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Numerical simulation of electric discharge machining of functional graded material

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Abstract. In the present scenario, advanced material is required for higher end applications whose material properties can be preassigned according to the performance demands. This lead to the development of functional graded material. These kinds of materials are divided into different layers with varying material properties. The Functionally Graded Materials are heterogenous in nature but in layer wise it can be considered homogenous in nature. The material properties can be calculated by using Rule of Mixture. However, this material possesses challenges during the machining process. Machining of these materials using conventional process is challenging due to its improved mechanical properties. However, such materials can be machined using unconventional machining processes. This work involves a development of finite element simulation model to simulate the Electric Discharge Machining (EDM) process on Functional Graded Material (FGM). The EDM is a material removal process through multiple occurrence of single spark on the workpiece. This single spark will create a crater due to the excess heat of the spark and the molten material can be removed by using the dielectric fluid. The heat input for a single spark can be defined by using the Gaussian distribution of the spark profile. The centre point will have maximum heat inputted and as the heat passes in the work piece it decreases. The size of the crater will vary with the varying the process parameters such as Discharge current, Discharge Voltage, Pulse on-time, off-time and Energy Partition. The effect of the process parameter on material removal rate (MRR) is evaluated using the FEM simulation. The predicted result shows that with increase of pulse on-time and discharge current, the crater size was found to be increased. This increase in the crater size attributes in the increment of MRR. The predicted results can enhance the machining process of FGM.

1.Introduction

In the present scenario, more advanced materials with improved properties such as high strength, low weight, etc are required for higher end applications. This requirement has led to the development of Functionally Graded Material(FGM). These materials are designed for certain function and applications and the area of application is growing. FGM is developed by gradually distribution of the one or more material compositions over the volume, which results in variation of material properties. The motive is to develop a material which has required gradient in the property, and this is achieved by gradually distribution of various materials along the required directions [1]. Mainly, there are 2 ways the graded surface can be divided (figure 2) either continuous graded or layer-wise graded. In layer wise, each layer can be considered as homogenous material. The material properties of each layer can be calculated by using the "Rule of Mixture"[2]. Rule of Mixture, here the weight percentage of both the material is varied gradually. With the discovery of FGM, many different materials are combined with the required properties and application. A table with many FGM with its properties and application is shown in the table 1[1]

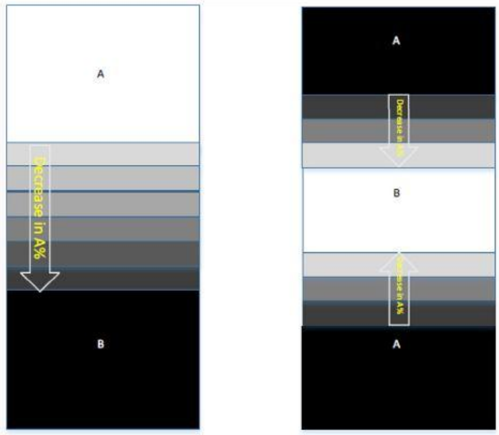


Figure 1. Functionally Graded Material [1]

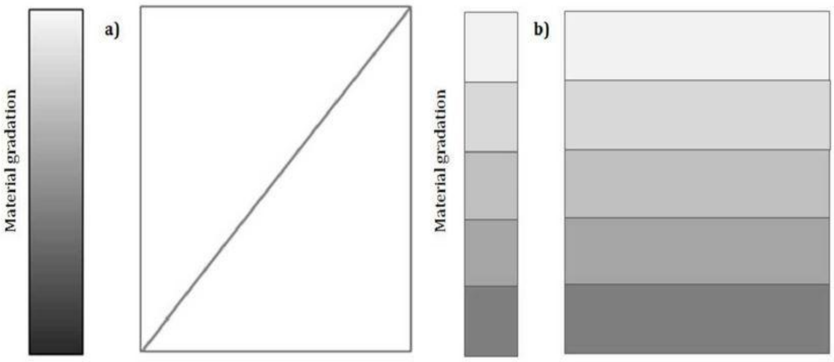


Figure 2. Different Graded Surface[2]

