Uncertainty of the electrode wear on-machine measurements in micro EDM milling

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A B S T R A C T

On-machine measurements play an important role in micro EDM milling. The measured tool electrode wear and the wear compensation have a strong influence on machining accuracy since the wear compensation methods require periodic measurements of the wear. The measurement uncertainties of the linear and volumetric wear measurements by the Touch and the Laser method were examined and results are presented in this paper. It was found that the linear wear measurements can be effectively performed by the Touch method when larger tool electrode diameters are used and sufficient machining is performed between the two control intervals, whereas the volumetric wear should be measured by the Laser method. To effectively compensate the tool electrode wear when tool electrodes with smaller diameters are used or low linear tool wear occurs between the two control intervals, the Laser method should be applied.

Introduction

A general development direction of modern machine tools is toward high automation and precise manufacturing. One of the approaches is the development and implementation of on machine measurement systems. There are four potential measurement scenarios where on machine measurement adds value to the manufacturing process [1]: a) monitoring of the machine tool geometry performance by employing a calibrated standard; b) workpiece set up on the machine tool coordinate system; c) in-process measurements to provide correction values for the manufacturing; and d) the performance of a final metrology validation of the finished product for final quality inspection as well as statistical trend analysis of the manufacturing process. Micro-electrical discharge milling (micro EDM milling) technology is under the scope of this paper and it utilizes in-process measurements to provide tool electrode wear correction values for the precise machining.

In micro EDM milling, electrical discharges occur in the gap between the workpiece and the tool electrode. Both, the workpiece and the electrode are submerged in the dielectric liquid, thus the gap is electrically insulated. Electrical and thermal phenomena are involved during the discharges in the contactless material removal mechanisms on electrically conductive materials. The tool electrodes are cylindrical rods most commonly of tungsten carbide with diameters down to 10 μm. To produce complex 3D features, the tool electrode is rotating and a trajectory is defined by CNC controller. Material is removed layer by layer with layer thickness ranging from 0.1 μm to a few micrometers depending on the diameter of the tool and on the discharge energy [2]. During machining the electrode wears and the reduction of the tool electrode length has to be compensated by movement of the electrode in z direction in order to compensate the linear wear. Aside from the inherent machining gap and the indispensable electrode wear, the edge radius of the tool electrode is also of prime importance in determining the machining accuracy [3] and thus the volumetric wear measurements are required.

Commercially available machines are using the anticipated tool wear compensation method, where the electrode wear ratio, described as a tool wear compensation factor, is experimentally determined for the process parameters used for machining. The compensation factor is calculated based on the reduction of the tool electrode length due to the wear and a continuous downward electrode movement proportional to the relative in-plane displacement is utilized. Due to the stochastic nature of EDM process the compensation factor has to be re-estimated every few machined layers and thus the reduction of the electrode length (electrode linear wear) has to be measured on-machine [4]. It is
obvious that accurate measurement of the electrode wear is required for the successful estimation of the tool wear compensation factor and hence to enable accurate machining in z axis. Therefore, the uncertainties of the on-machine measurement systems used to measure the electrode wear need to be examined.

Several tool electrode wear compensation methods have been proposed in literature, namely characterization of discharge population and estimation of the wear based either on tool wear per discharge [5] or workpiece material removal per discharge [4], by real time estimation of material removal [6], by real time pulse monitoring [7] and a combined off-line and in-line adaptive control of the tool wear compensation factor [8]. These systems are monitoring the current and/or voltage signal hence they are able to better estimate the electrode wear, but still the on-machine measurements are required in order to accurately compensate the wear.

Most often, a “Touch” method is used to detect the position of the tool tip by touching a reference surface and thus determine the electrode length – higher the wear, shorter the electrode. This is the most common method for electrode wear measurements implemented on commercial machines. In addition, the LSM can be used not only for on-machine measurements of electrode length but also to acquire the electrode profile and therefore extract the wear volume and edge radius, which is very important in the case of non-uniform wear distribution at the tool tip.

In this paper, on-machine measurements utilizing both the Touch and the Laser method are evaluated for both, linear and volumetric wear measurements. The measurement uncertainties are calculated based on the technical data of the equipment and experimental results. The analysis and comparison of measurement uncertainties provide a valuable information about sources of errors in estimation of the wear compensation factor and provide some guidelines to select appropriate number of control intervals. Additionally, the results show in which cases the methods are viable to use as a measurement technique for electrode wear detection and compensation.

