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Effect of CAM Path Strategies on Tool Life in Ceramics Micro-Cutting

Móricz, László[1], Viharos, Zsolt János[2,3], Büki, Máté[2]

[1]*University of Pannonia, Faculty of Engineering, Mechatronic Education and Research Institute, Zalaegerszeg, Hungary*
[2]*Institute for Computer Science and Control, Budapest, Hungary, viharos.zsolt@sztaki.hu*
[3]*John von Neumann University, Kecskemét, Hungary*

***Abstract* – The 21st century manufacturing technology is unimagined without the various CAM toolpath generation programs. The aim of developing the toolpath strategies which offered by the software is to ensure the longest possible tool lifetime and more efficiency of the cutting method. In this paper, we aim is to compare the efficiency of the 3 types of EdgeCam tool path strategy in the curse of micro-milling of the ceramic material. During the analysis we dealt with the evaluation of the dimensional distortion of the manufactured geometries and the recorded vibration signals.**

Keywords – ceramics, micro-milling, tool wear, machining strategy

I. INTRODUCTION

Machining of rigid materials with regular cutting-edge geometry is one of the main trends in the 21st century. Ceramics are such rigid materials that are employed more and more widely as raw materials thanks to their high hardness and thermal resistance [1][2]. There are various options for machining them, e.g. using water, laser or abrasive grinding [3][4][5], however, their high costs and complex setups are important drawbacks of these technologies. Therefore, the machining of ceramics with a classical, regular cutting-edge geometry is still a promising solution, however, considering the relative quick wearing process of the cutting tool without an appropriate technological optimization, this methodology will be economically not acceptable. Optimizing a technology is typically a multicriteria assignment, like here, the main aim is to find the smallest production cycle time, and in the same time the tool life has to be maximal, too. The effect of technology parameters on tool life has been investigated in several of the authors previous articles [6][7][8].

In this paper, the effect of toolpaths generated by CAM software on the tool lifetime were examined. The three most popular tool paths (strategies: wave form, cycloid, chained) are analyzed as described in the next three sections.

A. Wave form path

The wave form tool path (Fig. 1.) for milling technology results in that the tool is working with constant tool diameter sweep.

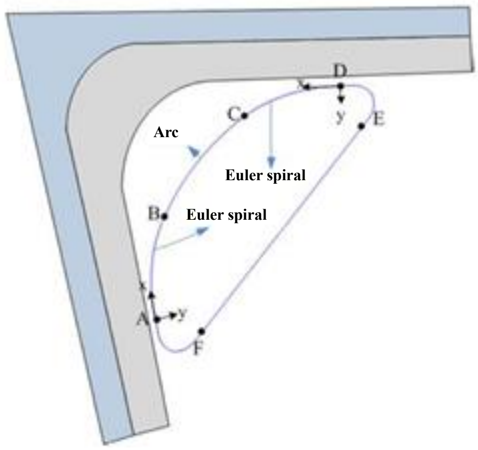

Fig. 1: Element of waveform path [10]

The contact angle along the toolpath has a direct effect on the cutting forces. By adjusting the contact angle, the cutting force can also be controlled. Owing to this the tool load is constant in every changing direction during the machining through avoiding sharp changes in direction, which couldn't be found among the average path generation methods [6][11].

The other advantage of the wave form strategy is that the value of material removal speed is kept constant, that is different to the other path generation methods. Cutting distributes wear evenly along the entire flute length, rather than just on one tip. The radial cutting depth is reduced to ensure consistent cutting force, allowing cutting material escaping from the flutes. So, tool lifetime is further extended as most of the heat is removed in the chip.

B. Cycloid path

The essence of the cycloid path strategy is to move the tool on a circle with the largest possible radius, thus reducing the kinematic contact (and tool load) (Fig. 2).

