FEM ANALYSIS WITH EXPERIMENTAL RESULTS TO STUDY EFFECT OF EDM PARAMETERS ON MRR OF AISI 1040 STEEL

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Abstract - *This paper consists of modelling of electrical discharge machining (EDM) process for single spark. The present model is axisymmetric thermo physical finite element model (FEM) for AISI 1040 steel where temperature dependent material properties of AISI 1040 steel are used to investigate the temperature distribution in AISI 1040 steel which is based on a Gaussian distribution heat source. The prepared model is solved by using ANSYS 16 software. This single spark model is extended to simulate the second discharge. By calculating the number of pulses MRR is found in case of multi discharge machining. This analytically prepared model is compared with actual experimental results for validating this model. The MRR values predicted by our analytically prepared model are much closer to the experimental results. Hence this prepared analytical model is validated. This analytical thermo physical model can be used for exhaustive studies on EDM process to find optimal process conditions in future.*

Key Words: EDM, material removal rate, FEM, ANSYS software, Gaussian distribution, spark radius, thermal modelling.

1. INTRODUCTION

Electrical discharge machining process (EDM) is a type of non-conventional machining process, which is used for manufacturing geometrically complex or hard and electrically conductive material parts that are extremely difficult to cut by other conventional machining processes. There is a small gap between workpiece and electrode where erosion pulse discharge takes place which removes the unnecessary material from the workpiece through melting and vaporizing in presence of dielectric fluid. Electrical discharge machining process finds its applications in a wide range of industries such as aerospace, automotive, micromechanics, die making and mould- making, medical, etc. The machining mechanism of EDM is complex because it involves numerous phenomena like heat conduction and radiation, phase changes, electrical forces, bubble formation and collapse, rapid solidification. The insulating effect of the dielectric medium has some importance in avoiding electrolysis effects on the electrodes during an EDM process. According to Kunieda M, Lauwers B, Rajurkar KP, Schumacher BM [4] as the electrode shape is copied with an offset equal to the gap-size, the liquid should be selected to minimize the gap (10-100 μm) to obtain precise machining. On the other hand a certain gap width is needed to avoid short circuiting, especially when electrodes that are sensitive to vibration (like wire-electrodes) or deformation are used. Several researchers attempted to develop process models by analyzing the spark phenomenon and material removal mechanism in electrical discharge machining process. These above process models of EDM process over- predict the process performance like material removal rate (MRR), tool wear rate and crater size due to the simplifying assumptions such as constant spark radius, disc or uniform shaped heat flux source, constant thermal properties of work and tool material, etc. These simplifying assumptions do not simulate the real life conditions of machining and hence limits the applicability of models. Various researchers made attempts in direction of developing EDM process models from experimental results using design of experiments (DOE) techniques such as response surface methodology (RSM), factorial analysis, regression analysis, Taguchi technique, etc. These models are specific to chosen cutting tool and work materials, experimental conditions and limited experimental data generated. Hence, this limits the applicability of models in terms of generality. Focus of research work done by S.N. Joshi, S.S. Pande [1] only on die-sinking EDM and effect of powder mixed di-electric fluid remains unexamined. H.K. Kansala, Sehijpal Singh, and Pradeep Kumar [4] work reported numerical simulation of powder EDM but parametric studies were not carried out in that particular work. Thus, a need exist to develop a thermo-physical model of EDM and its use for EDM parametric study. The theoretical data for the formation of plasma channel between the tool and the work piece, metallurgical transformations of material, micro structural changes and thermodynamics of the repetitive spark causing melting and evaporating the electrodes is still not clearly understood. However, it is widely accepted that the mechanism of material erosion is due to intense local heating of the work piece causing melting and evaporation of work piece. The thermal problem to be solved so as to model an EDM discharge is fundamentally a heat transmission problem in which the heat input is representing the electric spark. By solving this thermal problem yields the temperature distribution inside the workpiece, from which the shape of the generated craters can be estimated [1]. For solving these numerical models finite-element method or the finite-differences method are normally used with single spark analysis (Erden et al. (1995). Yadav et al. (2002) investigated the thermal stress generated in EDM of Cr die steel. The influence of different process variables on temperature distribution and thermal stress distribution has been reported. The thermal stresses exceed the yield strength of the work piece mostly in an extremely thin zone near the spark. Salah and Ghanem (2006) presented temperature distribution in EDM process and from these thermal results, MRR and roughness are inferred and compared with experimental explanation [1]. Literature reports extensive experimental and analytical studies carried on modelling of EDM process to improve accuracy and productivity. Researchers worldwide have attempted to model the electric discharge phenomena and the mechanism of cathode and anode erosion in the EDM process. Various researchers developed a process model of EDM by design of experiments (DOE) tools. Several researchers attempted to develop process models of EDM by analyzing the spark phenomenon and mechanism of material removal in EDM. Since the early seventies, researchers worldwide have attempted to model the electric discharge phenomena (plasma channel) and the mechanism of cathode and anode erosion in the EDM process. Two different mechanisms have been proposed to analyze the material removal viz., electro-mechanical analysis for short discharge pulses (less than 5 μs) and electro thermal analysis [6] for the normal EDM operation involving material