The developed FGM material needs to be machined to the require size and shape. The gradual variation of the material property provides challenges in the selection of the machining parameters. There exist established procedures for the machining parameters for the conventional and homogenous materials. However, for the case of FGM, due to the heterogenous nature, the machining parameters needs to be modified according the layer wise material property. Most of the literature have discussed on the fabrication of FGM but in very few literatures are available on the machining of FGM. Due to its variation of the properties in each layer, machining of these kind of the materials is quite challenging. Electro Discharge Machining (EDM) is one of the non-traditional machining process to machine difficult-to-machine materials. The working of EDM is using the multiple occurring of sparks. This spark locally vaporises and melts the material which then flushed away by the dielectric flushing. The distribution of heat flux can be described by using the gaussian distribution. One of the major advantage of EDM is that, the work piece and tool are not in contact Hence, there will be less tool wear.

Table 1. List of Different FGM and its Application with Properties[1]

FGM type	Requirements	Application
SiC-Sic	Corrosion resistance and hardness	combustion chambers
Al-SiC	Hardness and toughness	Combustion Chambers
SiC/Al-alloy	Thermal resistance and chemical resistance	Diesel Engine pistons
E-glass/epoxy	Hardness and damping properties	Brake rotors, leaf springs
Al-C		Drive Shafts, Turbine wheels
Al-SiC		Flywheels, Racing car brakes
SiC/Al-alloy	High Melting point, high hardness	Pulleys, shock absorber
Al-alloy/CNT	Light weight and high stiffness	Eyeglass frame, wheelchair
Al-Si	Hardness and toughness	combustion chamber, brakes

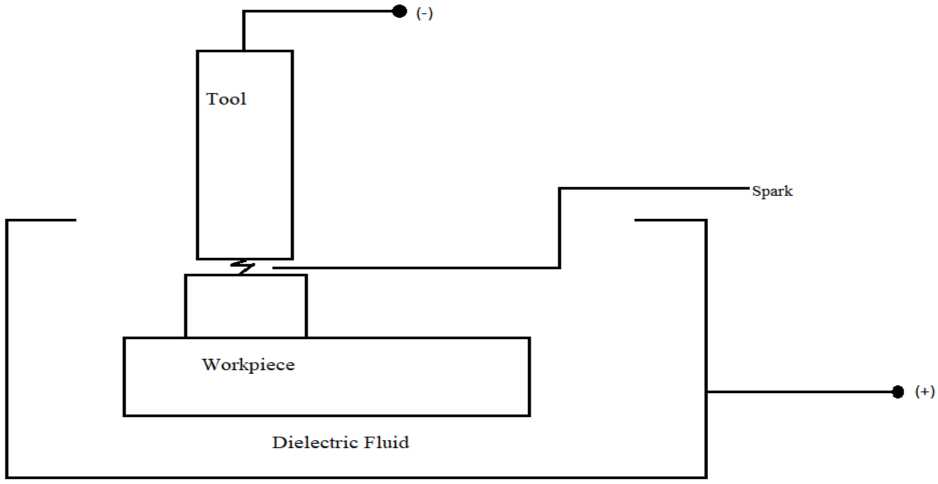


Figure 3. The EDM model and the spark formation on the workpiece

Shankar, Jain [3] a numerical analysis of spark discharge on EDM is proposed. The phenomena are occurring at microscopic level and suggested that the thermal diffusivity is directly proportional to spark radius. Singh, Singh [4] studied the EDM for machining process and have advised that the complicated shapes can be done with minimal cost is by using EDM. Here, they have studied the effect of various parameter like workpiece material, power, dielectric fluid etc on MRR. They found out that MRR is increasing with the increase of inputted current, and power. With the mixing of powder, the tool wear rate has been decreased significantly. Yildiz [5] found out that one of the most desirable machining process for electrically conductive material is EDM. By using theoretical thermal model and FEA model, MRR was evaluated and validated with an experimented study. The errors were minimal i.e. 1.98% of layer thickness and 3.34% of MRR.