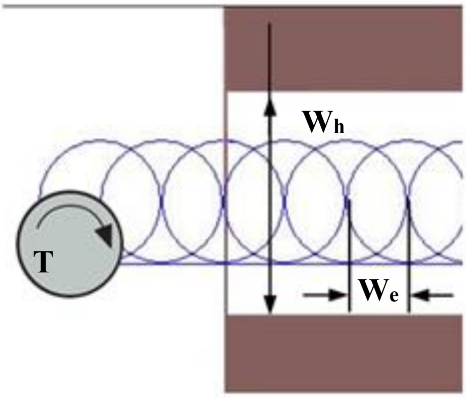

Fig. 2.: Cycloid toolpath [9]

The cycloid form is a milling technology where the tool milling is going along an arc, avoiding sharp changes in the direction. Although it doesn't control the tool, this strategy also can reduce the tool load, and the roughing strategy is optimized easier [6][8]. The problem with the average toolpath is that tool load increase significantly in the corners requiring shallower depths of cut and reduced feed. This problem can be avoided with cycloid and wave form path. Because the pocket was used during the experiment didn't have circle geometry, so the technology was made optimized with entremets. The entremets is an option in the software with which the tool load can be reduced in the corner. By choosing the correct stepover (We), the contact angle can be kept at a specified level. Another advantage of the strategy is that we can achieve high feeds along some paths.

C. *Constant stepover toolpaths (Chained path)*

Most software are usually capable of creating constant stepover toolpaths, contour-parallel, and direction-parallel paths, but these algorithms do not focus on machining parameters but only on material removal [9].

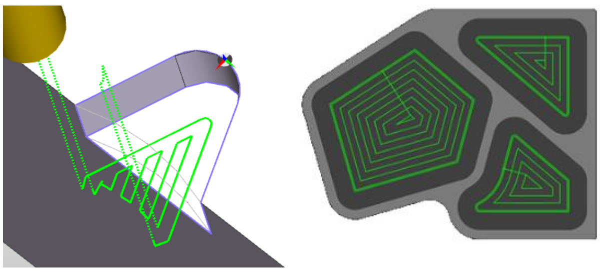

Fig. 3.: Contour-parallel, and direction-parallel stepover toolpaths (chained path)

During the generation of the constant stepover path (chained path), the cutting tool removes the material moving back and forth on the horizontal plane within each z (vertical) level (Fig. 3.). The strategy uses both directional and indirectional milling technology, leading to poor surface quality and short tool life.

II. EXPERIMENTS FOR THE MACHINING OF CERAMICS

The setup for the experiments is presented in Fig 4. One of the main aims is to follow the wearing process of the micro-milling tool during machining of ceramics and to compare it in an offline mode against the geometrical changes (length, width and depth of features) of the machined ceramic workpiece. Another goal is to using high-frequency online vibration measurement online, during the cutting process on the other hand.

Connections between the wearing stages and the measured online and offline parameters were determined using a self-developed, artificial neural network-based feature selection solution.

A. *Parameters of the milling machine*

The basis of the experiments was the milling machine that was planned and built by the CncTeamZeg group. It is operated in Zalaegerszeg (Fig. 4.). During the planning, the aim was to cut metal material but the preliminary calculations and first tests on ceramic material removal proved that it is able to cut ceramic material as well.

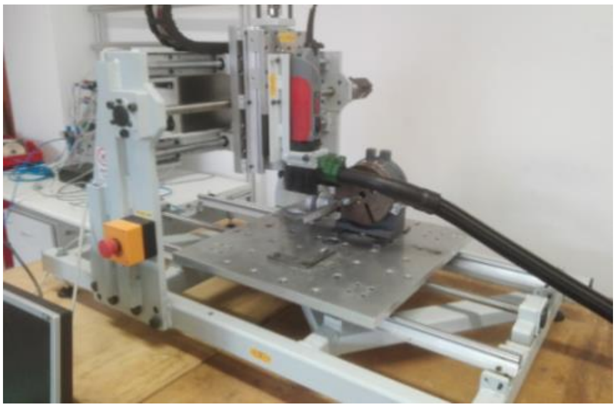

Fig. 4.: The applied CNC machine, detailed parameters are in [8]

III. INDIRECT, OFF-LINE TOOL WEAR ANALYSIS MEASURING THE PRODUCED WORKPIECE GEOMETRY

During the cutting process, microscopic images were taken repeatedly after a certain number of feature machinings in order to monitor in an offline way the wearing evolution of the workpiece geometry. Measurements were performed using Zeiss Discovery V8 microscope and the wearing in the pictures were evaluated by the authors.

