Drilling Microholes in Hot Tool Steel by Using Micro-Electro Discharge Machining

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This study presents an investigation into the drilling of microholes with a depth of 320μm in tool steel SKD61 by the Micro-EDM process. The electrode with the diameter of 26μm is machined by the method of wire electrodischarge grinding (WEDG). Optical microscopy, scanning electron microscopy, and confocal laser scanning microscopy techniques are used to determine the influence of the process parameters upon hole enlargement, electrode wear rate, material removal rate, wear ratio, and the observed surface topography. The results of the study reveal the optimum parameter settings for the Micro-EDM machining of a high aspect ratio microhole are as follows: (1) a pulse voltage between 60 and 100 V, (2) a capacitance between 80 pF and 220 pF. Finally when the depth exceeds 200μm, the shape of the micro hole almost becomes tapered due to the corner wear of the electrode and the secondary discharge along the side of the hole. [doi:10.2320/matertrans.48.205]

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1. Introduction

Technological advances have facilitated many developments in the MEMS, electrical, medical and aerospace industries in recent years. As the devices commonly found in these industries have become smaller, so the requirements for high-precision machining techniques have become ever more pressing. Nowadays, micro-machining processes are playing an important role in satisfying these requirements. Of these processes, Micro-Electro Discharge Machining (micro-EDM) is particularly important since its application is not constrained by the hardness or material strength of the material, and because no direct contact occurs between the electrode and the machined component. Therefore, it is highly suitable for the machining of all types of conductive metals, ceramics and semiconductors. Consequently, the technique merits intensive research and development studies.

The theory underlying the micro-EDM process is the same as that underpinning the conventional EDM technique. Both techniques rely upon the use of a dielectric fluid situated between the electrode and the workpiece. When a high voltage is applied, the electrons within the dielectric are consolidated to form a high-temperature electric arc which vaporizes or melts the surface of the material. Some of this molten material is then swept away by the dielectric. However, one important distinction between the two techniques lies in the intensity of the discharge energy. The micro-EDM process deliberately employs a lower discharge energy in order to improve the machining precision. This requires an amended electrical circuit design and a change in the traditional process parameter settings.

Microhole drilling has found widespread application in the fabrication of micro-nozzles, ink jet and micro-punches etc. In the previous studies, microholes can be formed by micro-EDM, laser beam machining (LBM), electron beam machining (EBM), micro electrochemical machining (Micro-ECM) and micro ultrasonic machining (micro-USM) etc. Nikumb et al. drilled a cavity with a diameter of 15μm in glass by using short pulse laser. Lu demonstrated a microhole in titanium plate by using micro-ECM. Joo fabricated a microhole with diameter of 25μm together with depth of 100μm by using micro-punches, while Liu investigated the performance of the microhole drilled in high nickel alloy by using micro-EDM. Although a literature review reveals several related studies, these investigations are restricted to the drilling of microholes in a thin plate. Meanwhile, the drilling of microholes and blind holes in a high strength, high toughness steel remains a challenging problem, which has yet to be satisfactorily addressed.

Therefore, the current study investigates the use of the micro-EDM technique in the drilling of microholes and blind holes in SKD61 tool steel, and considers the influence of different machining parameters on various process characteristics, including the electrode wear ratio (EWR), the material removal rate (MMR), wear ratio and the surface integrity of the EDMed surface.

2. Experimental Procedure

The present study uses a MG-ED72W micro-EDM machine, manufactured by Panasonic, and chooses Mitsui EDS as the dielectric oil. In order to avoid the serious wear of the electrode during the process, the investigation employs tungsten electrode with a diameter of 26μm manufactured by WEDG (Wire Electrodischarge Grinding), as reveals in Fig. 1. The subject material is tool steel SKD61, which has previously been quenched and then tempered twice. The hardness of SKD 61 after heat treatment is HRC 45. The depth of the microhole is set to be 320μm. The study considers pulse voltages of 60 V, 80 V and 100 V, and capacitance values of 20 pF, 80 pF, 220 pF and 3300 pF.

After completion of the EDM machining process, Optical Microscopy (OM) is used to confirm the contours of the micro holes to ensure that no machining errors have taken place (e.g. due to bending of the electrode). Scanning
Electron Microscopy (SEM), and Confocal Laser Scanning Microscopy (CLSM) is then used to examine the electrode and the surface integrity of the EDMed surface. Then surface topography, enlargement, electrode wear ratio, material removal rate and the shape of the drilled hole will be further discussed.

