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A novel high efficiency electrical erosion process

-- Blasting erosion arc machining

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Abstract

A novel low cost, high efficiency material removal process namely the Blasting Erosion Arc Machining (BEAM) is proposed and implemented to perform bulk removing of alloys including the difficult-to-cut materials. Compared with conventional EDM process, the BEAM process erodes the work piece materials with electrical arcing instead of sparking.

The most critical enabling mechanism of BEAM is how to make the arcing plasma column break off, and resulting in a consequent blast effect, by which the molten material is blown off from the molten pool efficiently. In order to avoid continuous and steady arcing, a strong multi-hole inner flushing is a prerequisite for the BEAM process. During BEAM, the high velocity flushing induces a strong hydrodynamic force into the gap, which distorts, elongates or even breaks the arcing plasma column. During the arc breaking process, an extremely strong blasting will blow off the molten material explosively. This arc breaking mechanism is named hydrodynamic arc breaking mechanism and it is the principle of BEAM process.

The preliminary experiments demonstrated the material removal rate of the BEAM process is extremely higher than that of traditional EDM or even the milling process. For example, the MRR of BEAM of Inconel718 exceeds 11,300 mm³/min as well as the tool wear ratio is lower than 1%. Obviously, BEAM is a promising process in the high efficiency machining of the difficult-to-cut materials. Besides, it is also an environmentally friendly machining process because the working fluid is water-based dielectric rather than hydrocarbon dielectric oil.

Keywords: blasting erosion arc machining (BEAM); high efficiency electrical erosion process; hydrodynamic arc breaking mechanism; multi-hole inner flushing

1. Introduction

Materials with excellent properties such as a high temperature strength and exceptional corrosion resistance have been utilized widely in modern industries especially the aerospace industries. However, almost all of the materials with such outstanding properties are difficult to machine by traditional cutting methods. So how to efficiently machining the so called difficult-to-cut materials is still a big challenge. Although some non-traditional machining processes especially the electrical discharge machining (EDM) and electrochemical machining (ECM) are able to handle the difficult-to-cut materials in an economic way, their machining efficiency is still limited. Since arcing usually carries much higher energy density than that of the spark discharging, it is considered as a promising high efficiency energy source. Processes such as arc dimensional machining (ADM)¹¹, electro-contact-discharge-machining(ECDM)²⁻⁴, electrochemical-arc-machining(ECAM)⁵⁻⁶ and electro-melting-explosion (Named Dian-Rong-Bao in China)⁷ are typical electro-arc machining process which applies electro arcing to remove the work piece materials. In the
ADM process, the arc welding converter with direct current was used instead of the pulse generator and a very thin electrode with a flushing channel was used. The machining zone was enclosed in a hermetic chamber through which the dielectric liquid is pumped under controlled pressure. During machining, the generated heat and debris are flushed out through the channel and an unstationary discharge was achieved by the hydrodynamic and cooling effect of the flushing dielectric. It was reported that when machining carbon steel material, the highest MRR achieved by using ADM was about 16,000 mm³/min.

Recently, another high speed electro-erosion process named high speed electro erosion milling (HSEM) was proposed and applied in hard alloy machining by GE, Inc [8-10]. By using a negative charged spinning tube electrode with a through hole and flushing conductive electrolyte into the gap, this process can remove the work piece material in a milling style which makes it capable of machining 3D convex shapes such as turbine bladed disk, blisk. Suzhou Electrical Machining Research Institute in China developed a commercial high speed electrical discharge milling equipment and achieved material removal rate is up to 3,000 mm³/min when removing high temperature alloy Inconel718 [11].

For the electrical arc erosion processes, the key of high efficiency machining is how to avoid stationary arcing which ruins both the work piece and electrode surfaces. In order to keep the arc in a moving or unstationary state, almost all of the above-mentioned electric arcing removal processes, except ADM, utilizes the relative movement between the tool electrode and the work piece to stretch or break off the arc plasma channel, consequently the explosion effect expels the generated debris out of the inter electrode gap. The stretch or even break off of the arcing plasma channel, which is called arc-breaking mechanism here, is dominated by the relative movement between the electrode and the work piece. This mechanism is categorized as mechanical motion arc breaking mechanism. Tool rotating is the most reliable arc breaking method applied by the existing arc erosion processes. However, this mechanism restricts the shape of the electrode, only the tube or disk can be applied, those are suitable of processing convex shapes. However, some complex concave cavities are inaccessible to these machining processes. Hence, how to effectively break the arc plasma channel during machining is the core issue of exerting the advantages of electro-arc-erosion process.

