Modeling and Simulation of Electrical Discharge Machining—A Review

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1 Introduction

Electrical discharge machining (EDM) is a non-conventional machining process where the material is removed following several short discharges between the workpiece and electrode, which are submerged within a dielectric. This process of EDM is very complex and the physical aspect of material removal remains unclear [1]. In general, attempts are being made to form a more comprehensive model that can help us understand the physics of EDM better [2]. Modeling in EDM is primarily focused on finding the material removal rate based upon electrothermal mechanism [3]. In several models, approach is to find the temperature distribution within the workpiece, using single discharges, wherein assumptions are taken regarding the material properties of the workpiece. Many analytical and numerical models have been formulated to characterize EDM discharges [4].

Various models can be differentiated depending upon the definition assumed for heat source [5]. The simulation is done in these models to establish the shape of the crater and then later results are verified. The models employ various heat sources to obtain simulation results, and often the heat source is assumed to be a disk [6]. These simulated solutions still have been found to have considerable differences when compared to the original results for crater formations. Another characteristic distinguishing these models depends upon the material properties. Generally, the thermo-physical properties of the workpiece are considered not changing with temperature. Moreover, the majority of these models do not take into account the latent heat of vaporization or fusion. The main objective of writing this review paper is to reevaluate all the existing model literature in EDM process and further pave the way for future developing models. Though the information on various models is already present, unfortunately there are very few reviews available on modeling and simulation of EDM processes.

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2 Modeling in Electro-Discharge Machining Process

In EDM, the workpiece and tool are submerged in a dielectric fluid separated by a small gap approximately in the range of about 5–10 μm [7]. A spark generates due to a potential difference that breaks the dielectric medium. The high order of heat generation vaporizes some of the work and tool material due to which material removal takes place [8]. The spark is controlled due to which the material removal rate is according to the desired value. The complexity of this process is primarily due to the spark of the plasma, flushing condition of dielectric, dielectric medium, etc., and it becomes very tedious to observe the crater formation due to the spark formation [6, 9]. Thus to simplify calculations and estimate, the thickness of the layers formed in the crater modeling is done in the EDM process. Various models are modeled, and simulation is done to obtain the closest experimental values.

Modeling of EDM revolves around many aspects of the process. The models are broken down into generalized individual steps, from finding the location of discharge to estimating the input machining parameters [10]. A generalized model for electro-discharge machining is shown in Fig. 1. Usually, in the generalized model, problems are encountered in some steps, and thus, it is recommended to involve iterations. Therefore, it is impossible to formulate a simulation of the entire EDM process by copying all the steps in the generalized model. It is recommended to stimulate the specific part of the generalized model to gain a basic understanding of the mechanism involved in the EDM process, further optimization to be done related to machining parameters, and then planning the further process. In this review paper, the various models based on the generalized model pattern are discussed.

2.1 *Simulation in EDM Process*

The simulation in the EDM process is usually characterized by two aspects the simulation of the arc plasma and the simulation of the material removal. Simulation of EDM arc plasma is done to estimate the boundary conditions and hence establish the temperature distribution in the EDM process. However, it is very complicated to model the arc plasma even if the gas discharge is assumed as steady. Further, the simulation in material removal owing to a single discharge helps us to establish a result for the EDM process as it is assumed to be cumulative of many discharges. The real problem, however, remains with the concept of single discharge material removal mechanism not being entirely clear. Another simulation design is based on locating the location of discharge and deriving an algorithm to study it. Finally, the results are combined and the final geometry is established.