Beyond the microscopic control of the cutting tool geometry the changes resulted by the tool wear on the machined workpiece was also measured. These dimensional changes of the manufactured geometries are summarized in Fig. 5. During the measurement, changes in the width, length and depth of the geometries were examined. The applied technology settings (axial depth of cut, radial depth of cut, cutting speed, feedrate) were the same in all three cases, only the machining paths (strategies: wave form, cycloid, chained) were varied.

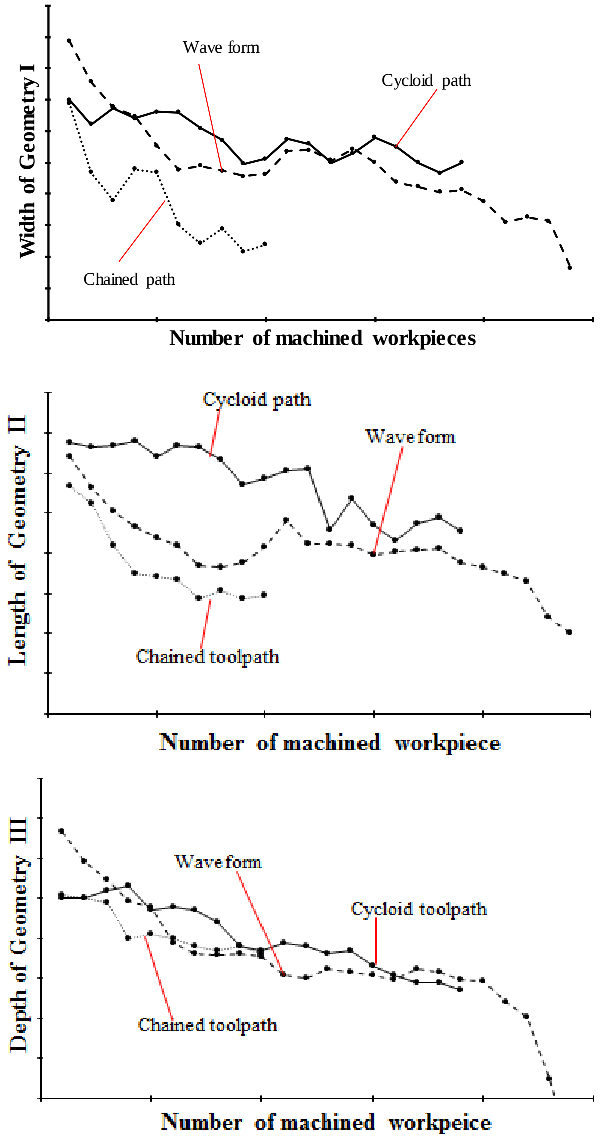

Fig. 5.: Changes in the Geometry I.- II. and III. of the machined geometries for the Wave form, Cycloid tool path and Chained path

These workpiece measurements represent clearly a complete and valid cutting tool life curves (Taylor curves) and various variable conclusions can be drawn from them:

- It can be seen in Fig. 5 that the tool lifetime achieved using chained toolpath is nearly half of the tool lifetime achieved using the wave form and cycloid tool path.
- During the application of the chained path, a tool break occurred early, under the machining of the 11th set.
- At the cycloid tool path, exponential tool wear and tool break were observed in 20th set.
- Using the waveform path, the manufacturing time of the one feature was 57% longer than in the case of the chained toolpath.
- With the cycloid path, the manufacturing time of the one feature was nearly five times more than at the chained tool path.
- Considering the tool lifetime and the manufacturing time, the waveform seems to be the most economical toolpath strategy during the ceramic machining.

IV. DIRECT ON-LINE TOOL WEAR ANALYSIS USING VIBRATION MEASUREMENT

The scientific literature mirrors that Acoustic Emission (AE) signals form increasing trend in the same way as the increase of the tool wear analysis in *metal* cutting but it is not evident for micro-ceramics milling.