Balaji and Yadava [6] have numerically simulating the Electro-discharge diamond surface grinding. It is a hybrid process where they have combined the EDM and grinding process. EDDSG is a surface grinding process. The complexity of this process includes the random occurrence of the spark during EDM process. Due to this spark the temperature variation occurred on the work-piece. Naebe and Shirvanimoghaddam [1] have explained the types of FGM material and their application and use of these materials in real like scenario. They have also discussed the fabrication process and how to control the process parameters. Most of the research have carried out work related to the ceramic or metal matrix. They found out the apart from several conventional traditional methods for fabrication of FGM, there are less utilized techniques that have more possibility of development in next generation like microwave sintering with more advanced additive manufacturing techniques.

Biermann, Menzel [7]they experimented on dry face turning on FGM of high treatable steel. The hardened zone is 60HRC and non-hardened zone is 30HRC. Meera Mirzana, Krishana Mohana Rao [8] in their work they have considered the metal-metal FGM disk and studied about the micro-structure. From the literature review of FGM it has been found out that the working or machining of the FGM is bit challenging due to the varying of the material properties. From literature of EDM, it can be summarised that the EDM process is effective for homogenous material. However, the FGM is a Heterogenous material if considered as whole but if it's taken layer wise it is homogenous material. Many methods have been used for machining of FGM. Mostly unconventional methods are used for preferred for FGM. The EDM is one of the unconventional machining process in which the workpiece and tool are not in contact with each other and this makes it more efficient to machine these kinds of advanced material. The objective of this work is to develop finite element model of a functionally graded material to numerically simulate the EDM on FGM material. And further to study the effect of process parameter on material removal rate.

2.Thermal modelling of EDM

2.1. Assumptions

Due to complicity in the machining of FGM by EDM, few assumptions have been considered to simplify the numerical modelling;

a. Layer wise distribution of FGM is considered.
b. Though the Entire FGM is considered as heterogenous material, and within each layer it is considered homogenous.
c. Thermal properties are temperature independent.
d. The spark is occurring at the middle of each layer was considered and in that, the whole spark radius in inside the respective layer.

2.2. Methodology

The transient temperature due to EDM process is given by

$$T_{TEDM} = T_0 + T_{EDM}$$

Where T_{TEDM} is total temperature rise due to EDM, T_0 is the ambient temperature and T_{EDM} is the temperature rise due to EDM process.

During the conductive process, the temperature distribution is governed by the Fourier heat transfer equation. The thermal diffusion differential equation in cylindrical coordinate system governs the temperature field during the EDM process,

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \theta}\left(k\frac{\partial T}{\partial \theta}\right)=C_s\rho\frac{\partial T}{\partial t} \quad (1)$$

Where r, ρ are cylindrical coordinate axes as shown in figure 4

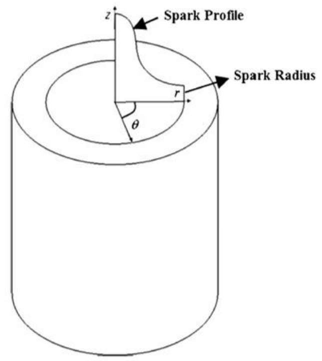


Figure 4. Thermal Model of EDM[6]

2.3. Initial Conditions

The coolant is in room temperature T_0 in which the workpiece is entirely dipped is taken as the initial conditions i.e. T= T_0 at t=0.

2.3.1. Boundary conditions

From the workpiece a small cylindrical piece around the spark is to be considered as the spark domain. The heat energy which is being transferred to the workpiece or domain acts as the thermal boundary condition on the top surface. Till the spark radius heat flux is given and the remaining part of the top surface works as a convection. The bottom face and the curve surface area of the domain is far away from the spark region due to which there is no heat transfer across them. The boundary conditions are,

$$k\frac{\partial T}{\partial n} = \begin{cases} h(T - T_o) & \text{for} \quad r > R_s, \quad 0 \leqslant \theta \leqslant 2\pi, \text{at } Z = 0 \\ q_{ws} & \text{for} \quad r \leqslant R_s, \quad 0 \leqslant \theta \leqslant 2\pi, \text{at } Z = 0 \\ 0 & \text{for} \quad \text{offtime} \end{cases} \tag{2}$$

$$k\frac{\partial T}{\partial n} = 0 \; on \tag{3}$$

The heat flux due to single spark is taken as single spark is taken as Gaussian Distribution and is given by,

$$q_{ws}(r) = \frac{4.55E_{ws}V_bI}{\pi R_s^2} exp\left\{-4.5\left(\frac{r}{R_s}\right)^2\right\} \tag{4}$$

