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Prediction of white layer thickness and material removal rate in electrical discharge machining by thermal analyses

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ABSTRACT

Electrical discharge machining (EDM) is one of the best alternatives in machining of electrically conductive materials. However, recast or white layer formation is either unwanted or inevitable output of EDM processes. On the other hand, material removal rate (MRR) can be slow and its prediction is difficult in that process. Therefore, exact determination of these outputs is critical for EDM performance. In this study, white layer thickness and material removal rate were predicted by using a theoretical thermal model and 3D finite element (FE) model. Numerical solutions of these models were compared with results of an experimental study. When compared to thermal model, finite element analysis (FEA) produced in good agreement with the experimental results. Errors of mean results are 1.98% and 3.34% by FEA in prediction of white layer thickness and material removal rate respectively.

1. Introduction

Electrical discharge machining (EDM) is an advanced manufacturing process, having a wide range of application in industry. In this method, electrical energy is converted to thermal energy and this energy melts the subjected material. Because of sudden heating, melting and re-solidification processes, EDM'ed surfaces are transformed into different structure. These surface structures are different from the microstructure of the base material and characterized by heat affected zone (HAZ). This region contains recast/redeposited layer, hardened and annealed layers [1]. Recast layer is also called as white layer, because they are usually seen as white under microscope after proper etching process and microstructural investigation. These regions were represented in Fig. 1. Grinding, polishing and lapping are some of the post-EDM processes and these processes are used for removing of those layers. Magnetic abrasive finishing (MAF) [2] and surface integrity machining for EDM (SIME) [3] are other up-to-date methods developed for eliminating of surface defects such as cracks, micro-craters and recast layer. However, all of these processes can increase the manufacturing time and cost. For this reason, exact determination of recast layer can facilitate those processes.

EDM recast layer has been studied well enough by researchers. Most of the studies were made based on variation of recast layer thickness by EDM parameters such as discharge current and pulse time. In a recent work [4], influence of various EDM process parameters on white layer thickness was investigated. However, recast layers are usually determined by experimental techniques. These methods are required to establish some laboring processes such as polishing, etching and microscopic analysis. EDM recast layer thickness can also be determined by theoretical thermal models. Pandit and Rajurkar [5] developed a stochastic approach with the help of Data Dependent Systems (DDS) to thermal modeling of EDM. In this approach, an equation for the melting isothermal curve was defined from the profiles of actual machined surfaces. Then, this equation was combined with the heat conduction equation to develop a transient temperature distribution. The predictions of that model were closer to the experimental results in comparison to the models proposed in the literature. Nevertheless, results of thermal models might be flawed because of regarding simplified assumptions. Another way to characterize recast layer is to identify it with other surface integrity parameters such as micro-hardness, residual stress and micro cracks as proposed by Rajurkar [6]. Surface roughness is other surface integrity parameter to identify recast layer. In a study [7], empirical equations were established between white layer thickness and three dimensional surface texture and spatial surface texture parameters. Satisfactory correlation was found between the average white layer thickness and the spatial surface parameters. Correspondingly, in a recent study [8], another correlation was established between surface roughness data and recast layer thickness data obtained from image processing. The correlation obtained by that study has the capability to predict the

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Nomenclature

CD	crater diameter (m)
EDM	electrical discharge machining
FE	finite element
FEA	finite element analysis
FEM	finite element method
HAZ	heat affected zone
MRR	material removal rate (mm^3/s)
PHSM	point heat-source model
WLT	white layer thickness (μm)
R^2	coefficient of determination
α	thermal diffusivity (m^2/s)
ρ	material density (kg/m^3)
C_p	specific heat (Wh/kg °C)
erfc	error function
F_c	fraction of power (%)
I_d	discharge current (A)
K_T	thermal conductivity (W/m °C)
m,n	empirical constants
N_p	number of pulses
P_t	total power (W)
Q_C	heat flux based on disk heat source model (W/mm^2)
q_c	heat flux based on point heat source model (W/mm)
r	radial axis or radial distance from the origin (m)
r_m	melt cavity radius (m)
r_p	plasma or discharge channel radius (mm)
r_r	recrystallization radius (m)
t	time (s)
t_{on}	pulse-on time or discharge duration (μs)
t_{off}	pulse-off time or idling time (μs)
t_{mach}	machining time (s)
T	temperature (°C)
T_0	ambient temperature (°C)
T_m	temperature on melt radius (°C)
T_r	reference temperature (°C)
V_c	volume of the melted crater (mm^3)
V_d	discharge voltage (V)
z	vertical axis (m)

recast layer thickness. However, these methods may also be flawed by considering different type of materials.