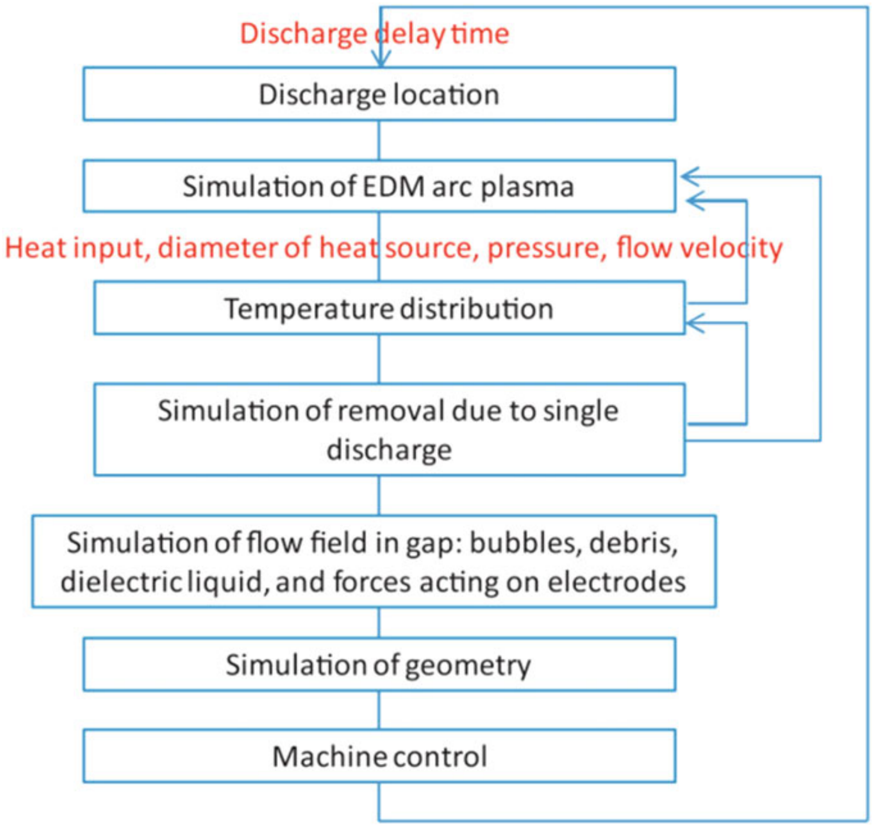


Fig. 1 Generalized model used in EDM process [11]

3 Various Types of Modeling in EDM Process

Since the early seventies models have been designed for electric discharge phenomena (plasma channel) and the mechanism of cathode and anode erosion in the EDM process, the two usually employed mechanisms to analyze the material removals are electromechanical analysis [12] for short discharge pulses (less than 5 μs) and electrothermal analysis [13–15] for conventional EDM process which usually involves the removal of the material due to the intense plasma energy generated between the cathode and anode. The electrothermal EDM analysis is of primal importance today. The material removal rate in EDM is generally estimated based on an electrothermal mechanism [6, 12, 16, 17]. In most models, the temperature distribution is done based upon a specific modeled heat source, and the volume of material that achieves temperatures higher than the melting temperature is assumed to be removed.

The distinguishing factor between different models is the application of heat sources. A heat source is usually assumed to be a point heat source [18]. In several models, the heat source is assumed to be a disk and then used for modeling [19]. The use of a Gaussian distributed heat source is used to calculate the temperature distribution, and then a solution is formulated in the form of a partial differential equation [20]. Another parameter while EDM modeling is the shape of the crater. Analytical solutions are mostly derived that determine the crater and molten pool.

3.1 Empirical Modeling in EDM Process

The empirical method is employed to formulate a thermal model via an energy distribution ratio that will determine the crater geometry and help us find the material removal during the EDM process. The energy distribution is formulated by iterating a simulation model that will eventually enable us to find the energy distribution ratio, and the simulation process is repeated until the values of the simulation are close enough to the actual values [5]. Use of these empirical methods has been employed in both micro and macro EDM to evaluate the energy distribution ratio [21]. The empirical methods, however, are a little less reliable when compared to the temperature-rising methods [22]. Jeswani et al. [23] for their 3-D empirical EDM model used a dimensional analysis approach considering pulse on time, spark frequency, gap current, gap voltage, and material properties as input parameters to find out the wear of the tool.

Van Dijck et al. [24] computed the temperature distribution in the plasma channel and the surface of electrodes to form a temperature-based empirical model for EDM. The figure shown was used to evaluate the melting volume per pulse at both electrodes. This volume found from the figure is then used in reference to Pappus–Guldin theorem, and the solid volume generated is found. Further, an FEA model was also formulated to estimate the surface roughness. Various thermo-physical models were formed in EDM, a thermal–structural model was formulated to study the relation between the process variables and the output machining parameters such as MRR, tool wear, and retained stresses [25]. A model formulation was done based on understanding the EDM plasma channel formed in the heat flux during the process [26]. A more realistic numerical model is formulated based on the thermal analysis, where the analysis is done on a small portion of the workpiece around the region of spark. The small portion is assumed to be cylindrical, and the boundary conditions are evaluated using the Gaussian distribution of heat. The boundary conditions as shown in Fig. 2 are solved using FEM software Ansys [27]. The properties of the materials including thermal conductivity, specific heat, and density were taken into account while solving the boundary conditions. The simulation results were used to obtain the crater and temperature distribution. The material removal rate was evaluated using Eq. 1.

$$\text{MRR} = \{(C_v \times 60)/(T_{\text{on}} + T_{\text{off}})\} \quad (1)$$

where C_v—Volume of the cavity above melting point temperature in mm^3, T_{on}—Pulse on time in µs, and T_{off}—is Pulse off time in µs and MRR unit is mm^3/min.

