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Review of size effects in micro electrical discharge machining

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ABSTRACT

Electrical discharge machining (EDM) is one of the most promising non-traditional micro-scale machining methods. Because several operating parameters that are insignificant in macro EDM cannot be neglected during micro EDM process, models derived from the macro EDM process may be inappropriate at the micro scale. This paper contains a comprehensive review of size effects in traditional micro-machining and characteristics specific to micro EDM compared to macro EDM techniques. The very concept of size effects in micro EDM is thoroughly defined and three categories of effects are presented: material microstructure, processing parameter and thermal conduction size effects. Future potential research directions on the subject are also summarized. We assert that careful research and precise attention must be given to size effects in micro EDM. Size effect information especially benefits the machining speed and machining precision of micro EDM.

Contents

1. Introduction

Seventy years after Lazarenko first proposed electrical discharge machining (EDM), the technique has become one of the most commonly utilized non-traditional machining technologies [1]. The process of a single electrical discharge involves several phases: dielectric breakdown, plasma and bubble formation, electrodes melting and vaporization, plasma and bubble extension, plasma collapse and material ejection. A diagram of the process is shown in Fig. 1. During EDM process, material is removed by means of a series of high-frequency, repeated electrical discharges between the workpiece and tool [2,3]. Owing to non-contact, the forces at work in EDM are very small compared to those of the traditional machining methods; to this effect, EDM is able to process miniature

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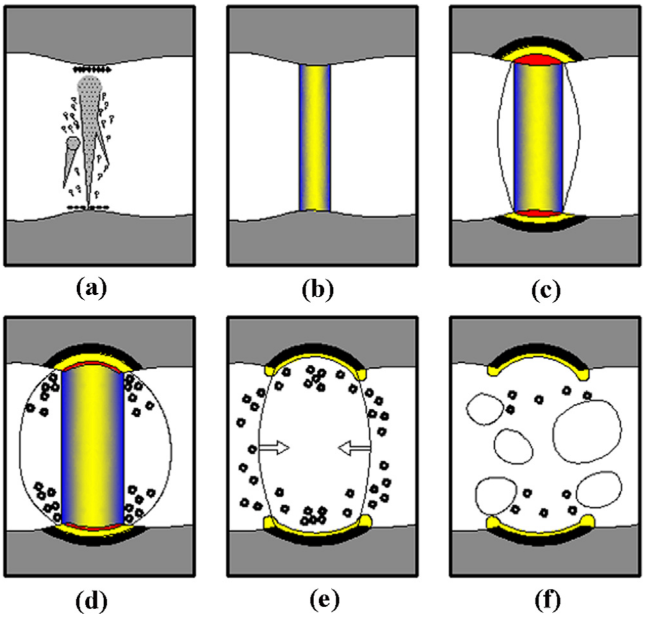

Fig. 1. Phases of electrical discharges: (a) dielectric breakdown, (b) plasma formation, (c) electrodes melting and vaporization, (d) plasma and bubble extension, (e) plasma collapse and debris ejection, and (f) bubble collapse and deionization.

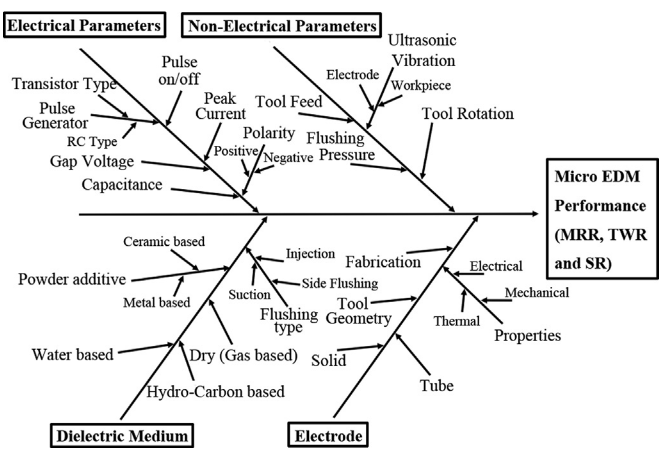

Fig. 2. A fishbone diagram of parameters have influences on micro EDM [15].

parts without distorting the workpiece [4,5]. In fact, EDM is not only capable of machining features in sub-micron scale, but also in nano-scale, suggesting sizeable economic benefits [6–8]. For this and other reasons, micro EDM has garnered considerable research attention [9–11].

