ON-MACHINE COORDINATE MEASUREMENTS IN MICRO EDM MILLING

Gianluca Tristo[1], Manuel Balcon[1], Simone Carmignato[2], Giuliano Bissacco[3], Enrico Savio[1]

1 University of Padova, Department of Industrial Engineering, Italy, gianluca.tristo@studenti.unipd.it
2 University of Padova, Department of Management and Engineering, Italy, simone.carmignato@unipd.it
3Technical University of Denmark, Department of Mechanical Engineering, Denmark

Abstract:
In micro electrical discharge milling material is removed by electrical discharges while driving a cylindrical tool electrode along tool paths as in conventional milling operations from the workpiece and the tool electrode. Hence, to achieve high precision machining it is necessary to accurately adjust the tool-workpiece relative position implementing a tool wear compensation strategy, which has to be empirically calibrated for the specific machining conditions. The measurement of the material removed from both tool and workpiece is of paramount importance, since tool wear compensation and machining simulation rely on this information. On-machine volume measurements enable process parameters optimization and tool wear compensation strategy calibration based on self-learning procedures as well as the implementation of process monitoring algorithms. In commercially available electrical discharge machines electrical contacts between the tool and the workpiece electrodes are detected by sensing low voltage short-circuits. This capability can be exploited to set the workpiece coordinate system and to perform dimensional measurements of tool and workpiece, using the tool electrode similarly to the touch probe in a coordinate measuring machine. However, accurate and traceable measurements of volumes can be challenging and a metrological validation of the method is missing. In this work an investigation of the accuracy of the on-the-machine volume measurements in a micro electrical discharge milling setup is carried out and an evaluation of the error affecting on-machine measurements is provided.

Keywords: Micro manufacturing, on-machine metrology, volume measurements

1. INTRODUCTION

Micro electrical discharge milling (µEDM milling) is a particular configuration of µEDM where material removal is achieved exploiting electrical discharges occurring between two electrodes and microfeatures are fabricated driving a cylindrical tool electrode along tool paths as in conventional milling operations [1].

During the EDM process, material is removed by electrical discharges not only from the workpiece but also from the tool electrode. Furthermore, material removal and tool wear rates are strongly dependent on selected set of EDM process parameters, dielectric fluid and electrodes materials. Hence it is mandatory to calibrate empirically tool wear compensation strategies before proper machining in order to produce high precision micro features [2]. The accuracy in assessing the amount of material removed from both tool and workpiece is thus of paramount importance, as tool wear compensation and machining prediction software rely on these information. For instance, in recent studies the volume of material removed from the tool has been combined with the number of discharges occurred during the machining process and the obtained tool wear per discharge has been successfully employed for tool wear compensation [3].

In micro EDM, on-machine volume measurements enable tool wear strategies and process parameters optimization based on iterative, automatic, self-learning procedures as well as the implementation of process monitoring algorithms, simplifying the adaptation of the process to industrial environments. On-machine dimensional measurements are commonly performed to inspect and measure both tool and workpiece electrodes with additional instruments such as laser micrometers, touch probes and optical microscopes [4]. However, in commercially available EDM machines it is possible to exploit the hardware that is used for the electrical discharge machining process also to obtain dimensional data. As a matter of fact in µEDM on-machine dimensional measurements based on short-circuits detection system are common practice: it is employed to set the workpiece coordinate system registering tool/workpiece relative position, but also to measure tool diameter during its fabrication process and to update tool length at regular intervals during machining operations for tool wear compensation.

The short-circuit detection system has been adopted for roundness deviation evaluation [5] and the repeatability and reliability of tool length measurements performed with this method has been assessed [6]. However the use of the short-circuit detection system and the tool electrode to perform coordinate measurements similarly in a CMM have not been reported and a metrological validation of the method is missing [7].