removal due to the intense plasma energy generated between the cathode and anode. The electro-thermal analysis of EDM process is considered more relevant in the present context. M.R. Shabgard, M. Seyedzavvar [2] reported a numerical method for predicting heat affected zone in Electrical discharge machining process for AISI H13 tool steel as workpiece material and reported influence of Electrical discharge machining process input parameters on the state of thermal distribution in heat affected zone of AISI H13 tool steel using ABAQUS/CAE software. H.K. Kansala, Sehijpal Singh, and Pradeep Kumar [3] reported numerical simulation of powder mixed EDM. The simulation based on the several important aspects such as percentage distribution of heat among tool, work piece and dielectric fluid, shape and size of heat source (Gaussian heat distribution), temperature sensitive material properties, pulse on-off time, phase change and material ejection efficiency etc. to predict the temperature distribution in the work piece material. Numerical comparison and assessment of various electro-thermal and EDM models were carried out by S.H. Yeo, et.al. [5] in EDM. Five EDM models from Snoeys, Van Dijck, Beck, Jilani, and DiBitonto are analyzed in terms of the temperature distribution, crater geometry, and material removal at the cathode. This work shows the comparative analysis on the material removal rate (MRR) ratio of the predicted result to experimental data and concluded that DiBitonto‟s model shows a better agreement with experimental data as compared to the other models. However, DiBitonto's process model also over-predicts the results to a large extent when compared with the experimental results mainly due to the simplifying assumptions such as the approximation realistic. J. Marafona, J.A.G. Chousal [6] reported development of a thermal–electrical model for sparks generated by electrical discharge in a liquid media. A cylindrical shape has been used for the discharge channel created between the electrodes. The discharge channel being an electrical conductor will dissipate heat, which can be explained by the Joule heating effect. Focus of research work done by S.N. Joshi, S.S. Pande only on die-sinking EDM and effect of powder mixed dielectric fluid remains unexamined. H.K. Kansala's work reported numerical simulation of powder EDM but parametric studies were not carried out in that particular work. Thus, a need exist to develop a thermo-physical model of EDM and its use for EDM parametric study. S. K. Sahu and Saipad Sahu [9] modeled electrical discharge machining process using ANSYS 12 software and AISI D2 tool steel as a work piece material, in this work an axisymmetric model was prepared considering the model as semi-infinite and dimensions as six times the spark radius. In this investigation, an axisymmetric thermal model is developed to predict the material removal. The important features of this process such as percentage of heat input to the tool and work piece, shape and size of heat source (Gaussian heat distribution), individual material properties and pulse on-off time are taken into account while developing the model. FEM based model has been developed to analyze the temperature distribution and its effect on material removal rate. The model is validated by comparing the predicted theoretical MRR values with the experimental MRR values for AISI D2 tool steel. Excellent agreement between theoretical MRR values and experimental MRR values has been obtained. This developed model can be used for finding out residual stress distributions, thermal stress distribution mechanism of reinforcement particle bursting phenomenon into the workpiece material. The effect of material transfer to the machined surface from the electrode and powder mixed with dielectric for various die steels have been analyzed. Material characterization during EDM machining of cemented tungsten carbide, 20 Fe–Mn–Al alloy 21 using proper process settings has been reported. Many studies have reported EDM and PMEDM process optimization for multiple responses. This work reports the results of FE simulation of a PMEDM process to predict the volume removed in a single crater. Experimental studies were subsequently carried out to compare the actual measurements with the simulation results for crater shape and dimensions. In this present research work, a finite-element modelling of the electrical discharge machining process using ANSYS 16 software is carried out. Conduction, convection, thermal properties of material with variation in temperature, the percentage of discharge energy transferred to the tool and work piece, the thermal and mechanical properties of AISI 1040 steel work piece material, the plasma channel radius and Gaussian distribution of heat flux based on discharge duration has been used to develop and calculate a numerical model of the electrical discharge machining process.

2. MATHEMATICAL MODELLING AND NUMERICAL SIMULATION OF EDM

In EDM, a series of rapid, repetitive and randomly distributed discrete electric sparks occur in the gap between tool and work piece for a cycle of few micro seconds. For simplifying the analysis a few reasonable assumptions without affecting the basic EDM process should be made.

The following assumptions are to be made without sacrificing the basic features of the EDM model to make the problem mathematically feasible.

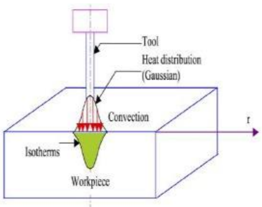
2.1 Assumptions

1. The work piece domain is axi-symmetrical around r–z plane of its geometry.
2. Work piece material thermal properties are considered as a function of temperature and it is assumed that due to thermal expansion within the work piece material, density and element shape of it are not affected.
3. The effect of latent heat of fusion and vaporization on simulation study has been neglected.
4. The heat source is assumed to have Gaussian distribution of heat flux on the work piece and temperature analysis is considered to be of transient type.
5. There is hundred percent material flushing efficiency.
6. Heat is transferred to the tool and work piece by conduction.
7. The model is prepared for a single spark EDM process.
8. The composition of the material of work piece is assumed to be homogeneous and isotropic.
9. The work piece material is elastic-perfectly plastic and yield stress in tension is same as that in compression.
10. The work piece is assumed to be stress free before electro discharge machining operation.
11. Fraction of heat that goes into work piece material (Kw) remains constant during pulse.