Where, R_s - Radius of the spark, q_{ws} - Heat flux on the workpiece (w/m2), E_{ws} - Energy partition during the EDM process, V_b - The breakdown voltage (V), I - The discharge current(A), t_{on} - Discharge on-time (μs)

The spark radius during EDM process is,

$$R_s = (2.04*10^{-3})\, I^{0.43} t_{on}^{0.44} \tag{5}$$

3.Functionally Graded Material(FGM)

Aluminium and Silicon combination are considered for this work due to their vast application in the mechanical engineering domain. The Aluminium material generally considered light weight. Additionally, it is also having medium strength and high conductivity. The strength of the Al can be improved by combining with the Silica. Since, Silicon is hard and a semi-conductor in nature. The individual material properties of aluminium and Silicon are given below as shown in table 2. The layer wise distribution of material is considered. The percentage of Al-Si is each layer is shown in the Table 3.

Table 2. Material Properties of Aluminium and Silicon

Material Properties	Aluminium	Silicon
Density(kg/m^3)	2700	2329
Poisson Ratio	0.33	0.25
Melting point(°C)	854	1415
Thermal Conductivity(k) W/m.k	151-202	148
Specific Heat Capacity(C_p) J/kg.K	897	711.756

Table 3. Material Weight distribution of Aluminium and Silicon

Layers	Aluminium (%)	Silicon (%)
L1	100	-
L2	90	10
L3	80	20
L4	70	30
L5	60	40

3.1 Properties of Each Layer

As the work is related to thermal analysis, hence the thermal properties of the material such as Thermal Conductivity(K), Specific Heat(C_p), Density(ρ) are required for the simulation. The rule of mixture was used for the calculation of properties using the individual properties in the available proportion of each material. The sample estimation of the properties is shown below and the Table 4 shows the material property in each layer.

According to the table 4, the material properties will vary.

For first layer(L1) referred from tables 4 and 2:
Thermal Conductivity(K) = 175 W/m.K
Density(ρ) = 2700 kg/m^3
Specific Heat = 897 J/kg.K

Second Layer(L2):
Thermal Conductivity(K) = 175 of 90% + 148 of 10% = 172.3 W/m.K
Density(ρ) = 2700 of 90% + 2329 of 10% = 2662.9 kg/m^3
Specific Heat = 897 of 90% + 711.756 of 10% = 878.4 J/kg.K

Like L1 and L2, other layer's properties are calculated by using the "Rule of Mixture" shown in the table 4

Table 4. Material Properties in each layer

Layers	L1	L2	L3	L4	L5
K(W/m.k)	175	172.3	169.6	166.9	164.2
C_p (J/kg.K)	897	878.4	841.4	822.9	804.37
ρ(kg/m^3)	2700	2662.9	2625.8	2588.7	2551.6

4.Thermal FE simulation of EDM

The simulation of the EDM is carried out using the single spark analysis concept [5] which is the conventional approach for EDM simualtions. The spark region can be considered axis symmetric and gaussian distribution of heat flux was used for the spark heat input. The boundary condition was given as per Eq(2). Here, kerosene was used as the dielectric fluid with a convective coefficient of 10,000

W/m^2K. The domain is modelled as an axis symmetric rectangular region whose radius is twice the spark radius and the length is 4 times of the spark radius. The main reason to consider the height 4 times is, so that the domain is within the influence of the spark. The domain was discretized with the 8-noded brick element as shown in figure 5. The meshing was done using the spacing ratio, in way that the fine mesh was taken near to the spark point and gradually increased the mesh size at the last, to enhance the accuracy of the model. From the convergence test, it is revealed that the domain consist of 500 elements and 1591 nodes is adequate for the problem. The heat flux is applied on the top left corner where the mesh is finer for the EDM process. So that the value of the heat flux can be calculated in a small distance. The top surface is facing the spark of EDM, so heat flux is applied to the top surface and the outside the spark region of the top surface is given for convection. The transient analysis was performed using the ANSYS APDL codes.