In [12], Bhuiyan et al. pointed out: the increase in the tool wear increases the tool-workpiece contact area and friction coefficient, as well. In another experiment, the opposite, so, the decrease in the vibration amplitudes were detected during measurements, in metal cutting field, too. In the paper of the authors they reported a similar phenomenon during ceramic machining [8]. Based on the results of the measurements, decrease in the vibration amplitudes were detected during the wear evolution of the tool, consequently, the contact surfaces between the cutting tool and workpiece became smaller during the wearing of the tool for ceramics milling, because of the complex and multiplicative wearing forms. The related frequency analysis showed that the wear-out process of the tool resulted also in a shift of the dominant frequencies into higher frequency ranges.

In this research, the authors supplemented the results of the previous paper [8] with an Acoustic Emission (AE) study on various toolpath strategies. In the reported previous research, vibration measurement of ceramics milling was established with a sampling frequency of 100kHz measuring in one direction. Instead of analyzing over millions of individual measured values, as time series of the vibration amplitudes, several description features (e.g. statistical measures, like amplitude, standard deviation, 3rd moment, etc.) were calculated. Such a feature vector was calculated for each workpiece/machining process, while during the experiments the same tool is used, until the tool wear-out, or tool break.

Feature selection was applied to find the most descriptive features for distinguishing three typical different stages of the tool life. For this division, in the first step, the tool wear curve was determined from the geometry produced on the workpiece by an indirect method (based on the workpiece geometries measured). After this, the curves were divided into three sections depending on the wear phase of the tool and the degree of geometry reduction (worn-in, normal, wear-out (or brake)).

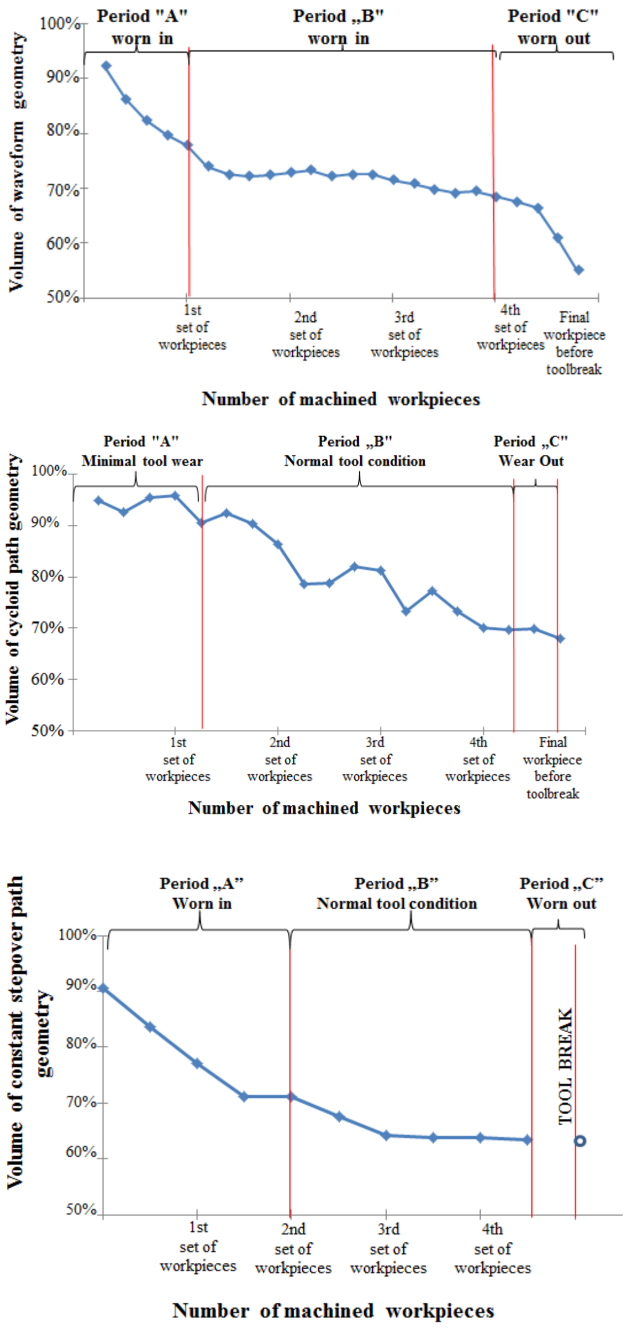

Fig. 6.: Changes in the Volumes of the manufactured geometries for the Wave form (upper), Cycloid tool path (middle) and Stepover (Chained - bottom) tool path

