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Length-wise tool wear compensation for micro electric discharge drilling of blind holes

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ABSTRACT

Blind hole drilling using micro electric discharge machining (EDM) faces the difficulty to achieve intended depth as the tool electrode erodes continuously. A practical solution for this problem is to give a lengthwise compensation during the machining process. There are two kinds of compensation strategies exist. Online strategies compensate for the reduction in length by counting the discharge pulses and mapping it with a material removal model. Offline strategies often use the periodical measurements of tool length or electro thermal models to predict the anticipated tool wear for a particular depth. Periodical measurements are much simpler and effective compared to the discharge counting techniques, but the machining operation has to be stopped for the measurements. In this paper, a new tool wear compensation method is realized which integrates the micro EDM machine tool to an image processing module and computer controlled tool wear prediction algorithm. The proposed system is capable of updating the part program constantly according to the forecasted tool wear. A series of blind holes of 200 μm intended depth is drilled using the proposed methodology and compared it with hole drilling without compensation along with the other compensation methods. The proposed method gives 0.3–1% deviation from the intended depth of the hole. This will help in drilling blind holes with a minimum relative error with respect to the intended depth which will be useful for fabrication of series of holes or pattern.

1. Introduction

Drilling is one of the basic machining processes to create holes in different materials for different applications. Micro-drilling is an essential operation in the fabrication of small and high aspect ratio micro holes for micro-fluidic systems [1], fuel injection nozzles [2], micro dies [3], starting holes for wire electric discharge machining (EDM) [4], etc. Making accurate blind micro holes is a necessary in fabrication of micro molds which are further used for making micro patterns. Reverse EDM (R-EDM) uses tool electrodes with through or blind micro holes to fabricate micropillars on workpiece surface [5,6]. Unlike through holes, blind holes in R-EDM electrode demands high depth accuracy as the machined pillar height will be entirely depends on it. To ensure the uniform height of electrodes, the depth of micro hole has to be uniform and accurate. Blind micro holes are used to improve the carrying capacity of biomaterials like Ti6Al4V [7]. Light addressable potentiometric sensors with micro blind holes have demonstrated the improvement in performance regarding increased photocurrent amplitude, sensitivity, mechanical strength and linearity [8]. Micro EDM drilling can be used to drill blind micro holes in the silicon wafer to be used as part of MEMS devices and 3D IC/Si integrations [9,10]. Metallic micro fluidic circuit demands micro holes with exact depth equal to the channel depth to facilitate inlet and outlet flow. Considering the case of machining of micro holes, the scope of using conventional drilling process is very limited. Even though commercial tools are available up to 50 μm or less, the tools are susceptible to early breakage due to tool rigidity problems. Micro EDM drilling is a dependable alternative in this case. In EDM, the material is removed by melting and evaporation. Therefore, there is no need for any physical contact between the tool and workpiece. It eliminates the problems of tool rigidity during machining. Apart from the advantages of using EDM, shape and dimensions of the features are very much dependent on the shape accuracy of the tool electrode. During machining, the tool electrode also wears out in lengthwise and sidewise direction. This will cause dimensional inaccuracies and distort the shape of the final hole to be made. Due to this reason, machining blind holes using micro EDM drilling often fails to achieve the intended depth. The constant reduction in length of the tool electrode will result in a reduced depth of the hole. A solution to this problem is to add a lengthwise compensation to the total tool travel during drilling. This becomes a very tricky due to the inability to measure and monitor the machined

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depth of a hole simultaneously during machining. Therefore, blind hole drilling using micro EDM demands accurate calculation of the tool wear rate.

Öpöz et al. [11] characterized the shape deviations and dimensional errors in EDM blind micro hole drilling. A different set of experiments with different machining time (1–80 min) have done on plastic mould steel with tungsten carbide rods of 300 μm diameter for characterization. Drilling of micro-holes on beryllium–copper using tungsten carbide tool electrode has done to study the characteristics of blind micro holes for different depth to diameter ratios [12]. It is concluded that the diameter, roundness error, and taper angle are proportional to the aspect ratio of the hole and are increased in almost the same rate as the tool goes descents. A simple method is proposed to calculate volumetric wear in EDM drilling at different depths and different kinds of tool electrodes (solid and hollow) [13]. It is recognized that the variation in volumetric wear in different depths is the primary reason for inaccuracies in EDM drilling. The feasibility of drilling high aspect ratio micro holes is investigated by Puranik and Joshi [14] considering the depth as a function of machining accuracy. They fabricated micro holes of 5 mm depth and 200 μm diameter (aspect ratio = 25), but secondary sparks and difficulty in debris removal distorted the profile of the drilled hole. In all these studies, researchers reported the inaccuracies generated on the blind hole profile because of the tool wear and the importance of controlling the tool wear to get accurate dimensions of the micro features.

To improve the dimensional accuracy of the blind hole drilled with EDM, different researchers employed different strategies. Ferraris et al. [15] tried to use different coatings on tool electrode to overcome the side wear during machining and successfully machine high aspect ratio holes with a uniform profile with tool electrodes coated with Parylene C polymer. EDM tools fabricated by electro deposition process reported superior wear resistance. The composite coated electrodes could almost retain its shape and dimensions during blind hole drilling [16]. These methods will reduce the effect of side wear during the drilling process. However, tool wear in the direction of tool length cannot be controlled easily which generates some depth wise inaccuracies in the machined hole. The practical solution to this problem is to employ some tool wear compensation strategy in which some extra distance is added in the tool travel which erodes out eventually and compensates the reduction in tool length.

