Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 75 (2018) 391–396

www.elsevier.com/locate/procedia

15th CIRP Conference on Computer Aided Tolerancing – CIRP CAT 2018

Can A Low Cost Sensing System Be Exploited For High Precision Machining?

Francesco Modica[a], Vito Basile[a]*, Serena Ruggeri[b] , Gianmauro Fontana[b] and Irene Fassi[b]

[a] *National Research Council - Institute of Industrial Technologies and Automation, CNR ITIA, via P.Lembo 38/F, 70128 Bari, Italy*

[b] *National Research Council - Institute of Industrial Technologies and Automation, CNR ITIA, via A. Corti 12, 20133 Milano, Italy*

* Corresponding author. Tel.: +39-080-5481265; *E-mail address:* vito.basile@itia.cnr.it

---

Abstract

The aim of the present study is the assessment of the integration of a low cost optical measurement device into a high-precision machine tool for micro manufacturing applications. The measurement system can be effectively integrated into the working volume of different types of machines allowing both tool and workpiece measurements and avoiding its disassembly from the machine stage for off-line measurements and, consequently, reference losses. The fast measurements of tool and workpiece during the machining contribute to increase the accuracy and reduce the overall machining-measurement iterations. The assessment is achieved by a test case where a low cost USB microscope is applied to a micro-EDM machine. The low cost device has been applied for tool electrode measurements and tool wear evaluation after an accuracy enhanced calibration procedure and high performance image processing algorithms, which effectively reduce the lack of the hardware performance. The measurement performance gives a feedback on the deviations of the machined features from nominal geometry and allows their compensations by an adequate machining strategy.

Peer-review under responsibility of the Scientific Committee of the 15th CIRP Conference on Computer Aided Tolerancing - CIRP CAT 2018.

Keywords: On Machine measurement; Image processing; Geometrical accuracy; Optical sensor.

---

1. Introduction

Metrology is an important aspect of manufacturing, and it has indeed fundamental relevance in precision machining and micro manufacturing. It can be executed at different steps of the process chain in order to assess machining accuracy and products quality. In a classical process chain model, the processes are used from the roughest to the finest and the metrology step is often the last operation. This model is indeed suitable for the component with geometrical features that can be generated through independent machining. For more complex components, many high precision machining steps must be chained together adding tool setup steps and intermediate metrological steps (measurements of the component or its position in the machine tool). In order to reduce the number of manufacturing-metrology iterations, it is possible to adopt hybrid machines (combining many processes into a single machine), specialized fixtures and integrated measuring devices [1]. The integration of measuring systems into the machine tool is already widespread used for monitoring the wear of micro-tools in precision-milling [2, 3, 4, 5] and for alignment systems [6]. It must be underlined that specialized equipment used in metrology is obviously costly and can be a barrier for the integration of the measurement task. However, nowadays the market offers many Low Cost Optical measuring Device (LCOD) that could be used for measurements and can be adopted for the integration into the machine tool. The evaluation of the measurement performance of low cost sensing systems allows the uncertainty management and can be used to evaluate their applicability in high precision machining. The performance of these devices generally decreases with their cost but it is possible to improve their accuracy by calibration procedures and compensation algorithms.

The aim of the present study is the assessment of the integration of a LCOD into a high-precision machine. The considered case study includes a micro-EDM machine and a mould of a micro-filter have been chosen in order to evaluate the performance and capability of the integration. The LCOD

2212-8271 © 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the Scientific Committee of the 15th CIRP Conference on Computer Aided Tolerancing - CIRP CAT 2018.
10.1016/j.procir.2018.04.034

has been tested after a calibration phase. Results show that the integration of a LCOD can be very effective in improving the machining accuracy.

Nomenclature

LCOD	Low Cost Optical measuring Device
EDM	Electro Discharge Machining
FoV	Field of View
ROI	Region Of Interest
Mpx	Mega Pixel

2. High precision Micro-EDM machine and case study

A first attempt for integrating the LCOD automated measuring system into a machine has been done with a micro-EDM machine.

