# A study of micro-electro discharge machining electrode wear

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# A study of micro-electro discharge machining electrode wear

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**Abstract:** This paper studies the influence of factors contributing to electrode wear during the micro-electro discharge machining (EDM) process. The paper proposes a method for calculating the volumetric wear ratio based only on geometrical information obtained from the process. The objective of the work is to investigate the suitability of micro-EDM electrode wear compensation methods. Electrode shape deformation and random variations in the volumetric wear are studied as two main factors affecting the applicability of wear compensation methods as well as indicating the accuracy achievable with micro-EDM. EDM drilling and EDM milling are regarded as separate processes as they require different approaches in investigating and implementing the results of the study.

**Keywords:** micromachining, micro-EDM, EDM accuracy, electrode wear, microfeatures

## 1 INTRODUCTION

In conventional die-sinking electro discharge machining (EDM), the problem of wear occurring on the tool is well known [**1**]. This problem is normally overcome by using a number of electrodes to produce a cavity. The errors caused by electrode wear are often negligible when considering the feature sizes and tolerances required.

In micro-EDM, it is possible that holes have to be machined with diameters smaller than 5 μm and with surface roughness ($R_{max}$) less than 0.1 μm [**2**]. In such cases, in order to produce accurate three-dimensional cavities, electrode wear becomes a difficult issue and methods to compensate for it are required. The machining conditions in micro-EDM differ significantly from those in conventional EDM [**3**]. The usual die-sinking method based on employing electrodes for roughing followed by electrodes for finishing is not applicable because of the cost of multiple electrodes with microfeatures. In addition, the microfeatures will suffer severe wear resulting in the need for even more electrodes.

Thus, in the production of micro-three-dimensional cavities, the use of micro-EDM milling employing simple-shape electrodes might be the preferred strategy, because the sparking conditions and the wear ratio will not change drastically and the result of the machining will be more predictable. However, because of the physical size of the features, the accuracy required for the methods used in micro-EDM milling, wear compensation is much higher than in conventional EDM milling. Many types of electrode wear compensation methods have been studied and applied successfully in research laboratories [**4**], but their introduction into an industrial manufacturing environment is not straightforward.

This paper studies the electrode wear behaviour, electrode wear variation in different situations, and possibilities for electrode wear compensation methods. The paper comprises three main sections. Section 2 discusses methods for estimating wear and electrode shape deformation. Section 3 proposes a simple way to calculate the volumetric wear ratio, the key parameter in most wear compensation methods. Section 4 describes the experimental measurement of electrode wear and estimation of spark gap variation.

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## 2 WEAR ESTIMATION

In micro-EDM, accurately measuring the amount of wear is a difficult task especially when very small wear volumes are involved.

The first consideration concerns the deformation of the electrode shape due to wear. This is because wear occurring on the side of the electrode and distorting the shape cannot be ignored. For instance, when eroding with a microcylindrical (rod or tube) electrode, the shape of the electrode rapidly changes during machining [**5**] (Fig. 1), which causes geometric errors in the produced microcavity.

The second consideration is the volumetric wear occurring on both electrode and workpiece and the volumetric wear ratio, which is the ratio of the volume removed due to wear of the electrode $V_e$ and the volume eroded from the workpiece $V_p$. This ratio is the main criterion for electrode wear estimation

$$\sigma = \frac{V_e}{V_p} \tag{1}$$

### 2.1 Electrode shape deformation

A number of experiments were carried out to analyse the shape change of the electrode. These have confirmed that the electrode tends to change during machining towards a constant shape.

Figure 2 shows the evolution of the cavity shape when tool steel is EDM drilled and the constant electrode shape obtained after drilling a certain depth.

It was noticed that the shape change occurred during the first 180 μm of erosion depth. After this, the electrode continues to wear but its shape remains constant. A logical explanation is that, initially, the intensity of the electrical field is stronger at the corners and they wear first, becoming blunt in the process. Then, the highest intensity of the electric field shifts to the middle of the electrode where there are the most sparks. It is hypothesized that the shape of the electrode changes in such a way as to achieve uniform electric field intensity eventually (Fig. 2(b)).