A. Micro-cutting tool wear lifecycle stages

In contrast to the previous research [8], not the changes of parameters of the geometry (width, length, depth) were analyzed, but the volume changes calculated from the geometries obtained by each toolpath strategy (Fig. 6.).

During the analysis of the graphs, 3 well-separable sections of the Taylor curve were observed for the waveform graph (worn in-tool, normal condition, worn out). In contrast, in the cycloid path, no significant tool wear was observed until a certain geometry was manufactured (period "A"), followed by steep but uniform tool wear (period "B"). At the chained toolpath, the rapid wear process (period "A") as well as the normal wear condition (period "B") were observed, however, the tool was already broken at the very beginning of the wear out phase (period "C").

B. Most descriptive vibration signal behavior in respect to the micro-cutting tool wear-out

After running the feature selection method developed by some of the authors, the *variables/features (calculated based on the vibration signal) that most accurately describe the change in 3 sections of the Taylor curve were determined*. It has to be mentioned that the feature selection identifies the first, so called most informative feature, however, the second one serves with the additional most informative one, etc., consequently, *the features are not independent*, it is really important for the evaluation of their meaning and effects.

Selected features for the *waveform strategy*:

- *Number of the times the signal crosses its mean value*
- *Standard deviation*
- *Fourth momentum - kurtosis*

Having identified the most informative features calculated from the measured vibration signal, their evolution along the wearing progress can be presented, partly for engineering approval of the results of the mathematical algorithm. The progress in the values of the three, selected vibration signal features are presented along the wearing stages of the cutting tool in Fig. 7.

The first identified variable name of "*Number of times the signal crosses its mean value*" describes the intersection density of the X axis of the vibration signal. In the stage of wear-in (Period "A") the curve is at a high level, but there is a continuous decrease. This means that the tool vibrates at a high frequency in the initial stage. In the normal wearing (Period "B") phase, the signal oscillated at a lower frequency compared to the "A" phase. In the wear-out (Period C) phase, there was a further decrease in the number of X-axis incisions.

The second feature identified was the *standard deviatio*n. The standard deviation showed change, similar to the previous variable. In the wear-in period (Period "A"), the signal shows large variance. In the normal period of tool lifetime (Period "B"), there was a decreasing trend of the standard deviation. In the period of wear out (Period "C"), the standard deviation of the signal showed a drastic decrease.

The third parameter identified is the *fourth momentum, also called as kurtosis*. The fourth momentum describes the distribution-flatness of the signal. In the case of a sharp tool, the kurtosis follows a flat trend, while in the case of a worn tool, the distribution curve takes on an increasingly sharper shape.