Researchers mainly employed two different methods for measurement of tool wear rate – offline methods and online methods. The offline methods either use the idea of periodical measurement of tool length or theoretically model the process to predict the tool wear rate for a particular machining condition. There are some empirical models formulated [17] to predict tool wear ratio – which is the ratio of eroded tool length to the eroded depth in the workpiece. Theoretical models often fail to predict the exact tool wear because of the complex stochastic nature of the machining process. Empirical models can only be used for particular machining condition and a particular tool-workpiece material combination. Periodical measurements use the idea of measuring the tool wear by frequently stopping the machining process and calculating an anticipated wear value for further machining. In all these methods, a predicted tool wear compensation is added at the beginning of the machining or at frequent intervals to reduce the machining error. Thus it is called offline compensation method. Kaneko and Tsuchiya [18] developed a touch sensing circuit for periodical measurement of the size and shape of the tool. Mizugaki [19] employed a laser range sensor for understanding the tool wear trends. Yan et al. [20] developed a machine vision system for periodical measurements of the eroded tool length for EDM milling operations.

Online tool compensation methods calculate the eroded tool length by sensing the accumulated duration of effective (normal) discharges during machining. Then it will map those data to the removed volume of the tool electrode by certain models, and the machining is stopped when eroded volume equals the expected volume. One of the main contributions in developing this strategy is attributed to Bleys et al. [21]. They further developed a tool wear sensing and compensation method by combining the anticipated wear method and discharge pulse counting strategies [22]. This idea is further improved by combining the real-time tool wear sensing methods with electro thermal models of EDM [23]. First one will count the discharge pulses, and the later one determines the expected erosion volume of the workpiece. A tool compensation strategy by discharge counting statistical characterization of discharge population is also proposed by Bissacco et al. [24]. It helps in reducing the dimensional errors in micro EDM drilling. Lee et al. [25] used a machining hole count based model and machining time-based model to fit exponential tool wear curves. They managed to develop a model which predicts the tool wear with a 3% error margin. The geometric prediction of the conic tool during EDM drilling process is done by simulation [26], and the shape distortions are compared with experimental results. A virtual EDM simulator which predicts the shape of the tool after each machining stage is also developed [27].

Compared to the tool wear compensation methods using periodical measurements, real-time compensation strategies demand complex modelling with the advantage of avoiding frequent machining terminations for measurement. However, periodical measurements are simple in nature as well as effective in maintaining dimensional accuracy. In the studies mentioned above, a little attention is given to the tool compensation strategies to reduce the gap between the actual depth and the intended depth of the hole. Most of the offline tool compensation strategies focused on predicting tool wear either from periodic measurements or some theoretical/empirical models. According to wear rate calculated by different methods, anticipated tool wear is added to the total tool travel distance for compensating tool erosion in the next machining step. Most of the time, a part of this compensation value will also erode out so that the intended depth will never be achieved. To overcome this problem, a new methodology needs to be developed for drilling intended depth in micro EDM.

In this paper, a tool compensation strategy for drilling series of holes of uniform depth is realized using image processing techniques and tool wear compensation algorithm. The system is programmed in such a way that the tool wear is compensated in terms of total tool travel distance during drilling. Thus, the measurements-calculations-part program modifications are brought under a single MATLAB program which considerably reduces the delay time associated with offline compensation methods. A camera is used to capture the images of the tool electrode, and an image processing unit (IPU) helps to analyze the tool length and determine the tool wear compensation value. The strategy is used to machine a series of blind holes and the depth of each hole is measured to evaluate the effectiveness of the tool compensation strategy.

2. Experimental setup

A 3 axes CNC EDM machine (DT 110, Mikrotools) is used for drilling holes in Tungsten carbide (WC) workpiece using WC tool electrode of 300 μm diameter. The process parameters which are identified as the optimum parameters for minimum entrance diameter, maximum hole depth and maximum material removal rate according to previous experiments are mentioned in Table 1.

Table 1
Process parameters for EDM drilling.

Parameters	Value
Source voltage	96 V
Capacitance	10 nF
Feed rate	0.2 mm/min
Electrode material	Tungsten Carbide (WC)
Workpiece material	Tungsten Carbide (WC)
Electrode diameter	300 μm
Dielectric fluid	EDM-3 oil
Spindle speed	2019 rpm
Polarity	Workpiece (+), Tool electrode (−)

The tool electrode is used to drill a series of micro-holes in the workpiece with an intended depth of 200 μm. The tool images are captured by a microscope with charge coupled device (CCD) camera set up near to the EDM working zone as shown in Fig. 1(a). Fig. 1(b) shows the photograph of the experimental set up. Shadow images of the tool is captured (800 × 600 pixel) and stored in the computer for analysis. The images are accessed by a tool wear compensation algorithm written in MATLAB®. An edge detection function is used to detect the outer profile of the electrode. The tool electrode profile is further analyzed to determine the tool wear and exact tool travel distance for drilling intended depth.

The experiments are conducted in four sets. In the first set, no compensation strategy is employed. 4 holes with 1 mm gap between them are drilled on the WC block with the defined machining parameters as given in Table 1 to an intended depth of 200 μm.

In the second set of experiments, the eroded length after drilling a hole is accessed by finding the Z_0 position using a touch probe of the machine. After drilling the first hole, the tool is moved to the position of the next hole. Before drilling of the second hole, touch probe finds the top surface of the workpiece and make that reading as Z_0. Then the drilling operation is started with the same tool travel distance as the first hole as explained in Fig. 2.