2.2. Thermal Model

The discharge phenomenon in EDM can be modelled as the heating of the work electrode by the incident plasma channel. In this process, electrodes are submerged in dielectric medium and are separated by a gap, called inter-electrode gap. Fig-1 shows the idealized case where work piece material surface is being heated by a heat source having Gaussian distribution nature. The mode of heat transfer in solid is conduction. There is axisymmetric nature of heat transfer in the electrode and the work piece, so a two-dimensional physical model is assumed. The various assumptions made to simplify the random and complex nature of EDM and as it simultaneously interact with the thermal, mechanical, chemical, electromagnetism phenomena [3].

Fig -1: Discharge Phenomenon [3]



2.3. Governing equation

For the transient, non-linear thermal analysis of EDM process, Fourier heat conduction equation is taken as the governing Equation. The differential equation governing the heat conduction in an axi symmetric solid surface is given by [1] [5].

$$\rho Cp\left(\frac{\partial T}{\partial t}\right) = \left[\frac{1}{r}\frac{\partial}{\partial r}\left(Kr\frac{\partial T}{\partial t}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right)\right] \quad (1)$$

Where, ‘r’ and ‘z’ are coordinate axes shown in fig-1
‘T’ is the temperature, ‘t’ is the time,
‘K’ is the thermal conductivity of work piece material,
‘ρ’ is the density of work piece material ,
‘Cp’ is the specific heat,
The work piece is immersed in dielectric medium, the temperature of the domain is thus assumed to be ambient temperature (Ta) to start with. The top surface of the work piece (boundary 2) is in contact with the dielectric medium. Heat flux (Q) boundary condition is applied on this surface.

2.4. Heat Distribution

For analytical tractability, many authors have used uniform disc heat source. However, Gaussian heat distribution is more realistic than disc heat source. Moreover, the assumption of Gaussian distribution is well-accepted for modelling the heat input in EDM. Therefore, Gaussian heat distribution has been considered in this modelling [1]. Discharge behavior within the spark region was modelled assuming Gaussian distribution as shown in Fig-2. Heating of the work piece material is considered as a heat source inside the spark which is conducted to the work piece and dissipated to the environment (dielectric fluid) by convection outside the spark region on work piece top surface. Though many studies involving analysis of EDM process have used a uniform disc heat source inside the spark plasma, Gaussian heat distribution is still more realistic for EDM or PMEDM process as concluded by many researchers. The Gaussian curve mathematically becomes zero at infinity so a 6σ range (−3σ to 3σ) that covers 99.73% of the total area under the curve was used in the present case. σ represents the standard deviation of the process. By rotating the Gaussian curve about its vertical axis (z-axis) a three-dimensional Gaussian heat source was achieved. The heat flux input was thus calculated for each small discretized region to be used for the analysis. During earlier analysis of EDM process, most models were constructed with an assumption that no heat is lost to the tool material and dielectric fluid medium i.e. the total heat produced is transferred only to the work piece material. Further it was concluded that out of total heat supplied, about 8% is absorbed at the anode and 18% at the cathode and the remaining heat is transferred to the dielectric fluid medium. Shanker et al. calculated that 40%–45% of the heat input is absorbed by the work piece when machined with water as the dielectric fluid at different processing conditions.

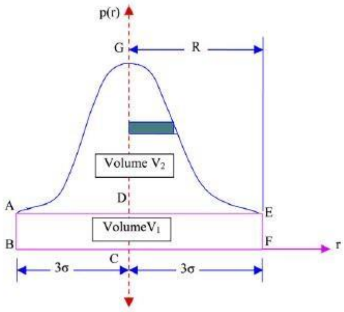


Fig -2: Gaussian heat distribution [3]

However, due to addition of powder in the dielectric its electrical conductivity increases thus the fraction of the energy transferred out of total heat to the work piece (Kw) is likely to be higher than conventional EDM process. This will result in a higher MRR and has been validated and confirmed experimentally. However, no methodology has been reported to calculate the value of Kw during EDM. Kansal et al. varied this factor from 5% to 20%. In the present study, Kw was varied from 0.1 (10%) to 0.25 (25%) which means that a maximum of 25% heat was assumed to be transferred to the workpiece.