Material and methods

Experimental setup

The experiments were performed on a Sarix SX-200 micro EDM milling machine equipped with a wire EDM grinding device and a Laser scan micrometer Mitutoyo LSM-500 s (Fig. 1). Blind holes were machined where the electrode was performing circular motion in x-y plane. The tungsten carbide tool electrode with 300 μm in diameter was used to machine blind holes with a diameter of 500 μm, depth of 100 μm.

![Fig. 1. Machine setup.](image)

The workpiece was martensitic stainless steel AISI 420 modified (STAVAX ESR). The machining direction of a circular path has been changed alternatively between clockwise and counterclockwise for each layer to minimize the residual material on the bottom of the hole that can occur due to the tool wear. No wear compensation was applied during the machining. Before each test run, the electrode tip was removed by the wire EDM grinding device unit to restore the electrode tip profile. Each experiment with a given process parameters combination was repeated five times. The dielectric used was hydrocarbon oil HEDMA 111. Experimental work covers a broad range of machining parameters from rough (E350 in Table 1) to fine machining (E15 in Table 1). A G-Code program was prepared and used on the machine with all the instructions needed to perform the tasks of each test run in the following order: machine the blind hole, measure the electrode by the two on-machine measurement systems, cut the electrode to restore the tip and position the electrode to the starting point of the following test. The layer depths were selected to achieve a stable machining with no short-circuit discharges. As provided in Table 1, six energy indexes were used to perform the machining of the blind holes. Since EDM is a stochastic process, each experiment is repeated five times. In total, 30 experiments were performed.

Touch method

Measurements by the Touch method are performed by touching the reference point by the tool electrode (Fig. 2). Between the reference point and the tool electrode is a low voltage and the voltage drop indicates the contact. When the voltage drop occurs, the movement of the tool electrode is stopped, and the coordinates are stored in the memory of the machine tool controller. The reference point is usually defined on smooth surface of the workpiece. A drawback of the Touch method is that the electrical contact produces a small amount of erosion, which would cause an error in the measurements of the actual linear wear. It was found that the wear due to five or less repetitive measurements is insignificant [9].

Laser method

The Laser method utilizes the LSM for a continuous scanning of the tool electrode along a linear array of sensors with origin at a fixed machine coordinate position. When the tool electrode intercepts the laser beam, the tool section that is at the z level of the sensors is projected to the sensors and recorded (Fig. 3a). The readout from the instrument corresponds to the tool electrode diameter and its center position. The tool length is measured by recording the tool z position in machine coordinate reference system when the presence of the electrode is detected. The laser method is also employed for accurate 3D dimensional characterization of the tool. Several diameters corresponding to different tool z positions are recorded and data is interpolated along z direction to calculate the tool silhouette area (Fig. 3b). The volume of the tool tip is obtained by rotation of the area around the tool axis.

| Energy index | Polarity | Peak current $I_p$ / A | Pulse duration $t_p$ / μs | Voltage $U_i$ / V | Layer depth $Δz$ / μm |
|--------------|----------|------------------------|--------------------------|-----------------|---------------------|
| 15           | –        | 0.79                   | 0.1                      | 80              | 0.5                 |
| 150          | –        | 4.92                   | 11.5                     | 100             | 0.9                 |
| 206          | –        | 9.60                   | 6.4                      | 130             | 2.5                 |
| 250          | –        | 8.38                   | 108.4                    | 130             | 2.5                 |
| 300          | –        | 11.41                  | 168.5                    | 130             | 2.5                 |
| 350          | –        | 8.16                   | 98.7                     | 130             | 2.5                 |

* According to the machine manufacturer denotation.
Measurements of the tool electrode linear wear

The length of the tool electrode is measured by the movement in \( z \) direction and the movement is stopped when the voltage drop is detected (in the case of Touch method) or when the presence of the electrode is detected (in the case of Laser method). The measurement of the tool electrode length before the machining was repeated five times and average length (\( x_{\text{before}} \)) was calculated. The same was done after the machining (\( x_{\text{after}} \)). The electrode linear wear is calculated as the difference of the both measurements (Eq. 1).

\[
l = x_{\text{before}} - x_{\text{after}}
\]  

(1)

Measurements of the tool electrode volumetric wear

The volumetric wear measurements of the tool electrode are significantly different when using the Touch or Laser method. Hence, the measurement methods will be explained separately.