In the third set of experiments, the tool wear is found out as the difference in surface coordinates in Z direction between the successive drilling points. This tool wear is added to the total intended depth of the hole (200 μm). The procedure of the experiment is schematically explained in Fig. 3, in which w stands for the eroded tool length after drilling a hole. For the very first hole, where no

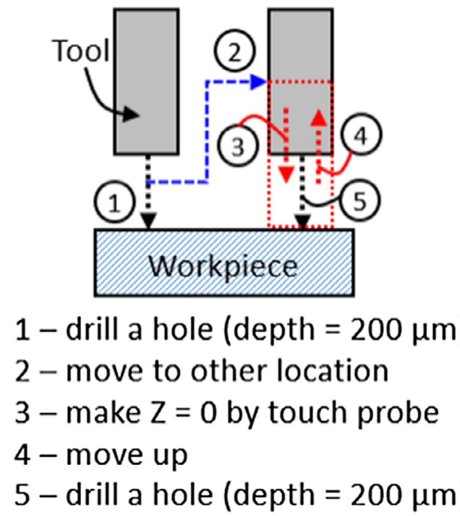

Fig. 2. Experiment procedure for series hole drilling with updating surface coordinates.

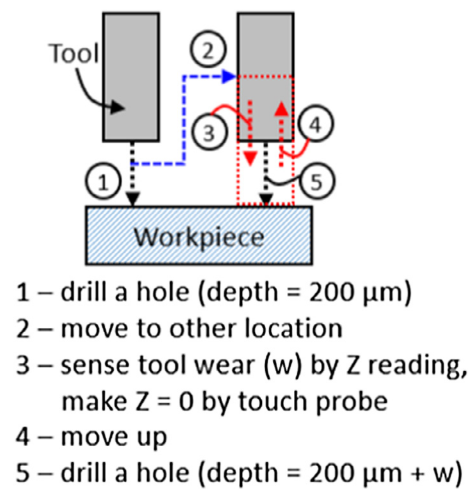

Fig. 3. Experiment procedure for series hole drilling with updating surface coordinates and compensating for eroded tool length.

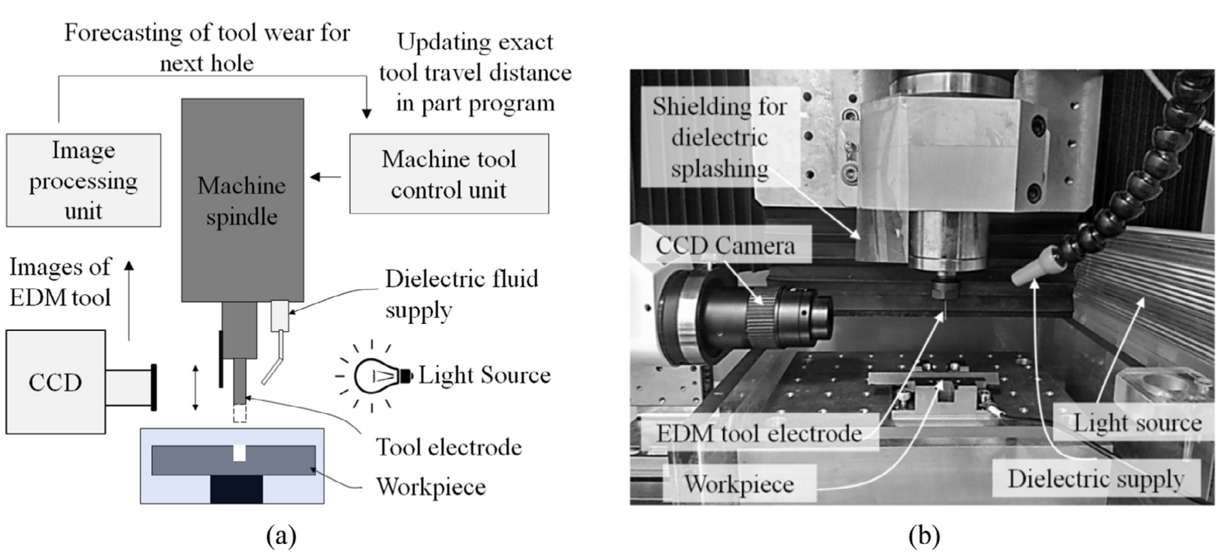

Fig. 1. (a) Schematic diagram and (b) photograph of tool wear sensing and compensation system for micro EDM drilling.

data is available for the eroded tool length, the average tool wear value from the previous set of experiments is used.

Finally, the fourth set of experiments is conducted with the proposed strategy of tool wear compensation. It starts with a pilot experiment to understand the approximate tool wear per unit tool travel and a series of four holes are drilled according to the average forecasting principle. This is explained thoroughly in the next section. The goal is to keep the depth of four holes to the same value and to reduce the difference between the actual depth and intended depth of the hole to an acceptable range. Depth measurements of the blind holes are carried out using a 3D non-contact optical profilometer.

3. Tool compensation using image processing unit (IPU) and average forecasting method

The principle of periodical measurements for tool wear compensation is to measure the eroded length of the tool in a particular interval of time and predict the tool path for the next operations by calculating the anticipated wear. Here, the measurement part is done with an image processing module and the calculation part is done by a tool wear compensation algorithm utilizing the idea of average forecasting. Before starting the experiments, the efficiency of image processing module has to be analyzed to approve the feasibility of the system for off-line measurements.

3.1. Calibration of IPU

For analyzing and calibrating the image processing module, a reference point is defined with fixed coordinates in which the tool is focused on the camera and enough length of the tool is visible. The tool electrode is moved upwards to the coordinates of the reference point each time after drilling. During the upward movement, the spindle is stopped and restarted to the maximum speed to remove the droplets attached to the tool electrode. An image of the tool is taken and stored which is accessed by the image processing unit (IPU).