2.5. Heat transfer model and boundary conditions

The work piece is symmetrical around z-axis, so taking advantage of its symmetry; a small half-plane is cut from the work piece surface (CDEF) with negligible thickness. The considered work piece domain is shown in Fig-3. In the domain, heat flux for a single spark is applied on the surface B1 up to spark radius R using Gaussian distribution. The convection heat transfer takes place due to the cooling effect caused by the dielectric fluid on the remaining region on B1 surface. No heat transfer conditions have been assumed for B2 and B3, because these are very far from the spark radius and also the spark has been made to strike for a very little moment on them. The heat flux is taken as zero for B4, which is the axis of symmetry, as there is no net heat gain or loss from this region. [2]

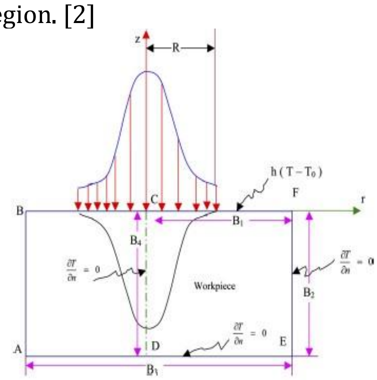


Fig -3: Heat transfer model of EDM [3]

In summary, the boundary conditions are given as follows:
For boundary B1:

A) Up to spark radius R

$$K\frac{\partial T}{\partial z} = Qw(r) \tag{2}$$

B) Beyond spark radius R

$$K\frac{\partial T}{\partial z} = h(T - To) \tag{3}$$

For boundary B2, B3, B4

$$\frac{\partial T}{\partial n} = 0 \tag{4}$$

Where,
h - Heat transfer coefficient between the work piece surface and dielectric,
Qw (r) - the heat flux owing to the spark,
T_0- The initial temperature which is equal to room temperature, T - Temperature.

2.6 Spark radius

The tool material, polarity and the dielectric are some of the factors that decide the radius and the growth of a spark in EDM process. No exact mathematical expressions or even experimental measurement is available to accurately calculate the spark radius. However, theoretically and experimentally many researchers have attempted to determine the spark radius with varied assumption.

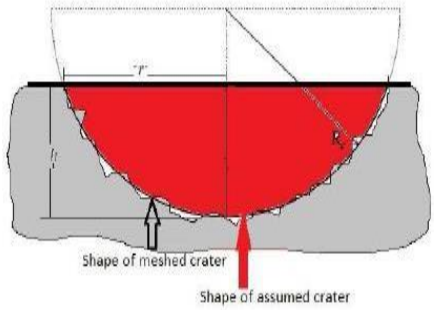


Fig -4: Assumed crater morphology [8]

The important factor in modelling of electrical discharge machining process is plasma channel radius and the size of heat flux on the work piece material surface. Evolution of the plasma channel radius and its shape has been studied by many authors. In practice, it is extremely difficult to experimentally measure spark radius due to very short pulse duration of the order of few microseconds. Some research work shows the plasma channel radius is considered as only time dependent factor while others as time dependent as well as current dependent factor. A semi empirical equation of spark radius termed as "equivalent heat input radius" which is assumed as a function of the duration of the spark, t (μs) and the current, I (A). It is more realistic compared with the other approaches. [2]

$$R(t) = 0.00204 \times I^{0.43} Ton^{0.44} \ \mu m \tag{5}$$

Where 'I' is current, 'T_{on}' is pulse on time

2.7. Heat flux

Most researchers have considered the hemi-spherical disc heat source for thermal modeling in EDM. However, this approximation is neither realistic nor reliable. It has been reported in [1] that the isothermal curves obtained for EDM thermal model can be accurately approximated by Gaussian distribution. Yadava et al. have reported a heat flux equation for EDM considering the Gaussian distribution.

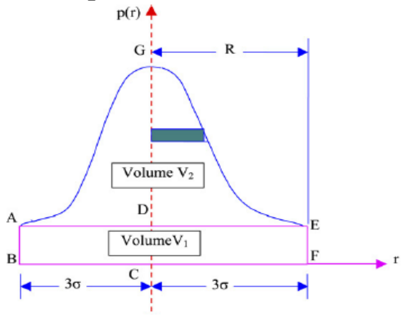


Fig -5: Gaussian distribution [2]

The probability density function of Gaussian distribution for a random variable r is shown in Fig-5 and is given by the relation.

$$P(r) = \frac{1}{\sigma\sqrt{2\pi}} e^{-r^2/2\sigma^2} \quad (6)$$

'$\frac{1}{\sigma\sqrt{2\pi}}$' is the peak value of the distribution and 'σ' is the standard deviation. Since the Gaussian curve does not mathematically become zero until infinity, it becomes necessary to select some finite large value of its argument to represent the bottom of the crater. Usually six times of (-3σ to $+3\sigma$) is taken for dropping the response to 0.25% of its initial value i.e. 99.75% of the values lies between $r = \mu-3\sigma$ and $r = \mu+3\sigma$ (Fig-2). The profile of a three-dimensional crater can be obtained by rotating the Gaussian curve around the vertical axis. Therefore, $R = 3\sigma$. Substituting the value of σ into Eq. (6)

