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On the Use of Deformed Geometry in EDM Modelling: Comparative Study

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Electrical Discharge Machining (EDM) is one of the earliest non-conventional machining processes, which still finds extensive application in modern industry. It is a non-contact process, with capability to handle any conductive material, regardless of other properties, like its strength and hardness. In EDM, the material is removed by repetitive sparks, which melt and ablate material from the machined surface. In this way, high dimensional accuracy can be achieved along with the creation of complex shapes and geometries. There are many machining parameters that affect the process, which have a nonlinear effect to the final machining result. Thus, modelling and simulation of the process provide an advantage on understanding the undergoing physical phenomena, and the subsequent optimization of the process. Nevertheless, there are many aspects that have to be taken into consideration, in order for realistic and accurate results to emerge from simulations. The most common method of modelling the EDM is by simulating a single spark caused by plasma channel. One crucial parameter is the use of a deforming geometry with moving mesh, to simulate the heat transfer and the simultaneous material removal. The current paper presents a comparative study of EDM modelling and simulation, between a constant mesh model and a moving mesh one. Heat transfer models are solved, with same thermal boundary conditions, but they differ in the use of a constant or a moving mesh.

topics: Electrical Discharge Machining, modeling and simulation, moving mesh

1. Introduction

Electrical Discharge Machining is a non-conventional machining process, which is widely used in machining conductive materials, in complex shapes and geometries, regardless their hardness, or other physical properties. EDM utilizes repetitive electrical sparks to remove material from a workpiece [1]. During EDM, successive electrical pulses form plasma channels between the electrode and the workpiece melt and/or ablate material from the workpiece. At the end of the electric pulse, and as the plasma channel collapses, a fraction of the melted material is removed from the workpiece.

Along with the experimental studies, which are conducted for a better understanding and optimization of EDM, modeling and simulation of EDM is a powerful tool towards that effort. Nevertheless, it is a real challenge, as complex thermo-physical phenomena are taking place, and so, assumptions and simplifications are necessary. As a result of this complexity, there is not a commonly accepted and robust modeling method. Weingärtner et al. [2] studied how different types of heat sources influence the simulated crater in EDM modelling. The comparison was made between a point heat source, a disc heat source and a time dependent heat source, and other modelling parameters, as well as the material thermo-physical properties, and the latent heat of melting and evaporation. Tlili et al. [3] presented a model that integrates the assumption of the instantaneous material removal throughout the pulse-on time, and the evolution of the boundary conditions as a result of the growth of the plasma channel and the instantaneous modification of the crater shape. Assarzadeh et al. [4] suggested a Finite Element Model (FEM), making the assumptions of a Gaussian non-uniform heat source distribution, a spark radius that grows over time, and temperature dependent material properties. They concluded that their model presents higher prediction accuracy in comparison with models which are adopting point or disc heat sources. Finally, Tang et al. [5] developed a thermo-hydraulic model, using the level-set method, to simulate the crater formation process in EDM.

The current paper presents a comparison on the use of deformed geometry in EDM modeling. Simulations with and without the use of deformed geometry have been carried out using the same machining parameters. The deviation in results from adopting different semi-empirical relations for the plasma radius estimation was studied as well.

2. Modeling methodology

For both models, the following general and necessary assumptions/simplifications have been made:

- Conduction is considered as the primary mode of heat transfer.
- The material is homogeneous and isotropic, with temperature dependent properties.
- All discharges during the process are considered identical.
- The current pulse has a trapezoid waveform, reaching its nominal peak value in the first 10% of the pulse-on time, and zeroes in the last 5% [6].
- The plasma channel heat flux is approached as heat source with Gaussian distribution [7].
- The plasma channel radius and the workpiece heat absorption coefficient, are estimated as a function of the pulse-on current I_P and the pulse-on time T_{on} [7].

The mathematical model for conduction heat transfer is:

$$\rho C \frac{\partial T}{\partial t} - \nabla \left(k \nabla T\right) = Q_i \quad (1)$$

with temperature T, the density ρ, with the heat capacity C at a constant pressure C_p or for a constant volume C_V, with the thermal conductivity k and Q_i as a heat source or a heat sink.