3.2 Semiempirical Modeling in EDM Process

Researchers developed several semiempirical models that would help us evaluate material removal rate, surface finish, and wear of the tool using the design of experiments. Patel et al. [28] designed the anode erosion empirical EDM model that used Gaussian distributed heat flux as the basis to evaluate the boundary conditions at the anode. A very unique approach to formulating an empirical EDM model via an artificial neural network was established by Gopal and Rajurkar [29]. Tsai and Wang [30] formulated the artificial neural model based on MRR and then compared the results to the actual experiments and found them to be in order. Machining parameters, namely the tool radii, depth of offset, duration of the pulse, peak current, depth of cut, were considered. Further, the ANN model was verified to give better and faster results compared to other models (Fig. 3).

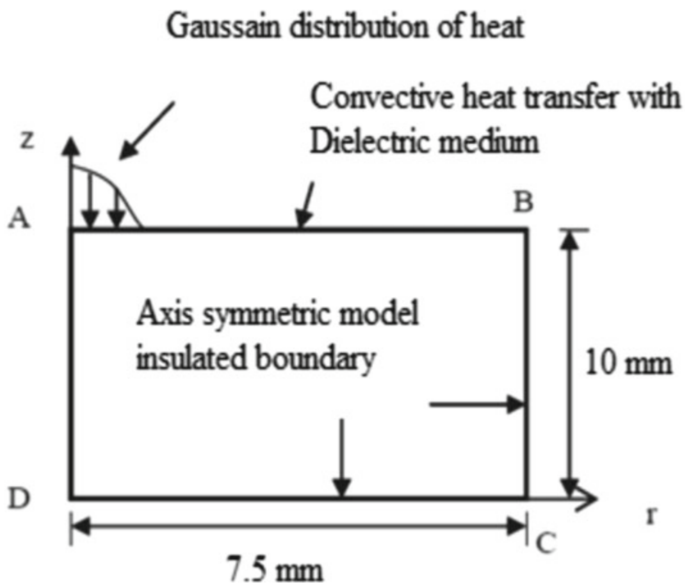
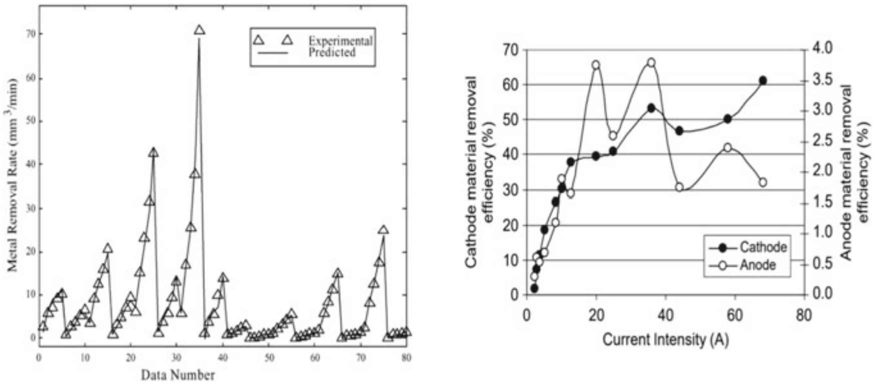


Fig. 2 Boundary conditions subjected to the workpiece [27]



(a) (b)

Fig. 3 Material removal rate results in (**a**) ANN model (**b**) anode erosion model [28, 29]

4 Conclusions

In conclusion, the empirical and semiempirical models discussed had obtained the best simulation results when they were did not assume the work material to be homogenous and the material properties were considered temperature-dependent. In addition to this, the latent heats of fusion and vaporization had a major involvement in the simulation results. The various empirical models which were based on thermal analysis have a limited scope of applicability, as they assume the spark radius to be a constant; further, the heat source is reduced to a point and thermal properties are assumed for homogenous and isotropic materials for work/tool materials. Thus, there remains a further need for developing a more realistic and concise mathematical model for thermal analysis in EDM process which can help us predict and analyze the crater more accurately by modifying the assumptions and obtaining precise experimental values. Finally, a good correlation between simulation and experimental results can be established by using a time-dependent heat source and taking into account the temperature-dependent material properties and the latent heats of fusion and vaporization.

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