$$P(r) = \frac{3}{R\sqrt{2\pi}} e^{-4.5r^2/R^2} \quad (7)$$

In EDM, p(r) is the intensity of heat imparted to the work piece surface, which is denoted by QW and is a function of r. At r = 0, p(r) = Q_0, Where 'Q_0' is the maximum intensity of heat applied at the center of the work piece surface. Therefore, the heat flux of the system is given by

$$Q_w(r) = Q_0 e^{-4.5r^2/R^2} \quad (8)$$

And the energy incident on the work piece is given by

$$\oint Q(r)\,dA = \int_0^R Qw(r)\,2\pi r\,dr$$
$$= \int_0^R Q_0 e^{-4.5r^2/R^2}\, 2\pi r\,dr$$
$$= \frac{\pi R^2}{4.5} Q_0\left(1 - e^{-4.5}\right)$$
$$= 0.2191\pi Q_0 R^2$$

The rate of energy incident on the work piece is equal to the rate of energy supplied which is KW × Vb× I
Where, I is the current, Vb is the breakdown voltage and KW is the fraction of heat input to the work piece. Therefore,

$$K_w \times Vb \times I = 0.2191\pi Q_0 R^2 \quad (9)$$

Or

$$Q_0 = \frac{4.57 \times Kw \times Vb \times I}{\pi R^2} \quad (10)$$

Upon substitution of Eq. (08) into (10)

$$Q(r) = \frac{4.57 \times Kw \times Vb \times I}{\pi R^2} e^{-4.5\left(\frac{r}{R}\right)^2} \quad (11)$$

Here Kw is a constant, I is current, Vb is breakdown voltage and Q(r) is heat flux at any radius r. Equation (11) of heat flux was used to calculate the heat flux intensity between 0 and R and the heat flux input within the spark region was discredited into 20 smaller regions of 5 μm each. [11]

3. FEM WORK

3.1. Simulation condition and Procedure

The single discharge analysis procedure for EDM employs the commercial finite element code ANSYS to determine both temperature distribution and deformation of molten material by plasma pressure. ANSYS is a generally used finite element code to solve engineering problem. EDM is a complicated thermal process that involves complex interaction of different physical phenomena. FEM makes it possible to simulate temperature and stress distributions into the work piece material. To develop the FEM based EDM model, powerful software is required which can consider all complicated aspects of the process. ANSYS is one such powerful tool that can be used in FEM analysis of the different models. Any complicated geometry can be analyzed easily using ANSYS. It has many finite element analysis capabilities, ranging from a simple, linear, static analysis to a complex, nonlinear, transient dynamic analysis in the fields such as structural mechanics, thermal systems, fluid mechanics, and electromagnetic. In the present work, the modelling and simulation of results for EDM have been performed using ANSYS 16 software. The work geometry has been created in ANSYS 16 using appropriate boundary conditions. The different kinds of loads are applied on the work domain. Meshing of the work piece domain is done using mapped meshing technique. For a single discharge test, copper and AISI 1040 Steel is used as specimens. The copper is used widely with the electrode material. The EDM process was initially simulated using finite element (FE) simulation for AISI 1040 steel work-piece material by varying various process parameters. Results and equations developed by many researchers were used in this study to generate the temperature variation and profile for predicting the volume removed during the formation of a single crater. The thermal analysis was performed when the electrical discharge machining conditions and the material properties were given. The heat flux intensity varied with discharge gap current trace and the diameter of plasma. During the discharge on-time, the melting region and the evaporating region were found. The material was assumed that certain part whose temperature goes over the evaporating point would be removed. Numerical model and the analysis of the EDM process is completed using FEM software ANSYS (ANSYS/Metaphysics) utilizing transient thermal analysis module [6].

3.2. Meshing

Model was created with a domain of 1×1×1mm with AISI 1040 steel material. Meshing of the work piece is completed using 2 dimensional, 4 Noded Thermal solid plane of 20 μm size. [3]

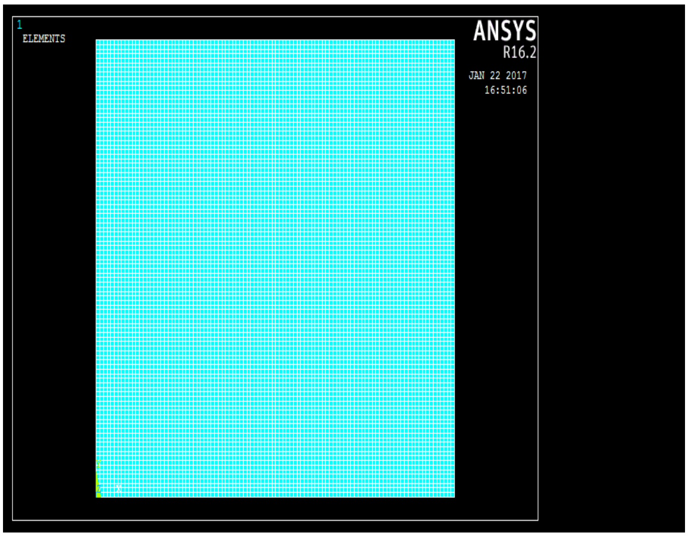


Fig -6: Meshing of the work domain

3.3. Process parameter

Using the variables in mentioned in Table-1 and heat flux equation, the heat flux values are calculated for different process settings. These calculated heat fluxes were used in transient thermal analysis as a thermal loading. The region under spark is directly affected by the heat flux of spark channel. Beyond spark radius, the whole surface is exposed to a convection heat loss due to dielectric medium. The material having the simulated temperature above the work piece melting temperature was removed to form the crater.