The simplest way to measure the electrode volumetric wear by the Touch method is to assume that the edge wear of the electrode is negligible, and thus the volumetric wear can be estimated by considering the electrode linear wear measured by the Touch method and the electrode diameter. In general, the electrode diameter can be measured by the Touch method by utilizing e.g. the wire EDM grinding device normally used to dress (grind) the tool electrode to a certain diameter or shape. The wire may be used as the reference surface to measure the tool diameter. In practice, this procedure is used for a quick measurement of the electrode diameter in roughing and also to align the tool and the wire EDM grinding device. But this procedure is not practical, since it does not allow precise measurements of the tip of the electrode (see the measured electrode profile using Laser method in Fig. 4 and consider that sparks produced by the touches erode some of the material on the electrode to be measured and on the reference wire). In this research, the volumetric wear is calculated based on the tool electrode diameter provided by the manufacturer (nominal diameter) and the linear wear measured by the Touch method (Eq. 2), hence the electrode diameter is assumed to be constant along the electrode length (Fig. 4a).

\[
V = \frac{\pi d^2 l}{4}
\]  

(2)

Due to the higher electrical field on the edge of the electrode, the edge wear occurs that causes rounding of the edge of the electrode tip as measured and presented in Fig. 4b. The measured electrode profile is much smoother than e.g. shown in Fig. 7a, therefore it is assumed that presented profile is filtered by the LSM system. This is not taken in consideration for uncertainty calculations. Taking advantage of the

Fig. 2. The reference point utilizing the Touch method is on the workpiece.

Fig. 3. Measuring the electrode length and diameter by Laser method.

Fig. 4. Representation of the electrode wear and electrode profiles as measured by the Laser method before and after machining.
information provided by the Laser method, the volumetric wear can be calculated from the electrode profile. In this case, the profile is acquired by the Laser method without removing the electrode from the clamping head. Here, the real electrode profile is used in a calculation of the volumetric wear measurement. The volumetric wear in this case is calculated as the difference in electrode volume before and after machining. The volumes are calculated according to Eq. 3, where \( f(x) \) describes the distance of the measured electrode profile from the electrode axis (shown as value on the ordinate in Fig. 4b).

\[
V = \int_a^b f(x) \, dx
\]  

(3)

The electrode volume was calculated based on the points of the electrode profile acquired over a length corresponding to the depth of the machined cavity. The profile acquisition before and after machining started by positioning the electrode clamps to the same point in the machine coordinate system, thus taking into account the alteration of the electrode profile due to the reduction of the electrode length and the tip rounding (Fig. 4b). The uncertainty given by the assumption of the tool being axial symmetric was checked and it is negligible for this application.

Theory and calculations

The estimation of standard uncertainty and relative standard uncertainty and related terminology are following the JCGM 100:2008 [10] and JCGM 200:2012 [11]. The on-machine measurement methods, namely the Touch and the Laser method, and procedures to measure the tool electrode linear and volumetric wear described above have been analyzed in order to identify sources of uncertainties.

Sources of uncertainties

Sources of uncertainties for both methods and both wear measurements are given in Table 2 in a full range of a nominal indication interval and the factor values are adopted, accordingly. Standard uncertainties are calculated as a quotient of the uncertainty and its factor. The latter depends on the probability distribution of the quantity and the level of confidence at which the range of a nominal indication interval is provided.

The uncertainty of the tool electrode length measurements performed by the Touch method is determined as Type A uncertainty. The repeatability of the electrode length measurement by the Touch method \((Z_{T})\) was calculated based on the five touches performed in each test run.

The estimate of \( x \) employed in this study is the arithmetic mean of \( n \) independent observations \( x_k \) (with \( n = 5 \) for all the carried out experimentations):

\[
\bar{x} = \frac{1}{n} \sum_{k=1}^{n} x_k
\]  

(4)

The experimental standard deviation of the electrode length is

\[
s(x_k) = \sqrt{\frac{\sum_{k=1}^{n} (x_k - \bar{x})^2}{n-1}}
\]  

(5)

and the best estimate of the variance of the mean value of the measured lengths is

\[
Z_{T} = s(x) \sqrt{\frac{n}{\mu}}
\]  

(6)

A similar procedure was performed for determining the uncertainty of the tool electrode length measurements performed by the Laser method \((Z_{L})\), but all the repetitive measurements ended up with the same result, which does not mean the uncertainty of the measurements is zero as indicated in Table 2. The LSM system used for the on-machine measurements is approximately 10 times more accurate than the machine tool, which uses file resolution of 0.1 \( \mu \)m. Hence, the errors due to the uncertainties of the LSM system can not be detected on the tool machine. Therefore, the uncertainty of the Laser method for linear wear measurements will be evaluated as Type B uncertainty.