It is thus important to estimate the accuracy of the µEDM machine in performing volume and dimensional measurements using the short-circuit detection system and the tool electrode as the probe in a CMM. In this work the uncertainty of dimensional measurements is determined and the influence on volume measurements of machining defects such as surface roughness, walls draft angle and corners rounding is assessed.

2. EQUIPMENT

On-machine measurements tests as well as machining of reference microfeatures were performed at University of Padua on a Sarix SX-200 µEDM milling machine. The machine is equipped with a wire dress unit for micro tool fabrication and a Mitutoyo LSM 500S laser micrometer (resolution and repeatability of 0.01 µm and ±0.03 µm respectively) for on-machine micro tool calibration. A low viscosity hydrocarbon oil (HEDMA 111) was used as dielectric medium and rods made of tungsten carbide with a nominal diameter of 300 µm were chosen as tool electrodes.

Werth VIDEO-CHECK-IP 400 multisensor CMM was employed in optical and tactile configurations to calibrate the reference features for comparison with on-machine measurements tests. Sensofar PLµ NEOX confocal microscope with 100x magnification lens (maximum slope of 51 degrees and XY and Z resolution respectively of 0.166 µm and 2 nm) was used for surface characterization. FEI Quanta 400 scanning electron microscope (SEM) was employed for microfeatures and microtool qualitative inspection.

3. EXPERIMENTS

In order to evaluate the accuracy of the measurements that are performed on a µEDM machine a series of preliminary tests were performed to identify the optimal probing speed and tool-probe tip size. Then specific experiments were conducted to estimate typical volume measurements errors and the uncertainty of on-machine dimensional measurements.

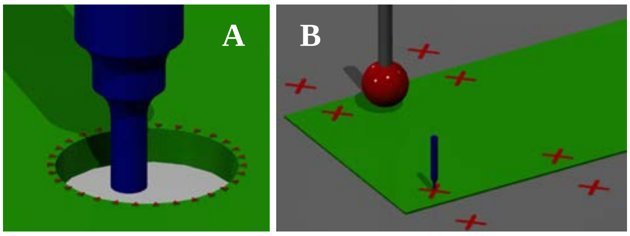

Fig. 1: Illustrations of on-machine probing of through-hole diameter (A) and step height (B)

3.1 Probing Speed

The relation between probing speed and probing accuracy was investigated repeating unidirectional measurements with speeds ranging from 0.002 to 0.020 mm/s along each of the machine linear motion axes. A step specimen assembled as shown in figure 1-B and calibrated with the CMM was used as reference. Results were compared to the reference measure obtained with the CMM. For further experiments a probing speed of about 0.007 mm/s was selected as a compromise (figure 2) between minimum error and minimum standard deviation relative to all of the three machine axes.

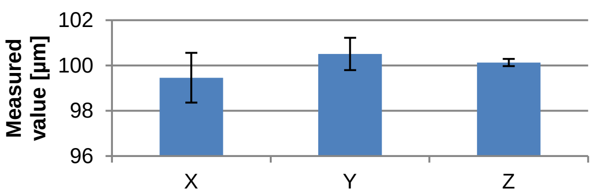

Fig. 2: Average values with range error bars obtained measuring 10 times the length of a calibrated 0.1 mm gauge block, with a probing speed of about 0.007 mm/s along each of the machine axes

3.2 Tool-probe diameter

All the tool-probes used for on-machine measurements were fabricated at the wire dress unit with a cylindrical shape and measured with the laser micrometer. The tool-probe used for the evaluation of dimensional measurement uncertainty was scanned with the laser micrometer before and after the experiments on 40 levels along its axis at every 5 µm starting from the tip and at 0, 45 and 90 degrees of spindle axis positions. After the tests the tool-probe was characterized also with an optical CMM and qualitatively inspected with SEM (figure 3). The profiles of the tool-probe have been reconstructed from data acquired with laser micrometer and optical CMM and then compared section by section as reported in table 1.