The final shape of the electrode was scanned and a three-dimensional image of the electrode was created together with the initial cylindrical shape and one intermediate shape of the electrode. The three shapes of the electrode were used in electrostatic field modelling software [**6**] to check the above hypothesis. The results are given in Fig. 3. Figure 3(a) shows that the

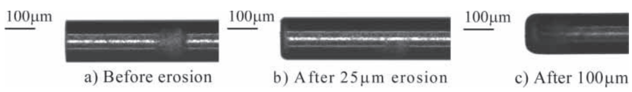



**Fig. 1** The shapes of a Ø150 μm rod electrode (a) before, and (b) and (c) after two erosion depths

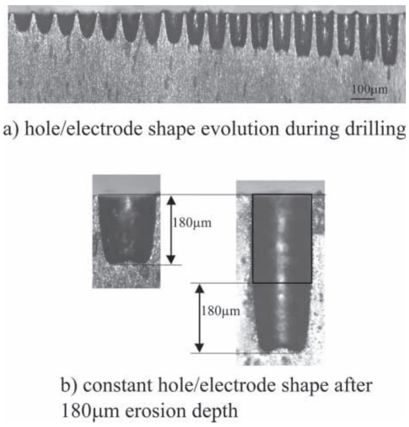



**Fig. 2** Evolution of the cavity/electrode shape during EDM drilling of tool steel with Ø170 μm WC electrode

intensity of the electric field in the spark gap is highest around the edge when the cylindrical electrode is electrically charged. Figure 3(b) shows the decrease of the intensity of the electric field in the spark gap and shift of the position of highest intensity towards the middle of the electrode as the edge of the electrode wears. Figure 3(c) shows the uniformity of the electric field intensity in the spark gap after the constant electrode shape has been reached.

It is not simple to calculate the volume of the electrode material lost in reaching the constant shape. The volumetric wear ratio in this initial period of erosion with non-uniform electric field intensity is difficult to predict as the electric field intensity continuously changes causing sparking to appear at different parts of the electrode.

Similar effect was noticed in EDM milling, where, due to electrode wear, the depth of cut varies during the process. In this case changes to the electrode shape are even more complex to envisage. Depending on the depth of cut and the degree of overlapping of the tool paths, the electrostatic field intensity changes constantly, which will result into constant change of the shape of the groove milled.

A number of parallel grooves were EDM milled in a steel block (Fig. 4(a)) starting at two different depths of cut. The electrode was allowed to wear till there was no more contact with the workpiece. The difference of the grove shape depending on the starting depth of cut, which is shown in Fig. 4(b).

Electrostatic field modelling software can be used in this case as well to predict the shape of the electrode change at any moment. The electrode shape deformation should be a function of both the intensity of the electrostatic field and the relative wear ratio $\sigma$ (equation (1)). Electrostatic field modelling shows where the next sparks are likely to appear and the relative wear ratio determines how much material is removed from the electrode and from the workpiece.

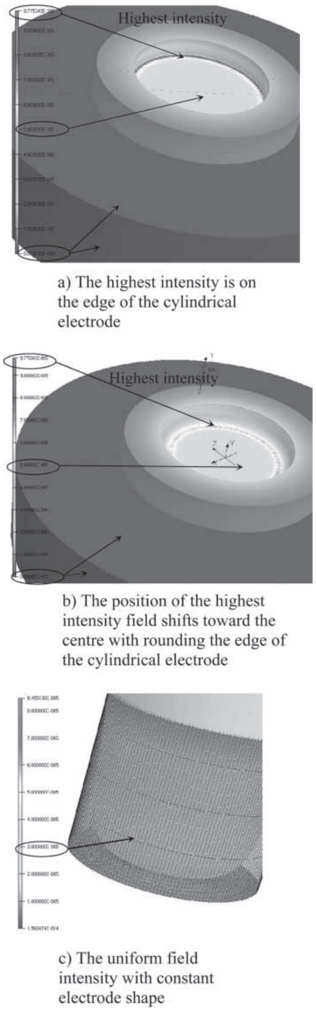



**Fig. 3** Electric field intensity dependency on the electrode shape changes

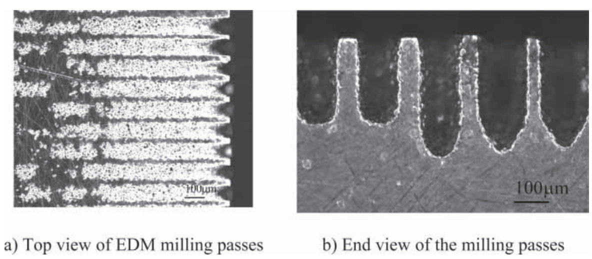



**Fig. 4** Groove shapes obtained for two different milling depths

By combining different electric field intensities and different wear ratios, various final shapes can be achieved, that give uniform field intensity.