3. Results

3.1 Enlargement

Figure 2 presents the microhole drilled by the micro-EDM process under four different operating conditions. The diameter of electrode is 26\(\mu\)m. Meanwhile, Fig. 3 the variation in hole enlargement with pulse voltage and capacitance, respectively. From the results presented in Fig. 3 it is clear that when the pulse voltage is fixed, the hole enlargement is largely unaffected by changes in the capacitance. However, as indicated in Fig. 3, there is a significant increase in the hole enlargement when the pulse voltage is increased. Therefore, the results indicate that the pulse voltage has more significant influence than capacitance in hole enlargement.

3.2 Electrode wear ratio

The Electrode Wear Ratio (EWR) is a fundamental consideration when using the micro-EDM process to drill a blind microhole. Owing to the very small size of the electrodes involved in the process, the size effect leads to rapid electrode wear, which diminishes the precision of the machined microhole. It is clear then, that a correct electrode specification and an accurate positioning of the electrode are crucial if the micro-EDM process is to be successfully used in the drilling of precise microholes.

Figure 4 demonstrates the wear morphology of the electrode after drilling. The volumetric electrode wear is a well-recognized method to assess the electrode wear. It is composed of the linear wear and corner wear of the electrode. The pulse voltages together with capacitances in Fig. 4(a) and Fig. 4(b) are 80 V, 20 pF and 80 V, 220 pF respectively. The reduction of length due to linear wear in both electrodes...
However, according to the three dimensional measurement with the assistance of CLSM, the corner wear can be further calculated. It is clear that the corner wear of 20 pF is larger than 220 pF. For this reason, the electrode wear in 20 pF is greater than 220 pF.

Figure 5 indicates that the relationship between the electrode wear ratio and capacitance. The result demonstrates that electrode wear ratio increases as pulse voltage increases. When pulse voltage is fixed, the electrode wear ratio decreases as the capacitance decreases. However when the capacitance is smaller than 20 pF, the electrode wear ratio will increase inversely. The reason for this is because of stray capacitance in the circuit.13) The stray capacitance will increase the pulse energy and cause the unstable of the process. Therefore it will deteriorate the surface integrity and increase the electrode wear ratio.

### 3.3 Material removal rate

Figure 6 presents the relationship between the material removal rate and capacitance. It shows that the material removal rate increases as the pulse voltage increases. However, the material removal rate decreases as the capacitance increases. The main reason is the difficulty of flushing debris away. Although increasing capacitance also leads to increase the pulse energy, but the debris is not easy to be flushed away as the depth increases, therefore during the process the material removal rate decreases inversely as capacitance increases.

### 3.4 Wear ratio

Wear ratio is an index to judge the wear characteristic in EDM process. In this paper it is defined as the ratio between the total wear volume of the electrode and the total removal volume on the workpiece. Figure 7 reveals the relationship between wear ratio and pulse voltage. Wear ratio increases as pulse voltage increases. Owing to high electrode wear during the process of deep hole drilling, the wear ratio of micro-EDM is normally greater than conventional EDM. Tsai13) investigated different materials of electrode and pointed out that tungsten electrode had the smallest value of electrode wear. This is also the reason that tungsten electrode is performed in this study.

Figure 8 presents the relationship between wear ratio and capacitance. It also indicates the wear ratio is between 2 to 4 percent when the capacitance is smaller than 220 pF, however, wear ratio increases when capacitance is greater than 220 pF. This effect becomes more significant as pulse voltage increases. In addition, the wear ratio decreases as the capacitance becomes smaller. However when the capacitance is smaller than 20 pF, the wear ratio will increase inversely due to stray capacitance.13) It enhances the pulse energy.
3.5 Surface topography

The distinctive morphology of an EDMed surface is caused by the enormous amount of heat generated by the discharges, which causes melting and vaporization of the material, followed by rapid cooling. Figure 9 presents the surface topography of the microhole drilled using the micro-EDM process. The surface topography exhibits similar features to those commonly associated with the conventional EDM process, namely fused structures, debris globules, shallow craters, pockmarks and voids. However, the reduced discharge energy of the micro-EDM process results in one significant topographical difference between the two surfaces. Since the discharge energy is substantially decreased in the micro-EDM process, the energy in each spark is also decreased. This reduces the width and depth of the cracks that are formed on the micro-EDMed surface, and therefore, less molten metal is produced. The molten metal that is not flushed away by the dielectric undergoes rapid solidification and forms a randomly distributed series of overlapping craters. Hence, the trace of each individual spark is clearly visible upon the micro-EDMed surface.

