



Off-line geometrical and microscopic & on-line vibration based cutting tool wear analysis for micro-milling of ceramics

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ARTICLE INFO

Article history:

Received 19 November 2019

Received in revised form 3 May 2020

Accepted 21 May 2020

Available online 28 May 2020

Keywords:

Ceramics machining

Cutting tool

Wearing process

Vibration analysis

ABSTRACT

Based on their favourable mechanical features, applications of ceramics are continuously spreading in industrial applications. Hardness and the resistance against heat shock make them usable, so, currently they are widely used, e.g. as coating material for gas turbines. The main aim of the paper 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 of the machined ceramic workpiece. Further goal is to monitor the tool wearing process offline, by a microscopic tool measurement on one hand, and using high-frequency online vibration measurement online, during the cutting process on the other. Relations between the wearing stages and the measured online and offline parameters were determined using an own-developed, artificial neural network based feature selection solution.

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1. Introduction

1.1. Ceramics machining with milling

Machining of rigid materials with regular cutting edge geometry is one of the main trends in the 21st century. Ceramics are applied more and more widely as raw materials thanks to their high hardness and thermal resistance [1–3]. There are various options for machining them, e.g. using water, laser or abrasive grinding [4], however, the related 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. Considering the relative quick wearing process of the cutting tool, this methodology is economically acceptable only with an appropriate technological optimisation.

Optimizing technology is typically a multicriteria assignment, like here. The main aim is to find the smallest production cycle time, while maximising the tool life as well. The actual tool condition serves with information about the actual wearing stage of the tool.

Bian et al. [5] used ultra-miniature diamond coated tools to mill fully sintered ZrO₂ ceramics. The wearing of the tool was characterised by three stages:

- (1) Early coating delamination;
- (2) Extended coating delamination with slight wear of the exposed cutting edge;
- (3) Severe wear of the tool blank.

Heleen et al. [6] analysed the tool wearing process and the resulting surface quality during cutting of ZrO₂ ceramics, machined by diamond and cBN-coated milling tools. They observed the same three stages of the wearing.

Bian et al. described experimental results in [7] using WC milling tool coated by different sizes of diamond grains for analysing the peeling process of the diamond coating. They concluded that when the machining was performed in the classical “X-Y” direction, the cutting force is significantly smaller than in the case when the process is performed in the “Z” direction. The reason is that in case of “X-Y” they managed to keep the cutting in the plastic deformation area, while in the “Z” direction the brittle area was dominating. They also identified that the cutting force will grow significantly with the increase of the feed per tooth and axial cutting depth.

Based on the literature review one can identify that *the research on cutting of hard and brittle materials by advanced tools is still in an*

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early stage, especially as far as it concerns micro scale applications. Based on the analysis conducted, the main challenges can be summarized as follows:

- Availability of ultra-miniature tools having appropriate cutting edge geometry to ensure proper compression/tensile stress distribution in the chip zone.
- Appropriate tool stiffness and sufficient wear resistance.
- Identification of suitable cutting parameters to ensure ductile material removal and damage-free machined surfaces [6].

The aims of the paper are - continuing a previous research [9,10] - to follow the wearing process of the micro-milling tool during machining of ceramics and to compare it against the geometrical changes of the machined ceramic workpiece, applied as a special monitoring technique. In the same time, establishing a high-frequency online vibration based tool wearing supervision, consequently, a further goal is to determine the relationship between the cutting vibration and the wear of the tool. The wearing of the tool results in inaccuracies in the produced workpiece geometry, in the remaining ceramics material, consequently, measuring the deviation between the theoretical and real produced geometry of the resulted workpiece feature can be applied for measuring the milling tool wear in this proposed, indirect way. The indirect tool wear monitoring helps to avoid losses caused by unnecessary tool change for measuring its actual wearing by microscope [9].

1.2. Main challenges in ceramics milling

Based on the literature review, two main challenges can be identified in ceramics milling:

- Short tool lifetime because of the high material toughness [11].
- High brittleness cause crack on the surface during the cutting process. This problem limits the ceramics applicability as structural material [3].