Table -1: Process Parameters for FEM

Sr.N	Parameter	Values
1	Discharge Voltage (V)	70 V
2	Current (I) (Amp)	18,16,14,12,10,08,06,04,02
3	Pulse duration Ton (μs)	50,75,100,150,200,300,400, 500,750
4	Pulse off time, T off (μs)	50,75,100,150,200,300,400, 500,750
5	Tool electrode material	Copper
6	Tool electrode diameter	25 mm
7	Di-electric medium	Commercial Electra EDM oil
8	Ambient Temperature	298 K

3.4. Element type for the analysis Procedure

Two-dimensional, 4 Noded Quadrilateral Element, Thermal solid plane 55 with 20 μm size. Plane 55 can be used as a plane element or as an axi-symmetric ring element with a two-dimensional thermal conduction capability. The element has four nodes with a single degree of freedom, temperature, at each node. The element is applicable to a two-dimensional, steady-state or transient thermal analysis. The element can also compensate for mass transport heat flow from a constant velocity field.

3.5. Material properties for FEM

Following are the material properties and chemical composition of AISI 1040 steel, which are used as input parameters for ANSYS.

Table-2: Chemical composition of AISI 1040 steel

Sr. N	Element	Weight
1.	Iron (Fe)	98.6 to 99.03 %
2.	Carbon (C)	0.37-0.44
3.	Manganese (Mn)	0.60-0.90
4.	Phosphorous (P)	0.04 (max)
5.	Sulphur (S)	0.05 (max)

Table-3: Physical and thermal properties of AISI 1040 steel

Sr.N	Property	Value
1.	Density (kg/m3)	7800
2.	Conductivity (W/m K)	60
3.	Specific Heat (J/Kg K)	434
4.	Specific Heat Capacity J/kg-K	450

3.7. Procedure used for thermal modeling

The following steps describe the detailed procedure used for thermal modelling of EDM using ANSYS [3] [1]
Step 1: Objective: The objective of this analysis is to find out the temperature distribution on the work piece processed by EDM.
Step 2: Units: S.I.
Step 3: Product selection: ANSYS
Step 4: Analysis method: Thermal, h method
Step 5: Type of analysis: Transient
Step6: Problem domain: In this step, the geometry of the problem is created using ANSYS.

Three-dimensional work piece geometry is created. However, the domain is axi-symmetrical around z axis so taking the advantage of its symmetry, whole geometry of workpiece material is minimized to a two-dimensional figure. The dimensions of the work piece material domain are 1×1 mm. [7]

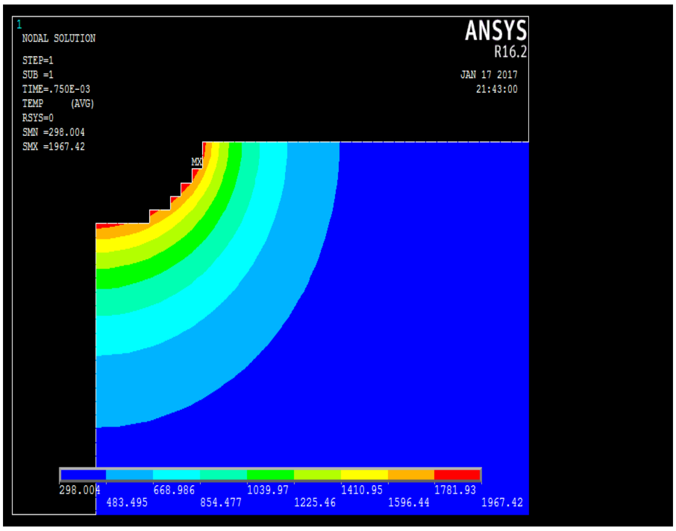


Fig -7: Temperature distribution obtained for a current intensity value of 2 amp and pulse duration 750 µs

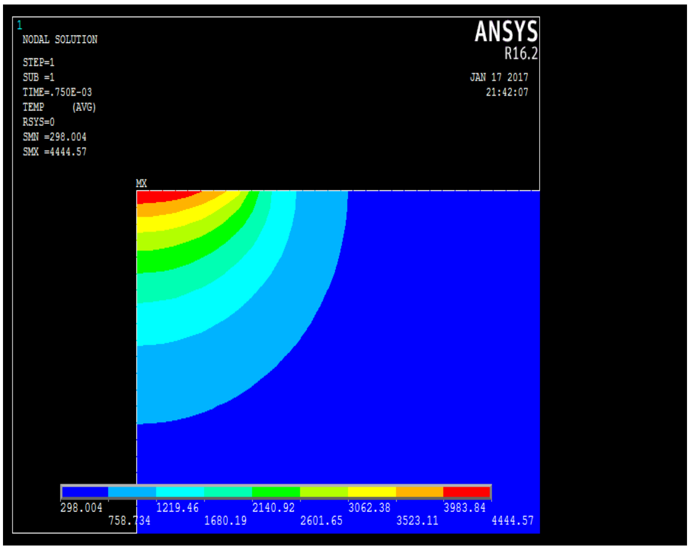


Fig -8: Volume of material removed for current intensity value of 2 amp and pulse duration 750 µs