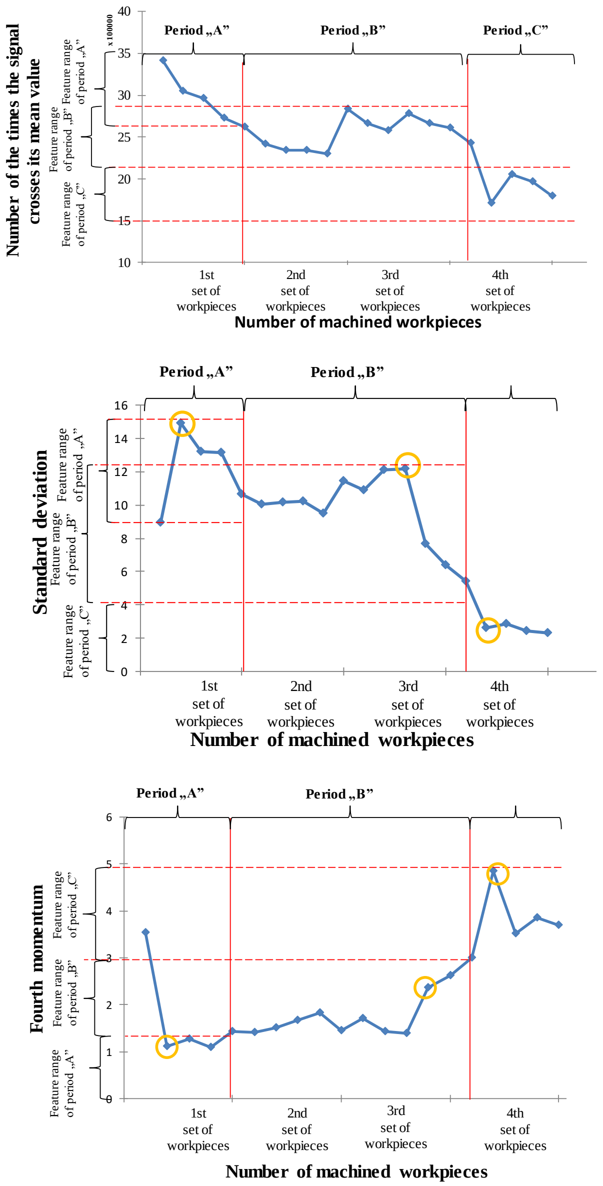

Fig. 7.: Changes in the vibration signal behavior: "Number of the times the signal crosses its mean value "- "Standard deviation" – "Fourth momentum" along the tool live-cycle

Selected features for the *cycloid strategy*:

- *Number of the times the signal crosses its mean value*
- *Mean value*
- *Second momentum*

The progress in the values of the three, selected vibration signal features are presented along the wearing stages of the cutting tool in Fig. 8.

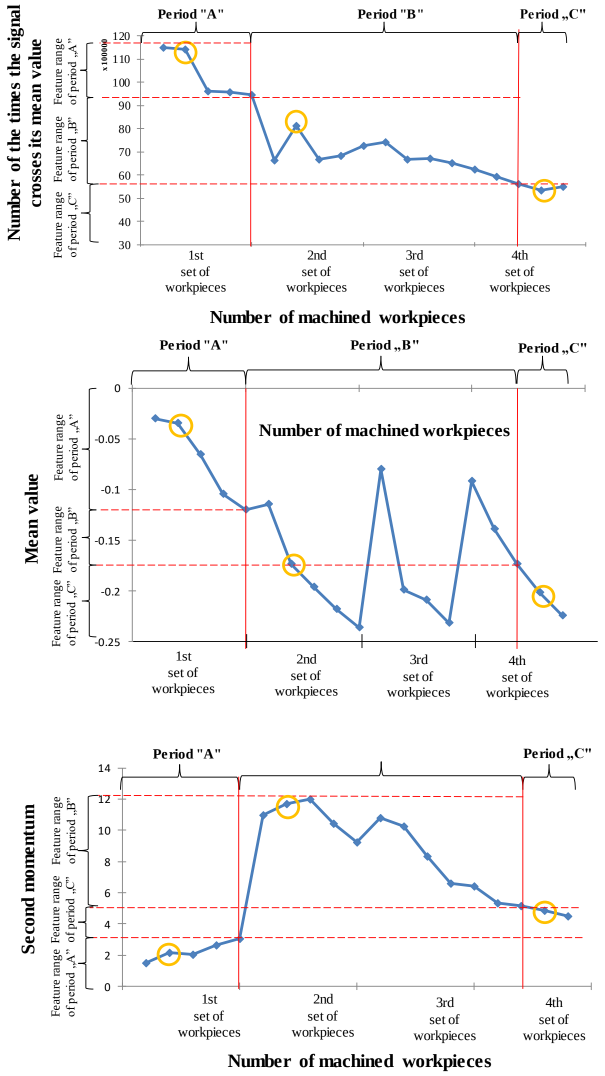

Fig. 8.: Changes in the vibration signal behavior: "Number of the times the signal crosses its mean value "- "Mean value" – "Second momentum" along the tool live-cycle

Selected features for the *chained strategy*:

- *Mean value*
- *Fourth momentum*
- *Number of the times the signal crosses its mean value*

The progress in the values of the three, selected vibration signal features are presented along the wearing stages of the cutting tool in Fig. 9.

