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Residual Stress Modeling in Electric Discharge Machining (EDM) by Incorporating Massive Random Discharges

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Abstract

EDM induced residual stress is a great concern for product performance. Current modeling methods of EDM are limited to a single discharge. However, a single discharge simulation is far from the reality to predict the residual stress due to the accumulating effect of massive random discharges. In this study, a new modeling method accounting for massive random discharges has been developed to simulate residual stress formation in die-sinking EDM of the ASP 23 tool steel. Both local residual stress and average residual stress characteristics in the subsurface have been investigated. The effects of discharge voltage on residual stresses are also studied.

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Keywords: residual stress, electric discharge machining (EDM), random discharge, finite element simulation

1. Introduction

1.1. EDM background

Electrical discharge machining (EDM) is a flexible manufacturing approach to machine difficult-to-cut materials. The non-contact nature and low force between the workpiece and the tool allow the machining of complex geometry, high aspect ratio structures, and deep grooves regardless of the material's strength. Those advantages make EDM an alternative competitive process in many industries such as molds/dies, turbomachinery components, and medical devices [1]. However, process-induced tensile residual stress is detrimental to the fatigue life of EDMed components [2].

Klink *et al.* [3] studied residual stress distribution in the subsurface of ASP 23 tool steel machined by wire-EDM. They showed a high tensile residual stress zone within 30 µm of the top surface. Antar *et al.* [4] found a similar trend in wire-EDM of Ti alloys and Ni alloys. Antar *et al.* [5] also showed that wire-EDMed Udimet 720 parts had a high tensile residual stress on the surface and a low fatigue life in four point bending tests, while milled parts had surface compressive stresses and showed a much higher fatigue life. Therefore, understanding the mechanism of residual stress formation is necessary to produce high quality EDMed parts.

1.2. Pressing issues and research objectives

Research on modeling has been conducted to investigate the residual stress mechanism in EDM. Murali [6] developed a single discharge model in ANSYS to simulate the temperature field and residual stress in micro EDM of Ti-6Al-4V. Yang [7] used a molecular dynamics approach to simulate residual stress in EDM of Cu. Shabgard [8] developed a sequentially coupled model in ABAQUS to predict residual stress of EDMed AISI H13 tool steel. However, all of previous modeling works were based on a single discharge effect. Residual stress distribution after massive discharges has not yet been modeled. The effect of multiple discharge craters overlapping on residual stress remains unknown. Massive high-frequency discharges induce large temperature variations and steep temperature gradients which need to be taken into account to model residual stress characteristics.

Hinduja and Kunieda [9] pointed out that the process effects of multiple discharges need to be simulated sequentially instead of linearly superimposing the process effect of a single discharge. High-frequency discharge will

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occur at a random location and not at a deterministic spot on the workpiece. The inherently random nature of discharges makes the unpredictable discharge location very challenging to simulate. A probabilistic method is needed to simulate the stochastic process in order to model the massive discharges effect in EDM.

This research aims to: (1) develop an efficient 3D finite element model to simulate residual stress characterises induced from massive random discharges; (2) study the effect of EDM parameters on the residual stress distribution.

2. Residual stress modeling approach

2.1. Model dimension and mesh design

Fig. 1 shows a finite element model of the workpiece created in ABAQUS. The model is 1500 μm × 1500 μm × 400 μm to accommodate massive random discharges and exhibit the stochastic nature of EDM. The model is meshed with both 8-node and 4-node finite elements. The discharging area on the top surface has the finest mesh (4 μm × 20 μm × 20 μm) to achieve a high resolution for spatial convergence.

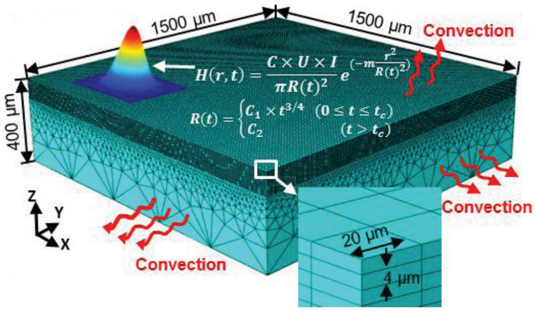

Fig. 1. 3D finite element model of EDM.