The machine used for the integration is a Sarix SX200 (Fig. 1) with three Cartesian axes having a resolution of 0.1 µm with a position repeatability of ±2µm, and a rotational axis C. The machine is also equipped with a wire unit for shaping the electrode tool and for direct Wire EDM machining. Wire EDM is usually adopted to machine the electrode, typically a tubular or solid rod, to a desired shape, reducing the rod diameter or giving a more complex shape. Nevertheless, it is also possible to use it for directly machining the workpiece. In this latter case, the workpiece is typically mounted on the machine spindle and it is moved into the machining volume relatively to the wire EDM head. It is important to remark that the tool electrode wears during the erosion producing a variation in its dimension and shape. These modifications are the main cause of the machining error in micro-EDM and a relevant research effort has been employed to investigate and identify the wear process.

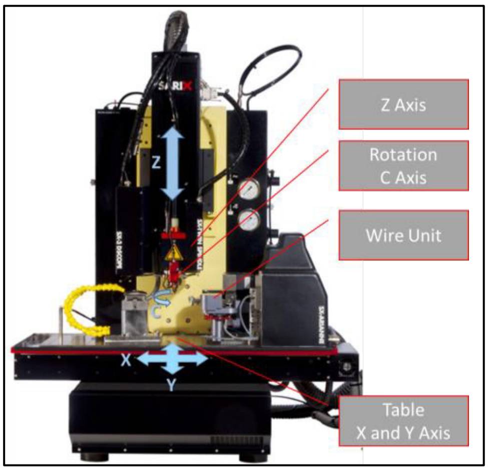


Fig. 1. Sarix SX200 and its axes.

In order to achieve high precision and accuracy, the machine adopts some dimensional check procedures based on electrical touch for calculating the shaped tool electrode dimension (section diameter, length), or for measuring the electrode length worn during the machining. Tristo at al. [7] have assessed the measuring performance of the electric touch in the Sarix machine showing that the measuring error of the electric touch method can be less than 3µm.

The LCOD system based on optical sensors can improve the dimensional checks providing the profile of the tool electrode. The measurement can be performed both automatically and manually and returns information that could not be previously acquired. A test case has been set in order to highlight how to use the developed automated measuring system and improve the machining accuracy.

2.1. Test case: micro-mould of a polymeric micro-filter

As a case study, the machining of a micro-mould of a polymeric micro-filter [8] is considered (Fig. 2).

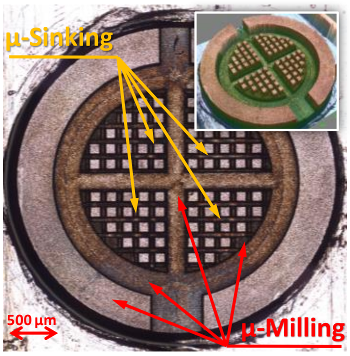


Fig. 2. Micro-filter mould.

The mould cavity consists of 76 pins having square section, with a side of 80 µm, height equal to 0.15 mm and side-walls draft angle of 2 deg. The pin-to-pin distance is 70 µm and the machining strategy was based on combined sinking/milling approaches with a shaped electrode (Fig. 3) [9].

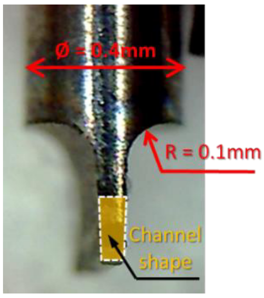


Fig. 3. Shaped micro-tool electrode for fabricating micro-channels.

The micro-channels have three different lengths (Channel A = 0.4, Channel B = 0.6 and Channel C = 0.75 mm) and they are fabricated with two tool movements: Z-vertical movement for machining the channel shape into the workpiece and a planar movement in order to obtain the whole channel length when it is longer than the tool diameter equal to 0.4 mm.

Fig. 4 reports a grid of micro-channels for testing the machining approach by measuring the machining error reported in Table 1 (average and standard deviation of three measurements for each feature). Since the electrode tool wears during the machining, in order to obtain the nominal width for the three nominal lengths, an extra stroke of the planar movement has been performed. Measurements have been taken on the disassembled sample by a Zeiss CSM700 confocal microscope.

