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Experimental study on horizontal ultrasonic electrical discharge machining

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ABSTRACT

Electrical discharge machining (EDM) is usually used to machine conductive difficult-to-machine materials by pulse discharge, which can achieve high processing quality, but the machining efficiency is low. Ultrasonic vibration of the electrode changes the discharge gap and enhances the chip removal ability, which is deemed as an excellent method to increase the EDM efficiency. In this paper, firstly, a new ultrasonic vibration unit is designed with the assistance of finite element method (FEM) simulation for the resonance oscillation of the workpiece on the end of the amplitude transformer in horizontal direction. Secondly, the machining parameters, including the gap voltage, pulse interval, pulse width and peak current in the traditional EDM process, are optimized by experiments, and the optimized condition is applied to the horizontal ultrasonic electrical discharge machining (HU-EDM) process. In comparison with the traditional EDM, HU-EDM increases the material removal rate (MRR) by nearly 3 times, and improves the processing accuracy by 20%. Through this research, it is confirmed that both advantages of machining accuracy and machining efficiency are achieved in HU-EDM.

1. Introduction

Electrical discharge machining (EDM) is by transforming electrical energy into heat energy between the tool electrodes and the workpiece in liquid medium, like EDM fluid or kerosene, to process conductive difficult-to-machine materials. As there is no machining force between electrodes and workpieces, the processing quality is high, especially in the micro EDM that is widely used in precision machining and micro manufacturing described in Choudhary and Jadoun (2014) and Chung et al. (2011). However, the machining efficiency is low because of the weak energy density of a single pulse discharge and the longtime deionization. Ultrasonic vibration can increase the total energy, including the pulse energy and the ultrasonic vibration energy, change the discharge gap and enhance the chip removal ability, which is deemed as an excellent method to improve the EDM efficiency by Singh (2012) and Castro and Capote (2007).

Assisted vibration is considered as the most popular and effective method to improve the machining efficiency. There are two ways of combination of electrical discharge machining and ultrasonic machining.

One is to superimpose the ultrasonic vibration on the electrode. Dong et al. (2011) studied the modification layer performance with the aid of ultrasonic vibration, and proved that the surface roughness improved and the melting material was well-distributed. Kremer et al. (1989, 1991) reported that the EDM efficiency increased and the machined surface quality improved by using the ultrasonic vibration. Yeo and Tan (1999) studied the ultrasonic vibration assisted EDM on stainless steel, who found that the machinability improved obviously. Liew et al. (2014) studied the effect of ultrasonic on EDM. They reported that the ultrasonic vibration of dielectric fluid was effective to improve the performance in hole machining in terms of material removal rate (MRR), surface topography and process stability. The research by Huang et al. (2003), which machined micro holes in Nitinol with ultrasonic vibration, showed that ultrasonic vibration can improve the machining efficiency but increase the tool wear. These studies indicated that with the aid of ultrasonic vibration, the machining efficiency and surface quality had improved apparently. These were

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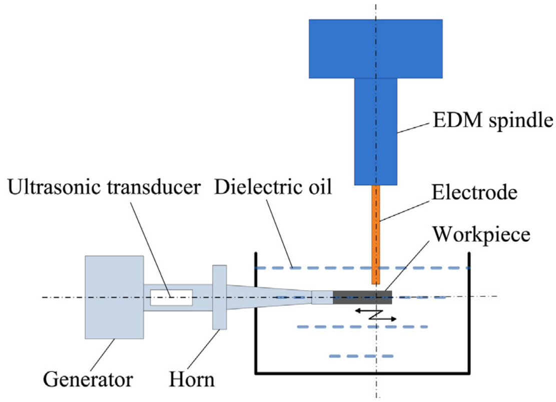

Fig. 1. Sketch of horizontal ultrasonic EDM.

attributed to the stirring effect caused by ultrasonic vibration which strengthened the effect.

The other is to apply ultrasonic vibration on the workpiece. Using ultrasonic vibration-assisted EDM, Gao and Liu (2003) proved that the machining efficiency increased significantly and the complexity of the system reduced greatly. Zhang et al. (2002) investigated the effect of the ultrasonic vibration on the EDM in gas and concluded that their proposed system could achieve higher efficiency than conventional EDM in dielectric liquid. When the vibration is applied to the micro-WEDM process, the machining efficiency can be increased by 2.5 times greater than without vibration as described in Hoang and Yang (2013). To improve the machining efficiency and accuracy, Tong et al. (2008) introduced a new method using the tool electrodes with non-circular cross-section and the results revealed that higher frequency vibration can get higher machining efficiency.