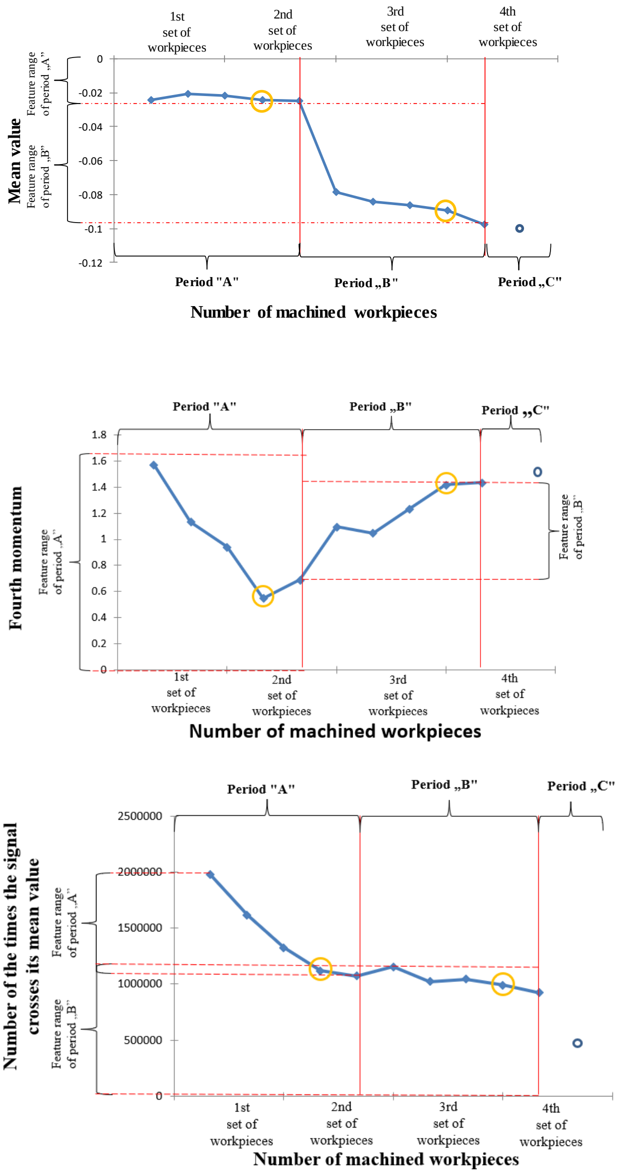

Fig. 9.: Changes in the vibration signal behavior: Mean value - Fourth momentum - Number of the times the signal crosses its mean value along the tool live-cycle

V. VALIDATION OF THE FOUNDINGS ACCORDING TO THE ORIGINAL VIBRATION SIGNAL CURVES

During the final analysis of the vibration signals, moreover, for engineering-oriented validation, some selected experiments marked as yellow circles on the Fig. 7., Fig. 8. and Fig. 9. are presented in a tabular form in Fig 10. It represents clearly that the data mining methodology works well; it found the most relevant signal features and the original, "pure" signal measurements mirrors the identified behavior, consequently, there is an open floor for realizing vibration based monitoring and supervision of the micro-milling of ceramics.

VI. CONCLUSIONS AND OUTLOOK

In this paper, tool wear monitoring was investigated using direct and indirect methods under three CAM path strategies (waveform, cycloid and chained). Based on the indirect monitoring, it was found that by applying the chained toolpath, the tool life was reduced almost to 50% compared to the other tool path strategies. However, in aspect of the production cycle time, it requires only one-fifth (20%) of the other toolpath strategies. The key conclusions of the results are:

- The results represents clearly that the data mining methodology works well; it was found that the most relevant signal features and the original, "pure" signal measurements mirrors the identified behavior, consequently, there is an open floor for realizing vibration based monitoring and supervision of the micro-milling of ceramics.
- The appointed features of the vibration signal describe the three typical stages (worn-in, normal, wear-out) of the tool life cycle according to the Taylor curve identified.
- In general, the feature "Number of the times the signal crosses its mean value" has the highest relevance on the basis of the vibration signal, so, this measure describes in the most accurate way the tool wearing determined using the indirect tool wear measurement technique.