To calibrate the IPU, pixels per unit length for the image has to be calculated. Before starting the experiment, exact diameter of the tool electrode is found out. Number of pixels in the X direction is counted within the dark region, and equated to the diameter of the tool which has been entered as an input to the program. From this, the pixel per unit length value is calculated to convert all the pixel data to coordinate points as shown in Fig. 4.

To get the length of the tool, the same strategy is used. The coordinates of the top most point and the lowest point has been recognized. The number of pixels in that direction or the difference in the coordinates of those two points has been converted to the length of the tool with respect to the pixel per unit length calculated in the previous step. Tool wear is calculated as the difference in tool lengths by comparing the images taken before and after drilling a hole. The steps in tool wear measurement using IPU is consolidated in Fig. 5.

$$\text{Number of pixels in X direction} = x_2 - x_1 \ (pixels) \tag{1}$$

$$\text{Pre - measured diameter of tool } (\mu\text{m}) = \text{d} \tag{2}$$

$$\text{Calibration Factor, k}(\mu\text{m/pixel}) = \frac{d}{x_2 - x_1} \tag{3}$$

$$\text{No. of pixels in Z - direction} = (z_i - z_r) \tag{4}$$

$$\text{Length of the tool, h } (\mu\text{m}) = (z_i - z_r) \times k \tag{5}$$

$$\text{Tool wear, W}_\text{n} \ (\mu\text{m}) = (h_\text{n} - h_{n-1}) \tag{6}$$

To calibrate the accuracy of the image processing system for measurement, the tool is moved up to a known height of 2 mm in 4 steps of equal distance (500 μm) and the images of each position is captured. The height difference in each step is calculated using the IPU, and the difference between actual tool length difference and value calculated by IPU is used for calibrating the measurement unit. In Fig. 6(a), W stands for the tool length difference (or tool wear) in successive movements. Fig. 6(b) shows the graph plotted according to the hole number and depth measured by IPU. Variation in the tool length measurement is found to be less than 2.4%. To reduce the repeatability errors in the algorithm, 3 tool images are taken with different orientation of the tool at each time of measurement, and the average height difference is taken as the input to the tool wear compensation algorithm.

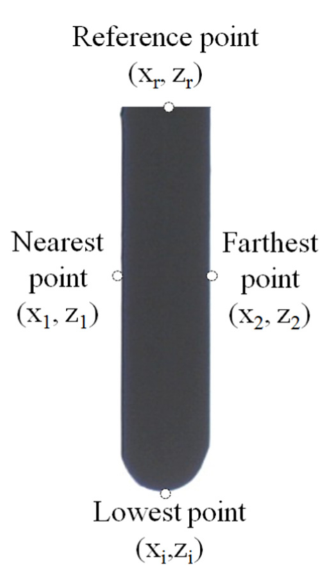

Fig. 4. Shadow image of the EDM tool after drilling with specific points used for calculation of pixel per unit length.

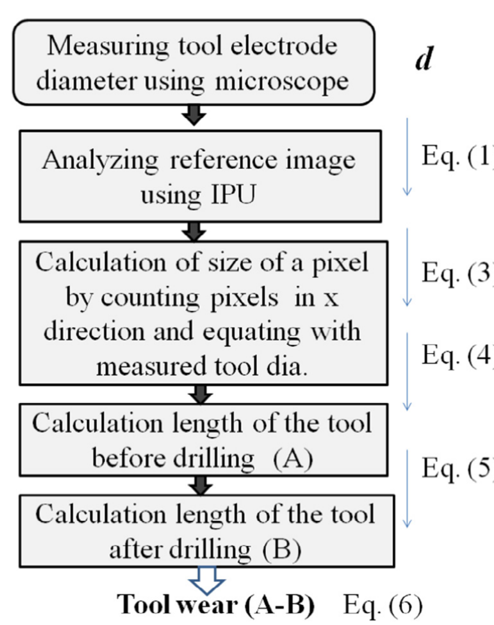

Fig. 5. Process flow in the calibration of the image processing system.

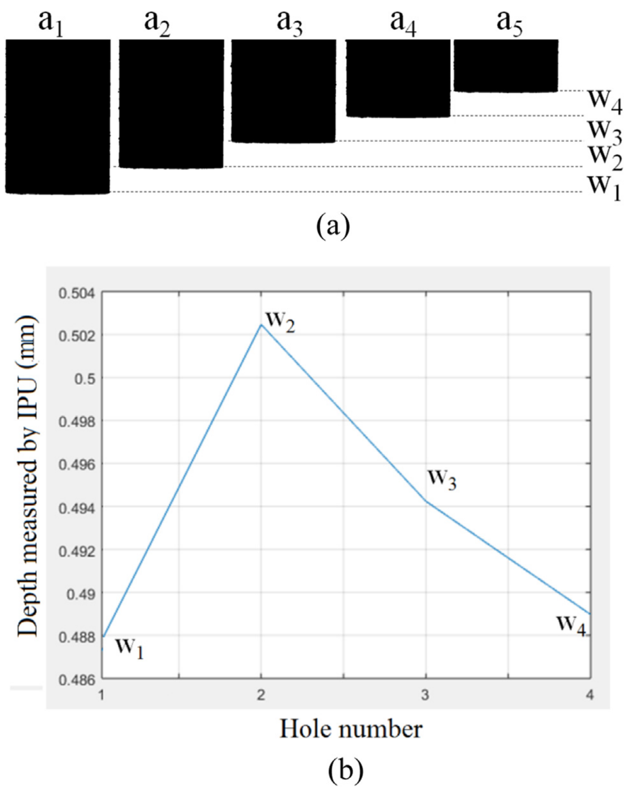

Fig. 6. (a) Calibration strategy for IPU, (b) difference in the distance measured by IPU for a sequential tool travel of 500 µm.

