FEM of Residual stress of EDMed Surfaces

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Keywords: EDM, residual stress, FEM

Abstract

Objective of the present work is to model EDM process using ANSYS software, and to investigate the effects of most significant machining parameters (pulse current and pulse duration) on the residual stresses developed in the beneath the spark produced by a single spark. The workpiece material is AISI D2 tool steel. The FEA model is then used to study the relation between these parameters and maximum temperature attended at the end of heating cycle along with residual stress produced at the end of cooling cycle. To establish the residual stresses in the work piece during EDM, the temperature distribution at the end of pulse duration in the work piece has to be estimated first, latter on after cooling the residual stress is determined. In addition, residual stress, which is the main aspect responsible for component failure, and the location of tensile peak stress, at the end of cooling cycle, are investigated.

Introduction

Electro Discharge Machining (EDM) is among the earliest nontraditional machining process that is most extensively used in industry. For making moulds, Punch & dies for blanking, shearing, and progressive die tooling, automatic stamping dies, the components/products used in biomedical, automobile, aircraft, and microelectronic industries. In the past 50 years, various researches have been done to develop and improve the different model of material removal from both tool and workpiece. Many research works are also carried out on experimental as well as theoretical estimation of MRR, surface finish, surface integrity, metallurgical and chemical characteristics and mechanical properties.

The electric spark among the anode and the cathode produces huge heat over a tiny area of the work piece. A fraction of the produced heat is conducted through the cathode (8%), a fraction is conducted through the anode (18%), and the rest is dissipating by the dielectric [1]. The formation of surface cracks has attributed to the differentials of high contraction stresses exceeding the material’s ultimate tensile stress within the white layer. Mamalis el al. [2] experimentally investigated on low-carbon steel ST37, medium carbon steel C45 and alloyed steel 100Cr6 work piece and found that the peak stresses are almost independent of the discharge energy and approach the ultimate tensile strength of the material. Rebelo el al. [3] in his investigation using XRD methodology found that the residual stress of steel work piece increases from the bulk material to a maximum and decreases again approaching the surface. In addition, the peak stresses are almost independent of the discharge energy and the greater the discharge energy, the greater the depth at which the maximum value of residual stress occurs. A qualitative relationship with the operating parameters was presented by Ekmekci el al. [4] using DIN 1.2738 (AISI P20) work piece material. For solving these problem present trends of most of the research work are devoted to numerical models based the finite element method. Yadav et al. [5] applied FEM to investigate the thermal stress generated by a single spark in EDM of Cr die steel. Marafona et al. [6] developed a thermal-electrical model for sparks generated by electrical discharge in a liquid media. He claims as innovative model, where he considered Joules heating factor.

Although EDM is quite old, only a few theoretical and numerical studies on the EDM exist, mainly due to the complex physics involved in this process. The EDM process mixes indeed breakdown of liquids, plasma physics, heat transfer, radiation, hydrodynamics, materials science, and electrodynamics. The existing models still contain several parameters, which are empirically determined, or artificially introduced. Different works that aim at EDM modelling were limited to the temperature field prediction. The prediction of residual stresses has been rarely attempted. Efforts are made to model the process to understand the behaviour of process and influence of the machining parameters on the responses in order to trim down the experimental cost associated.

Theory and Formulation

In recent years, the finite element method has become the prominent method for computer prediction. In the present study, an attempt to FE model, simulate and analyze the temperature profile and residual stress during a single spark in a liquid dielectric media for an axisymmetric domain. A thermal-electrical model is being developed for spark generation by electrical discharge. During the spark, the dielectric medium break downs and the current start flowing between electrode and workpiece. The following assumptions are made due to the random and complex nature of EDM.

i. The domain is considered axisymmetric.
ii. Material is homogeneous and isotropic.
iii. Workpiece material is stress-free before EDM.
iv. Heat transfer to the workpiece is by conduction.
v. Gaussian heat flux distribution on spark incident surface of the workpiece material during pulse time period.
vi. Inertia and body force effect are negligible during stress development.

The workpiece is represented by a semi-infinite rectangle bounded by four boundaries Γ1, Γ2, Γ3 and Γ4 as shown Fig. 1. The coordinate axes are r and z, where z is the axis of symmetry. The process consists of heating period (T_{on}) and cooling period (T_{off}). The initial and boundary conditions for heating period are listed below.

- Q(r) if r=R on boundary Γ1.
- $h_f (T - T_0)$ if r > R on boundary Γ1.
- $\partial T/\partial t = 0$ on boundaries Γ2, Γ3 and Γ4.

Whereas, the initial and boundary conditions for cooling period are listed below.

- $h_f (T - T_0)$ on boundary Γ1.
- $\partial T/\partial t = 0$ on boundaries Γ2, Γ3 and Γ4.

