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A model of tool wear in electrical discharge machining process based on electromagnetic theory

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ABSTRACT

In electrical discharge machining (EDM) process, tool wear is an inevitable phenomenon that adversely affects the geometrical accuracy of machined features. A theoretical model accounting for tool wear during EDM process is hence the basis study for high precision machining. However, in most modeling studies on tool wear and electrode shape, the sparking process is only factorized by the geometric configuration, i.e. the distance between electrodes. The real sparking process related to the fundamental physics is not addressed in these geometric models, which can produce large discrepancies with the experimental results. In this paper, a model of tool wear in EDM is proposed, which accounts for the electric field inside the dielectric fluid using electromagnetic (EM) theory. The spark is proposed to occur at the position where the local electric intensity reaches maximum and exceeds the breakdown strength of the dielectric fluid. This model is shown to provide the physical insight of the real EDM situation, and to give a more accurate prediction of tool wear compared with traditional geometric property based modeling. With these merits, this proposed model can be applied to predict tool wear in various machining processes. To evaluate this model, simulations of EDM die sinking and ED milling are carried out. The results by this electric field model were compared with both geometric model and experiments. By analyzing the profiles of the tool end, the differences in mechanism between the electric field and geometric model are identified. In addition, this electric field model is also applied to simulate the conic tool forming process in the fix-length compensation with micro-milling, which cannot be thoroughly addressed by the geometric model. The model presented in this paper is capable of capturing the key features of the tool wear in a variety of machining processes.

1. Introduction

Electrical discharge machining (EDM) is one of the most extensively used non-conventional material removal processes [1]. Its unique feature of using thermal energy to machine electrically conductive parts regardless of their hardness has been a distinctive advantage in the manufacturing of mold, die, automotive, aerospace and surgical components, which are difficult to manufacture by conventional machining [1].

The thermoelectric heating process occurring in EDM process erodes the electrode, and thus renders wear [2]. The errors caused by the electrode wear result in decreased machining accuracy in the workpiece geometry [3]. In the EDM drilling of blind holes, the electrode length is worn, and thus the real depth of the hole is significantly shorter than the target. Moreover, the wear of electrodes adversely affects the geometric precision of deep holes [4]. While machining complex 3D micro-cavities, such change becomes more complicating [3]. Particularly, in micro-EDM, the machined microstructures will suffer from tool wear severely, which can eventually produce unacceptable errors [5].

To better understand the tool wear process, many experimental and modeling methods are developed [6,7]. Mohri [2] observed the time dependence of an electrode shape through on-the-machine measurement. Pham et al. [8] conducted a series of die-sinking machining and ED milling experiments to investigate the shape change of electrodes, and their experiments confirmed that the electrode evolves to a stable shape during machining.

Besides the experimental investigations, Yu et al. [4] proposed a wear model of simple-shaped tool using analytical methods. This model could be applied to uniform tool wear conditions. Young et al. [9] developed a two-dimensional geometric model of EDM drilling with cylindrical tools. The model, taking both end and corner wear of tool

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into consideration, was applied to on-line compensation methods. Heo et al. [10] introduced a three-dimensional geometric simulation method for micro-EDM milling process to predict machined geometry, which could be used to optimize the parameters of actual machining processes and to provide improvements for CNC programs by implementing compensation. Kunieda and Kivohara [11] developed a geometric simulation for EDM die-sinking inverse process to obtain the appropriate tool electrode shape for retrieving the desired workpiece shape. Several coupled key factors were taken into account, including tool wear, debris particle concentration and tool motion. Zhang et al. [12] developed a two-dimensional geometrical simulation for fix-length milling with cylindrical tools. A clear explanation of the forming mechanism of cone-shaped electrode was provided, and precise predictions of the cone angle were made when layer thickness was less than 85.5 μm.

Generally, the simulation process includes three steps: (1) searching the discharge point pair; (2) removing materials from the tool and the workpiece; (3) tool feeding. The first step is to search the discharge point pair. Physically, the discharging occurs when the local electric intensity exceeds the breakdown strength of medium. In traditional tool wear modeling, however, spark is commonly located at positions with the shortest gap distance between electrodes, assuming that the electric intensity is inversely proportional to scale of gaps. Unfortunately, this assumption is not necessarily true especially when the tool end has large curvatures, in which the corona discharge is dominant. In such cases, geometric prediction based on gap distance failed. Therefore, an electric field model needs to replace the geometry-based model to predict the sparking positions more intrinsically.

