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Research on a single pulse discharge to discriminate EDM and EAM based on the plasma tunnel and crater geometry

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ABSTRACT

Many electro-arc machining (EAM) processes have been put forward in recent years. Theories of electrical discharge machining (EDM) are utilized to study EAM processes frequently. Though EDM and EAM are different in their ranges of discharge current and pulse duration, there is no specific discrimination between EDM and EAM. To find different characters of EDM and EAM, experiments adopting a single pulse discharge were designed and carried out. Fundamental phenomena of EDM and EAM including the plasma tunnel and crater geometry were researched and discussed. Results show that the discharge current and pulse duration influence the diameter and temperature of the plasma tunnel, and then determine the crater geometry, causing a short circuit of the discharge gap finally. Whether a short circuit appeared after a single pulse discharge was researched and adopted for the discrimination between EDM and EAM. A discriminatory line was proposed based on the theoretical analysis and experiments. An experimental verification was conducted and the results were coincident with the deduction.

1. Introduction

Electrical discharge machining (EDM) is a nontraditional machining process widely adopted for the machining of electro-conductive materials without considering their hardness. But the low efficiency of EDM restricts its applications. Because the arc usually carries more energy density than that of the spark, machining processes using arcs were researched and developed, including arc dimensional machining (ADM), electro-melting-explosion (EME), short electric arc machining (SEAM) and blasting erosion arc machining (BEAM), as indicated by Zhao et al. (2013). Such machining processes have been classified as electro-arc machining (EAM) in contrast with EDM. EDM and EAM can also exist simultaneously. A hybrid process combining EDM and EAM named super high speed EDM milling and arc machining was proposed by Wang et al. (2014) recently.

However, it is hard to distinguish between EDM and EAM definitively. EDM should take advantage of sparks while EAM should adopt arcs to finish their machining processes by literally understanding. The spark is defined, in Physics, to be an unstable discharge, generated without enough power. A spark will disappear rapidly and another spark discharge will appear immediately afterwards. An arc is generated with enough power and stable. Arcs can bring a great amount of heat in contrast with sparks. Yu (2011) concluded that the spark is an unstable physical process with the duration less than 1000 μs, while the arc is a stable or pulsed physical process with the duration more than 100 μs. EDM process is carried out by many repeated, successive pulsed discharges. A normal single pulse discharge generated by a rectangular pulse generator includes a breakdown delay duration (the discharge voltage remains a constant value and there are no discharge current), a spark discharge duration (the discharge voltage drops and the current grows rapidly) and an arc discharge duration (the discharge voltage and the current keep in a range, oscillate up and down with a high frequency component separately), as described by Li (1989). A summation of them is named a pulse duration. Kiyoshi (1983) pointed out that EDM is carried out by pulsed spark discharges or arc discharges after spark discharges, not continuous arc discharges. Therefore DC and pulsed power sources could be adopted by EAM processes, while only pulsed power sources could be adopted by EDM processes. However, pulsed discharges with the pulse duration between 100 μs and 1000 μs are hard to categorize.

Now there is no available definition to discriminate between EDM and EAM because of the lack of fundamental research on

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Table 1
The maximum discharge currents and common range of pulse durations of EDM and EAM.

Process	Category	The maximum discharge current and common range of pulse duration
EDM		The maximum discharge current is no more than 100 A in general, indicated by Zhao et al. (2012). The common range of pulse duration is usually less than 100 μs, indicated by DiBitonto et al. (1989), though the range of pulse duration is 0.1–1000 μs by Li (1989) and 1–1000 μs by Zhao (2003).
EAM	SEAM	The maximum discharge current is 8000 A. The power source is pulsed or DC, reported by Zhou et al. (2008). The pulsed power source can achieve continuous adjustment of the output pulse frequency within 50 Hz–100 kHz, reported by Zhou et al. (2013).
	BEAM	The maximum discharge current is 600 A, reported by Zhao et al. (2013). The common range of pulse duration is 100–2000 μs, reported by Zhao et al. (2012).
	ADM	The maximum discharge current is 450 A. An arc welding converter with direct current is used as the power source, reported by Meshcheriakov et al. (1988).
	EME	The maximum discharge current is 3000 A. The power source is DC, reported by Liang et al. (2004).
	Super high speed EDM milling and arc machining	The maximum discharge current is 700 A. A composite power supply comprised of a pulse generator and a DC power is used, reported by Wang et al. (2014).

them. Differences exhibited are their ranges of discharge current (I) and pulse duration (T_{on}). The maximum discharge currents and common ranges of pulse durations from different literatures are listed in Table 1. It could be found that their discharge currents and pulse durations have some differences. Generally, the maximum discharge current of EDM is usually less than 100 A while that of EAM is higher. Though the maximum pulse duration of EDM is about 1000 μs, pulse durations frequently-used in EDM are less than 100 μs. So the pulse duration range of EAM is longer than that of EDM. A conclusion could be gotten that the higher discharge current and longer pulse duration are the characteristics of EAM when compared with that of EDM. However, the reasons why the higher discharge current and longer pulse duration cause discrepancies between EAM and EDM are still unknown. The exact values of discharge current and pulse duration to discriminate between EDM and EAM are vague too.