The diameter of each crater can be measured under SEM image. Figure 10 presents the relationship between the diameter of the crater and parameters. It reveals that capacitance has a more evident influence upon the diameter of the crater. When the pulse voltage is elevated from 60 V to 80 V, the
diameter of the crater is only slightly increased. When the voltage is further elevated to 100 V, the diameter of the crater is almost the same as that of the voltage of 80 V. The diameter of the crater increases significantly as the capacitance increases. In other words, the diameter of the craters decreases as the capacitance decreases. However when the voltage is small together with the capacitance is smaller than 20 pF, the diameter of the crater is inversely increased owing to the stray capacitance in the circuit.

4. Discussion

Figure 11 indicates the shape of the micro blind hole and the electrode with the drilling depth of 170 μm. It shows that the bottom of the hole still remains perpendicular since the corner wear of the electrode is still pretty small. However, when the depth exceeds 200 μm, due to difficulties of flushing debris away, the corner of the electrode begins to wear. As the depth increases, the corner wear increases drastically. This also leads the bottom of the hole change to a cone. Moreover, the shape of the micro hole almost becomes tapered because of the corner wear of the electrode and the secondary discharge along the side of the hole. Figure 12 indicates the relationship between the shape of the hole and the working parameters.

From the present study, it is now known the use of the micro-EDM technique in the drilling of microholes and blind holes in SKD61 tool steel, the spark voltage is of the order 10 to 25 V. If the value of the open circuit voltage is too close to the spark voltage, not only will the process become unstable, but the surface integrity will also deteriorate. Moreover, large pulse voltages also increase the gap between the electrode and the specimen, thus increasing the electrode wear ratio. The results of the present study suggest that the optimal pulse voltage for microhole drilling using the Micro-EDM process lies in the range of 60 to 100 V. Besides, it is also necessary to specify a capacitance value. Although increased capacitance improves the material removal rate, it also increases the electrode wear ratio and degrades the surface integrity. Nevertheless when capacitance is smaller than 20 pF, the surface integrity will also deteriorated due to the stray capacitance exists in the circuit. To counter this effect, it may be concluded that capacitance lies in the range of 80 pF to 220 pF if the surface integrity is to be optimized.

5. Conclusions

The present study has investigated the use of the Micro-EDM process in the drilling of microholes in SKD61 tool steel. The present results confirm that the process is assuredly capable of meeting the machining requirements of microholes providing that the process parameters are correctly specified. The main conclusions of the present investigation may be summarized as follows:

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Fig. 11 The shape of the micro blind hole and the electrode with the drilling depth of 170 μm (CLSM Image).

Fig. 12 The relationship between the shape of the hole and the working parameters (CLSM Image). (a) Voltage 80 V, Capacitance 20 pF, (b) Voltage 80 V, Capacitance 220 pF, (c) Voltage 100 V, Capacitance 20 pF, (d) Voltage 100 V, Capacitance 220 pF.
The pulse voltage influences the hole enlargement, Electrode Wear Ratio (EWR) and Material Removal Rate (MRR). In order to guarantee a stable and precise machining operation, its value should be specified within the range of 60 to 100 V.

The value of the EWR generally increases at elevated capacitance. However, when the capacitance is smaller than a value of 20 pF, the value of the EWR is seen to increases due to the problems involved in stray capacitance and flushing away the increased volume of debris.

The material removal rate increases as the pulse voltage increases. However, the material removal rate is negative related to pulse capacitance.

The Micro-EDM and conventional EDM processes generate similar surface topographies. The chief difference between the two is that the effect of reducing the pulse energy in the former technique is to leave a random series of clearly visible, overlapping craters on the machined surface.

The diameter of the craters decreases as the capacitance decreases. When the voltage is small together with the capacitance is smaller than 20 pF, the diameter of the crater is in the contrary increased owing to the stray capacitance in the circuit.

The shape of the micro hole almost becomes tapered because of the corner wear of the electrode and the secondary discharge along the side of the hole as the depth exceeds 200 μm.

REFERENCES