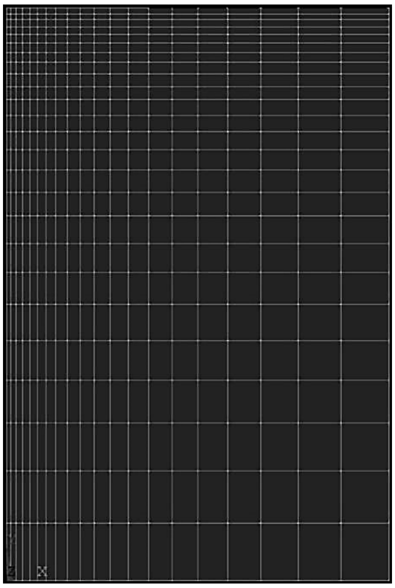


Figure 5. The simulation of EDM with fine mesh

5. Result and Discussion

The program which have been used in this EDM is developed by using the ANSYS APDL Programming tool. This program is solved in Mechanical APDL18.1. As the FGM's each layer is considered as homogenous material so the EDM model is been validated by comparing it with Balaji and Yadava [6] in figure 6 and it can been seen that the simulation is having good agreement with the with the crater radius however the crater depth as some differences. This difference is due to the formation of recast layer. However, in the simulation the molten material is assumed to be flushed out. But during the experiment some amount of the molten layer is solidifies and settles at the bottom of the crack depth. This results in the variation of the crater depth. Each layer of the FGM was given thermal properties as per the composition of the layer and as given in Table 4. The Material Removal Rate (MRR) was evaluated by varying the process parameter.

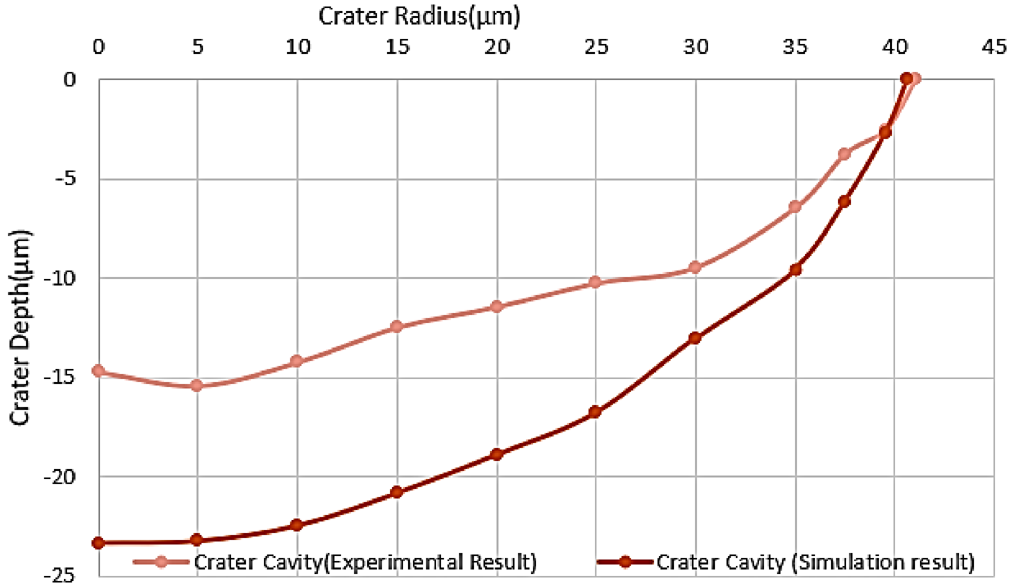
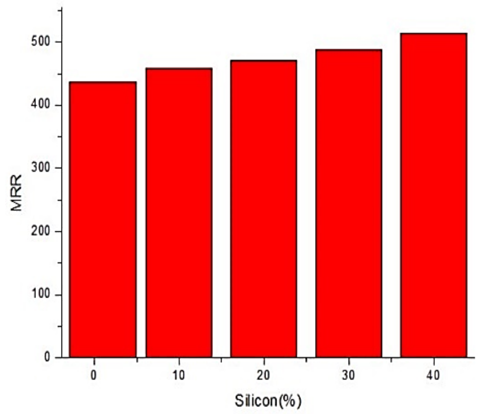