Eubank et al. (1993) pointed out that plasma tunnel and discharge crater of a single pulse discharge are the foundations of EDM research. Researches on them are helpful for understanding the distinctions between EDM and EAM deeply. Considering that few literatures to discriminate EDM and EAM were carried out, this research, adopting a single pulse discharge with considerations of the plasma tunnel and crater geometry, was conducted to find a clear discrimination between EDM and EAM.

2. Models of the plasma tunnel and crater geometry

A plasma tunnel is formed and expanding rapidly at the beginning of a spark discharge. Kojima et al. (2008) used a spectroscope to measure the arc plasma of EDM in air under the discharge voltage of 120 V and current of 17 A. The plasma tunnel had expanded to the maximal diameter of 250 μm in 1.7 μs after breakdown, then the plasma tunnel remained the diameter, but the temperature of the plasma dropped dramatically. Kitamura and Kunieda (2014) have similar finds using oil dielectric. The diameter of the plasma tunnel will grow if a higher discharge current is adopted. According to the model of the plasma tunnel in liquid dielectric proposed by Eubank et al. (1993), the plasma tunnel grew to 271.8 μm after 1.7 μs when the discharge current was 2.34 A, while 9405.25 μm after 600 μs when the discharge current was 68 A. However, according the research of Zhang et al. (2014a), the temperature of the plasma tunnel was decreasing when the plasma tunnel was expanding. Based on Steenbeck principle presented by Steenbeck (1932), a stable arc will burn at the minimum voltage applied on the arc under given current and boundary condition, which means the diameter of the plasma tunnel is stable when the arc is stable, it can be deduced that the plasma tunnel diameter will grow quickly after the breakdown, then remains a constant value until the end of the pulse duration. The above experimental results conform to Steenbeck principle. The temperature of the plasma (refers to its center temperature in this paper) will drop to a constant value when the arc is stable. Since the complex discharge situations of EDM and EAM, the diameter and temperature of the plasma tunnel can only be measured but not be calculated theoretically. An empirical formulae was put forward by Wang (1991) to describe the diameter of the arc burning freely in air.

$$D = 260 \times I^{0.5} \tag{1}$$

where D is the diameter of the arc, in micron, and I is the discharge current, in ampere. An equation was educated to indicate the plasma tunnel temperature with the assumption that the plasma is perfect gas mixture by Eubank et al. (1993).

$$T = \frac{216.7P}{\lambda\rho} \tag{2}$$

where T is the temperature of the plasma tunnel, in Kelvin, P is the pressure of the plasma, in bars, λ is a multiplier providing the average number of particles present in the plasma per molecule of water originating at ambient conditions, and ρ is the density of the plasma, in kg/m^3.

The following conclusions could be deduced from Eqs. (1) and (2). The diameter will grow with the growing of discharge current. The temperature of the plasma tunnel decreases because of the decreasing of plasma pressure. The plasma pressure is dropping with the expanding process, which means its temperature drops at the same time.

An empirical formula was also proposed by Li (1989) to describe the diameter of the crater (The view that the plasma diameter is equal to the crater diameter, as described by Zingerman (1956), was adopted in this paper. So the term "D" indicates the diameter of the plasma tunnel and the diameter of the crater meanwhile.) with consideration of the influence of the expanding of the plasma tunnel, which is commonly used in the researches of EDM as:

$$D = 0.151 I^{0.4} T_{on}^{0.4} \tag{3}$$

where D is the diameter of the crater, in micron, and T_{on} is the pulse duration, in microsecond. The crater geometry is determined by the plasma tunnel actually, furthermore, the plasma tunnel is determined by the discharge current and pulse duration largely. Though many researches about the diameter of the crater (D) have been done, little research about other features including height of the crater (H), ratio of H/D, height of the bulge (H_b) and width of the bulge (W_b), as shown in Fig. 1, has been carried out. The researches of this paper are about these features based on the plasma tunnel and crater geometry.

Only a fraction of this heated area known as removal volume is removed in the form of debris particles per pulse. The ratio of removal volume to molten volume per pulse is called the removal efficiency. The removal efficiency is low. According the research of Zahiruddin and Kunieda, (2012) the removal efficiency of Macro-EDM is 1–10%, while that of Micro-EDM is 19%. Zhang et al. (2014b) carried out research on crater geometry in five kinds of dielectrics