To determine the optimal tool-probe diameter a through hole with a diameter of about 500 µm was used as reference. The diameter of the hole was calibrated with the CMM and then measured on the Sarix SX-200 using 3 tool-probe tips with the same length of about 250 µm and different diameters, namely 50, 100 and 200 µm. Experimental results showed no differences in measurements that could be imputable to tool-probe diameter, as a consequence for further experiments it was set arbitrarily to 100 µm.

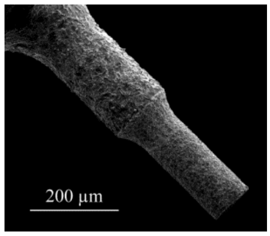

Fig. 3: SEM image of a typical tool-probe fabricated at the wire dress unit. The tip has a diameter of 100 µm and is 250 µm long

Table 1: Comparison between laser micrometers and optical CMM results in tool-probe diameter measurements.

Tool-Probe Diameter [µm]	Avg. value	St. dev.	Min	Max	Range
Laser	106.5	0.6	105.8	107.9	2.1
CMM	106.0	0.7	104.9	107.4	2.5

3.3 Pocket characterization

Features machined by µEDM usually are characterized by surface roughness, walls draft angle and corners rounding (figure 4). These imperfections are not considered in on-machine volume measurements, which are based only on diameter and depth values and consequently correspond to the simplified volume calculation model of an ideal cylindrical pocket.

The typical surface produced by means of µEDM finishing operations is characterized by a distinctive isotropic pattern made of craters. While waviness can be considered negligible, Ra depends on the selected process parameters but is hardly lower than 0.1 µm. The rounding of the edges is a consequence of tool wear and sparking gap. The draft angle of holes walls is caused by secondary discharges induced by the debris that are being flushed out of the working area.

A blind hole having a diameter of about 500 µm and a depth of 435 µm was machined in milling configuration driving the 300 µm tool electrode through circular interpolations, on a sacrificial workpiece made of Stavax ESR, a modified AISI 420 mould steel, with a set of process parameters typical for finishing operations and an incremental depth of 0.5 µm. The cylindrical pocket was then cross sectioned in correspondence to the centre axis in order to characterize all the surfaces and all possible form errors. The surfaces on both walls and floor of the pockets were characterized with a confocal microscope and the corner rounding radius and walls draft angle were measured with an optical CMM.

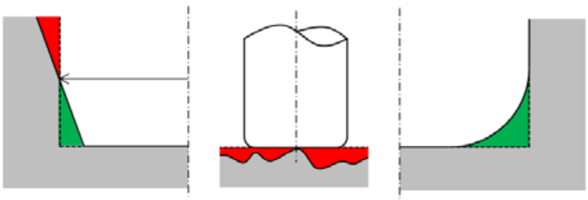

Fig. 4: Representation of the principal causes of error in measuring the volume of a blind hole produced by µEDM. Draft angle, surface roughness and corner rounding

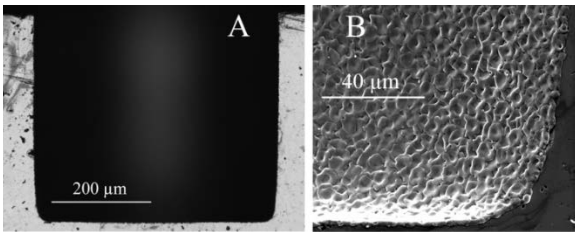

Fig. 5: Micrograph (A) and SEM image (B) of the cross section of a blind hole characterized by a diameter of about 515 µm and a depth of about 435 µm. Corners rounding have a radius of about 45 µm and draft angle is less than 1 degree

SEM images (figure 5-B) and confocal measurements of the cross sectioned pocket show that floor and wall surfaces have comparable surface roughness. As a consequence, when the cylindrical tool-probe is used to measure the diameter and depth of the cavity it touches craters peaks instead of the average profile of surfaces (figure 4), producing a systematic under-estimation of the quantity of material removed during the erosion of the pocket. The volume that is under-estimated per unit of surface was evaluated examining portions of floor and wall surfaces with the confocal microscope and it was evaluated that up to 0.7% of the pocket volume was not considered because of surface roughness. The corners rounding radius on the floor of the pocket was measured with the optical CMM to be about 45 µm and the related over-estimation of the pocket volume was evaluated to be within 1% for a blind hole with a diameter of 500 µm and a depth of 400 µm.