### 2.2 Volumetric wear

Conventional EDM requires knowledge of the wear ratio for a standard electrode/workpiece materials combination and sparking conditions (voltage current, time on, time off, etc.) in order to estimate the number of electrodes needed. The differences of the wear ratio for one material are considered negligible (for instance different quality steels, grain sizes, feature positions, flushing conditions, etc.), as the requirements for the final accuracy are not as high as in micro-EDM. In micro-EDM, it is not clear how such variations will affect the erosion process, and therefore the wear ratio, in spite of the electrode shape being simple. Thus a small change of the sparking conditions (temperature of dielectric, workpiece material structure and purity, electrode purity, variation of spark energy, etc.) might affect the wear ratio.

The accuracy with which the volumetric wear and the wear ratio can be estimated will determine the accuracy of the compensation method used, the strategy of machining, and finally the accuracy of the machined features.

Even in the laboratory, methods such as weighing the electrode and the workpiece before and after erosion, using ultra precision scales, cannot achieve accurate wear measurements and thus cannot yield sufficiently reliable wear ratios. Another approach could be mapping of the electrode and workpiece surfaces before and after EDM machining and using software to calculate the removed volume of material. In this case, the accuracy of the scanning method, software approximation and positioning to scan the same patch before and after machining will determine the accuracy of the approach.

The assessment of the wear ratio should be carried out for each new setting (environment changes, generator parameters, etc.) and electrode/workpiece materials combination.

## 3 WEAR RATIO CALCULATION

As mentioned previously the volumetric wear ratio is the ratio between the volume removed due to wear of the electrode $V_e$ and the volume eroded from the workpiece $V_p$. Measuring each of these volumes would allow calculation of the volumetric wear ratio $\sigma$ (equation (1)). A number of electrode wear compensation methods require the value of the volumetric wear ratio [**7**, **8**]. The usefulness of such compensation methods will depend on how accurately and how repeatable the wear ratio can be determined as it depends on a number of machining conditions, such as the generator parameters (voltage, current, time on, time off, etc.), the flushing conditions, and the materials used for workpiece and electrode. A small modification of any of those conditions might have a non-negligible effect on the value and variation of the volumetric wear ratio. Thus, in order to obtain an accurate estimation of the wear ratio, rather than relying on existing and approximate data, it should be obtained for each machining problem.

At a macro scale, a constant wear ratio can be assumed, because discrepancies in the machining conditions will on average lead to negligible variations in wear characteristics. However, in micro-EDM, it is questionable if the ratio can be assumed constant. This is because uncontrollable factors might affect its value in a non-negligible way due to the small dimensions involved. This casts doubt on the validity of a number of compensation methods, which rely on such an assumption.

The method for volumetric wear ratio measurement proposed here could easily be applied even in a production environment. The method is based only on the geometrical information derived from the process.

As mentioned previously, the usual way of assessing the volumes $V_p$ and $V_e$ is to measure the weight of the electrode and the workpiece before and after the EDM process. From the weight of each part, based on the material density the volumes removed in the EDM process are then calculated. This requires the removal of electrode and workpiece from the machine and very accurate scales. In the case of micro-EDM, this method is not applicable as it is not sufficiently accurate and will introduce critical errors in the micro-EDM process.

As explained in section 2, after a certain depth of erosion in EDM drilling, the shape of the electrode remains constant. If drilling proceeds further from that point down to a target depth $Z$ (Fig. 5), it can be assumed that the volume of wear $V_e$ occurring on the electrode is equivalent to a cylinder of diameter $D_e$, and length $W_e$ (Fig. 5(a)).

$$V_e = \frac{\pi \cdot D_e^2}{4} \cdot W_e \tag{2}$$

A similar assumption can be made when using a tubular electrode (Fig. 5(b)). In this case

$$V_e = \frac{\pi \cdot (D_e^2 - d_e^2)}{4} \cdot W_e \tag{3}$$

The length $W_e$ can be measured on the machine by using a datum plane. After each drilling, the electrode tip is brought to the datum plane to establish electrical contact. The position along the $Z$-axis before and after machining determines the loss of length of the electrode.

The drawback with such a method is that the electrical contact produces a small amount of erosion (Fig. 6(a)), which would cause an error in the measurements of the actual $W_e$ value. Figure 6(b) shows the deviation in $Z$ position of 100 attempted measurements on the same spot of the same datum plane.

