysis as given in equations below:

$$MRR=3.59+1.95*Ip+0.87*Ton+0.43*\tau+0.94*Ip*Ton+0.15*Ip*\tau+0.14*Ton*\tau+0.39*Ip^2-0.45*Ton^2-0.058\tau^2 \quad (5)$$

$$TWR=2.81+0.98*Ip-0.20*Ton+0.55*\tau+0.77*Ip*Ton+0.27*Ip*\tau-0.050*Ton*\tau-0.031*Ip2-0.30*Ton^2-0.10*\tau^2 \quad (6)$$

$$Residual\ Stress=15.64+1.27*Ip+0.51*Ton+0.16*\tau-0.025*Ip*Ton+0.063*Ip*\tau-0.20*Ton*\tau-0.40*Ip^2-0.61*Ton^2-0.076\tau^2 \quad (7)$$

The empirical relation between the process parameters and process responses established from the RSM analysis is used as functional equations in MATLAB tool (optimtool) for solving the multi-objective problem. An initial population size of 45 is set with simple crossover and bitwise mutation with a crossover probability, Pc = 0.8, migration interval 20, migration fraction 0.2 and pareto fraction 0.35. Ranking and sorting of results have been done as it is stated in the algorithm.

Figure 9 shows the pareto-optimal solution front for responses MRR and TWR. This shows the development of the pareto-optimal front leading to the prime set of results. A sample optimal solution with process parameters has been given in the Table 3.

Table .3. Pareto Optimal solution set and corresponding variable settings

No.	Current (Ip) in Amp.	Pulse on time (Ton) in µs	Duty Factor (τ) in %	MRR (mm^3/min)	TWR (mm^3/min)	Residual Stress of work piece (MPa)
1	6.999792	299.4526	89.98557	7.9441003	4.00844415	16.3374152
2	3.014311	299.9759	80.54262	1.10390892	0.94397101	13.940755
3	3.004692	101.2464	80.23795	1.47289907	1.37723192	12.5021202
4	6.933666	281.7111	86.94395	7.25220029	3.70995251	16.494532
5	6.999792	299.4526	89.98557	7.9441003	4.00844415	16.3374152
6	4.47574	189.2565	85.22521	3.05025545	2.59279917	15.2243496
7	3.425573	131.6706	83.48598	1.92687461	1.93563331	13.663845
8	4.639985	299.4316	84.5271	3.45173301	2.07972933	15.3109889
9	3.32529	110.023	81.15174	1.62003383	1.61958449	13.0584637
10	6.789518	283.9734	86.94095	7.02245701	3.61632435	16.4427882
11	3.660246	272.6231	84.92217	2.38921056	1.79347601	14.6709901
12	5.892175	299.4247	88.37893	5.77793082	3.15355387	15.9779398
13	5.74526	299.7538	85.30013	5.17760229	2.73716173	15.9489143
14	4.22531	256.9455	81.15647	2.65391331	1.81799318	15.1245889
15	6.761685	290.2828	85.68406	6.86955057	3.3850482	16.3950233
16	5.139985	299.4316	84.5271	4.15862401	2.33833831	15.6317862
17	6.874792	299.4526	89.98557	7.70722696	3.92933536	16.3041008

4. Conclusions

A numerical approach is presented in this work to estimate material removal rate, tool wear rate and residual stresses on work piece in EDM process. The results obtained by numerical analysis and experimental methods have been compared. It can be concluded that numerical method provides reasonably accurate estimation of responses. Therefore, the method can be adopted to predict the responses before going for actual cutting operation. It may save time and cost of experimentation. Non-dominated sorting genetic algorithm (NSGA II) is used for multi objective optimization of responses and pareto fronts are obtained. Any solution in the pareto front is an optimal solution. The tool makers have a wide choice of selecting best parametric combination for cutting operation. A coupled thermo-structural FEM analysis has also been done to know how the extreme temperature gradient generated between tool and work piece affects the surface integrity of the machined surface. The proposed model can be used for selecting ideal process states to improve EDM process efficiency and finishing capability.

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