NUMERICAL ASSESSMENT OF RESIDUAL STRESSES INDUCED BY EDM PROCESS

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Abstract

We propose in this study an improved thermomechanical model in order to predict numerically the state of the residual stresses in the surface layers of parts, in AISI 316L, machined by EDM.The comparison of the numerical results with the experimental measurements shows a satisfactory prediction of the profile form and the max and min values of the residual stresses. However, a certain shift is still observed in the depths perturbed by the EDM process.

keywords:*EDM, numerical simulation, residual stresses*

1. Introduction

In order to calculate the residual stresses left by the electro-discharge machining process (EDM) within the surface layers of machined workpiece, it is necessary to model the coupled thermal, metallurgical and mechanical phenomena involved in the HAZ. In the case of steel type 316L, the absence of structural transformations in solid state allows to only deal with a thermomechanical problem. The main metallurgical phenomena to be taken into account in this case are the melting and the vaporization of the material.The mechanical phenomena induced by heat are expansion and shrinkage due to changes of temperature, and the temperature dependency of the mechanical properties. Conversely, the thermal phenomenon induced by the mechanical is the intrinsic dissipation: the evolution of the irreversible deformation and internal variables of hardening leads to a dissipation of energy as heat. However, thesuppliedheat of a mechanical origin is often negligible compared to that provided by the EDM process.

In order to achieve an accurate prediction and calculus of the residual stresses left by the EDM process, a fully coupled thermomechanical consistent model is required and to make the problem mathematically available, the subsequent main assumptions were made [1]:

- The model is developed for a single spark;
- Two-dimensional axisymmetric work domain;
- The temperature-dependent material properties are homogeneous and isotropic;
- During the EDM operation, heat is transferred from plasma to workpiece only by conduction;
- Base movements or jumping of the plasma channel are neglected;

Two main phenomena are taken into account here in this study to enhance the accuracy and to be more close to the real physics of the EDM process. the first is the latent heat of fusion and vaporization and the second is the time-dependency of the discharge current.Other specific assumptions will be mentioned throughout this paper.

In the following, we will present a summary and the essential of the thermo-mechanical model used to calculate the residual stresses at the end of an electrical discharge.

2. Thermal model

EDM is, basically, a thermal process where the spark energy is absorbed in the metals through interaction between plasma and mater [2] by means of two mechanisms. The first is the high density of ionic impacts which transmit their kinetic energy to the surface of machined part (cathode) and the second is the high current densities in the hot spot region which yields to a joule heating phenomenon [2, 3].

The main purpose of the thermal model assumed in this study is to calculate accurately the temperature diffusion and evolution, during the heating and cooling stages, in order to compute efficiently the thermal expansion which, represent the principal mechanical load.

2.1. Heat source model

The heat Q incoming the workpiece due to electric discharge is given by eq. (1) [9].

$$Q(r,t) = \frac{4.57 \cdot U \cdot I(t) \cdot Fc}{\pi \cdot R(t)^2} \cdot \exp\left(-4.5 \cdot \left(\frac{r}{R(t)} \right)^2 \right) \qquad (1)$$

Where U and I are the discharge voltage and current, respectively and r the radial distance from the plasma center and $R(t)$ the time-dependent plasma radius and Fc=18% is theenergy fraction transferred to the workpiece according to DiBitonto et al. [4] and Yeo SH et al.[5]and S. Assarzadeh et al. [6].

The machining parameters used in this study are listed in table 1:

Table 1: EDM machining parameters

Discharge current (A)	5
Discharge voltage (V)	46
Discharge duration t_{on} (µs)	5

2.2. Discharge current function

As defined in Eq. (1) the heat flux becomes infinite when the discharge time is in the nanosecond regime. To avoid this numerical singularity Y.B. Guo et al. [7] proposed to define the evolution of the current by the following three functions that are activated sequentially in accordance with the natural evolution of the signal during an electric discharge.

$$I(t) = K_1 \cdot t^n, \quad t \in [0, T_1] \quad (2)$$

$$I(t) = K_2, \quad t \in [T_1, T_e - T_2] \quad (3)$$

$$I(t) = K_3 t + b, \quad t \in [T_e - T_2, T_e] \quad (4)$$

T_1 and T_2 are assumed to be 2.5% of the discharge duration t_{on} [24], K2=I, K1=1.92E+21, K3=1.20E+08, b=1.20E+03

2.3. Plasma expansion model

The expansion of the plasma canal was modeled using the following equation. [1, 8]

$$R(t) = 0.788 \cdot t^{3/4} \quad (5)$$

2.4. Heat diffusion

The heat conduction problem is assumed axisymmetricand without internal heat generation. the partial differential equation for heat conduction problem is given as:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot \left(K_t \nabla T \right) \quad (6)$$

The Density ρ and the heat capacity C_p and the thermal conductivity K_t are assumed to be temperature dependent.