New, more detailed tool wearing symptoms will be analyzed in the future, moreover the milling process/tool path will be split up into individual, homogenous sections and a more sensitive and more detailed process monitoring will be built up.

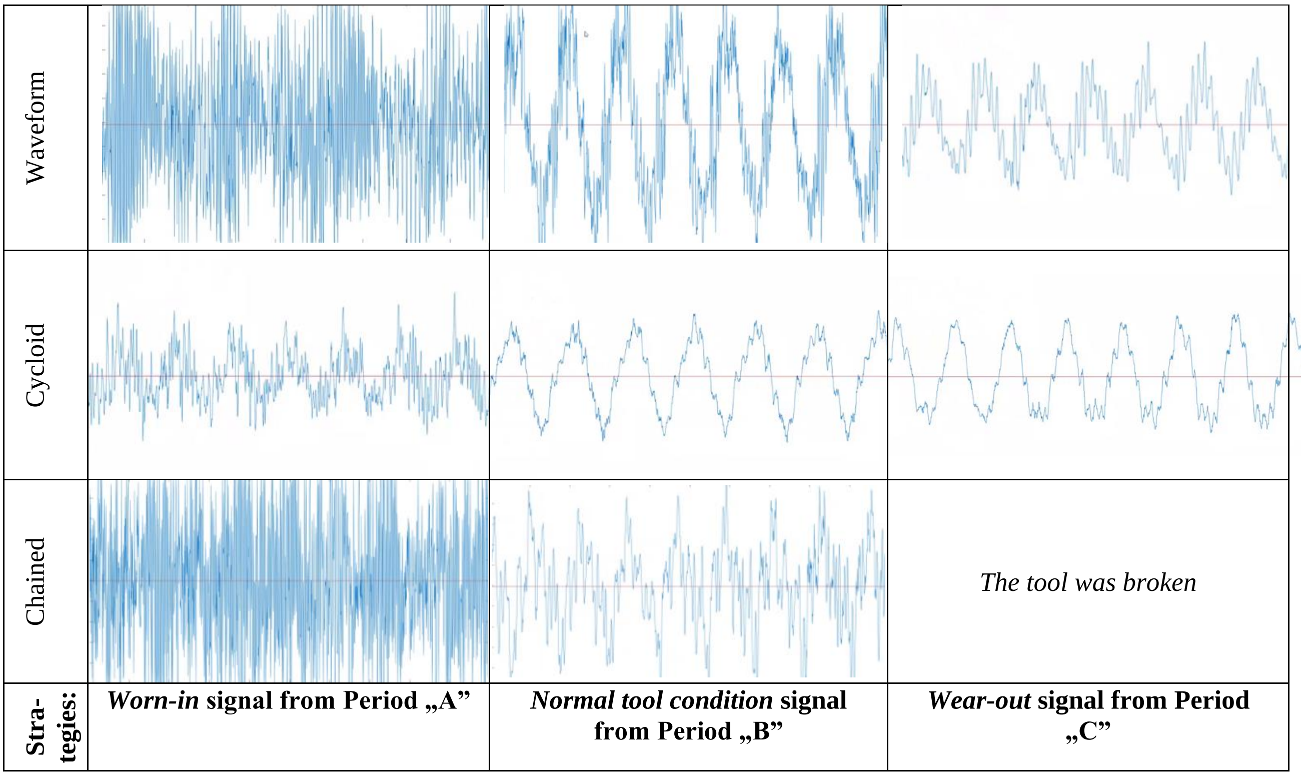

Fig. 10.: Vibration signal examples representing the behavior at different tool wearing stages (worn-in, normal condition, wear-out) at the three analyzed strategies (Waveform, Cycloid, Chained)

VII. ACKNOWLEDGEMENTS

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