The uncertainties attributed to the LSM are provided by the manufacturer (Mitutoyo, Japan) [12] and are determined as Type B uncertainties. Repeatability \((L_{Rep})\), linearity \((LL)\) and positional error \((LP)\) are provided for environment temperature 20 \( ^\circ \)C ± 1 \( ^\circ \)C and humidity 50 % ± 10 % as the range of values within which the true value of a measurand lies, therefore \( L_{Rep}, LL \) and \( LP \) are assumed to have rectangular distributions and corresponding factor is 3.46. The LP is the error due to the positional shift of the workpiece in the optical axis direction or scanning direction. The resolution \((L_{Res})\) is selectable and a suitable resolution for the tool electrode diameters used in micro EDM milling \((d \leq 300 \mu m)\) is 0.01 \( \mu \)m. It is also provided as the range of values within which the true value of a measurand lies and thus the assumed probability distribution is rectangular.

Using the Touch method, the diameter is estimated from the data provided by the electrode manufacturer whereas the electrode diameter is measured when using Laser method. In the former case, the source of uncertainty is provided by the tool electrode manufacturer: nominal electrode diameter \( d \) is 300 \( \mu \)m with tolerance range from 0 to −4 \( \mu \)m. Since the range of values is given, the rectangular probability distribution is assumed.

Uncertainties of the volume measurements

The uncertainties of the Touch and Laser methods for the electrode length measurement are rather straightforward and provided directly in the next sections. But the uncertainty of volumetric wear measurements involves the uncertainty of electrode length and diameter measurements. The basic equations are presented here, since they are used for both methods.

The subtraction of the volumes before and after machining gives the electrode volumetric wear. Assuming the electrode diameter and length are independent quantities, the combined variance is calculated according to the Eq. 7. In this case, \( g \) is defined according to the equation for volume calculation (Eq. 3) and the combined variance of the volume measurement is calculated according to the Eq. 8. Further on, the combined standard uncertainty of the volume measurement is a square root of combined variance.

\[
\frac{\partial}{\partial x} (V) = \frac{\partial g}{\partial x} x^2 + \frac{\partial g}{\partial y} y^2
\]  

(7)
\[ u_l^2(V) = \left( \frac{\pi}{2}d \cdot l \right)^2 u_l^2(d) + \left( \frac{\pi d^2}{4} \right) u_l^2(l) \]  
\text{(8)}

Note that combined standard uncertainty of volumetric wear measurements \( u_l(V) \) depends on the specific measured value of the electrode linear wear \( l \), thus the combined standard uncertainty of the volumetric wear can only be calculated for each measurement separately.

**Uncertainties of the touch method**

The linear wear is calculated by subtraction of the measured electrode length before and after machining (Eq. 1) and thus the combined standard uncertainty of linear wear measurement \( u_{c,T}(l) \) is defined by Eq. 9:

\[ u_{c,T}(l) = \sqrt{2 \cdot Z_l} \]  
\text{(9)}

Change of the electrode volume is calculated from the estimated electrode diameter and the difference of the electrode length before and after machining. Both measurements have some uncertainty. The combined standard uncertainty of the electrode volumetric wear measurements is derived from Eq. 8 and for the Touch method \( u_{c,T}(V) \) is given in Eq. 10.

\[ u_{c,T}(V) = \sqrt{\left( \frac{\pi}{2} d \cdot l \right)^2 u_l^2(d) + \left( \frac{\pi d^2}{4} \right) u_l^2(l)} \]  
\text{(10)}

**Uncertainties of the laser method**

Both, electrode linear and volumetric wear are measured by the Laser method, too. As explained above (sec. 3.1), the uncertainty of the Laser method measurements described in Sec. 2.4, the linearity of LSM \( \frac{L_{Rep}}{L_{Res}} \) and positional error of machine tool has no effect on it. The expanded standard uncertainty \( u_{c,T}(l) \) is calculated by Eq. 11. Again factor 2 is applied from the same reason as in Eq. 9.

\[ u_{c,T}(l) = \frac{2(u_{l,Rep}^2 + u_{l,Res}^2)}{Z_l} \]  
\text{(11)}

But all uncertainties attributed to the LSM system and listed in Table 2 contribute to a combined standard uncertainty of the volumetric wear \( u_{c,L}(V) \) calculated by Eq. 12. Here, the first term under the square root is multiplied by 2 since the electrode diameter is measured as the difference of two points on the electrode profile at the same \( z \) level.