Due to the weight of the ultrasonic device, the control accuracy of the EDM spindle was deteriorated. In order to combine the advantages of EDM and ultrasonic machine, the ultrasonic vibration-assisted EDM, which vibrates on workpiece, is an efficient method. The vibration-assisted EDM can be applied to from micro-EDM to macro EDM, and the present study focuses on the mechanism of ultrasonic vibration-assisted EDM, and expects to make it useful in micro-EDM and precision EDM.

In this paper, a new process method, named horizontal ultrasonic EDM (HU-EDM), is proposed. Compared with the ultrasonic vibration assisted EDM process on the EDM spindle, a set of ultrasonic vibration unit is designed and installed on the workpiece to make it vibrate horizontally. In order to identify the HU-EDM characteristic, various experiments are carried out on 45# steel. The results indicate that the machining accuracy and machining efficiency improve apparently.

2. Ultrasonic vibration setup

2.1. Ultrasonic vibration unit design

The HU-EDM system used in this study is shown in Fig. 1. The system consists of two units: an EDM machine and an ultrasonic vibration unit. The ultrasonic vibration unit usually contains three major parts: ultrasonic generator, ultrasonic transducer and ultrasonic horn.

Generally, according to the specific requirements of experiments, the matched ultrasonic generator and ultrasonic transducer are purchased commercially, but the connection of ultrasonic horn with workpiece needs to be designed. In consideration of the specific shape of the workpiece, the overall design of workpiece and ultrasonic horn is adopted, which the horn and the workpiece are connected together by a stud. Due to the small amount of the material removal, the impact of reducing the mass of the workpiece to the resonance oscillation of the ultrasonic horn is neglected in theoretical calculation. All the sizes of ultrasonic horn as well as the workpiece should be designed, as shown in Fig. 2.

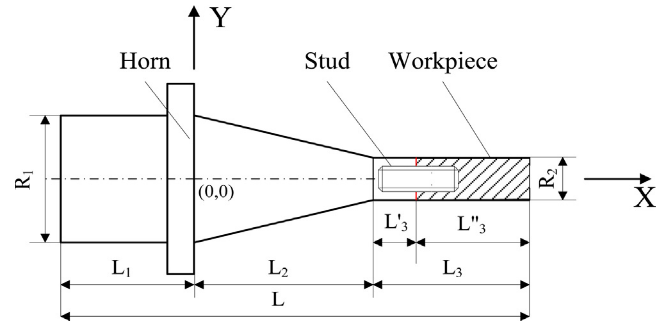

Fig. 2. Sketch of the overall design of the workpiece and the ultrasonic horn.

Table 1
Designed parameters of ultrasonic system.

Parameter	Value
Density ρ (kg/m^3)	7850
Elasticity modulus E (Gpa)	210
Ultrasonic frequency f_d (kHz)	20
Vibration amplitude A_d (μm)	21
Longitudinal velocity v (m/s)	5170
Diameter at large end D_1 (mm)	Φ40
Diameter at small end D_2 (mm)	Φ22

The wave equation of longitudinal vibration of variable cross-section rod is given in Eq. (1) (Lin, 1996; Peshkovsky and Peshkovsky, 2007).

$$\frac{\partial^2 \varepsilon}{\partial x^2} + \frac{1}{S} \times \frac{\partial S}{\partial x} \times \frac{\partial \varepsilon}{\partial x} + k^2 \varepsilon = 0 \quad (1)$$

where $S = \pi R(x)^2$is area function and $k = \frac{2\pi}{\lambda}$ is the circular wave number, where λ is the wave length.

According to the displacement equations and boundary conditions of each particle, the frequency equation of free ends is shown in Eq. (2).

$$\tan(kL_2 + \alpha_2) = \frac{N\alpha}{k} - \tan(kL_3) \quad (2)$$

where constant $\alpha = \frac{D_1 - D_2}{D_1 l} = \frac{N-1}{Nl}$ and area coefficient$N = \frac{D_1}{D_2}$, where D_1 and D_2 is the end face diameter of cone, respectively.

And the amplification coefficient equation can be calculated by Eq. (3).

$$M = |\frac{A_3}{A_1}| = |N \frac{\cos(kL_2 + \alpha_2)}{\cos \alpha_2} \frac{\cos(kL_1)}{\cos(kL_3)}| \quad (3)$$

The designed parameters of ultrasonic system are summarized in Table 1. An ultrasonic system is to be designed with a theoretical frequency of 20 kHz and theoretical vibration amplitude of 21 μm. According to the above equations and material parameters, the theoretically characteristic values and the size of the ultrasonic system, including the length, nodal displacement and amplification coefficient, can be calculated, as shown in Table 2.

2.2. Simulation results and discussion

In order to identify the resonance oscillation characteristics with the workpiece mass reduction in the EDM process, the resonance frequency of the ultrasonic horn is recognized through finite element modeling (FEM) simulation when the workpiece is removed