Effect of single spark micro-EDM on crater size of different alloys

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Abstract. Owing to the fact of continuous discharges in RC circuit based μ-EDM process, it is indeed very difficult to analyse difficult-to-control single discharge pulse. This work is thus aimed to develop an innovative technique for generating single discharge in the process. An electrical circuit, parallel to the existing discharge circuit of μ-EDM, has been integrated in-house for the purpose and verified for its applicability over a wide range of metal alloys. For example, single crater diameters of approximately 7μm, 10μm and 18μm have been achieved for stainless steel, Inconel and brass respectively at minimum energy input. The single discharge generator has been developed expecting it would be helpful in gathering information such as volume removal by each discharge which will definitely lead to development of a robust thermal model for material removal in μ-EDM.

Keywords: Single spark, Micro-EDM, micro crater, crater diameter, RC circuit

1. Introduction
A method to manufacture miniature components is required to fulfill the requirement of complex and smaller features in the present and future micro fabrication industries. The requirement of products like dozers for drugs [1], hydro-pneumatic valves [2] consisting of precise micro holes and other features have depicted a prominent and continuous growth in last few years. μ-EDM has been described as the most widely employed non-conventional machining method for manufacturing these miniature and micro hole components due to its high precision. The μ-EDM process is significantly capable of manufacturing different features with dimensional range from 1-999μm [3]. Despite proven potentials, the process has got a few inherent issues which have always been a topic to be addressed by the researchers. Input variables dependentsurface quality, tool wear, and non-uniform material removal rate (MRR) with machining progress are few of those. The issue of tool wear is inevitable and well known as it leads to inaccuracy in diameter and depth of micro crater. Since the minute of errors are magnified in realm of micro manufacturing, the tool wear in μ-EDM became an essential task to be addressed. In this context various tool wear compensation methods such as machine vision [4], electrical circuit [5] and laser range sensors [6] were established. These methods have not shown their potentiality in tool wear compensation due to the interruption in machining and longer machining period. These limitations were later taken care by introducing an in-process (real-time) tool wear compensation method. A real-time tool wear compensation technique in machining micro holes with accurate diameter and depth by counting the effective pulses was introduced by Bleys et al. [7]. Bissacco et al. [8] further improvised the study by estimating the wear in tool per discharge and revealed that pulses in μ-EDM are non-isoenergetic. By considering all these issues, Aligiri et al. [9] introduced an online monitoring and tool wear compensation technique in μ-EDM process based on the volume removed by a single discharge pulse. The technique for generation of a single discharge adopted by the author seems to be an inbuilt facility with the respective machine setup. The facility is also seemed to have less robust which led to a percentage error of up to 9% in fabrication of a micro hole as reported by the authors. It is to be noted that the RC based circuit of μ-EDM controller do not let the operator to define the charging and discharging phenomenon of the circuit, hence the on-
machine monitoring of a single discharge became a very difficult task. Considering the importance of volume of a micro crater generated by a single discharge, it is essential to have a robust single discharge generator for the process and can be integrated with any existing µ-EDM setup in general.

This work therefore aimed to develop an innovative technique for generating single discharge in the µ-EDM process. An electrical circuit, parallel to the existing discharge circuit of µ-EDM, has been integrated in-house for the above purpose and verified for its applicability over a wide range of metal alloys. Feasibility has also been checked on stainless steel, Inconel and brass as work material.

2. Experimental details

Due to commercial unavailability of a single discharge circuit for µ-EDM having automatic and manual setting has been especially designed and fabricated in-house. The circuit is as robust as it is required for difficult-to-control single discharge pulse of RC based µ-EDM. The circuit is capable of generating a unique discharge by producing a single pulse. The µ-EDM experiments were performed on the multi-purpose hybrid micro machine (Model: DT 110; manufacturer: Mikrotools) which has CNC motion controller with 100 nm programming resolution. This machine setup along with the externally developed single spark circuits shown in Fig. 1. Figure 2 shows a sample of random pulses for reference which is captured from an ongoing µ-EDM process as reported by Nirala et al [10]. A varying nature of charging and discharging locations of the respective pulses shown in this figure would have been very difficult to analyse if the single discharge generator would not have been developed. The brass, Inconel and stainless-steel alloys were taken as work material in the present experimentation with the dimension of 130 mm × 150 mm × 60 mm respectively. The tungsten electrode of 300 µm diameter having high wear resistance and melting point was used for machining. The dielectric medium used during machining was commercially available EDM oil having high dielectric strength, flash point, and ignition temperature. The speed of the spindle holding the tool was set at 1000 rpm. The discharge gap was varied from 20 µm-0.1 µm corresponding to the discharge energy. The energy was estimated by using the following Eq. 1 which gives the energy stored in capacitor for a particular setting.

\[ Q = \frac{1}{2} CV^2 \]  

(1)

Here q is the stored energy in capacitor, C is the capacitance value of capacitor and V is the amount of voltage.

The different experimental conditions and parameters used during the single discharge experimentation are depicted in table 1. An L0 orthogonal array with three levels and three values of capacitance and voltage is applied to conduct experiments. To confirm the reliability of achieved data each analysis was performed three times at different selected parameters. A straight polarity is defined during the machining where the workpiece is connected to the positive terminal and tool is connected to the negative terminal of the EDM circuit. The thermo-physical properties of different alloys (anode) and tungsten (cathode) used during the testing is shown in Table 2.