3.8. Calculation for theoretical (ANSYS) MRR

Temperature profile obtained from FEM is used to calculate amount of material removed from specimen, exposed to heat flux. Crater formed due to each discharge can be assumed to have circular parabolic geometry (Fig-9) [2]

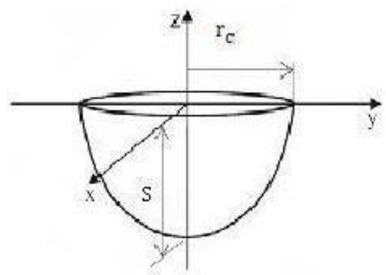


Fig -9: Circular parabolic geometry

Theoretical crater volume defined by paraboloid geometry is described as

$$Vc = \frac{1}{2} \times \pi \times S \times r_c^2 \quad (12)$$

Where Vc (FEM) is volume,

S is depth and r_c is radius of crater.
3D points comprised in Vc (FEM) represent points over liquid temperature.
Values of r_c and S were obtained by computing temperature distribution profiles along radius and depth directions of work-piece.

3.9. Theoretical (ANSYS) Results

Table-4: Theoretical (ANSYS) MRR values

Sr.N.	Ip (Amp)	Ton (μs)	S (m)	rc (m)	MRR (mm^3/ min)
1	18	50	2.00E-05	2.00E-05	7.536
2	16	75	1.00E-05	4.00E-05	10.048
3	14	100	3.00E-05	4.00E-05	22.608
4	12	150	2.00E-05	5.00E-05	15.700
5	10	200	3.00E-05	4.00E-05	11.304
6	8	300	3.00E-05	3.00E-05	4.239
7	6	400	4.00E-05	4.00E-05	7.536
8	4	500	2.00E-05	3.00E-05	1.696
9	2	750	1.00E-05	2.50E-05	0.393

5. EXPERIMENTAL WORK

This chapter deals with the experimental details and procedure followed for the machining and estimation of material removal rate (MRR). Objective of experimental studies is to validate the developed theoretical model. Few EDM experiments were conducted under the same machining conditions at which simulation results are obtained. Experiments are conducted on a die-sinking EDM (ZNC), Electronica, available at Rajarambapu institute of Technology, Sakharale, Islampur, India. The Electric Discharge Machine, model ELECTRONICA- ELECTRAPULS PS 50 ZNC (die-sinking type) with servo-head (constant gap) and positive polarity for electrode is to be used to conduct the experiments. This study deals with the experimental and procedure followed for the machining and estimation of material removal rate MRR. The experiments were performed on an experimental setup which is designed and developed in the laboratory for said purpose. The theoretical MRR values calculated from the temperature distributions in ANSYS software were compared with the corresponding experimental MRR values.

5.1. Tool and work piece used for experiment

A cylindrical shape copper electrode having 25 mm diameter is used as a tool material. The work piece material is AISI 1040 steel plate with dimensions 100 × 50 × 10 mm.

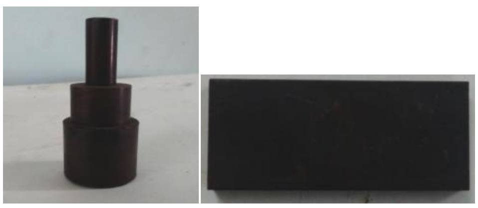


Fig -10: Tool and work piece used for experiment

Fig -11: Work piece before and after machining

6. RESULTS AND DISCUSSION

Above analytical and experimental results have been found out for the single spark Electrical discharge machining process and taking AISI 1040 steel as work piece material.

Table-5: Material removal rate found in the experiment conducted with varying current (Ip) and Pulse on time (Ton) values

Expt no.	Ip (amp)	Ton (μs)	Initial wt (gms)	Final wt (gms)	Expt MRR (mm^3/min)
1	18	50	488.066	486.302	11.308
2	16	75	486.302	484.374	12.359
3	14	100	484.374	481.126	20.821
4	12	150	496.548	494.722	11.705
5	10	200	494.722	493.139	10.147
6	8	300	493.139	492.218	5.904
7	6	400	499.160	498.024	7.282
8	4	500	499.516	499.160	2.282
9	2	750	499.564	499.516	0.308

Temperature distribution in the surface of work piece material has been carried out and it is clearly evident that the maximum temperature occurs at the top surface on the center line of the work piece, where the intensity of heat flux is maximum according to Gaussian distribution of heat flux. After the application of heat flux, it is evident from the FEM (analytical) model that the temperature distribution during the spark, in the surface of the work piece is sufficient enough to melt the material due to its low melting temperature and removal of material.