In order to increase both the machining and economical efficiency of EDM, bundled electrode was proposed in 2007 [12]. A bundled electrode is applied which is composed by bundling a number of rods or pipes together to form an electrode with a 3D end surface. Compared to conventional solid electrode, the multi-hole structure of the bundled electrode enables a strong inner flushing in the gap to expel the debris much effectively. It not only improves the gap discharge conditions, but also enhances the material removal rate remarkably [13, 14].

During EDM with bundled electrode, a unique phenomenon so called trailing discharge crater was discovered. As shown in Fig. 1(a), when the flow velocity of the multi-hole inner flushing exceeds a certain value, many trailing craters can be observed around the peripheral of machined area. Experiments show that the trailing craters were formed at the beginning of discharge process. As shown in Fig. 1(b), the gap voltage increases associated with the decrease of discharge current while trailing crater is generated. Fig. 2 shows the simulation of the multi-hole flushing effect in the discharging gap. It is obviously that the flow velocity around the peripheral of electrode is extremely high. By considering the observation and simulation result, it can be inferred that the discharge plasma channels are distorted by the extremely high velocity dielectric fluid from the inside out and the trailing craters were formed accordingly.

![Trailing discharge crater](image1)

(a) Trailing discharge crater  (b) Waveform of voltage increasing  

![Close-up of trailing discharge crater](image2)

(c) Close-up of trailing discharge crater

Fig.1 Trailing discharge crater in bundled electrode EDM

Trailing craters on the surface could damage the work piece and should be avoided in the EDM process, but it also discloses a clue on how to make the arcing plasma channel moving by controlling the dielectric fluid flow. In this paper, a novel electro-arc-ing-
erosion process named Blasting Erosion Arc Machining (BEAM) is proposed. By employing bundled or laminated electrodes which has multiple inner holes, the flow velocity within the narrow gap in between the electrode and the work piece is maintained extremely high during the BEAM process. The high velocity dielectric working fluid induces a strong hydrodynamic force, which stretches, elongates or even breaks the arcing plasma channel. An extremely strong blasting occurs while the arcing plasma column breaks, the coexisting shockwave blows off the molten material explosively from the molten pool on the work piece. Although both BEAM and ADM processes utilize the hydrodynamic force to achieve an unstationary arc discharge or even break the plasma channel, during BEAM the dielectric fluid is flushed into the gap via multiple holes; while during ADM the working fluid is suctioned from a inner hole inside the electrode by an exerted inlet pressure. Compared with mono-hole suction, the dielectric liquid flow velocity can increase rapidly from the center of the bundled electrode to periphery while applying multi-hole flushing, which also indicates a higher arc breaking efficiency. The principle of BEAM based on hydrodynamic arc breaking mechanism is shown in Fig.3. In the following section, preliminary experimental result will be introduced.

2. Experimental conditions and procedure

A 3-axis CNC machining center was reconfigured by adding a pulse power supply system to perform the experiments. According to the principle of BEAM, a strong flushing conducted with multi-hole is the prerequisite of this process. So a bundled electrode was selected to perform BEAM process. Moreover, the enhanced flushing brings out munificent amount of heat generated by discharge and makes it capable of sustaining a rather higher discharge current than that of conventional EDM process. The electrodes used in the experiments were made of graphite because it is less sensitive to thermal shocking as compared with another conventional EDM electrode material such as copper. The electrode was bundled by a number of tubular cell electrodes. The outer and inner diameters of the cell electrode are 3mm and 1mm respectively. The cell electrodes were bundled with a specially designed fixture to shape them into a die-sinking electrode. The setup of machining test and a bundled electrode are shown in Fig.4. The water-based dielectric fluid flushing system consists of a pump, a throttle valve, a flow-meter, and an inlet pipe connected with the inlet of the bunched electrode. The open voltage of the in house developed power supply system is 60 V and its peak current is up to 600A. Electrical parameters such as discharge current, duty factor, open voltage and pulse frequency are all adjustable during machining. The values of current and voltage were measured and recorded dynamically by a digital oscilloscope (DSO512). The weight of work piece and electrodes were measured by a precision electronic balance before and after machining to calculate the material removal rate and tool wear ratio. The work piece material was Inconel718 and the polarity of the work piece was positive. The flushing pressure is about 1.5MPa.