The problems mentioned above generated the following main trends of the research in ceramics milling:

- Determination of parameters which influence the brittle and ductile removal areas [7,12].
- Exploration of the tool wear mechanism to ensure economically efficient tool life time [5,6].
- Improving the surface quality (avoid the cracks, at least similar to the polished surfaces) [3].
- Optimization the technological parameters (axial-radial cutting depth, cutting speed, feed, type of cooling, etc.).
- Mixing of manufacturing technologies (e.g. combined technologies) [13].

1.3. Factors influencing the cutting tool life in micro-milling of ceramics

There are plenty of technological parameters that influence the micro-milling of ceramics. According to the literature the most influencing parameters are the following [9,14]:

Technological parameters

- Axial cutting depth
- Radial cutting depth
- Cutting speed
- Feed(rate)
- Tool tilt angle

Geometry of cutting tool

- Flank angle
- Rake angle
- Number of teeth

Tool material, coating

- Basic tool material
- Type of coating
- Thickness of coating
- Grain size
- Number of coating layers

Type of cooling

Other parameters

- Combined shaping technology

An important challenge for the cutting process with regular geometry tool is to keep the cutting in plastic deformation area instead being in the brittle area [7]. Ueda et al. cut plenty of ceramics materials to find solution for this challenge, they found that materials that have high fracture toughness can be cut easier in plastic deformation area with optimal cutting speed and feed [8]. However, with low fracture toughness they did not find combination of parameters that can cut in the ductile deformation zone. Muhammed conducts research into the ductile-brittle range in shaping method, he tried to determine these cutting parameters, and how they influence the ductile range [15]. It was identified that the critical parameters belong to the cutting depth and feed values, which affects the chip-removal mechanism. These results are summarized in Fig. 1. If the value of the feed and cutting depth is too high, the cutting process will be in the brittle removal area (Zone D) where the tool wear is accelerated. During their experiments it was found that there is a critical value of cutting depth and feed, where the analysed material machining can be kept in the ductile removal area (Zone A). Under a certain cutting depth, the value of feed can be increased without the removal of the cutting mechanism from the brittle area, but if the feed and cutting depth is below a critical value, the cutting process loses its stability and there is no chip formation (Zone B). This means that the plastic deformation strongly depends on the value of the cutting depth. Differences should be considered between two types of cutting depths, axial cutting depth and radial cutting depth [6,9].

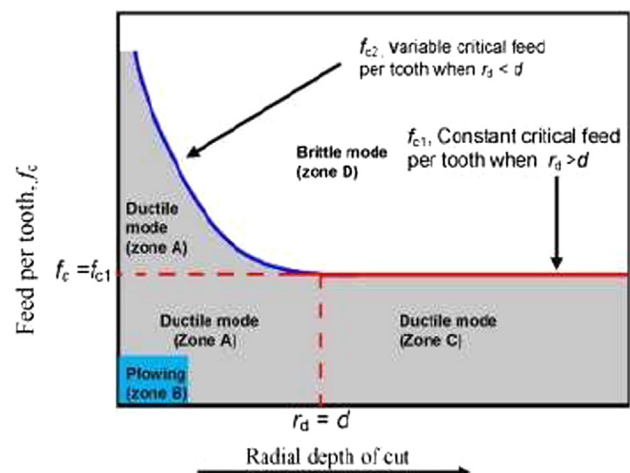


Fig. 1. Critical ranges of feed-depth and radial depth of cut to reach the plastic deformation range [15].

Another important aspect of the mechanism is the tilt angle of the tool [12] (Fig. 2). This parameter is highly important in cutting with ball milling tool, as the cutting speed depends on the tilt angle. In vertical cutting tool, the working diameter of the tool is smaller than the nominal value of that, so the cutting speed is reduced. However, if the tilt angle is too high, usually the workpiece geometry does not allow such removal. The literature shows that the optimal tilt angle is between 40 and 60°, depending mainly on the ceramics' material [12].

The combined technology is a further interesting method for enhancing the lifetime of a cutting tool: Toru et al. [13] combined the conventional cutting process with laser technology. Feng et al. [16] performed machining with irregular cutting tool geometry while they make inferences on the cutting tool's wear based on cutting force and vibration measurements. Xiaohong et al. [17] performed similar research with laser-assisted cutting. They found that the laser has a strong influence on the grinding characteristics. The normal and tangential grinding forces for laser assisted grinding is 15% lower than that in the conventional grinding method. In previous research of the authors the linear, Taguchi based Design of Experiment (DoE) were applied to analyse the effect of the varying technological parameters on the tool wearing process [9]. The results served with a quasi (linear) optimal technology concerning the maximisation of material removal speed; however, the analysis of the wearing process is still an open issue because a novel indirect measurement should be applied before [9].