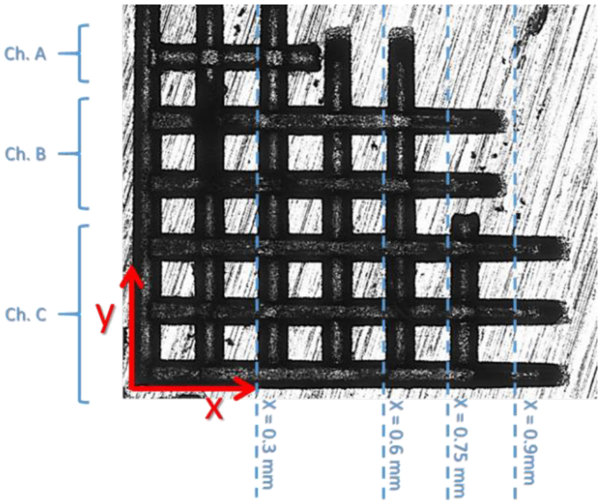


Fig. 4. Grid of micro-channels for fabricating the array of micro-pins.

Table 1. Micro-channel measured widths.

Channel	Nominal width	Average Value *(standard deviation)* Channel width @position y (mm)			
		@x=0.3	@x=0.6	@x=0.75	@x=0.9
#	[µm]	[µm]	[µm]	[µm]	[µm]
A	70	68*(2.6)*	-	-	-
B	70	71*(1.4)*	71*(1.9)*	-	-
C	70	70*(1.1)*	*70(1.2)*	68*(1.1)*	*63(1.8)*

Table 1 shows that the difference between nominal and measured channel width increases along the channel reaching a maximum value of 7 µm. This difference is due to the narrowing of the worn electrode tool. For the same reason the channels have different depth as shown in Table 2.

Table 2. Micro-channel measured depths.

Channel	Nominal Depth	Average Value *(standard deviation)* Channel depth @position y (mm)			
		@x=0.3	@x=0.6	@x=0.75	@x=0.9
#	[µm]	[µm]	[µm]	[µm]	[µm]
A	150	150*(1.4)*	-	-	-
B	150	151.7*(2.8)*	153.5*(1.9)*	-	-
C	150	152.7*(1.7)*	155.4*(1.2)*	154.1*(2.4)*	150.5*(6.4)*

It must be underlined that the shape at the bottom of the channel is more complex and not accessible by the confocal microscope because of the orientation of wall surface.

Adopting the control touch method, none of the previous measures can be directly acquired, and only the channel depth can be roughly estimated.

3. Experimental Test

3.1. Experimental setup

In order to test the integration of LCOD into a high-precision machine, the measurement of the tool geometry during micro-EDM machining was considered. According to [10], an effective vision system would require a measurement resolution R_m of at least 1/20 of the electrode manufacturing tolerance (3 µm), that is R_m = 0.15 µm. Since the measurement resolution capability in pixels M_p is of 1/10 (i.e. sub-pixel capability of the used machine vision algorithms), the required spatial resolution is $R_s = R_m/M_p$ = 1.5 µm. However, the sensing system was chosen aiming at the lowest setup cost then considering the poor performance of the system (Fig. 5).

It consisted of a USB digital microscope, with a HD color CMOS sensor, 24 bit DSP, a resolution of 640x480 pixels and a 800X maximum magnification, a frame rate of 30 f/s under 600 LUX brightness, USB 2.0 compatible, and supported by all the most recent Windows releases. It is sold for different application possibilities, including industrial inspection (PCB, material, etc.), jewelry and stamps inspection, textile industry, print industry, etc. It is sold together with a digital measurement software, a calibration ruler, and a jointed holder for a current price of less than 20 euros. The magnification can be set by a knob on the microscope body.

The microscope is equipped with a ring light of 8 white LEDs with adjustable brightness. However, according to the sample to be measured or inspected and the features of interest (geometry, surface defects, color changes), a different light source and configuration can be preferred. In the current work, the tool electrode was measured to evaluate its geometric variation due to the wearing during the machining operation. Moreover, the electrode surface induced reflection when subject to bright-field front light. For this reason, a bright-field diffuse backlight illumination was preferred to the LED ring.

The microscope was mounted on a holding structure in order to have a top view of the substrate and with the possibility of continuous displacements along the vertical axis, that is of adjusting the distance of the microscope from the sample.