Using a similar assumption for the workpiece regarding the shape deformation and assuming that the spark gap $g$ is constant, it can be seen from Fig. 5 that

$$W_p = Z - W_e \tag{4}$$

In the case of a rod electrode

$$V_p = \frac{\pi \cdot D_p^2}{4} \cdot W_p \tag{5}$$

Therefore, the volumetric wear ratio can be defined as

$$\sigma = \frac{V_e}{V_p} = \frac{D_e^2}{D_p^2} \cdot \frac{W_e}{W_p} = \frac{D_e^2}{D_p^2} \cdot \frac{1}{(Z/W_e) - 1} \tag{6}$$

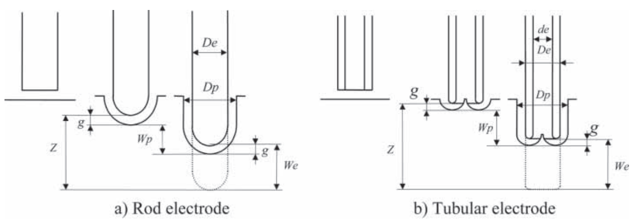
In the case of a tubular electrode

$$\sigma = \frac{D_e^2 - d_e^2}{D_p^2} \cdot \frac{1}{(Z/W_e) - 1} \tag{7}$$

Thus, the volumetric wear ratio is proportional to the ratio $R_w$ assuming that diameters $D_e$, $d_e$, and $D_p$ stay constant

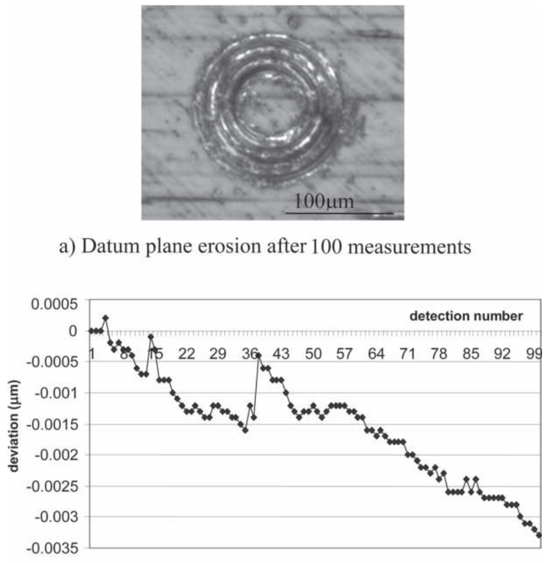
$$R_w = \frac{1}{(Z/W_e) - 1} \tag{8}$$

This method was used to record the evolution of the wear $W_e$ on the electrode when drilling holes 1 mm in



a) Rod electrode b) Tubular electrode

**Fig. 5** Schematics of erosion to a fixed depth $Z$ with rod and tubular electrode



a) Datum plane erosion after 100 measurements

b) Error of surface detection

**Fig. 6** Repeatability of electrode measurements depth with an electrode 170 $\mu$m in diameter. Drilling was performed in 60 stages and the electrode was measured 60 times to monitor the electrode wear. According to Fig. 6(b), the error due to the electrical contact should not exceed 1.5 $\mu$m.

## 4 EXPERIMENTS

Three different workpiece materials were investigated: tool steel P20, brass, and aluminium. The selection of materials was based on their applicability for conventional tooling and prototype microtooling.

The electrode material was tungsten carbide (WC) in 170 $\mu$m diameter tube and rod forms. Before each machining operation, the tip of the electrode was EDM ground flat and taken as a reference in the $Z$-direction for further calculations and measurements.

The sparking conditions were as follows:

- Voltage ($U = 60$ V);
- Current ($I = 0.8$ A);
- Time on ($T_{on} = 1\,\mu$s);
- Time off ($T_{off} = 4.2\,\mu$s);
- Electrode polarity = negative;
- Compression = 10. The gap compression (a factor between 1 and 50) is the parameter controlling the ignition delay;
- Gain = 1. The gain (a factor between 1 and 50) is the parameter controlling the sensitivity of the motors to the servo error signals.

The electrode was clamped in a high-speed EDM spindle and was rotated at 2000 r/min.

Data for electrode wear was collected for the drilling of 6 holes in the three workpiece materials using both rod and tube electrodes. Each hole was drilled in 60 steps. The results obtained for a hole form a data set.