The following paper goes beyond the previously applied methods, because the complete wearing behaviour of the tool is described and a vibration-based process supervision is introduced.

The paper is structured as follows: the paragraph 2 describes the machining conditions of the experiments performed in the field of micro-milling of ceramics and the coupled measuring and signal processing equipment. Paragraph 3 introduces the first off-line tool supervision solution using a microscope, while the paragraph 4 details the second novel, off-line monitoring of the tool wear through measuring of the produced workpieces' geometries. These off-line techniques serve with labelling of the tool wear statuses used by the novel, on-line, vibration based monitoring solution for robust identification of the wear-out status of the micro-milling tool as introduced in the 5th paragraph. Conclusions, Acknowledgements and References close the paper.

2. Machining conditions for ceramics micro-milling experiments

2.1. Cutting tool

Micro-milling tools were applied for the cutting experiments on ceramics (Fig. 3).

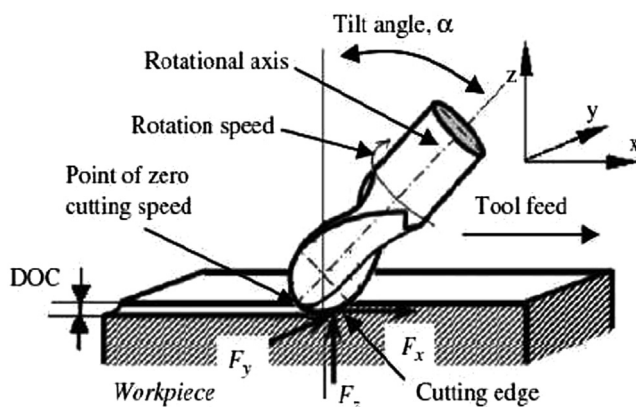


Fig. 2. Tilted milling tool [12].

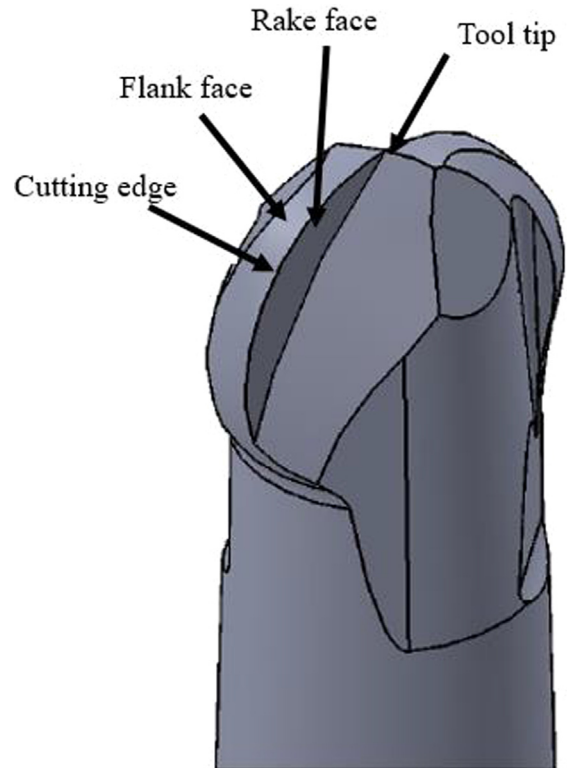


Fig. 3. Cutting tool geometry in 3D view.

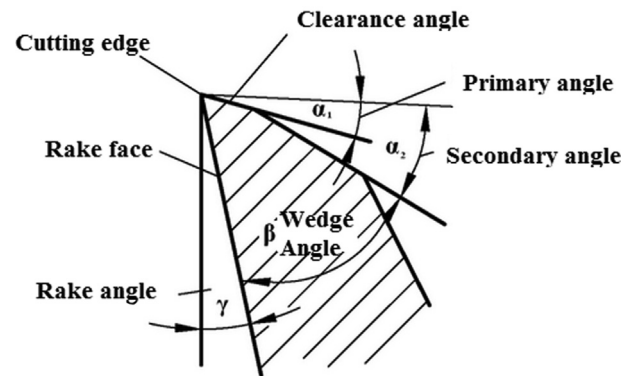


Fig. 4. Tool angles in 2D view.