6.1. Reasons for deviation in values of Analytical (ANSYS) MRR and Experimental MRR

When compared to the experimental data some deviations are seen in analytical MRR values. The possible reasons are some simplifying assumptions made in the present analytical model like hundred percent material flushing efficiency, no ignition delays while machining, no deposition of recast layer inside the workpiece after machining, etc. But in actual practice, the melted workpiece material is not fully flushed from the crater; a considerable small amount of melted material again solidifies in the crater and forms the recast layer. The ideal machining conditions are not realized due to improper flushing of debris and arcing into the inter-electrode gap during the machining with high energy discharges, which reduces the actual experimental MRR. The MRR is mainly influenced by sensitivity, spark gap, lift and dielectric fluid medium. In present analysis dielectric fluid medium is not playing an important role as it is coming into picture only for convection, but actually it is a very important factor to be considered while machining. The material removal from the workpiece is mainly caused by melting and vaporization of material. Molten metal is taken away by the dielectric fluid, but at the same time the molten metal is under very high pressure due to plasma channel. In addition to this adhesive property of molten metal also causes problem in material removal from workpiece. Hence it is difficult to model and incorporate all these practical effects in the analytically prepared model.

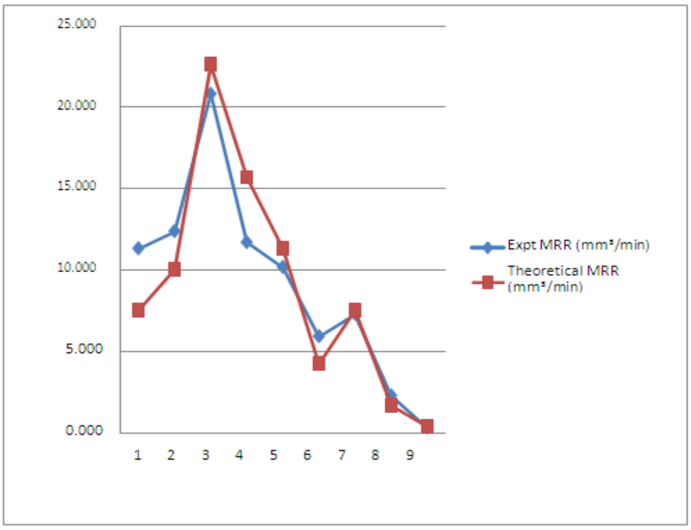


Chart -1: Comparison of Theoretical (ANSYS) MRR with Experimental MRR values

FEM Model for EDM process validation has been done by comparing the predicted MRR by the ANSYS software with the experimental results following table and chart-1 shows the comparison between theoretical MRR and experimental values.

Table-6: Experimental MRR and Theoretical (ANSYS) MRR with respective to current (Ip) and Pulse on time (Ton) values

Expt no.	Ip (amp)	Ton (μs)	Expt MRR (mm^3/min)	Theoretical MRR (mm^3/min)
1	18	50	11.308	7.536
2	16	75	12.359	10.048
3	14	100	20.821	22.608
4	12	150	11.705	15.700
5	10	200	**10.14**	**11.304**
6	8	300	5.904	4.239
7	6	400	**7.282**	**7.536**
8	4	500	**2.282**	**1.696**
9	2	750	**0.308**	**0.393**

7. CONCLUSION

In this paper, an axisymmetric thermo physical model of Electrical discharge machining process is prepared to predict the material removal rate (MRR) of AISI 1040 steel. Analytical calculations and experiments have been done to analyze the performance of EDM with input parameters. Finite element method (FEM) has been used to analyze the temperature profiles on the surface of workpiece. The FEM based model has been prepared and solved using ANSYS 16 software. Comprehensive thermal analysis of the process was carried out and the temperature distribution is obtained from FEM model. Further, from the temperature distributions, the MRR is predicted. To validate the prepared model, the analytical MRR values given by the software are compared with the experimentally determined MRR values under same parametric conditions. After comparing the results it was found that the MRR values predicted by our analytically prepared model are much closer to the experimental MRR values. Similarly, Incorporation of factors such as the Gaussian distribution of heat flux, EDM spark radius as a function of discharge current and discharge duration have possibly made our model closer to actual process conditions, thus improving its prediction accuracy. The thermo physical model developed in this present work for EDM can be used to find the temperature and residual stress distributions in surface of workpiece material, metal flow and surface cracks on the machined part of the work pieces. This means that the prepared analytical model can be used as an industrial tool to predict the evolution of temperature, stress, strain and cracks that may occur on the surface of the machined work pieces. The model developed can be used to consider the effect of multi sparks and effect of various process parameters on the residual stress distributions and surface cracks. It can be further used for the modeling of dielectric fluid, molten material and plasma channel at the discharge crater, using CFD tool. Various exhaustive studies on the electrical discharge machining process can be carried out using this prepared analytical thermo physical model in future.

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