3.2. Tool wear compensation strategy

The current tool wear compensation strategy works on the principle of average forecasting. To calculate the tool wear ratio (depth of the hole/eroded length of the tool) demands accurate measurement of hole depth, which is practically not possible during drilling a series of holes. X is the tool travel distance, and z is the depth of the hole drilled using EDM. Depth of the final hole will be the difference between the tool travel distance and tool wear (W). The tool wear can be represented as the product of tool travel distance X and tool wear per unit tool travel distance (w). Eqs. ((7)–(15)) explain the method of applying average forecasting for predicting the tool wear. A pilot experiment is done to understand the approximate tool wear per unit tool travel (w_0) by drilling a hole to a depth (X_0). After completing the pilot experiment, the tool ascends to the reference position for image capture and the image processing system compares the tool length with the reference image (captured before machining) and calculates the tool wear (W_0). From the tool wear value and the known tool travel distance, w_0 is calculated by dividing the tool wear by the tool travel distance. $w_0 = \frac{W_0}{X_0}$ as explained in Fig. 7. This gives an idea about the approximate length of the tool to be eroded while moving a depth near to the intended depth.

$$z_0 = X_0 - W_0 = X_0 - w_0 X_0 \tag{7}$$

$$w_0 = \left(\frac{W_0}{X_0}\right) \tag{8}$$

where, z_0 = actual depth in the pilot experiment, X_0 = known tool travel distance in pilot experiment, W_0 = measured tool wear after drilling the pilot hole, w_0 = tool wear per unit tool travel

$$z = X_1 - w_0 X_1 \tag{9}$$

where, z = intended depth, X_1 = tool travel distance for the first hole

$$X_1 = \frac{z}{(1 - w_0)} \tag{10}$$

Adding the eroded depth (W_0) in the pilot experiment for exact tool travel distance,

$$X_1' = X_1 + W_0 \tag{11}$$

where X'_1 = exact tool travel distance for the first hole

$$X_1' = \frac{z}{(1 - w_0)} + W_0 \tag{12}$$

$$X_2' = \left[\frac{z}{1 - \left(\frac{w_0 + w_1}{2}\right)}\right] + W_1 + W_0 \tag{13}$$

where, X'_2 = exact tool travel distance for the second hole

$$X_3' = \left[\frac{z}{1 - \left(\frac{w_0 + w_1 + w_2}{3}\right)}\right] + W_2 + W_1 + W_0 \tag{14}$$

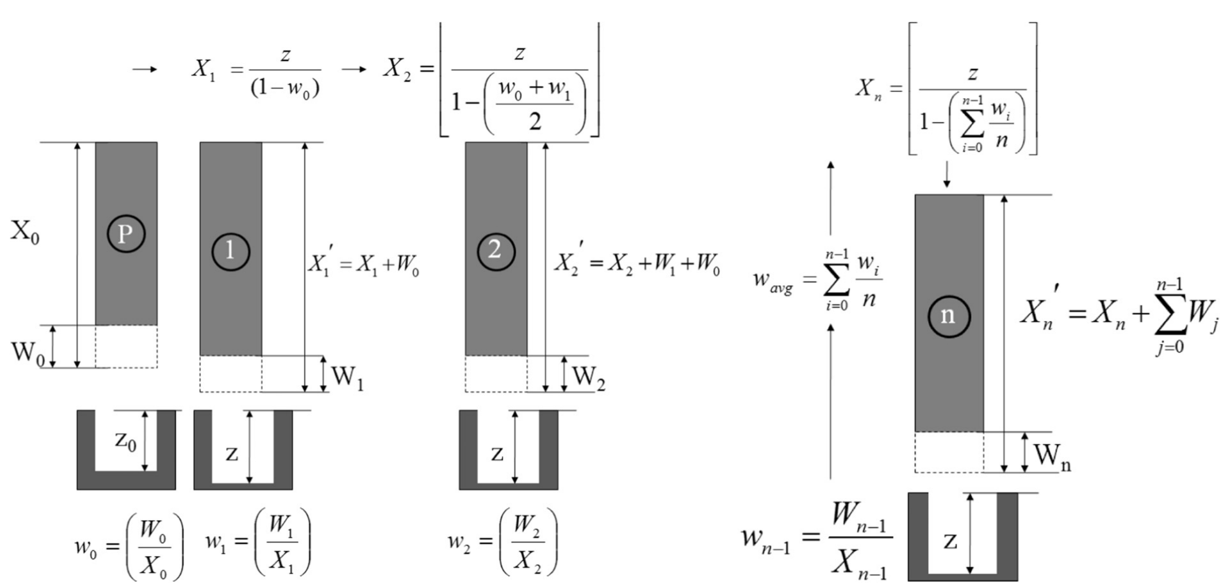

Fig. 7. Schematic diagram of the sequence of the proposed tool wear compensation method.

where X'_3 = exact tool travel distance for the third hole

$$X'_n = \left[\frac{z}{1-\left(\sum_{i=0}^{n-1}\frac{w_i}{n}\right)}\right] + \sum_{j=0}^{n-1} W_j \tag{15}$$

where X'_n = exact tool travel distance for nth hole.