Figure 6. Comparison of experimental[6] and simulation results

Table 5. Different process Parameter

Discharge Voltage(V_b)	40	50	60
Discharge Current(A)	5	10	15
Energy Partition(E_{ws})	0.16	0.24	0.32

With the variation of different thermal properties, the MRR is found varying. As the silicon percentage is increased, the average thermal conductivity is decreasing which assist in the accumulation of the heat input which results in higher material removal rate as shown in the figure 7. With increasing voltage, the MRR is also found to be increasing. The higher voltage results in the increased heat input of the spark which leads to higher material removal rate.



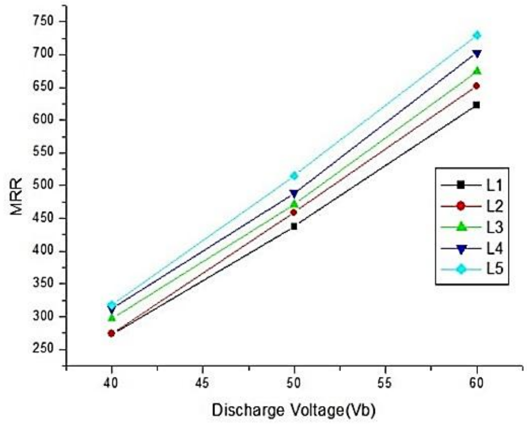
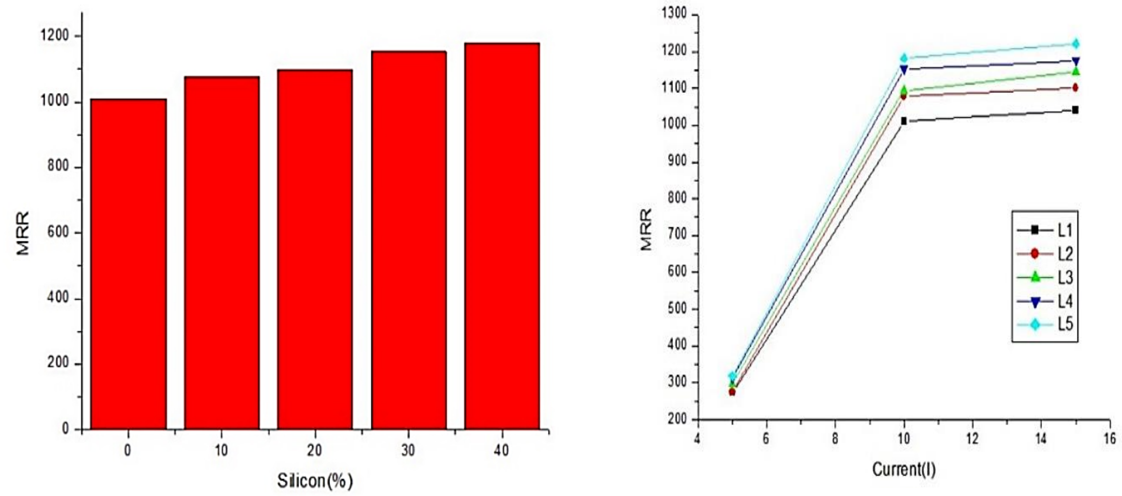


Figure 7. (A)Different thermal properties for different layers for V_b=50. (B)For different values of V_b i.e. 40, 50 and 60 for different layers



With increasing current, the MRR is also found to be increasing in figure 8. The higher current results in the increased heat input of the spark which leads to higher material removal rate.