Measurement of electrode wear was performed for each of the 60 steps of the drilling process along the $Z$-axis. To avoid long distance positioning errors, the measurement was carried out by using the top surface of the workpiece as a datum. The accuracy of surface detection for 60 measurements is taken to be 1.5 $\mu$m (Fig. 6(b)).

### 4.1 Wear measurements for different materials

The evolution of the wear $W_e$ was measured for the three workpiece materials and the two types of electrode. Each measurement was repeated six times in order to check the repeatability of the process. Figure 7 shows the results obtained and a corresponding picture of the cross-section of the workpiece.

Aluminium and brass have much lower melting points than tool steel and the grain structure consists of much larger grains. With the same spark energy, more material from aluminium and brass will be melted and therefore larger pieces of material will float in the gap as debris than in steel. When using a rod electrode to erode a hole in soft materials like aluminium and brass, after reaching certain depth, the flushing conditions deteriorate rapidly and the larger the debris, the more difficult it will be to be flush them out of the sparking area. From that point onwards, debris starts causing sparking on the side of the electrode. This breaks the debris into smaller pieces and finally they are flushed out of the sparking area. This explains the sudden change in electrode wear behaviour, high rate of electrode wear and distortion of the holes as shown in the workpiece cross-section pictures when aluminium and brass are drilled using a rod electrode. If a tubular electrode is used, the

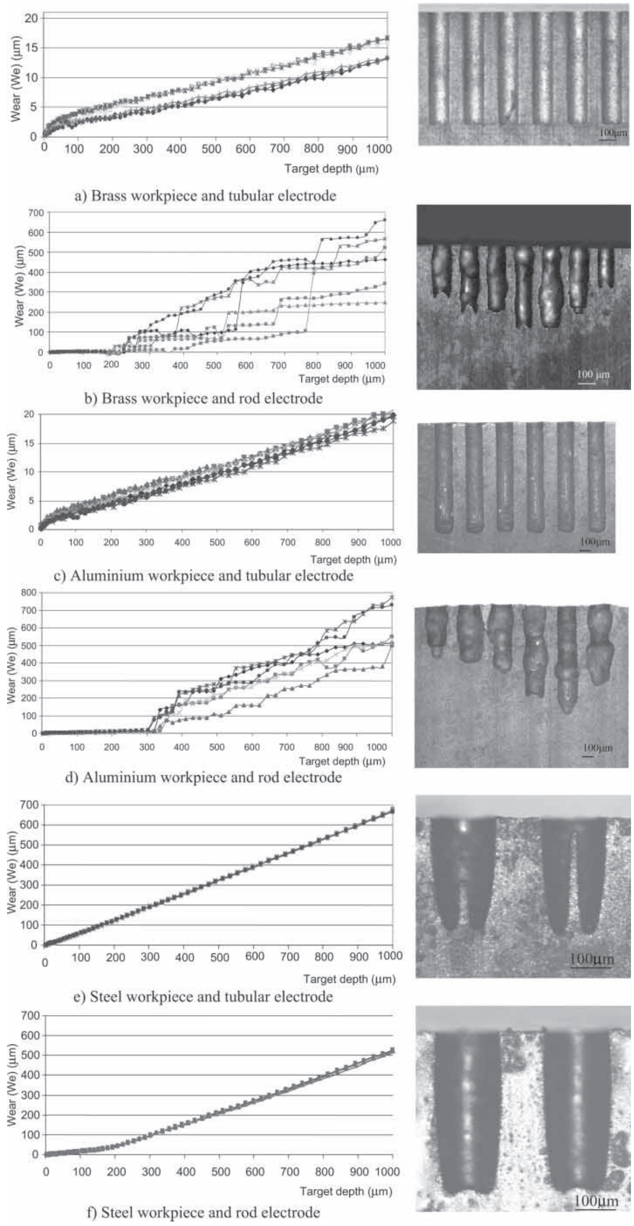



**Fig. 7** Electrode wear

flushing conditions do not change much for the whole depth. In spite of the size of the debris, they are forced out of the working area by the constant dielectric flow through the tube and the amounts of electrode wear and variations in wear behaviour are much smaller.