3.3. Drilling with tool compensation

Wear per unit tool travel value from pilot experiment (w_0) is used in Eq. (10) to calculate the tool travel distance to be covered (X_1). Here, z is taken as the intended depth of 200 μm. X_1 is the distance to be travelled from the surface to get an intended depth of the hole. Meanwhile, the tool tip is away from the surface by the eroded tool length in the pilot experiment (W_0). To get the exact tool travel distance (X'_1), W_0 is added to X_1. After calculating X'_1, the program will automatically update the total tool travel distance and positional coordinates for the first hole in the part program text file associated with the drilling operation. According to the modified positional coordinates, the tool electrode automatically moves to the next position for drilling the first hole. After machining, the tool electrode again moves up to the reference point, and the image is captured. This image is compared with the earlier image to get the difference in length (W_1), and w value for current drilling is calculated (w_1). While calculating w_1, the tool travel distance in the denominator must be taken as X_1 instead of X'_1 because in the distance added for accommodating the gap will not experience any discharges. To predict the tool wear and exact tool travel distance for the second hole, average forecasting is done with the available w values. Average of the two available wear per unit length data (w_0 and w_1) is taken as the tool wear per unit tool travel for the next hole. The gap between tool tip and the workpiece surface is again compensated by adding W_0 and W_1 to the calculated tool travel distance. After calculating the exact tool travel distance, the tool again moved to a new position and the procedure continues. The w matrix is updated after each drilling operation and the average of these values is taken as the new w to calculate the total tool travel distance for the next hole as shown in Fig. 7.

4. Results and discussion

Fig. 8 shows 3D images of the drilled holes of all the four sets of experiments captured by a non-contact optical profilometer (Taylor Hobson, UK). The depth of the drilled holes are measured at the cross-section passing through the centre of the hole. A sample reading of the 4th set (hole 4) is shown in Fig. 9. Similarly, the depth of all the holes are measured, and their trends are discussed below.

In the first set of experiments without employing any compensation methods, maximum depth of the holes is measured as 185.63 μm, 165.78 μm, 142.0 μm and 116.24 with a relative percentage errors of 7.1, 17.1, 29 and 41.9. This is because the eroded length of the tool is not compensated for the next hole. Fig. 10 ensures the need for an efficient tool compensation strategy in blind hole drilling.

In the second set of experiments which utilizes the touch probe to compensate the tool wear by updating the surface coordinates, the standard deviation in depth of holes is in the range of 5 μm, but the maximum percentage error with respect to the intended depth is 8.37. Even though the tool is moved down to compensate the tool length reduction by drilling the previous hole, the tool

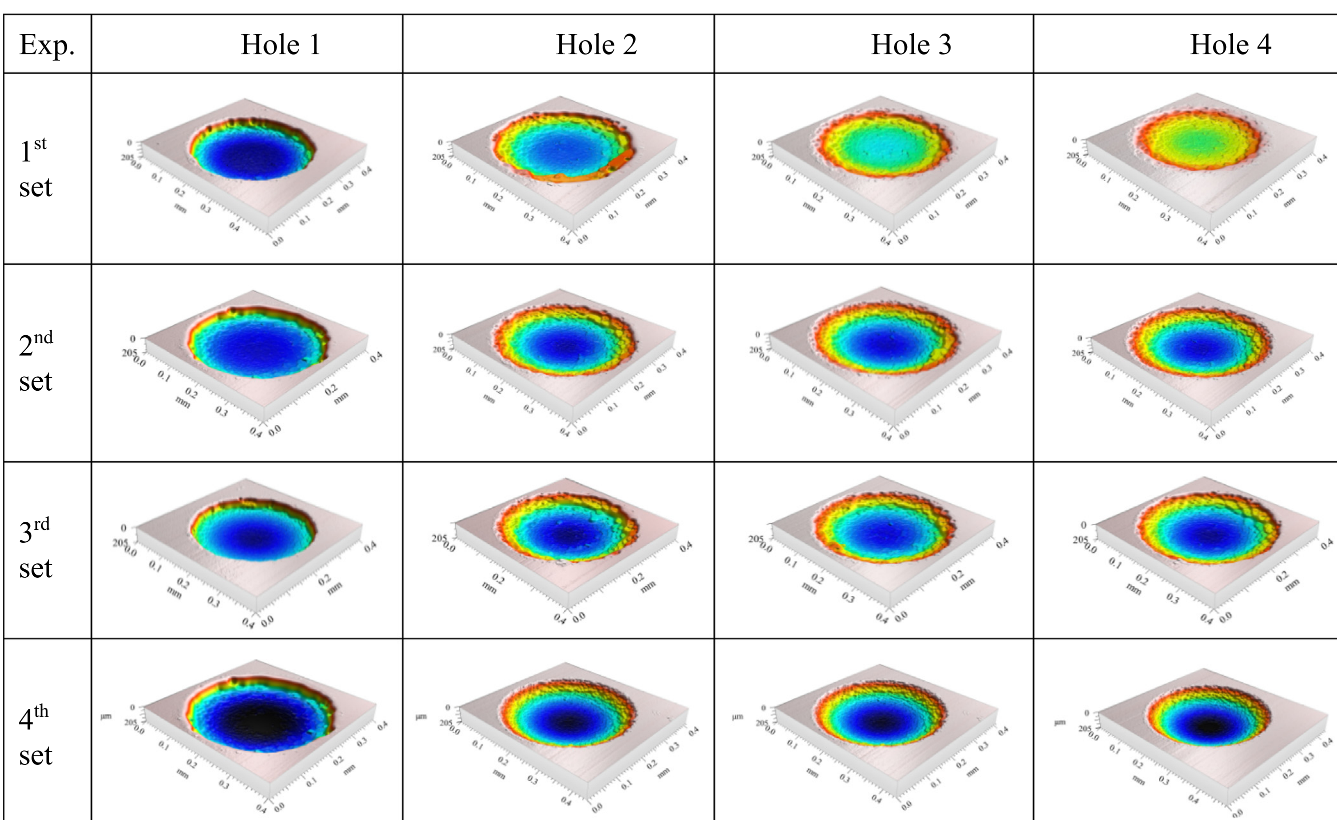

Fig. 8. 3D non-contact profilometric images of the drilled hole using four different methods (sets). (z-axis scale is in μm.)