The plasma heat flux power density is given by

$$Q_{pl} = \frac{V I_P F_W}{2\pi\sigma^2} \mathrm{e}^{-\frac{r^2}{2\sigma^2}} \quad (2)$$

where V is the machining voltage, I_P is the nominal pulse-on current, and F_W is the fraction of energy which is absorbed by the workpiece. The standard deviation σ is considered to be equal to three plasma channel radius, i.e., $\sigma = 3R_P$. For comparison reasons, two different semi-empirical relations for the plasma radius estimation are adopted [1]:

$$R_{P1} = 2.04 I_P^{0.43} T_{\mathrm{on}}^{0.44} \quad (3)$$

$$R_{P2} = 0.85 \times 10^3 I_P^{0.48} \left(10^{-6} T_{\mathrm{on}}\right)^{0.35} \quad (4)$$

with R_{P1} and R_{p2} the plasma channel radius, with the discharge peak current I_P, and the discharge duration T_{on} .

Based on the work of Shabgard et al. [7], the fraction of energy F_W in (%) can be expressed as:

$$F_W = 2.745 \times I_P^{-0.7701} T_{\mathrm{on}}^{-0.1411} R_{Pi} \quad (5)$$

with the discharge duration T_{on} and the plasma channel radius R_{Pi}.

The convection heat exchange of the top surface is mathematically described by

$$Q_{\mathrm{diel}} = h_{\mathrm{diel}} \left(T - T_{\mathrm{diel}}\right). \quad (6)$$

Above expression is understood as the heat flux from the workpiece to dielectric fluid due to convection, where h_{diel} is the heat transfer coefficient between the workpiece, and the dielectric fluid with value $h_{diel} = 100000$ W/(m^{2}K), and T_{diel} is the dielectric fluid temperature equal to 293.15 K.

Finally, the surface-to-ambient radiation is calculated using

$$Q_{\mathrm{rad}} = \varepsilon\sigma \left(T_{\mathrm{amb}}^4 - T^4\right). \quad (7)$$

The surface emissivity coefficient ε is defined as $\varepsilon = 0.75$ and ambient temperature as 293.15 K.

The normal mesh velocity is proportional to the material melting rate. One relevant assumption has to be made in order to define the normal mesh velocity, namely, when the material reaches temperature higher than the melting point, it has to be instantly removed. Thus, the boundary surface has to maintain as a maximum temperature value of the melting point, however a thermal flux is defined to remove the excess heat from the workpiece. The following expression applies:

$$Q_{\mathrm{melt}} = h_{\mathrm{melt}} (T_{\mathrm{melt}} - T), \quad (8)$$

where Q_{melt} is the heat flux due to material melting, T_{melt} is the material's melting temperature and h_{melt} denotes the heat transfer coefficient, which is zero for $T < T_{\mathrm{melt}}$ and takes a rapidly linearly increasing value for $T > T_{\mathrm{melt}}$.

The normal mesh velocity is given by:

$$\upsilon_{\mathrm{melt}} = \frac{\rho^{-1} Q_{\mathrm{melt}}}{C_p \left(T - T_{\mathrm{melt}}\right) + q_{LH}} \quad (9)$$

with υ_{melt} as the material's eroding velocity, the material's density ρ, the material's heat capacity C_p in, and q_{LH} the material's melting latent heat.

The theoretical Material Removal Rate (MRR) can be estimated according to the calculated crater volume. Based on the assumption of the identical sparks, the theoretical MRR is:

$$\mathrm{MRR}_{\mathrm{theor}} = 6 \times 10^7 \frac{V_{\mathrm{crat}} \eta f_{\mathrm{eff}}}{T_{\mathrm{on}}} \quad (10)$$

with the crater volume from a single spark V_{crat} which is calculated through simulation, and with η and f_{eff} as the duty factor and the efficiency of the process, respectively.

The Plasma Flushing Efficiency (PFE) is expressed as:

$$\mathrm{PFE} = \frac{\mathrm{MRR}_{\mathrm{exp}}}{\mathrm{MRR}_{\mathrm{theor}}} \quad (11)$$

with $\mathrm{MRR}_{\mathrm{exp}}$ the experimentally measured material removal rate. The PFE is a computational indicator of the proportion of the material that, after its melt, is eventually removed from the workpiece. The rest, in turn, forms a re-solidified and/or recondensed material volume, known as White Layer (WL). In other words, a 100% PFE means a zero-thickness WL, while an extremely low PFE indicates an extensive and thick WL, along with a notably low $\mathrm{MRR}_{\mathrm{exp}}$.

TABLE I

Simulation results.

No.	I_P [A]	T_{on} [μs]	PFE [%]			
			No Moving Mesh		Moving Mesh	
			Using R_{P1}	Using R_{P2}	Using R_{P1}	Using R_{P2}
1	12	300	82.6	38.1	97.4	29.0
2	15	500	101.7	46.7	113.8	35.1
3	12	300	59.0	29.2	66.7	21.6
4	15	500	98.8	46.9	104.1	33.7

For the simulations, and the respective experiments, AISI O1 work-steel was used as workpiece material, a copper electrode, 30 V close-circuit voltage, 12 A and 15 A pulse-on current, 300 and 500 μs pulse-on time, and 0.8 duty factor. Thus, in total, 16 simulations were carried out, four for each set of machining parameters [8].