When eroding steel with a tubular electrode, more than 50 per cent of the electrode is worn compared to only around 2 per cent for brass and aluminium. Electrode wear is very similar for rods and tubes in tool steel machining. This can be explained by the much smaller debris size due to the higher melting temperature and smaller grain size of the material. Therefore, the flushing conditions do not change much even when using a rod electrode. Figure 7(f) shows that for tool steel eroding with the rod electrode the change in the trend in electrode wear after reaching a depth of around 180 μm is distinctively noticeable. This is assumed to be the depth after which the electrode has a constant shape with uniform electric field intensity. When the tubular electrode was used, the trend change was not so distinct and generally the wear rate was slightly higher than when the rod electrode was employed, which can be explained by the smaller volume of material in the tubular electrode. Despite this difference, the final external shapes of the electrode are nearly identical (Figs 7(e) and 7(f)).

### 4.2 Electrode wear variation

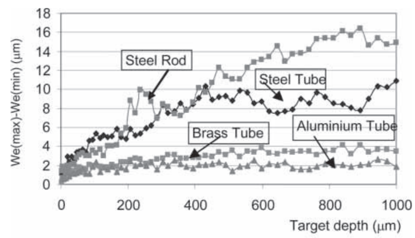
For the six sets of data, each obtained from drilling in one workpiece material with one electrode shape, the difference $M_{\text{dif}}^z$ between the smallest and largest measured wear for a specific target was calculated. This is used to indicate the variation of the electrode wear for the same sparking conditions

$$M_{\text{dif}}^z = (W_{\text{e}}^z)_{\max} - (W_{\text{e}}^z)_{\min} \tag{9}$$

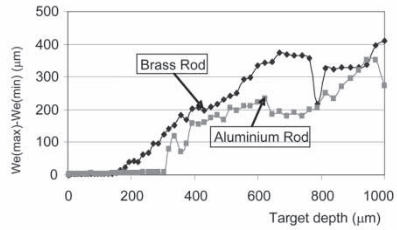
Figure 8 shows the values of $M_{\text{dif}}^z$ for the 6 holes at each targeted depth for each workpiece material and electrode type.

When using a rod electrode on brass and aluminium (Fig. 8 (b)), the differences in wear measurement start increasing dramatically from a certain depth. This is mainly because of the deteriorated flushing conditions. Due to the strong stochastic character shown, those measurements could not lead to useful conclusions regarding variations in the amount of wear and the wear ratio.

In the case of the steel workpiece, the flushing conditions do not have such a dramatic effect as explained above, but in comparison to the tubular electrode, the rod electrode shows an increasing variation in the wear ratio with the depth of the hole (Fig. 8(a)).




a) wear variation using WC rod and tubular electrode with steel, aluminium and brass workpieces




b) wear variation using WC rod electrode with aluminium and brass workpieces

**Fig. 8** Variation of electrode wear

With the tubular electrode used on the three workpiece materials, the variation in the wear ratio after a certain depth shows a tendency to stabilize (Fig. 8(a)).

The volumetric wear ratio proportionality factor $R_{\text{w}}$ (equation (8)) was evaluated for each of the six data sets. For the purpose of the experiment $W_{\text{e}}$ is not the measured value of electrode wear but the amount of wear predicted using the linear regression ($W_{\text{e}}^{\text{trend}}$). The regression line was created only for the data obtained after the electrode shape became constant, which eliminates the error from the initial period of erosion with non-uniform electric field intensity. Using the predicted wear instead of the measured values not only avoids errors in the measurement of electrode wear but also reveals the stochastic character of the trend lines indicating variations of the systematic factors.

For each of the six data sets, the relative deviation $\delta\sigma_i = (\Delta\sigma_i/\bar{\sigma}) = (|\sigma_i - \bar{\sigma}|/\bar{\sigma})$ is equal to the relative deviation, $\delta R_{\text{w}_i}$ which is defined as follows

$$\delta\sigma_i = \delta R_{\text{w}_i} = \frac{|R_{\text{w}_i} - \overline{R_{\text{w}}}|}{\overline{R_{\text{w}}}} \tag{10}$$

$\delta\sigma_i$ and $\delta R_{\text{w}_i}$ are the relative deviations for the $i$th data set, and $\bar{\sigma}$ and $\overline{R_{\text{w}}}$ are the mean values of the measured $\sigma_i$ and $R_{\text{w}_i}$ values for the $i$th data set.

Based on the experiments, the maximum percentage relative deviations $\delta\sigma$ are 4.67, 4.5, 9.83, and 3.66 per cent for WC tube on steel, WC rod on steel, WC tube on brass, and WC tube on aluminium, respectively (see Table 1).