3.2. Microscope calibration

The microscope calibration has to be performed to compute image pixel to real-world unit transformation and to compensate for perspective, distortion and spatial referencing errors [11]. In case the camera axis is not orthogonal to the object under inspection perspective errors can occur, whilst camera lens often introduces radial distortion, that is the image information is misplaced relatively to the optical center of the lens.

In order to calibrate a camera, it is necessary to compare the real coordinates (expressed in millimeters) of some points with their coordinates in the camera image (in pixels), exploiting a pin-hole model of the camera for the perspective compensation and a polynomials model of the lens for the distortion compensation [11, 12]. 2D calibration can be performed using a grid of points with precise circles at known positions traced on a flat rigid surface. The grid quality improves with the number and the precision of such markers and must fill most of the camera Field of View (FoV).

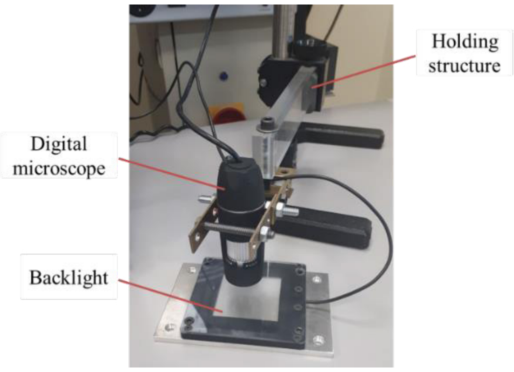


Fig. 5. The LCOD setup.

For the current setup, a grid of black dots on a white plate was used (model 62953 - Low Reflect Grid Distortion Target 3''x3'', 0.25 mm dot by Edmund Optics [13]). The dot diameter was of 0.25 mm and the dot spacing of 0.5 mm, with a total replication error less than 0.001 mm. The grid was fixed on the backlight device and placed to be seen in focus. A minimum number of dots is necessary to compute the calibration algorithm then the FoV was set to allow the view of a grid of 3x3 dots. The microscope took a picture of the grid and the vision algorithm provided for the identification of the dots and the calculation of their barycenters.

The origin of the x-y coordinate system of the calibration grid was set to coincide with the barycenter of the top left dot, the x-axis was aligned with the topmost row of dots and the y-axis was orthogonal and directed downwards in the image. In this way, the two sets of barycenter positions expressed in millimeters and pixels could be processed by the calibration algorithm. Then, the algorithm performed the transformation and compensated for perspective and distortion errors. For this work, all the vision algorithms were developed using NI LabView^{TM}.

According to the chosen setup, the FoV was of (1.876 x 1.407) mm with a spatial resolution R_s of 2.93 μm/pixel that allows for a feature resolution R_f of 9 μm considering 3 pixels spanning the minimum size feature and a measurement resolution R_m of 0.293 μm.

The dots on the calibration grid were also used as reference targets to evaluate the linear measurement uncertainty of the LCOD system after calibration, then the final measurement performance of the optical system. According to the "Guide to the expression of Uncertainty in Measurement" GUM (JCGM 100 standard [14]), the measurement uncertainty was evaluated by statistical analysis, and specifically applying the "Type A evaluation" to a set of $n = 50$ repeated readings of the radius of the grid dots. This evaluation could be carried out since, to measure the dot diameters, the LCOD system used the same algorithms (i.e. the calibration, and the circular and straight edge detection) that were adopted to measure the electrode (see Section 3.3). The calculated mean value of the dot diameters was of 119.1 μm, and the experimental standard deviation was of 2.4 μm, that represents the variability of the observed values (single observation of repeated measurements), and that can be considered as the evaluation of the linear measurement uncertainty.

3.3. Machine vision process and test

In order to perform the automated profile measurement of the micro-tool electrodes from calibrated images, it is essential to implement a machine vision program. The measurement process consists of the following three steps:

- Locate the component or part in the image.
- Locate the specific features to measure in different areas of the part.
- Make measurements using these features.