3. Results and Discussions

Fig.5 shows the machining process of BEAM and a severe blasting can be observed. Compared with
conventional EDM process, the discharging in BEAM is much more powerful and effective.

As shown in Fig.6, during the electro-arcing process of BEAM, the voltage and current volatiles continually, which means the arcing is in a transient rather than a steady state. The waveforms circled red revealed that the current decreases before the pulse duration ends, which indicates the arcing plasma column is distorted or even broken by the intensive inner flushing.

3.1 Material Remove Rate

When machining Inconel718, the material removal rate of BEAM was 11,300 mm³/min (I_p: 600A, T_on: 2,000µs, feed in Z direction only), much higher than that of conventional EDM, it may be even higher than traditional cutting process by some means. Therefore, BEAM has a great potential in machining difficult-to-cut materials.

3.2 Tool Wear Ratio

Experimental results of BEAM show that when using graphite as electrode material, the tool wear ratio (TWR) was less than 3%. Furthermore, if the bundled electrode feed in Z direction only, the TWR was less than 1%. One reason of the low TWR is that the graphite electrode material has very high melting point and has a good resistance to the thermal erosion. Furthermore, the energy distribution ratio also has a dominant influence on MRR and TWR. In BEAM process, most energy is distributed on the anode, which can effectively reduce the cathode erosion, resulting in lower TWR. This polarity effect makes it possible to achieve high efficiency yet low tool wear machining. It is also beneficial to predict and control the machining tolerance during BEAM process.

3.3 Heat Affected Zone

As shown in Fig.7, the metallographic analysis indicates that the thickness of the heat affected zone caused by BEAM is less than 200µm. The reason is the multi-hole inner flushing can effectively prevent the overheating of the work piece by taking the heat away from the discharge gap efficiently. Furthermore, the cooling efficiency of the water-based dielectric is better than that of conventional oil based dielectric. Hence, the deformation of the work piece during BEAM can be controlled in a certain range.

3.4 3D Cavity Machining

Because hydrodynamic arc breaking mechanism makes the relative movement between electrode-work piece no more essential, the BEAM process can bring in not only higher material removal rate, but also lower tool wear ratio, as well as limited thickness of heat-affected layer. It is also capable of machining complex cavity with a simple sinking motion.

Due to its nature of high efficiency machining, the BEAM is more likely suitable for bulk removal roughing process. By using a bundled electrode with 3D shaped end face, it is easily to make 3D cavities which are difficult or impossible to other arc-erosion processes relying on the mechanical movement arc-break mechanism. In order to fully utilize the advantages of BEAM and improve the accessibility of the electrode, the laminated die-sinking electrode was proposed. A laminated electrode is composed by many layers of sliced electrodes which have slots on their surfaces for the purpose of inner flushing. Fig.8 shows a laminated electrode and the machined 3D...
cavity. Compared with bundled electrode, the laminated electrode can be machined with smoother surfaces, and the shapes of the laminated electrodes are more flexible than bundled electrodes.

Fig. 8 3D cavity machined by laminated electrode

(a) multi-holes laminated electrode  (b) machined 3D cavity

4. Conclusions

A novel high-speed material removal process namely the Blasting Erosion Arc Machining (BEAM) is proposed based on hydrodynamic arc breaking mechanism. By performing a strong multi-hole inner flushing, the arc plasma column in the discharge gap will be stretched, elongated, or even broken by the strong hydrodynamic force. An extremely strong blasting occurs while the arcing plasma column breaks, the coexisting shockwave blows off the molten material explosively from the molten pool on the work piece. On the basis of preliminary experiments and analysis, the following conclusions can be drawn:

1) Hydrodynamic arc breaking mechanism is the most critical enabling mechanism of BEAM;
2) BEAM can achieve a rather high MRR with limited tool wear ratio and heat affected zone;
3) BEAM is capable of machining complex 3D cavity by using bundled or laminated electrode;
4) BEAM is a promising method for bulk removal rough machining of electrically conductive materials including difficult-to-cut alloys.

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References