The following assumptions are made for this simulation: (1) each discharge is ignited immediately, and discharge delay time is zero; (2) the heat transfer mode is conduction and convection, while the radiation is ignored; (3) materials removal occurs once workpiece temperature exceeds the material boiling temperature; (4) residual stresses are generated by thermal contraction upon cooling, microstructural changes are not taken into account; (5) the maximum temperature generated by each discharge will be held until all the discharges are completed, and then cool down to room temperature simultaneously; (6) the heating-induced stress in the discharging stage is ignored as materials are melted or soften in a high-temperature plasma channel.

2.2. Simulation conditions

Table 1 shows three simulation conditions of die-sinking EDM. Pulse/pause durations (50 μs) and discharge current (30 A) remain constant, while the discharge voltage ranges from 20 V to 40 V. According to a preliminary thermal analysis, the entire surface has been eroded and the temperature distributions in both surface and subsurface become stable after 1000 discharges. Therefore, 1000 random discharges are simulated as a case study. ASP 23 tool steel is chosen as the workpiece material. The temperature-dependent physical and mechanical properties are listed in Table 2.

Table 1. Die-sinking EDM simulation conditions.

Case #	Pulse duration t_i (μs)	Pause duration t_o (μs)	Voltage u (V)	Current i (A)	Discharge #
1	50	50	20	30	1000
2	50	50	30	30	1000
3	50	50	40	30	1000

Table 2. Physical and mechanical properties of ASP 2023 tool steel.

Material constant	Temperature		
	20 °C	400 °C	600 °C
Density (kg/m)	7980	7870	7805
Thermal expansion (10^{-6} per°C)	N/A	12.1	12.7
Thermal conductivity (W/m°C)	24	28	27
Specific heat (J/kg°C)	420	510	600
Elastic modulus (GPa)	230	205	184
Stress (GPa), plastic strain	(1.84, 0) (2.20, 4.35e-4) (2.50, 1.13e-3)	N/A	N/A

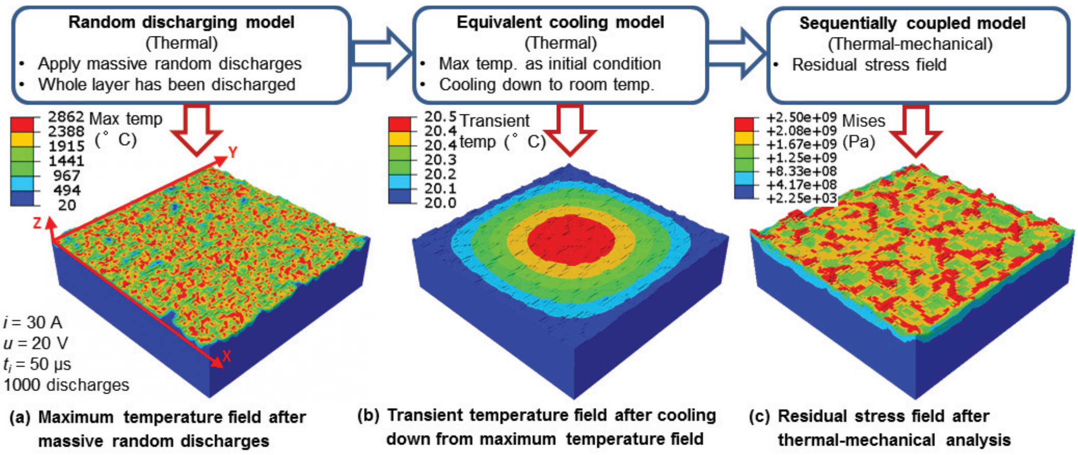

Fig. 2 Methodology for residual stress modeling in EDM.