In a machine vision application, the measurements are extracted from a Region Of Interest (ROI) rather than from the entire image. The object under inspection must always appear in the defined ROI in order to extract measurements from that ROI. When the object is shifted or rotated within an image, the search areas should shift and rotate with the object. Locating the object in the image involves determining the x, y position and the orientation of the object in the image using a reference coordinate system. The coordinate system is built adopting a pattern matching technique to locate a reference feature of the object (chosen by the user). The software searches for a template image in a rectangular search area of the reference image. The location and orientation of the located template is used to create the reference position of a coordinate system or to update the current location and orientation of an existing coordinate system. In this way, the ROIs used to locate the features of the object to measure are defined relative to the coordinate system. In case of integration in the Sarix SX200 machine, locating the object in the image is not necessary since the tool electrode is always moved to the same pose by the very precise machine axes.

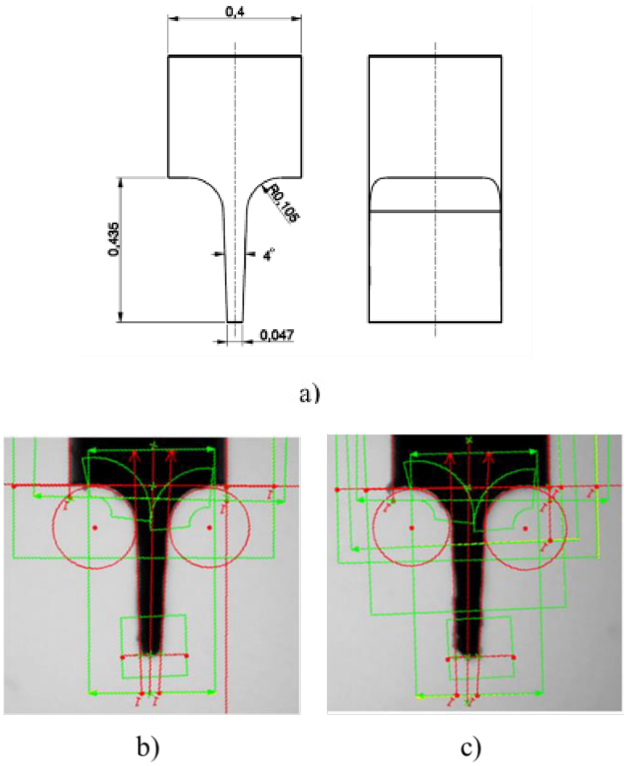
Before making measurements, it is fundamental to choose and locate the features used to make the measurements. The most common features used to make profile measurements in an image are points along the edges of the object. Adopting edge detection techniques, it is possible to find edge points along a single search contour or along multiple search contours defined inside a ROI (Fig. 6). The edge detection finds edges along one or more lines of pixels in the image identifying and locating discontinuities in the pixel intensities of an image. The discontinuities are typically associated with abrupt changes in pixel intensity values that characterize the boundaries of objects in an image.

After the feature points have been located in the image, it is possible to make distance or geometrical measurements. In particular, the following geometrical measurements can be performed from the feature points detected in the image [15]:

- The line that fits a set of points and the equation of that line
- The circle that fits a set of points and its radius

- The intersection point of two lines specified by their start and end points
- The line bisecting the angle formed by two lines
- The angle between two lines
- The midpoint of a line
- The perpendicular line from a point to a line, which computes the perpendicular distance between that point and the line

The LCOD was then used to measure the variation in shape and dimension of a number of micro-tool electrodes after machining. The nominal dimensions of Fig 6.a were measured showing a variation in the tool length and profile (Fig 6.b and 6.c).



a)

b) c)

Fig. 6. Electrode tool measurement: a) Nominal dimensions; b) measures of a new tool electrode; c) measures of a worn tool electrode. The green boxes represent the edge search areas and the green arrows indicate the edge search direction. The found edges are depicted in red.

It is worth to note that the above presented results can be easily improved. Indeed, the microscope used for this work has the lowest pixel resolution (a very rough sensor) compared to the current state-of-the-art commercial USB microscopes available.

Therefore, the spatial resolution of 2.93 µm limited the minimum detectable features in the image. However, increasing the sensor resolution to e.g. 5 Mpx, the results can be dramatically improved (Table 3), still keeping the cost of the system low compared to high-end measurement instruments.