2.5. Latent heat of fusion

To enhance the thermal simulation accuracy, it is important to take account of the latent heat of fusion and vaporization. an explicit manner is used to take in latent heat by replacing C_p in (6) by an effective specific heat defined as:

$$C_p^{eff} = C_p + \frac{L_{1\to 2}}{\Delta T_{1\to 2}} \quad (7)$$

Where $L_{1\to 2}$ is the latent heat from phase 1 to phase 2 and $\Delta T_{1\to 2}$ is the temperature transition interval from phase 1 to phase 2.

3. Mechanical model

3.1. Elastic behavior

The elastic deformation rate is given by Hooke's law:

$$\underline{\sigma} = \underline{\underline{A}} \cdot \underline{\varepsilon}^e = \underline{\underline{A}} \left(\underline{\varepsilon}^{total} - \underline{\varepsilon}^{ther} - \underline{\varepsilon}^p \right) \quad (8)$$

The thermal deformation, in the absence of metallurgical phases changes is written as:

$$\underline{\varepsilon}^{ther} = \alpha(T) \cdot \left(T - T^{ref} \right) \cdot \underline{I} \quad (9)$$

α being the thermal expansion coefficient, T^{ref} the reference temperature at which the thermal expansion is zero, and $\underline{I}$ the identity matrix.

3.2. Plastic behavior

With the decrease of the yield stress with temperature and the increase of thermal stresses in a confined zone, plasticity occurs with incompatible plastic strains. At high temperature the material exhibits a time-dependent behavior and then viscosity should be introduced. But in EDM process the temperature can easily rise to thousands and falls down to room temperature within few microseconds and under these conditions, the identification and calibration of the time-dependent plasticity model is a highly challenge technical issue. To overcome this difficulty, the time-independent plasticity model has been retained using the isotropic Von Mises plasticity criterion, with associated flow rule. The elastic domain is defined by:

$$f\left(\underline{\sigma}\right) = \sigma_{mises} - \sigma_{ys} < 0 \quad (10)$$

With σ_{ys} the yield stress and σ_{mises} the Von Mises equivalent stress. The flow rule is given by:

$$\dot{\underline{\varepsilon}}^p = \dot{\lambda} \frac{\partial f\left(\underline{\sigma}\right)}{\partial \underline{\sigma}} = \dot{\lambda} \frac{3}{2} \cdot \frac{\underline{\sigma}'}{\sigma^{mises}} \quad (11)$$

The flow rule is then accompanied by a linear hardening, which involves a linear hardening modulus $h(T)$:

$$\sigma_{ys}\left(T, \varepsilon_{pe}\right) = \sigma_{ys0}(T) + h(T) \cdot \varepsilon_{pe} \quad (12)$$

$\sigma_{ys0}(T)$ is the initial yield stress at the temperature *T*, and ε_{pe} is theeffective plastic strain.

4. Discretization

COMSOL software was used to simulate the thermomechanical model presented above.The work domain is considered as a two-dimensional domain 500µm by 500µm (figure 1). Complete mesh consists of 6282 domain elements and 200 boundary elements.

Thermal boundary conditions:

- Border AD: symmetry -n·(-k∇T)=0
- Border BC and CD: constant Temperature T= 25°C
- Border AB:
    - Under plasma -n·(-k∇T)=Q(r,t) ,
    - away from plasma n·(-k∇T)=h·(T_ext-T)

Mechanical boundary conditions:

- Border AD: symmetry -n·u=0
- Border BC and CD : fixed Constraint u=0
- Border AB: Gaussian distributed pressure

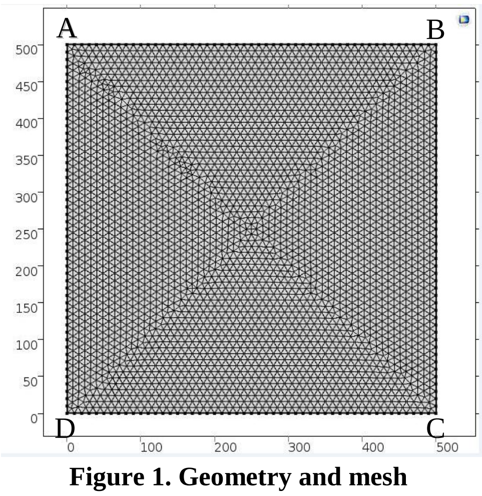

Figure 1. Geometry and mesh

5. Results

Numerical results are presented in the following.