Determination of the white layer thickness by using finite element method (FEM) can be an alternative to all approaches stated above. Sundaram and Yeo [9] developed a FE model to simulate of single-spark machining during micro-electro-discharge machining. A Gaussian distribution of the heat source was used in that study to perform transient thermal analysis. Main objectives of that study were to estimate the crater size, temperature distribution on workpiece and residual stress on and near the crater. The diameter-to-depth ratios of the crater obtained by simulation and by experiment were close to each other. Marafona and Chousal [10] developed a thermal-electrical finite element model based on Joule heating effect for EDM. In that model, a cylindrical shape discharge channel is created between anode and cathode materials as an electrical conductor and heat dissipation element. The radius of the conductor is a function of discharge current and pulse time. FEA results of tool wear ratio, material removal rate and surface roughness were compared with the experimental results of other related studies in literature and reasonable agreement was reported. Shabgard et al. [11] studied on prediction of white layer thickness, heat affected zone, and surface roughness by 3D-FEA in EDM process. A good agreement was found between experimental and the numerical results.

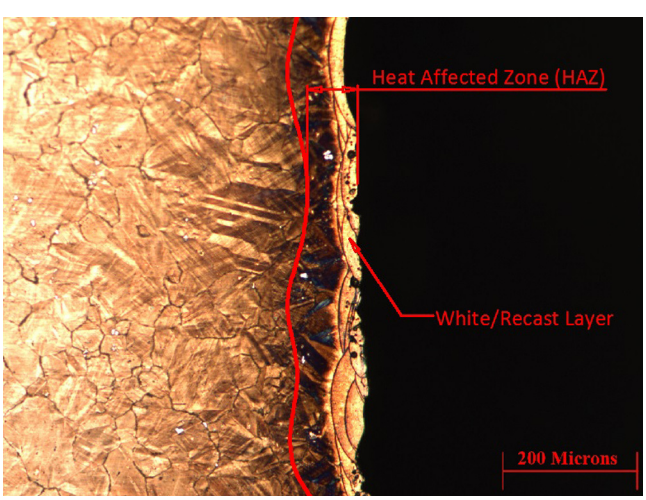

Fig. 1. Representation of heat affected zone (HAZ) and white/recast layer.

On the other hand, material removal rate (MRR) is the main performance measure of any EDM process. There are also lots of studies investigating material removal rate of EDM processes. Due to complexity of the process, experimental determination of MRR is also laborious. Taking into account all of these, white layer thickness and material removal rate have been predicted in this study by an efficient theoretical thermal model together with simplified FE model. Both white layer thickness and material removal rate were determined from the reference temperatures. Results of these analyses were compared with experimental results. The deviation of the predictions and the difference between predicted values and the experimental ones were also provided.

2. Modeling approaches

In this study, two main modeling approaches, theoretical thermal and FE were introduced together with an experimental model. A copper alloy (Cu–Be) was used in all modeling approaches as the workpiece material. Some properties of that material such as high electrical and thermal conductivity, corrosion resistance and good polishability make it widely used material in industry [12]. EDM offers a very good alternative in machining electrically conductive materials. Some temperature dependent properties of the copper alloy for the examinations were given in Table 1. It is assumed that the workpiece/cathode material is homogeneous and isotropic for the model solutions. The first assumption in terms of the material removal rate is that the molten material upon the border of the crater radius is completely removed at the end of discharge time (pulse-on-time). Therefore, boundary of crater radius is considered as isotherm of the melting temperature. The second assumption is that the crater is supposed to be hemispherical for numerical solution of the models. So, volume of the crater can be specified numerically from the isotherm profile where the temperature is greater than the melting temperature of the material.

Table 1
Some properties of the copper alloy.

Temperature (°C)	Density (kg/m^3)	Thermal conductivity (W/m °C)	Specific heat (J/kg °C)
20	8350	115	380
200	8275	153	480
300	8220	163	535