Moreover, the use of a denser calibration grid could allow for a smaller FoV including only the features of interest, that combined to a better sensor would further increase the overall performance.

Table 3 Improvement in the spatial resolution increasing the sensor pixel resolution (at a constant FoV of 1.876 x 1.407 mm).

Pixel Resolution [pixel]	640 x 480	1280 x 960	1600 x 1200	2048 x 1536	2592 x 1944
Spatial resolution R_s [µm/pixel]	2.93	1.47	1.17	0.92	0.72
Cost (*) [€]	< 20			55	70

(*) Reference costs have been estimated by online market (Feb. 2018)

4. LCOD Application

In order to improve the machining accuracy the LCOD can be used in different setups, measuring the tool electrode, or the workpiece, or both tool and workpiece.

The first setup allows an indirect method to evaluate the machining error by measuring the geometry modification due to the erosion effect on the tool electrode. By setting a control area where one or more cameras are fixed to the table, the LCOD can scan the tool electrode from different points of view using the C-axis of the machine. Thus, it is possible to acquire the electrode tool before and after any operation (i.e. tool shaping or erosion task) in order to measure and evaluate their effect on tool. It is also possible perform the same evaluation on the wear evolution during the machining by pausing the operation for the measurement.

Comparing the tool image profile, before and after the machining it is possible to evaluate:

- the tool electrode shortening that is the main cause of the depth error in the machining (channel depth).
- the tool electrode narrowing that introduces an error in channel length and width.
- the worn volume of the tool electrode that is an index for evaluating the process performance.
- the evolving shape of the tool electrode that is specular to the channel shape i.e. rounds at the bottom of the channel.

The procedure for measuring the electrode during the machining is executed by the following steps:

1. pause the erosion;
2. move the electrode tool to a fixed position where the cameras are mounted and protected from dust and oil spurts;
3. during the movement, blow compressed air at the electrode tool in order to clean it from dust and dielectric fluid;
4. perform the measuring algorithm;
5. move the electrode tool to the last position where the erosion has been paused.

Since the measurement is performed far from the workpiece-tool interface, it is evident that on board environmental conditions of the measuring step n.4 are similar to the laboratory setup and the difference between the two conditions mainly depends on the effectiveness of the cleaning step n.3.

Fig. 7 gives an example of the information that is possible to gather with the LCOD: in the considered case, the tool is 42 µm shorter and the orientation of the worn surface is around 55 deg.

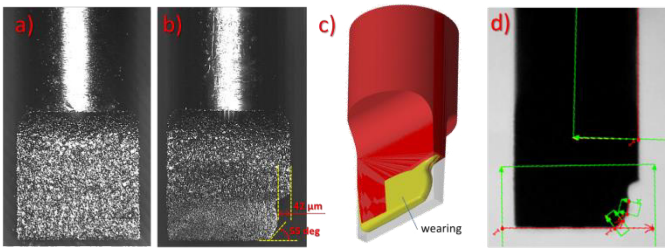


Fig. 7. Electrode tool (a) before and (b) after the machining and (c) 3D reconstruction of tool wear, (d) framework of automated image processing.

In the second setup (measurements of the workpiece) the LCOD is mounted on the Z-axis with a fixed offset from the chuck tip. In this case, it can scan the workpiece surface giving information similar to Fig. 4 and allowing the measurement of channel (width and length) and, consequently, the shape and size of the squared pins. However, this setup has some drawbacks which should be taken into account. First of all, for any kind of features, like channels, groves, bores or holes, only their top surface can be acquired and measured by an optical sensor. In addition, in order to achieve reliable measures, debris and dielectric fluid should be accurately removed from the workpiece surface before any measurements.