The limitations of the geometric model mentioned above was also verified by some recent works. For example, in a recent fix-length compensation milling research by Zhang et al. [12], when the layer thickness was larger than 85.5 μm, corresponding to a sharper conic angle at the end of electrode, the simulation resulted in large errors compared to the experimental results. Pham's experiment [8] also showed that the electrode shape should remain unchanged with a flat bottom and a worn corner when the drilling depth is greater than 180 μm. However, the simulation proposed by Zhang et al. [12] based on the shortest gap distance scheme affirmed a semispherical electrode in the end. Therefore, geometry based simulation does not work well when the electrode profile has large and varying curvatures.

To improve the prediction of tool wear, this paper proposes a model applying Gauss's law in Maxwell EM theory and incorporating the electric field between electrodes in the sparking process. The developed modeling tool is proved by experiments with better accuracy in finding the sparking points and predicting tool wear. Taking the fundamentals of physics into the sparking process, this model is thus able to explain and predict tool wear in various EDM processes.

2. Methodology

In this paper, an electric field model is presented, where the sparking points are determined based on the electric field distribution in the dielectric fluid. In brief, the sparking occurs at the position where the local electric intensity reaches maximum and exceeds the breakdown strength of the dielectric fluid. In this model, the mesh techniques are similar to what has been proposed by Jeong et al. [9] and Zhang et al. [12]: Both electrodes are meshed into squares of the same size, as shown in Fig. 1. The tool travels following an equation of motion determined by the machining parameters. The electrical spark occurs only once in each time step of the simulation. The time scale of each time is indicated in Eq. (1).

$$\Delta t = \frac{1}{f_{spark}} \tag{1}$$

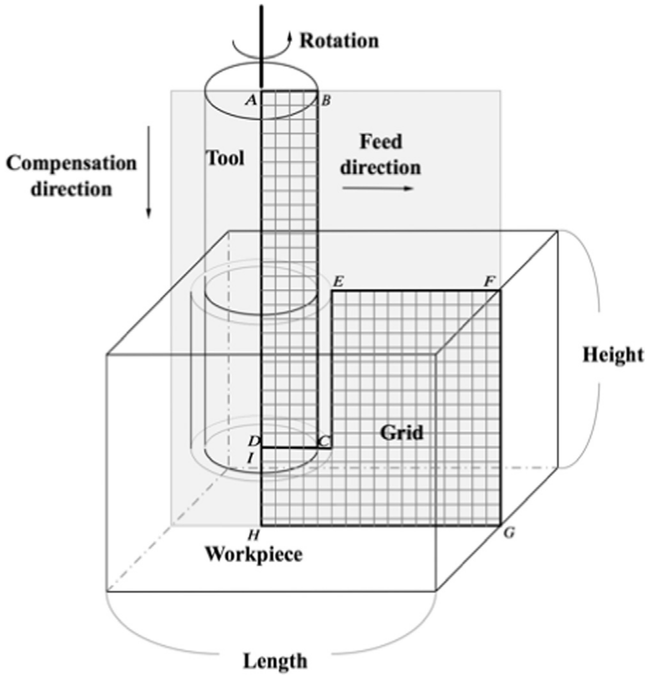

Fig. 1. The two-dimensional model of EDM machining process [12]. The color of the grids profiles both tool and workpiece.

where Δt is the span of the time step, and f_{spark} is the maximum spark frequency.

The electric field model in the present study is based on the following eight assumptions. The first five are from Zhang et al. [12].

(1) The cylindrical electrode remains axially symmetrical during the whole machining process due to rotation;
(2) There is only one spark in each simulation step [7].
(3) The energy delivered by one spark in each simulation step is a constant. That is to say, the removed volume of the material on the electrode is a constant [9,13].
(4) The size of plasma channel is ignored. In other words, the energy delivered by one spark is transferred point to point, rather than area to area [4].
(5) The crater generated by one spark is hemispheric. All the materials in the hemisphere are removed by the dielectric fluid.
(6) The electric field reaches its steady state before breakdown.
(7) The initial breakdown of dielectric fluid occurs at the point inside the fluid, where the electric intensity reaches the maximum and exceeds the breakdown strength of the dielectric fluid. The breakdown strength is estimated by voltage difference over sparking gap.
(8) The discharging channel coincides with the electric field line through the sparking point, which ends at the tool and workpiece surface, respectively.

It is worth mentioning that assumption (5) is valid as a trade-off between precision and simplicity. For one thing, several experimental studies have indicated the topological configuration of craters [14–16], and there are also researches proposing models and numerical simulations about the shape of a crater using molecular dynamics [17], atomistic-continuum model [18] or heat transfer equation in solid [19]. All these models provide good approximations of the crater shape, but as they all depict a single crater only, they are not applicable to machining process simulations. For the other, Zhang's results [12] demonstrate that assumption (5) is a good approximation for the machining process simulation to simplify the computational complexity. Thus, to ensure a calculation efficiency of this model, assumption