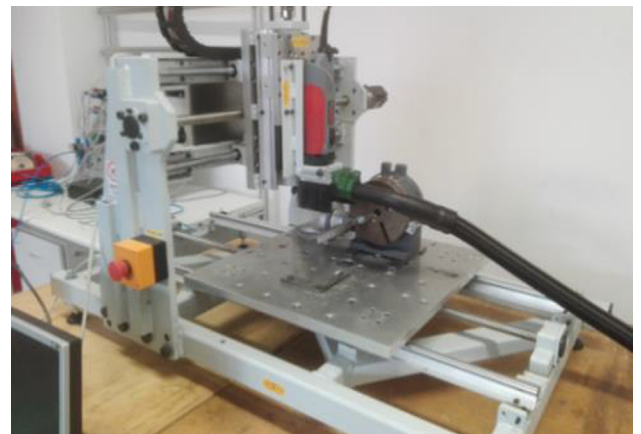


Fig. 5. The applied three axis cutting machine.

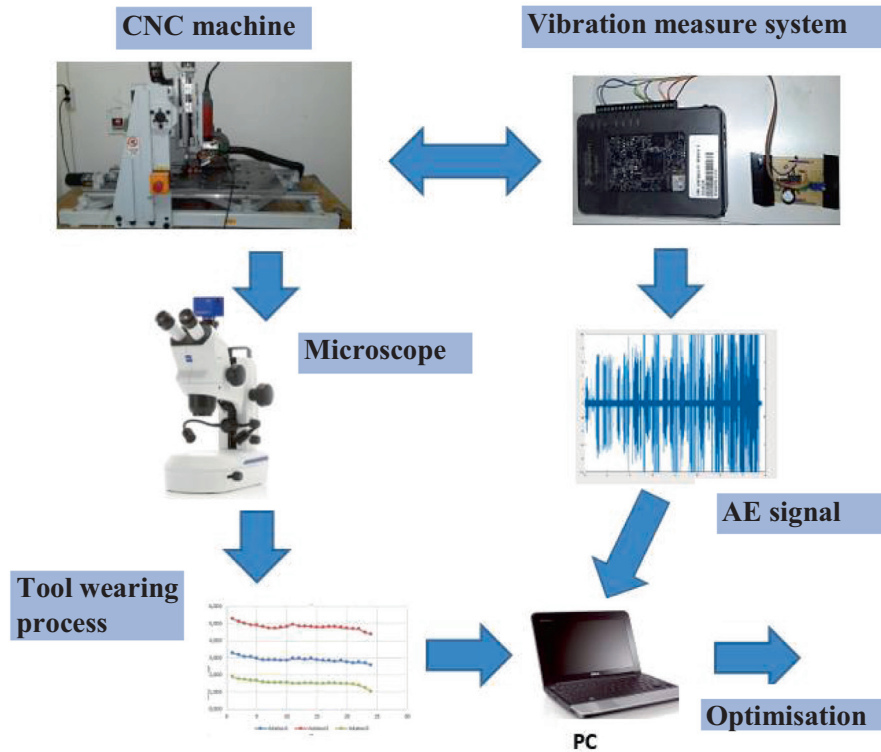


Fig. 6. Schematic illustration of the experiment setup.

According to the state-of-the-art, the cutting edge and the flank edge (Fig. 4) are loaded on the highest level during such machining [6,7,9].

Such tools should be chosen for cutting of this kind of brittle materials, which have small rake and flank angles. Due to the reduction in the friction surface between the tool and workpiece a minimum value for the flank angle is required.

2.2. Parameters of the (micro-)milling machine

The basis for the experiments was the milling machine that was planned and built by the CncTeamZeg (student) group. The machine is operated partly by the Mechatronics Institute of University of Pannon in Zalaegerszeg (Fig. 5). During 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 do machining on ceramic materials, too.