For the same amount of electrode wear, a relative deviation of $\delta\sigma$ would result in a non-negligible deviation in the volume eroded from the workpiece

Table 1 Electrode wear variation

| Workpiece | Electrode | Min $R_w$ | Max $R_w$ | Mean $R_w$ | Max $\delta s$ | Max $\delta V_p$ |
|---|---|---|---|---|---|---|
| Steel | WC tube | 2.123 634 | 2.284 15 | 2.182 234 | 0.046 703 | −0.0446 |
| Steel | WC rod | 1.422 847 | 1.556 779 | 1.489 695 | 0.045 032 | −0.0431 |
| Brass | WC tube | 0.011 923 | 0.014 522 | 0.013 223 | 0.098 335 | −0.0895 |
| Aluminium | WC tube | 0.018 228 | 0.019 61 | 0.018 92 | 0.036 581 | −0.0353 |

$\delta V_p = (\Delta V_p/\overline{V_p})$. The ratio between the actual eroded volume and the targeted volume allows the assessment of the relative deviation $\delta V_p$ as a function of the relative deviation $\delta\sigma$

$$\frac{V_p \cdot (1+\delta V_p)}{V_p} = \frac{V_e}{\sigma \cdot (1+\delta\sigma)} \cdot \frac{\sigma}{V_e} \Longrightarrow \delta V_p = \left(\frac{1}{1+\delta\sigma}\right) - 1 \tag{11}$$

The resulting maximum relative deviations $\delta V_p$ in the eroded volume due to the variation of $\delta\sigma$ measured during the experiments are also shown in Table 1. This clearly demonstrates the non-negligible variations in electrode wear ratio, where for instance the volume eroded from a brass workpiece shows potential deviations of upto 9 per cent.

The variations shown in Table 1 are not affected by any repeatability and machine positioning errors, because those errors are not cumulative and therefore should not influence the trend line orientation. They are due only to uncontrolled factors, which result in an inconstant wear ratio.

### 4.3 Spark gap variation

The spark gap is an important criterion for the micro-EDM process as it determines the final accuracy of the machined features. According to equations (6) and (7), the variation in the wear ratio $\sigma$ depends on the two parameters $D_p$ and $W_e$. $D_p$ is the diameter of the drilled hole and the main variation in $D_p$ is due to changes in the spark gap during the EDM process. By assessing both variable parameters ($D_p$, $W_e$), it is possible to draw conclusions regarding the variation of the wear ratio.

For each data set, the diameter of the drilled hole was measured and the results are plotted in Fig. 9. The photographs below each plot show the holes drilled with a WC electrode rod or tube and the marks left from the measurements of $W_e$.

Table 2 shows the measurements obtained and the calculated 6-sigma variation in hole diameter. Note that this variation includes the error in the positioning repeatability of the machine after each measurement of electrode wear. According to Pham *et al.* [**5**], for such short movements, this error does not exceed $\pm 1\,\mu$m. In the case of holes drilled in aluminium and brass, using rod electrodes, the distortion of the hole is obvious due to the side sparking caused by the debris. Although this makes the hole diameter larger than normal, for aluminium and brass workpieces, the variations in hole diameter were small. In the steel workpiece, there is no noticeable difference in the diameter of the holes, but the variation