In figure 5-A it is possible to appreciate the angle of inclination of the walls of the pocket, that was measured with the optical CMM to be about 0.7 degrees. The presence of the draft angle introduces an error that depends not only on the extent of the walls slope but also on the depth at which the diameter of the pocket is measured. As a matter of fact the draft angle leads to an over-estimation of the volume removed when the hole diameter is measured close to the top surface and at the opposite it involves an under-estimation when the measurement is carried out close to the floor of the cavity (figure 4). In the worst case and for a blind hole with a diameter of 500 µm and a depth of 400 µm, the error can be as high as 3% of the pocket volume. However, theoretically it is possible to calculate the exact depth where to measure the diameter to nullify the measurement error associated to wall slope.

Assuming that the characteristics of surface finish and corners rounding are independent of hole dimensions, the relative errors they induce on volume measurements can be combined together and studied in relation to depth and diameter of the feature (figure 6).

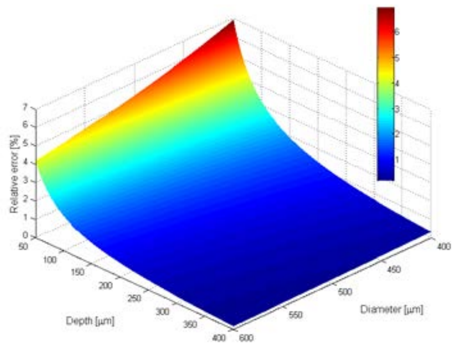

Fig. 6: Graphical representation of the relative error affecting volume measurements of a blind hole, as a consequence of surface roughness and corners rounding, relatively to depth and diameter of the feature.

The cross sectioned specimen was thoroughly inspected with the optical CMM and confocal microscope checking for floor planarity, floor and top surface parallelism, hole axis perpendicularity, scallops, top edge rounding and burrs, without noticing significant geometrical errors.

3.3 Dimensional measurements

The volume of material removed during the machining of the reference features can be estimated without removing the workpiece from the machine, measuring their diameter and depths separately. It is thus relevant to estimate the uncertainty in dimensional measurements performed on the µEDM in similar conditions. For this purpose a through-hole and a step specimen as in figure 1 were used as references to compare results of measurements carried out on the µEDM machine and a CMM.

The step specimen was obtained assembling a calibrated steel gauge block having a nominal length of 0.100 mm on a larger flat surface as illustrated in figure 1-B; the assembly was calibrated with Werth CMM using a tactile probe. The through hole with a diameter of about 500 µm was machined by µEDM on the gauge block with finishing process parameters and an axial depth of cut of 0.5 µm.

The uncertainty of dimensional measurements performed by the µEDM milling machine was determined using the experimental method given in ISO 15530-3 [8]. To this end, the diameter of the through-hole was measured on the µEDM machine acquiring 30 discrete points equally spaced along the circumference as in figure 1-A, while the height of the step specimen was measured as in figure 1-B. Measurements were repeated 20 times, unclamping and repositioning the specimen before each repetition as prescribed by ISO 15530-3. Reference calibrations of the diameter and depth were performed using the Werth multisensor CMM.

The experiments performed on the step specimen showed that the expanded uncertainty (determined with a coverage factor k = 2 for an approximated confidence level of 95%) for depth measurements (unidirectional measurements of the step height along the Z axis of the µEDM machine) is equal to 1.3 µm. These experiments showed good repeatability: the standard deviation of the 20 repetitions is 0.26 µm.