\[ u_{c,L}(V) = \sqrt{\left( \frac{\pi}{2} d \cdot l \right)^2 (u_{l,Rep}^2 + u_{l,Res}^2 + u_{l,LO}^2 + u_{l,LL}^2) + \left( \frac{\pi d^2}{4} \right) u_{l,L}^2(l)} \]  
\text{(12)}

**Relative and expanded uncertainties**

Relative standard uncertainty \( u_r \) is calculated according to Eq. 13, where \( x \) is a measured quantity. At given standard uncertainty, greater measured value means smaller relative standard uncertainty.

\[ u_r(x) = \frac{u(x)}{\mu} \times 100\% \]  
\text{(13)}

Due to the need to provide a higher level of confidence associated with a measurement, the expanded uncertainty \( U(x) \) is calculated, which is obtained by multiplying the combined standard uncertainty \( u_r(x) \) by a coverage factor \( k \) (Eq. 14). In accordance with generally accepted practice, a coverage factor of \( k = 2 \) is used to calculate the expanded uncertainty, which gives a coverage probability of approximately 95 %, assuming a normal distribution [15]. When a number of distributions of whatever form are combined it can be shown that, apart from in exceptional cases, the resulting probability distribution tends to the normal form in accordance with the Central Limit Theorem [14].

\[ U(x) = k \cdot u_r(x) \]  
\text{(14)}

**Results and discussion**

**Linear wear**

Combined standard uncertainties of the linear wear measurements performed by the two on-machine measurement system in scope of this paper are calculated according to Eq. 9 and Eq. 11. The relative standard uncertainty is calculated by using Eq. 13 and the expanded standard uncertainty by using Eq. 14. The results are given in Table 3 and shown in Fig. 5.

Combined standard uncertainties of linear wear measurements depend only on the measurement system and not on the measured value itself, therefore the selected process parameters combination and duration of the machining operation have no effect on it. The expanded standard uncertainty of the Touch method measurements \( u_{c,T}(l) \) is 0.34 \( \mu m \) and it is several times higher than that of the Laser method measurements \( u_{c,L}(l)=0.05 \mu m \).

Since the expanded standard uncertainty does not depend on the amount of linear wear measured and thus also does not depend on the number of control intervals, one could conclude that the number of control intervals for the given sequence of machining have no influence on the estimation of the tool wear compensation factor, which is determined based on the tool wear measurements. But the tool wear compensation factor is used to determine the tool movement in \( z \) axis during machining of the layer to compensate the tool wear [8]. Error in estimation of the compensation factor leads to less accurate machining in \( z \) axis. Expended standard uncertainty carries the information about absolute measurement error, and at given expended standard uncertainty, the error in estimation of compensation factor will be greater in the case of smaller tool electrode wear (Eq. 13). Therefore, lower the relative standard uncertainty, higher the accuracy of the compensation factor calculated.

When using any of the tool wear compensation methods, the number of control intervals selected for adjustment of the tool wear compensation factor not only determines the workpiece material removed between the two linear wear measurements, but also the material removed from the tool electrode, i.e. the electrode wear. Thus, higher the number of control intervals for the given machining sequence, lower the linear wear between the two consecutive control intervals and consequently increasing the number of control intervals causes higher relative standard uncertainty of the measured linear wear. As a result, selecting too many control intervals leads to a higher relative measurement uncertainty and hence to higher wear compensation errors, which further leads to a lower machining accuracy due to less accurate calculation of compensation factor. In addition, increased number of control intervals also increases the time needed to machine a given feature.

Hence, to compare the ability of both on-machine measurement systems for accurate estimation of compensation factor, the relative standard uncertainty should be used. It is clearly seen in Table 3 that
Laser method performs much better than the Touch method when a low linear wear is measured (up to approximately 40 μm), whereas at greater linear electrode wear the relative standard uncertainty of the Touch method improves significantly. Since the measurement of the electrode linear wear by the Laser method takes more time than by the Touch method, the Laser method for the linear wear measurements should be used only when measuring electrode wear below approximately 40 μm.

Volumetric wear

Combined standard uncertainties of the volumetric wear measurements performed by the two on-machine measurement system in scope of this paper are calculated according to Eq. 10 and Eq. 12. The relative standard uncertainties and expanded standard uncertainties are calculated using the same equations as in the case of the linear wear measurements (Eq. 13 and Eq. 14). The results are gathered in Table 4 and Fig. 6. The volumetric wear measured by the Laser method is always larger than the wear measured by the Touch method. The wear occurs on the electrode tool tip edge during the machining. This volume is not considered by the Touch method since the tool shape is assumed to be perfectly cylindrical. This is a systematic error that is not related to the uncertainty.