Where Q(r) is the heat flux entering the workpiece during the on-time and it has a zero magnitude during the off-time, R the spark radius, h_f the heat transfer coefficient for the dielectric fluid. Temperature of workpiece is T and T_0 is initial room temperature (300K). Heat flux entering the workpiece due to spark energy is assumed to be Gaussian distribution [7]. Heating of workpiece due to a single spark is assumed to be axisymmetric and the governed by the thermal diffusion differential equation [8].

ANSYS software [9] is used to model EDM with respect to changing voltage and current conditions with time. An axisymmetric model was created with a dimension of 60μm×60μm. A sequentially coupled thermal-structural analysis is performed in this study using the commercial FEM package ANSYS. The model is employed with element type Plane 55 for the thermal analysis and Plane 42 for the structural analysis. Owing to the workpiece material's temperature dependent thermo-physical properties, this type of problem is of nonlinear characteristic. The workpiece undergoes through a heating and cooling cycle due to spark. This is modelled in the software by two load steps, namely, heating period and cooling period. The heating period T_{on} is assumed to be 100 µs and cooling period, T_{off} =1000µs. Just after the heating period those elements attain the melting temperature are killed and excluded from further analysis.

Residual stress distribution

Sharp temperature gradient caused by the rapid thermal cycle at the surface and thermal contraction of re-solidified material on the base material, in conjunction with plastic deformation, results of the formation of tensile residual stress. Residual stress trend perhaps changed by the metallurgical alteration relating volumetric changes, as it is well known that the martensitic transformation from austenite with a concurrent increase in specific volume of about 3% [10].

To understand the nature of residual stress entrapped in the workpiece after machining, the stresses developed at the end of cooling cycle are plotted. Fig. 3, Fig. 4 and Fig. 5 represents the radial, axial and shear components of the residual stress, respectively for I_p= 9A and Ton=100 µs. It can be noted that the plots represented the state of the workpiece after crater formation, so the graphs profiles are initiated beyond the crater volume.

In Fig. 3, the residual stress in the radial direction is illustrated. The compressive stress induced just beneath the crater, during pulse on time is converted to tensile stress at the end of cooling cycle. With the increasing distance from the crater, the stress decreases and changes to compressive in nature. The maximum radial tensile stress is observed just beneath the crater attains a maximum value of 670 MPa. However, the minimum value attained is -215 MPa, and both the extreme values are observed along the line of symmetry. Axial and shear component of residual stresses are found to be comparatively small, although the stress patterns are found to be quite analogous to radial component. The maximum value of 236 MPa and 171 MPa, and minimum value of -122 MPa and -129 MPa are observed, for the axial and shear components of residual stress, respectively.

The Von Mises residual stress distribution at the end of cooling cycle is illustrated in Fig.6, it can be seen that the stress increases from 1 MPa to 549 MPa, when moved towards the crater. The iso-stress lines are almost parallel and having the shape of the crater. At room temperature (300 K) the yield stress is 450 MPa, and hence the region at about 42.2 µm depth yields, which is shown in Fig. 6 for Ip=9 A and Ton=100 µs. These stresses are predominately tensile and on yielding sub surface cracks are developed. Similar, observations are made for various Ip/Ton parameter combinations 1/20, 1/100 and 9/20 and are found to be 11.5, 16.6, and 23.06 µm, respectively.

Conclusions

In the present study, a two-dimensional axisymmetric model was developed to predict the residual stresses in AISI D2 steel using ANSYS software. The simulation was done for a single spark with temperature-dependent material properties and at various pulse on/off time. It is very interesting to observe that the magnitudes of the radial component of the residual stresses acquired from FEM are dominant than other components for all the machining parameter combinations. Von Mises residual stress show that the workpiece yields upto a depth of 11.5, 16.6, 23.06 and 42.2 µm for 1/20, 1/100, 9/20 and 9/100 discharge current/ pulse on time parameter combinations, respectively. The magnitudes of the maximum tensile and compressive residual stresses are not effected by pulse energy, but the depth at which they occur, increases with the pulse energy.

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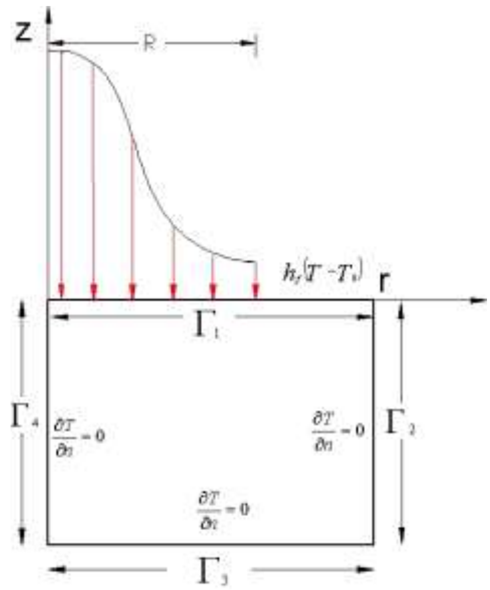