The experiments performed on the through-hole showed that the diameter measurements (multi-directional measurements of the hole on the X-Y plane of the µEDM machine) are subject to a systematic error quantified in 3.1 µm. After correcting this systematic error, the expanded uncertainty of diameter measurements was 1.9 µm. The standard deviation of the 20 measurement repetitions wss 0.5 µm.

These results show that the step height measurements are performed better (with lower uncertainty and repeatability) than diameter measurements; this was definitely expected also because step height measurements are unidirectional, while diameter measurements are multi-directional.

Propagation of uncertainty from dimensional measurements to volume measurements has been evaluated for the volume calculation of a blind hole, assuming that diameter and depth are uncorrelated variables. Results show that the relative volume measurement uncertainty is lower than 1.6% for holes larger than 400 µm in diameter and deeper than 100 µm.

4. CONCLUSIONS

An evaluation of the errors affecting µEDM on-machine measurements has been carried out. The microfeatures used as reference were produced by µEDM milling with finishing process parameters.

Preliminary experiments to optimize probing speed and tool-probe diameter have been conducted. While probing speed can influence the repeatability and the accuracy of a measurement, tool-probe diameter showed negligible effects on probing surfaces with a relatively good surface finish.

A blind hole has been cross sectioned and examined with an optical CMM and a confocal microscope to determine the influence in volume measurements of geometrical and form errors. The most relevant error can be induced by the slope of the walls, however this contribution can be neglected when measuring the pocket diameter at the proper hole depth. The uncertainty of dimensional measurements performed by the µEDM milling machine was evaluated both for diameter and depth measurements. Results show a good repeatability and expanded uncertainties below 2 µm after correction of systematic errors on diameter measurements.

In conclusion, defining accurately the reference pocket dimensions and with an appropriated measurement procedure, it is possible to limit the measurement errors within 3% of the volume. Hence µEDM measurements based on the short-circuit system is suitable for calibration of tool wear compensation strategies and process simulation software.

REFERENCES

[1] K. . Ho and S. . Newman, 2003. “State of the art electrical discharge machining (EDM)”, International Journal of Machine Tools and Manufacture, vol. 43, no. 13, pp. 1287–1300.

[2] P. Bleys, J.-P. Kruth, B. Lauwers, A. Zryd, R. Delpretti, and C. Tricarico, 2002. “Real-time Tool Wear Compensation in Milling EDM”, CIRP Annals - Manufacturing Technology, vol. 51, no. 1, pp. 157–160.

[3] G. Bissacco, H. N. Hansen, G. Tristo and J. Valentinčič, 2011. “Feasibility of wear compensation in micro EDM milling based on discharge counting and discharge population characterization”, CIRP Annals - Manufacturing Technology, vol. 60, no. 1, pp. 231-234.

[4] V. Schulze, P. Weber, and C. Ruhs, 2012. “Increase of process reliability in the micro-machining processes EDM-milling and laser ablation using on-machine sensors”, Journal of Materials Processing Technology, vol. 212, no. 3, pp. 625–632.

[5] D.-Y. Sheu, 2010. “Study on an evaluation method of micro CMM spherical stylus tips by µ-EDM on-machine measurement”, Journal of Micromechanics and Microengineering, vol. 20, no. 7, p. 075003.

[6] G. Bissacco, G. Tristo, and J. Valentinčič, 2010. “Assessment of Electrode Wear Measurement in Micro EDM Milling”, in Proceedings of the 7th International Conference on Multi-Material Micro Manufacture, pp. 155–158.

[7] S. Carmignato and E. Savio, 2011. “Traceable volume measurements using coordinate measuring systems”, CIRP Annals - Manufacturing Technology, vol. 60, no. 1, pp. 519–522.

[8] ISO 15530-3: 2011, “Geometrical Product Specifications (GPS) – Coordinate Measuring Machines (CMM): Technique for Determining the Uncertainty of Measurement – Part 3: Use of Calibrated Workpieces or Measurement Standards”. International Organization for Standardization. Genève.