The basic process mechanism of micro EDM is essentially analogous to that of macro EDM. There are significant differences, however, in the fabrication methods of tools, discharge energy, gap control, dielectric fluid flushing, and machining technology between micro EDM and macro EDM [12–14]. As shown in Fig. 2, micro EDM performances are influenced by various conditions and across several disciplines (e.g., electrodynamics, thermodynamics, and hydrodynamics) making it rather difficult to fully explain the material removal mechanism [15,16]. Furthermore, because discharge and material removal occur during a very short time and in a very narrow space, it is difficult to accurately observe the material removal process or measure the temperature distribution. Until till now, the dielectric fluid breakdown, material removal, and energy distribution during EDM are still under dispute. Uncertainties in electrical discharge characteristics, high discharge frequency, small discharge gap, and surrounding dielectric medium result in the high stochastic behavior of the crater size during EDM [17], and as a result, models derived from the macro EDM process are inaccurate when applied to micro-scale machining.

The important causes of the disparity between micro EDM and macro EDM processes can be attributed to size effects. Many influencing factors that are insignificant in macro EDM cannot be neglected when machining at the micro scale. For example, the workpiece cannot be considered as homogeneous isotropic material, because the crater size of a single spark (and even the electrode diameter,) in micro EDM is in the same scale as the crystalline grain size (Fig. 3). Therefore, the material microstructure actually influences the micro EDM process. In addition, the very short pulse duration and very low discharge energy inherent to the process result in different material removal mechanisms during micro EDM compared to macro EDM; this alters the machining performances of micro EDM as a result. Though size effects have been widely researched in the field of traditional micro-forming and micro-cutting machining, relatively little attention has been given to size effects in micro EDM.

The primary goal of this paper is to provide fundamental information regarding size effects in micro EDM field, including definitions, relevant classifications, and future research directions on the subject. We hope the information provided here helps to comprehensively reveal the formation mechanism and influence of size effects on micro EDM, and proves useful in improving machining speed, machining precision, and surface quality by optimizing the micro EDM process.

2. Size effects in traditional micro-machining

2.1. Definition of “Size effect”

Until now, there has been no a clear, standardized definition of the term “size effects”. Generally speaking, when up- or down-scaling the geometrical dimensions of the samples, unexpected results arise in the technical process or test results-these phenomena are best described as size effects [18,19].

Many previous researchers have attempted to establish fundamental knowledge regarding size effects in the traditional micro-forming and micro-cutting machining field through a systematic review of related studies. Geißdörfer et al. [20], for example, applied a mesoscopic model to micro-forming processes that included consideration of material microstructure, and proved their model to be feasible. Keller and Hug [21] conducted uniaxial tensile tests on high purity nickel polycrystals with different numbers of grains per thickness, and found that the effect of grain size is significant due to the hardening mechanisms induced by surface grains. Sevillano et al. [22] investigated the fundamental size effect on the flow stress and work hardening rate of crystalline materials, and found that size effect is qualitatively and quantitatively reflected in the difference between dislocation glide and other physical phenomena. Kals et al. [23] investigated several different second-order size effects, and found an increased share of imperfections to be responsible for the size effects during tensile testing, air bending, and punching of sheet metal. Peng et al. [24] developed a uniform constitutive model to describe size effects in the micro-forming process, and verified the accuracy of their model by conducting simulation experiments. Simoneau et al. [25] indicated that surface micro-defects such as dimples occur at the hard-soft grain boundary in the direction of cutting of dual-phase materials, because there is dramatic increase in material shear flow stress as uncut chip thickness decreases during micro-scale cutting. Kim [26] proposed an orthogonal cutting model to represent micro-cutting process physics at sub-micron scale. In short, the size