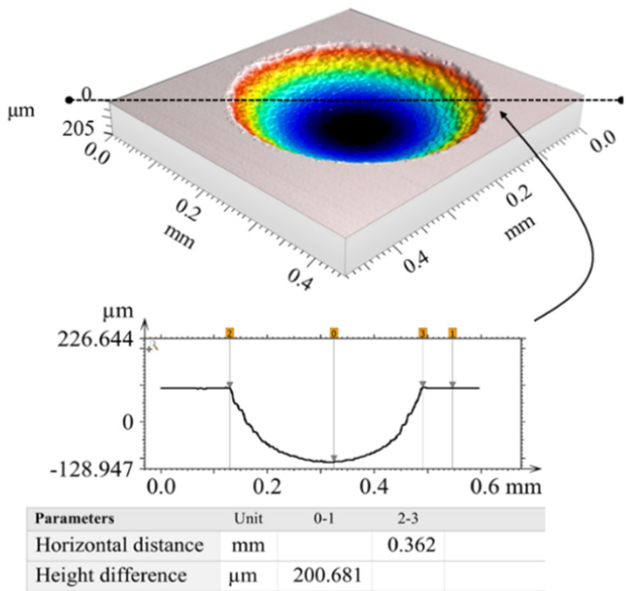

Fig. 9. Sample of measurement of depth at the cross-section of the hole.

wear during current hole drilling is not considered in this method. So, there will always be some difference between the intended depth and actual depth as shown in Fig. 11.

In the third set of experiments, the tool wear value is calculated from the change in surface coordinates after a pilot hole drilling operation and added to the tool travel distance during following hole drilling operation. However, some portion of the additional travel will also be eroded out. So, the intended depth will never be achieved as shown in Fig. 12. That means the total tool travel distance must be greater than the sum of intended depth and the tool wear length because a part of this compensated tool wear length will also get eroded.

Finally, the experiments employing the IPU and average forecasting are performed, and the results show the effectiveness of the tool compensation strategy. From Fig. 13, it is evident that the strategy can be used to drill blind holes to an intended depth with a higher degree of accuracy. The experiments started with a fresh tool with a flattened bottom which eroded out, and the shape was distorted due to corner wear. Once the corners are eroded out, and the tool reached to a particular shape, it retained that shape in the further drilling operations. Hence, the depth of the holes is improved by the proposed compensation strategy.

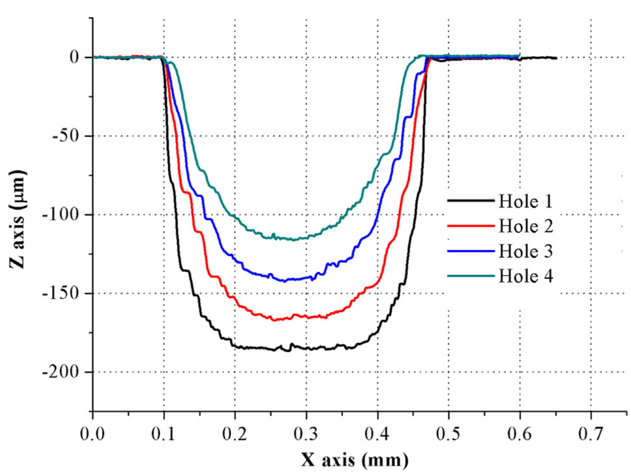

Fig. 10. Profile of holes drilled without any tool compensation strategies.

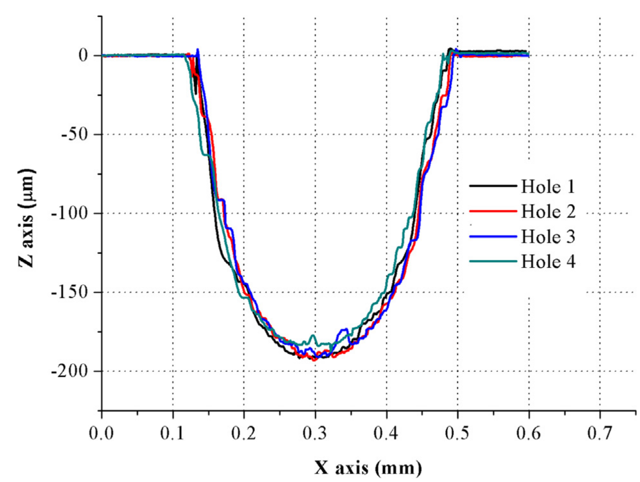

Fig. 12. Profile of holes drilled after updating z_0 and compensating with the tool wear.

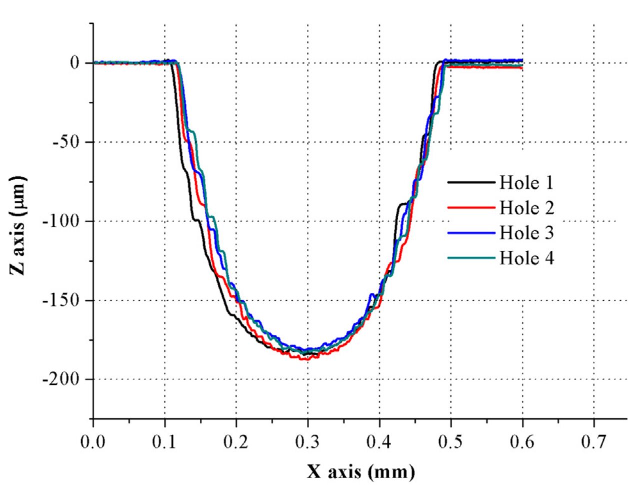

Fig. 11. Profile of holes drilled after updating Z_0 by touch probe.