Figure 1 Axisymmetric thermal model

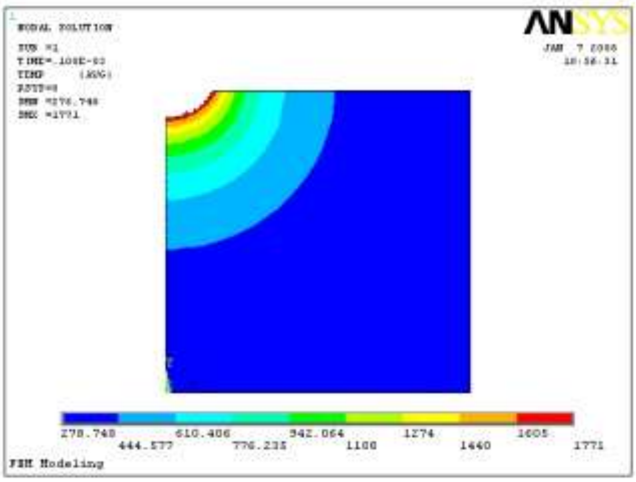

Figure 2 Temperature profile of workpiece after metal vaporization

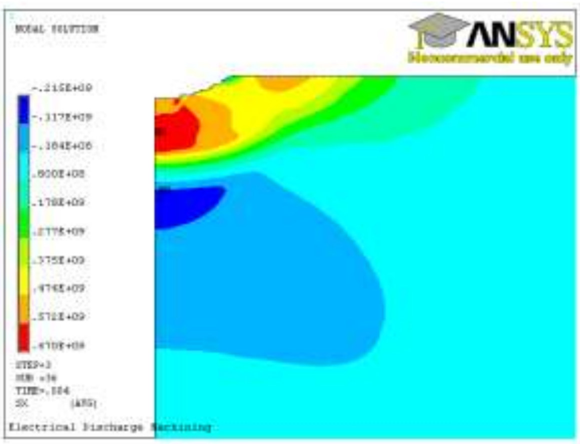

Figure 3 Radial component of residual stress (σ_{rr}) at the end of pulse period.

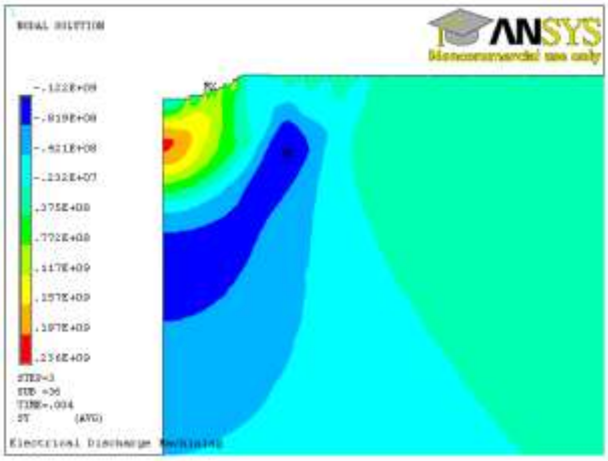

Figure 4 Axial component of residual stress (σ_{zz}) at the end of pulse period

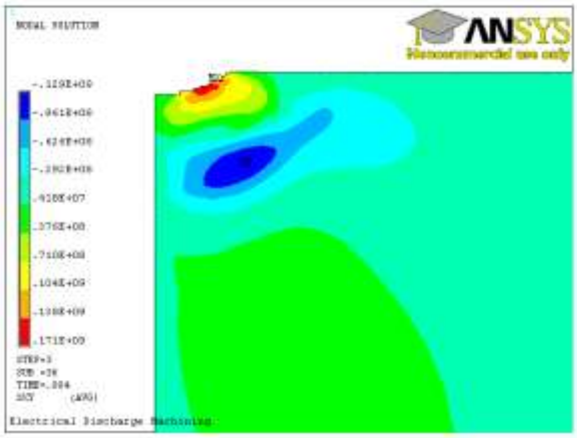

Figure 5 Shear component of residual stress (σ_{rz}) at the end of pulse period.

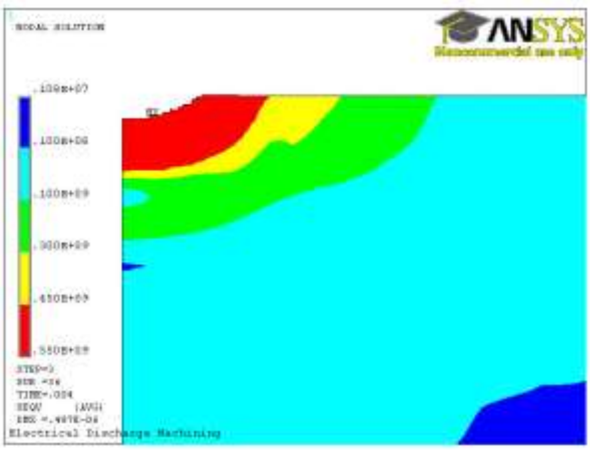

Figure 6 Von Misses residual stress at the end of pulse