**Table 1** Single discharge experimental conditions and parameters

| Machining conditions & parameters | Tool-electrode rotation speed (r/min) | Tool-electrode feed rate (mm/min) | Discharge gap(µm) | Open circuit voltage (V) | Capacitance (nF) | Energy setting(µF) |
|----------------------------------|-------------------------------------|----------------------------------|-------------------|-------------------------|----------------|------------------|
| 1000                             | 0.001                               | 0.1-20                           | 90-110            | 68-150                  | 275.4-907.5    |                  |

**Table 2** Thermo-physical properties of different anodes and cathode

| Sr. No. | Properties          | Units   | Inconel anode | Brass anode | Stainless steel Anode | Tungsten cathode |
|---------|---------------------|---------|---------------|-------------|------------------------|------------------|
| 1       | Temperature         | (°C)    | 965-980       | 900-940     | 800-815                | 3422             |
| 2       | Density             | (g/cm³)| 7.43          | 8.73        | 7.87                   | 15.8             |
| 3       | Thermal conductivity| (W/mK) | 105           | 111         | 54                     | 173              |
| 4       | Specific heat       | (J/gmK)| 0.597         | 0.380       | 0.490                  | 0.134            |
3. Results and Discussion

The single spark tests were carried out using different voltage and capacitance parameters. The craters formed during the experiment were examined by using scanning electron microscopy (SEM). The Fig. 3 depicts micro craters and recast layer formed during single spark with V = 90-110V and C = 60-150nF. Some part of the liquefied material is re-solidified and overlapped around the edge of the crater as shown in Fig. 3, Fig. 3(b) and Fig. 3(c). It is may be because of the immediate falling nature of discharge power at the specific end of the pulse on time or charging time as well as due to the influence of cold dielectric medium rushing between the discharge positions. Figure 3, Fig. 1(c) depicts a rim type circular zone around the single spark micro crater which is represented as recast layer. This recast layer is a combination of uninfluenced hardened parent material of metal alloys and re-solidified material which is extremely hard and brittle. There is a sublayer layer close to the recast layer as shown in Fig. 3, Fig. 3(a). This sublayer is known as heat affected zone (HAZ) and is not melted throughout the EDM process. There is a variation in the HAZ thickness between the centre and the boundary region of the removed surface. It is because the cooling rate at the HAZ boundary is higher as compared to the inner part of the eroded surface. The SEM image as depicted in Fig. 2(b) schematically plotted the Gaussian distribution of heat input energy. The marked portion distribution shows the volume of heat energy which is spread in the region of the actual plasma channel. This may be because of the dielectric medium existence having huge inertia and viscosity close to the narrowed plasma. In some of the cases poor quality of the surface is precisely revealed. This is due to the growth in internal energy of produced spark which removes the material from workpiece in debris form. The SEM image in Fig. 3 also depicts the shape of debris particles obtained after the machining of different alloy samples. It is ascertained that most of the debris particles are spherical and some of the debris particles show a wide range of sizes and geometries. The amalgamation phenomenon of small droplets in fragment describes the development of the most considerable spherical debris and unsystematic geometry of debris particles.
The amount of material removed at the very beginning of discharge is very significant, after that it reduces progressively until it vanishes entirely at the critical time. There is no removal of material after that beyond a threshold value of discharge energy. However, the work material continuously heated by heat flux. It has been found that the micro crater achieved after the single spark by considering the effect of input energy (voltage & capacitance) is always hemispherical and categorized by a micro crater diameter higher than that of its depth. The graph plotted below shows the similar diameter trends of different alloys used as the anode with the input energy for each point on the radial and vertical axis. For each moment of input energy, the single spark with maximum temperature always develops at the origin and gradually reduces due to the increasing distance from the midpoint. It is also obtained that the diameter of the micro-crater is varied for every combination of the capacitor and voltage, as depicted in Fig. 4. Higher the values of capacitance and voltage, higher will be the micro-crater diameter produced. It is observed to be about 7\(\mu\)m, 10\(\mu\)m and 18\(\mu\)m are achieved for stainless steel, Inconel and brass respectively while employing 68nF capacitance and 90V voltage. When 100nF capacitor with a voltage of 100V is used, the attained micro crater diameter increases significantly up to 19\(\mu\)m for stainless steel, 25\(\mu\)m for Inconel and 32.4\(\mu\)m for inconel respectively. This is because of the variation in discharge energy. Similarly, with the combination of 150nF capacitance and 110V voltage, the micro-crater diameter increases significantly.
4. Conclusion
Highlighting the importance of volume estimation by single discharge in \( \mu \)-EDM, an electrical circuit parallel to the existing discharge circuit of \( \mu \)-EDM has been integrated in-house for the purpose. It will definitely lead to development of a robust thermal model for material removal in \( \mu \)-EDM. To verify the potentiality of the circuit, single spark discharge has been performed on different metallic alloys to observe the shape and size of the micro crater at different input energy settings. The circuit has further been examined for applicability over a wide range of input parameters such as capacitance and voltage combinations by estimating profile and diameter of the micro craters. Approximate diameters of 7\( \mu \)m, 10\( \mu \)m and 18\( \mu \)m have been achieved for stainless steel, Inconel and brass respectively at lower discharge energy however they were 25\( \mu \)m, 38\( \mu \)m and 47\( \mu \)m for respectively at higher discharge energy setting.

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