Figure 2 shows the 2D temperature distribution within the workpiece at the end of the current discharge. The isotherm 1200 ° C delimits the molten pool.

Figure 3 showthe profiles of radial (σ_r) and angular (σ_{phi}) components of the residual stresses tensor. It can be easily seen the tensile character of the residual stresses induced in the heat affected layer of the EDM'ed workpiece.

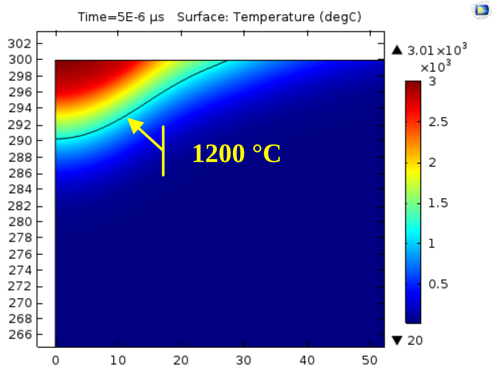

Figure 2. temperature distribution at 5 µs, the end of the current discharge

Figure 4shows a comparison between the components σ_{yy} of the experimental [10]and numericallycomputed residual stresses. when comparing numerical and experimental profiles, there is a discrepancy between them whose backgrounds still requires investigation and modeling effort.

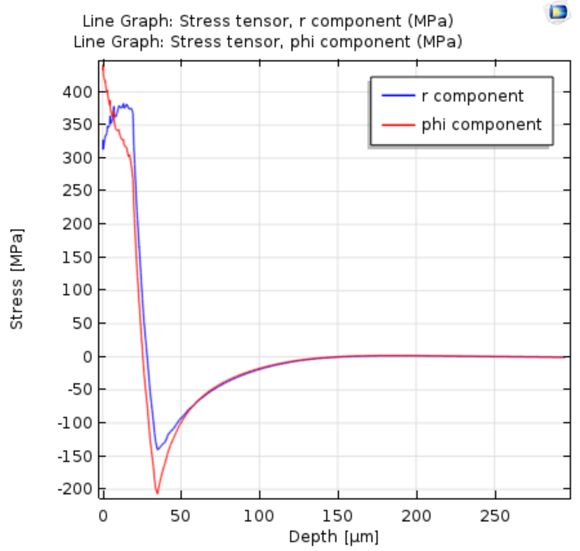

Figure 3. Profiles of radial (σ_r) and angular (σ_{phi}) component of the residual stresses tensor

6. Conclusion

In this study is presented a thermomechanical model for numerically predicting the residual stresses in the surface layers of the parts machined by EDM. The proposed model has been improved by taking into account the latent heat and the temporal evolution of the intensity of electric discharge.the results obtained are acceptable especially at the profile shape and the maximum and minimum values of the stresses. However, a shift is observed between the numerical and experimental results concerning the depths affected by the EDM process. A prospecting of the physical phenomena responsible for this shift is underway, especially at the pressures exerted by the plasma channel on the machined surface.

7. References

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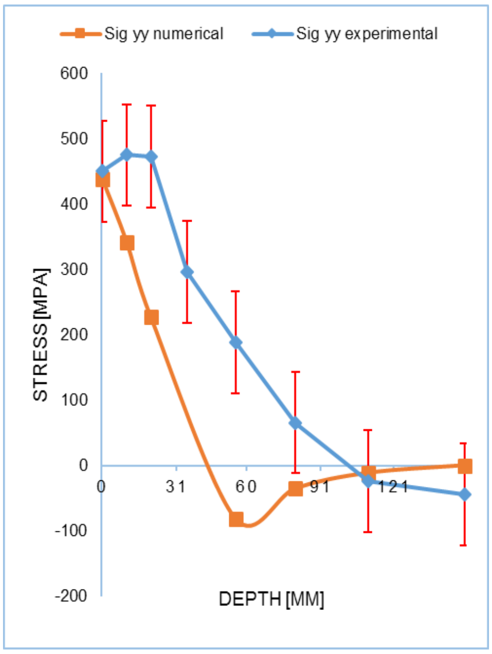

Figure 4. Numerical vs experimental σ_{yy} Profiles

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