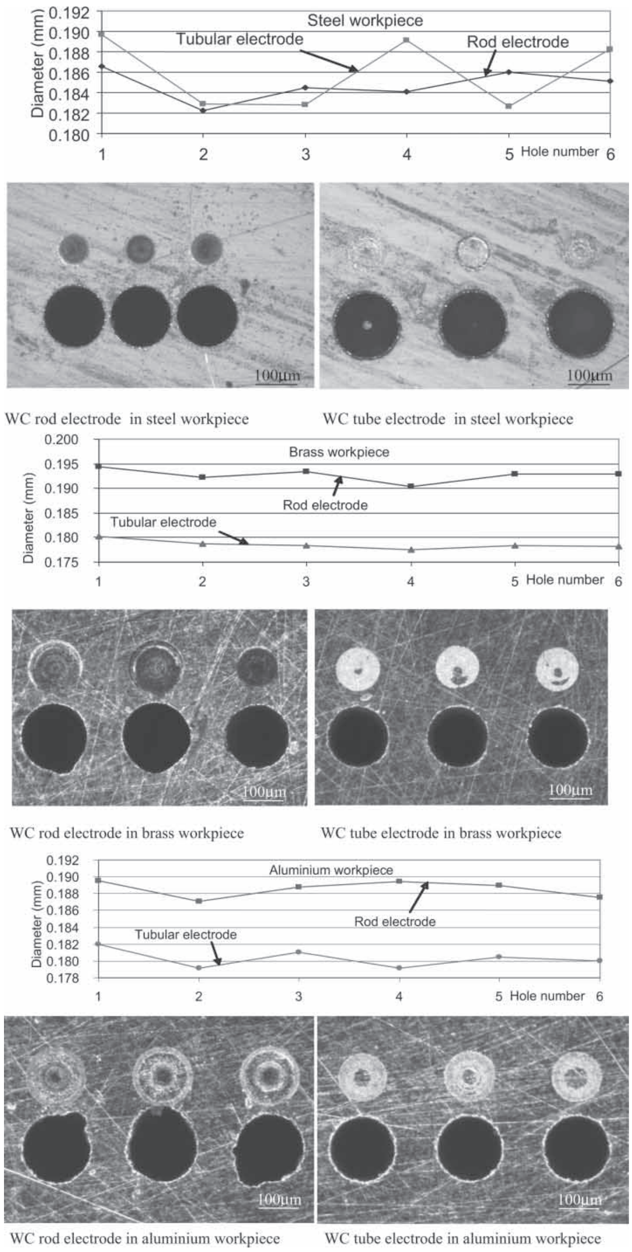



**Fig. 9** Variation of the spark gap

**Table 2** Spark gap variation

| Workpiece hole no. | Steel | | Brass | | Aluminium | |
|---|---|---|---|---|---|---|
| | Rod | Tube | Rod | Tube | Rod | Tube |
| 1 | 0.187 | 0.190 | 0.195 | 0.180 | 0.190 | 0.182 |
| 2 | 0.182 | 0.183 | 0.192 | 0.179 | 0.187 | 0.179 |
| 3 | 0.185 | 0.183 | 0.193 | 0.178 | 0.189 | 0.181 |
| 4 | 0.184 | 0.189 | 0.190 | 0.178 | 0.189 | 0.179 |
| 5 | 0.186 | 0.183 | 0.193 | 0.178 | 0.189 | 0.181 |
| 6 | 0.185 | 0.188 | 0.193 | 0.178 | 0.188 | 0.180 |
| Mean | 0.185 | 0.186 | 0.179 | 0.193 | 0.189 | 0.180 |
| Max. diff | 0.004 | 0.007 | 0.003 | 0.004 | 0.002 | 0.003 |
| 6-sigma | 0.009 | 0.021 | 0.008 | 0.006 | 0.006 | 0.0068 |

was larger when the tubular electrode was used. This can be explained by the forced flushing applied in the case of the tubular electrode, where larger debris were forced out of the spark gap possibly causing side sparking. This result also confirms the relative deviations $\delta\sigma$ shown in Table 1, which are similar for the two types of electrodes.

## 5 CONCLUSIONS

Understanding the electrode wear process and influencing factors is the key to more accurate and reliable micro-EDM.

Any electrode wear compensation method should allow for machining tolerances due to the variation of the volumetric wear ratio.

The above investigation shows that variations of the wear ratio due to uncontrolled factors are not negligible in micro EDM. This does not allow the use of compensation methods relying on the ratio staying fixed.

When machining soft materials like brass and aluminium, machining strategies that ensure good flushing, should be adopted to avoid side sparking on the electrode.

In cases where flushing becomes an issue, for instance when drilling small holes, steel is a preferred material because it is less affected by the flushing conditions.

Further research will concentrate on testing a wider variety of materials including different grain structures and investigation of inter-grain boundaries.

When using any new combination of electrode/workpiece materials and for any new diameter of electrode, tests should be done on the machine to measure the wear ratio and assess its repeatability. The results should be used to justify the chosen compensation method and enable the production of more accurate microcavities.

## ACKNOWLEDGEMENTS

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## APPENDIX

### Notation

| | |
|---|---|
| $d_e$ | internal diameter of the tube electrode |
| $D_p$ | diameter of the eroded hole |
| $D_e$ | external diameter of the electrode |
| $V_p$ | volume removed from the workpiece |
| $V_e$ | volume removed from the electrode |
| $W_p$ | eroded length from the workpiece |
| $W_e$ | eroded length from the electrode (electrode wear) |
| $Z$ | target depth of erosion |
| $\sigma$ | volumetric wear ratio |