The combined standard uncertainties of the volumetric wear measurements depend on the measured linear wear (variable l in Eq. 10 and Eq. 12). The expanded standard uncertainty of the Touch method is much more sensitive to the amount of volumetric wear than the Laser method (Fig. 6) due to the estimated electrode diameter in the former case and measured electrode diameter in the latter case. Additionally, edge wear is not considered when the Touch method is used, therefore even higher uncertainties than those presented here may be expected.

In both methods, a measurement of higher volumetric wear has higher expanded standard uncertainty, but lower relative standard uncertainty. But both, expanded standard uncertainties and relative standard uncertainties are significantly smaller in the case of Laser method. Therefore, the electrode profile acquisition by the Laser method is highly recommended for volumetric wear measurements. As in the case of linear wear measurements, the higher number of control intervals causes higher relative standard uncertainty of the measured volumetric wear.

The findings related to the volumetric wear need an additional clarification, which is based also on experimental results provided in [15]. When utilizing electrodes with relatively large diameter the edge wear is not significant and the linear wear compensation is sufficient for effective machining (Fig. 7). But when using electrodes with smaller diameter, the volumetric wear measurement using the Laser method is highly recommended.
diameters (approx. 20 μm), edge wear becomes significant since
rounding on the edge broadens over the whole electrode tip and the
machined surface under the electrode is not flat but round, which is a
problem if the wear compensation is performed on linear wear mea-
surements. Namely, the electrode is touching the ribs that are sticking
out of the machined surface when machining the next layer and
consequently a higher percentage of short-circuit discharges is detected.
Additionally, the machined surface is not flat, but some waviness can be
detected.

Therefore, it is important to acquire the edge profile and to
calculate not only the volumetric wear, but also the edge wear, espe-
cially when the electrodes with a diameter below 20 μm are used.
Consequently, suitable actions may be taken, e.g. to increase the elec-
trode stepover (overlap of the electrode width on the two consecutive
paths within the same layer) from usual 55 % to suitable value or to cut
the electrode by the wire EDM grinding device in order to flatten the
electrode tip.

Conclusions

Several tool wear compensation methods are proposed and used in
micro EDM milling. All of them involve on-machine measurements of
the tool wear. Therefore, the uncertainty of on-machine measurements
of the tool wear plays an important role in the determination of
achievable part accuracy. Based on the findings presented in this paper,
the following conclusions can be drawn:

- The (expanded) standard uncertainties of measurements performed
  by the Laser on-machine measurement method are significantly
  smaller than that of the Touch on-machine measurement method.
- At given expended standard uncertainty the error in estimation of the
  wear compensation factor will be greater in the case of smaller linear
  electrode wear due to higher relative standard uncertainty. Lower
  the relative standard uncertainty, higher the accuracy of the
  compensation factor calculated. Selecting too many control intervals
  for re-estimation of the tool wear compensation factor results in a
  higher relative standard uncertainty and thus in a lower machining
  accuracy. Hence, there exists an optimal number of control intervals
  for each given machining task.
- By comparing the relative standard uncertainties for the linear wear
  measurements, the Laser method should be used when linear wear is
  smaller than approximately 40 μm. This is valid for both, calculation
  of wear compensation factor and real time wear compensation.
- Higher the volumetric wear, higher the expanded standard uncer-
tainty of both methods, but lower the relative standard uncertainty.
  Both uncertainties are significantly smaller when measurements are
  performed by Laser method. Based on these facts, the electrode
  profile acquisition by the Laser method is highly recommended for
  volumetric wear measurements.
- When electrodes with larger diameters (approximately above 20 μm)
  are used, the measurement of the linear wear is rather sufficient to
  compensate the wear by the continuous downward electrode
  movement proportional to the relative in-plane displacement. For
  larger tool electrode diameters, the electrode profile should be ac-
  quired and the rounding of the electrode has to be considered, hence
  the usage of LSM system becomes a necessity for a precise machining.

CRediT authorship contribution statement

Josko Valentinić: Investigation, Data curation, Writing - original
draft, Visualization, Writing - review & editing, Project administration.
Giuliano Bissacco: Methodology, Conceptualization, Data curation,
Writing - original draft, Supervision. Gianluca Tristo: Investigation,
Validation, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial
interests or personal relationships that could have appeared to influence
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