Figure 8. (A)Different thermal properties for different layers for I=10. (B)For different values of I i.e. 5, 10 and 15 for different layers

With increasing current, the MRR is also found to be increasing in figure 9. The higher energy partition results in the increased heat input of the spark which leads to higher material removal rate.

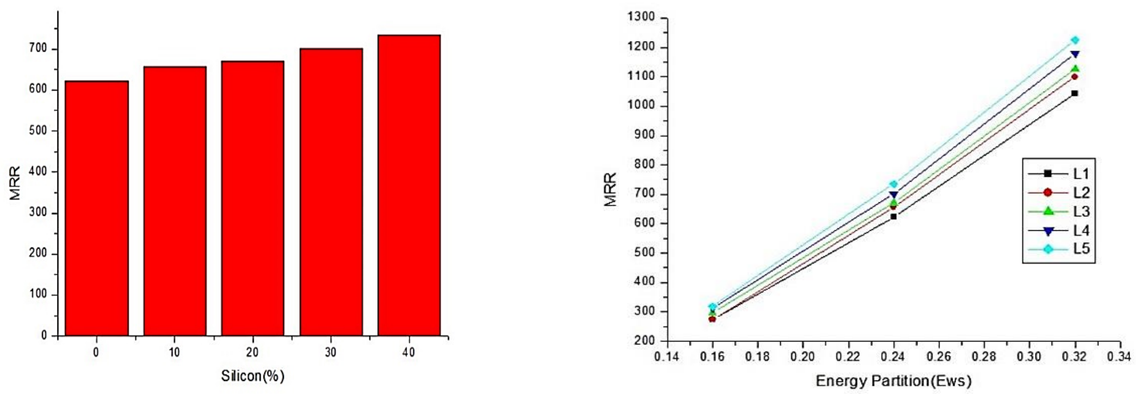


Figure 9. (a)Different thermal properties for different layers for Ews=0.24 (b)For different values of Ews i.e. 0.16, 0.24 and 0.32 for different layers.

In the figure 10 it is shown for L1 at Vb = 50V, I = 5A, the melting point of that layer is 858K. the red line which is shown is the melting line. Taking the coordinate of that line and putting it in CATIA software the volume can be determined.

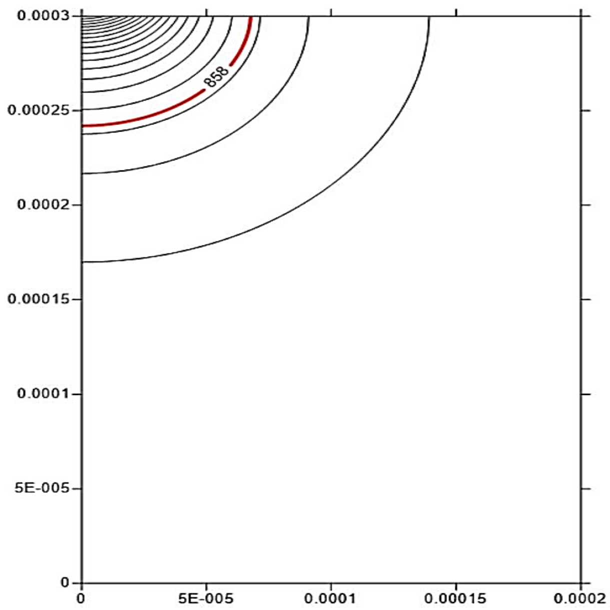


Figure 10. Temperature distribution of L1 for V_b=50

6. Conclusion:

The main objective of the work is to numerically simulate the EDM of FGM and to calculate the material removal rate with various process parameter on various layeres with different material properties. The simulation code is developed in ANSYS APDL and the temperature distribution which is found can be used to get the crater profile. From that profile the volume of the material removal and with respect to time MRR is found. The following conclusions are drawn in the present study

1. With the increase of silicon percentage, the MRR is increasing.
2. Higher the current, higher is the MRR.
3. Higher the Energy Partition, higher is the MRR.
4. Higher the discharge voltage, higher is the MRR.

7. Reference

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