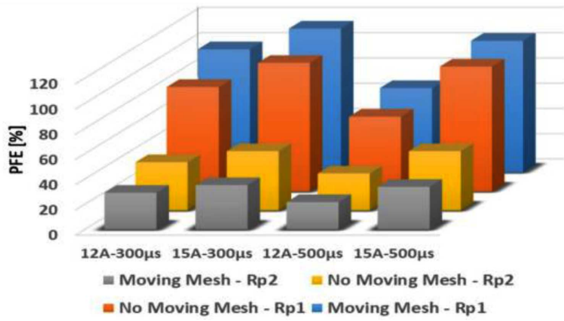

Fig. 1. Graphical presentation of the calculated results.

3. Results and discussion

The models' validation and their results are performed in terms of the calculated crater geometry and the PFE estimation according to the experimental MRR. From the theory, and according to experimental studies, it is known that the craters have elliptical shape, with the diameter being the ellipse's major axis. Moreover, the PFE must take reasonable values, indicating the existence of a WL with a realistic thickness, and permitting its calculation through simulation. In Table I and Fig. 1 the simulation results are presented.

The resulting PFE values follow the same pattern for all modeling methods. However when the R_{P1} value is used as the plasma radius, then the PFE is unrealistically high. It turns out that using (3) gives less accurate radius estimate than using (4), i.e., R_{P2}. This underestimation causes indirectly that the lower absorbed energy value arises, that a lower melt material volume is calculated, as well as a higher PFE. These observations allow to state that for the plasma radius calculation with (4), more realistic melting volume values are obtained, and thereinafter, even better PFE values that can explain and support the existence and formation of WL, which was observed in the experiments.

Various time steps that show the evolution of the crater formation are presented in Fig. 2, with and without the use of the deformed geometry. In the early part of the pulse, namely $t = 125$ μs, the difference is insignificant with similar crater shape. However, as the time passes, a differentiation occurs, which is clearly noticeable at the end of the pulse when $t = 500$ μs. This result clearly indicates how both the heat transfer and material removal are modeled simultaneously. As the heated surface is eroded, the heat transfer takes place in a more limited area, and so, the erosion rate is increased. Moreover, as the melted material is removed, the deposited thermal energy acts on "new" material volume without having to pass through the already melted one. Then, the erosion rate and the removed material volume increase. One can conclude therefore that the use of deformed geometry is more important in modeling EDM with high pulse-on time.

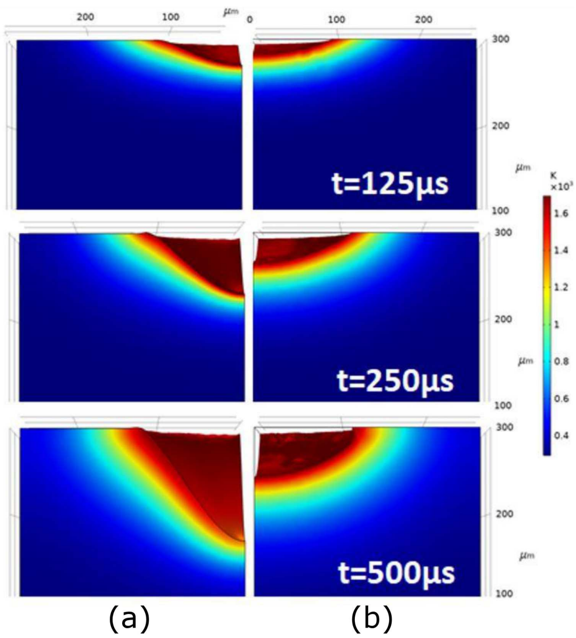

Fig. 2. Crater formation for I_P =15 A and $T_{\text{on}} = 500$ μs in different time steps (a) using deformed geometry and (b) without deformed geometry.

4. Conclusions

The current paper presents a comparison study for modeling EDM with different boundary conditions, both with and without the use of deformed geometry, along with heat transfer. In brief, the following conclusions were drawn:

- The selection of the proper semi-empirical relation for estimation of the plasma channel radius is important.
- The use of bigger plasma radius results in a more realistic PFE, which can explain the WL formation.
- The use of deformed geometry results to an increased erosion rate, and thus removed material volume, in contrast with the model that does not incorporate the deformed geometry feature.

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