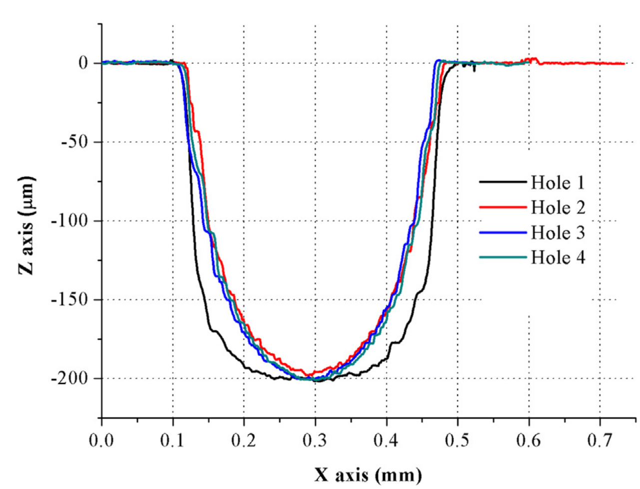

Fig. 13. Profile of holes drilled by the proposed tool compensation strategy.

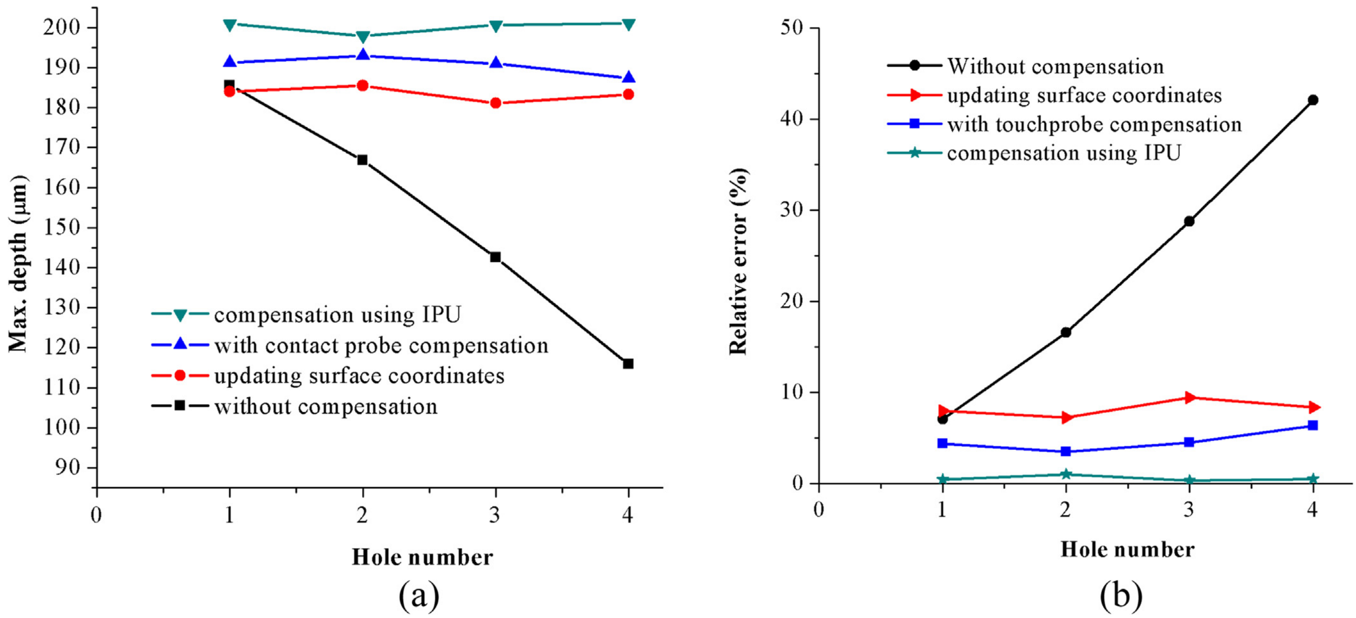

Fig. 14. (a) Max. depth of holes drilled with different strategies, (b) relative percentage error of the depth of the holes with respect to intended depth.

Fig. 14(a) shows that drilling of series of holes using the proposed method has negligible difference between the intended depth and actual depth of the hole. Fig. 14(b) shows the relative error between the intended depth and the actual depth of the hole. It is observed that the proposed method has 1% or less relative error as compared to other compensation strategies. This shows the need and effectiveness of a tool compensation system in blind hole drilling to reach the intended depth.

5. Conclusions

A new method for length-wise tool wear compensation in micro EDM is proposed. The following conclusions are drawn from the present work.

- The image processing unit (IPU) is proved its capability to measure the tool wear within the range 2.4% of error.
- The proposed method uses the image processing unit and computer program based on average forecasting of tool wear to predict tool wear compensation.
- The proposed tool wear compensation strategy is compared with other strategies regarding the intended depth and actual depth of the hole.
- The current tool compensation strategy is successful in machining series of blind holes to an intended depth constantly with a maximum relative error of 1% and less.
- The current strategy allows updating the part program automatically after each drilling operation which reduces the total idle time associated with the offline tool compensation methods.
- The idle time can be further reduced by automating the image capture and triggering of the IPU for calculating the exact tool travel distance to update the part program.

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