5. Conclusions

In the present study, the integration of a low cost USB microscope has been assessed and used to measure the tool wear on a micro-EDM machine. The lowest cost sensing system (around 20 euros) has been chosen in order to evaluate its limits of applicability. The uncertainty measurement of the system has been calculated equal to 2.4 µm with a spatial resolution of 2.93 µm. The algorithm for the feature recognition requires at least 3 pixels that determines a feature resolution R_f of 8.79 µm. With this performance, the selected system is unfit for the target required by the micro-EDM high precision machining that is estimated equal to 3 µm (Sarix axes repeatability is ± 2 µm). However, among the low cost sensors (cost below 100 euros), there is a wide variability in terms of spatial resolution. Table 3 shows that a low cost sensing system (last column in the table) can reach a resolution of 0.72 µm/pixel with a feature resolution R_f of 2.16 µm. It is evident that the latter LCOD sensor fits the requirements of high precision machining since it is close to the target spatial resolution of 1.5 µm declared in Section 3.1.

The test case on the main core component of a micro injection mould for micro-filter fabrication allows to perform measurements with the LCOD without changes in machine and workpiece setup. The LCOD coupled with an accurate calibration procedure and an effective post-processing, allows for reliable measurements without removing the workpiece from the machine stage and enabling a more effective wear compensation of the tool electrode. This latter result is very important since it always leads to a loss of accuracy. The proposed setup can be customized to any kind of high-precision machine tool. Furthermore, since the devices costs are very low the system can be increased in complexity with more than one device arranged according to a smart layout and achieving other advantages: more measurements of tool or workpiece at the same time, image processing of more than one image and estimation of additional measurements and information. Finally, it can be concluded that the use of LCOD in conjunction with a suitable calibration method and effective image processing algorithms allows to achieve higher machining precision with a favorable costs-performance ratio.

References

[1] Uhlmann E, Mullany B, Biermann D, Rajurkar KP, Hausotte T, Brinksmeier E. Process chains for high-precision components with micro-scale features. CIRP Annals-Manufacturing Tech., 2016; 65:549–572.

[2] Kim JH, Moon D, Lee D, Kim J, Kang M, Kim K.H. Tool wear measuring technique on the machine using CCD and exclusive jig. Jounal of materials processing technology, 2002; 130:668-674.

[3] Kerr D, Pengilley J, Garwood R. Assessment and visualization of machine tool wear using computer vision. International Journal of Advanced Manufacturing Technology, 2006; 28:781–791.

[4] Dutta S, Pal S K, Mukhopadhyay S, Sen R. Application of digital image processing in tool condition monitoring: A review. CIRP Journal of Manufacturing Science and Technology, 2013;6:212–232.

[5] Otieno A, Pedapati C, Wan X, Zhang H. Imaging and wear analysis of micro-tools using machine vision. Proceedings of the 2006 IJME Intertech Conference, IT301-071 (2006).

[6] Shih-Ming W, Ji-Jun L, Zhe-Zhi Y, Shambaljamts T, Chun-Chieh W. A Micro Cutter Auto-Alignment System with On-Machine Positioning Error Measurement and Compensation Methods. International Journal Of Precision Engineering And Manufacturing, 2014; 15, 1:177-182.

[7] Tristo G, Balcon M, Carmignato S, Bissacco G, Savio E. On-machine coordinate measurements in micro edm milling. 11th International Symposium on Measurement and Quality Control 2013, September 11-13, 2013, Cracow-Kielce, Poland.

[8] Surace R, et al. Design and fabrication of a polymeric microfilter, in Proc. of ICOMM 2015, March 28th-April 2nd, 2015, Milan (Italy).

[9] Modica F, Basile V, Marrocco V, Fassi I. A new process combining micro-EDM-milling and micro-EDM-sinking for fast fabrication of micro-channels with draft angle. Journal of Micro and Nano-Manufacturing 2016, 4 (2):024501-024501-8. Doi: 10.1115/1.4032324.

[10] West P. A roadmap for building a machine vision system. Imagenation.

[11] Zhang Z. A flexible new technique for camera calibration, IEEE Trans. on Pattern Analysis and Machine Intelligence 2000, 22(11): 1330-1334.

[12] Shapiro LG, Stockman GC. Computer Vision, Englewood Cliffs, NJ: Prentice-Hall, 2002.

[13] Edmund Optics website. www.edmundoptics.com

[14] JCGM 100: Evaluation of measurement data - Guide to the expression of uncertainty in measurement. Joint Committee for Guides in Metrology (Sèvres: Bureau International des Poids et Mesures, BIPM); 2008.

[13] NI Vision Concept Help. National Instruments, 2011.