Basic parameters of the CncTeamZeg milling machine:

- Power: 1050 W
- Maximum tool diameter: 8 mm
- Spindle speed: 5000–25000 1/min
- Work area: 500x250x180 mm

The setup for the experiments is presented in Fig. 6. One of the 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

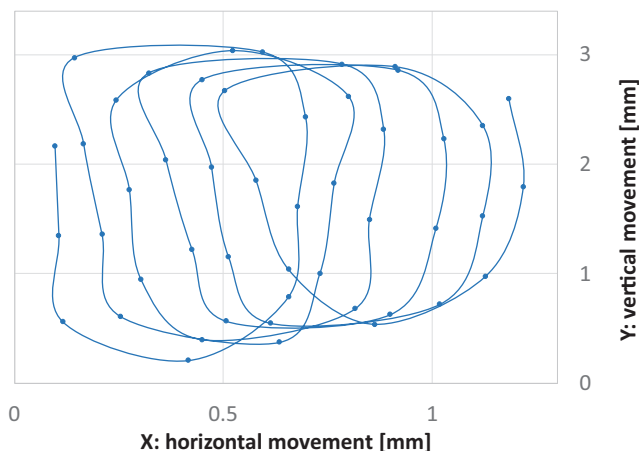


Fig. 7. A representation of one simple, small part of the generated cutting tool path.



Fig. 8. Setup of the microscopy system.

features) of the machined ceramic workpiece. Another goal is the tool wear monitoring by digital microscope on the one hand, and using high-frequency online vibration measurement during the cutting process, on the other.

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 [18].

2.3. Tool path, machining strategy

The tool path which was used during the experiments was created using the EdgeCam software. A very small, but typical part of the tool path is represented in Fig. 7.

The wave form milling technology used for constructing the tool path ensures that the tool is working with constant diameter

sweep. Owing to this, the tool load is constant during the machining in every changing direction. Another advantage of the wave form strategy is that the value of material removal speed can be kept constant, in contradiction to other path generation methods.

Theoretically, cutting distributes wear evenly along the entire flute length, rather than just on the tip. The radial cutting depth is reduced to ensure consistent cutting force, allowing cutting material escaping from the flutes. Tool life is further extended as the chip removes most of the heat [9].

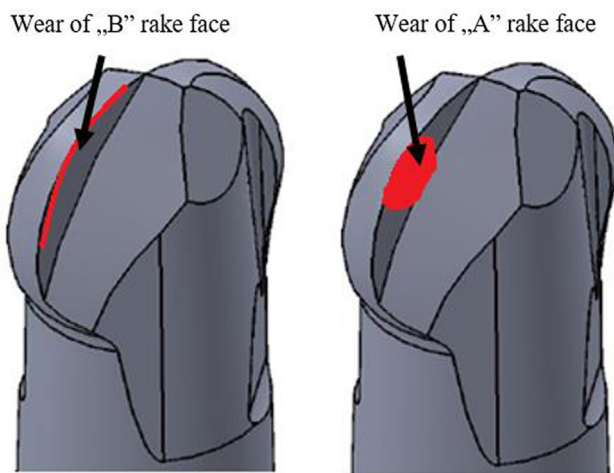


Fig. 9. Most important wearing places at the early tool life period.

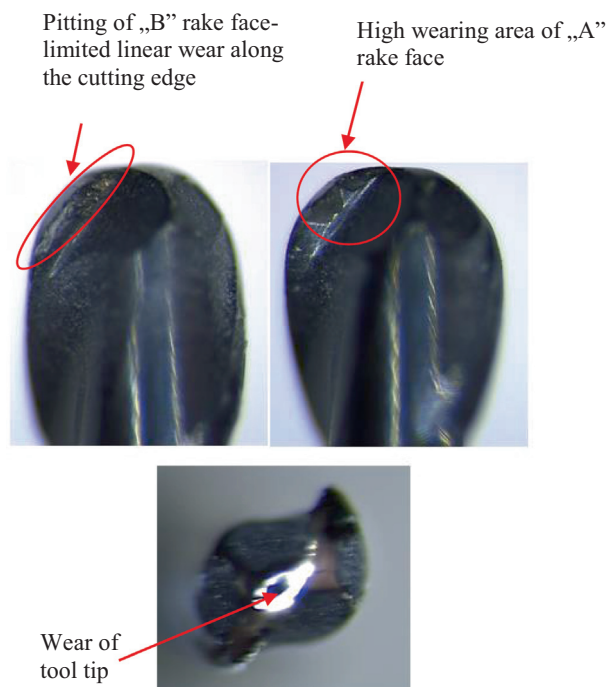


Fig. 10. Tool wear at 20% of the tool life.

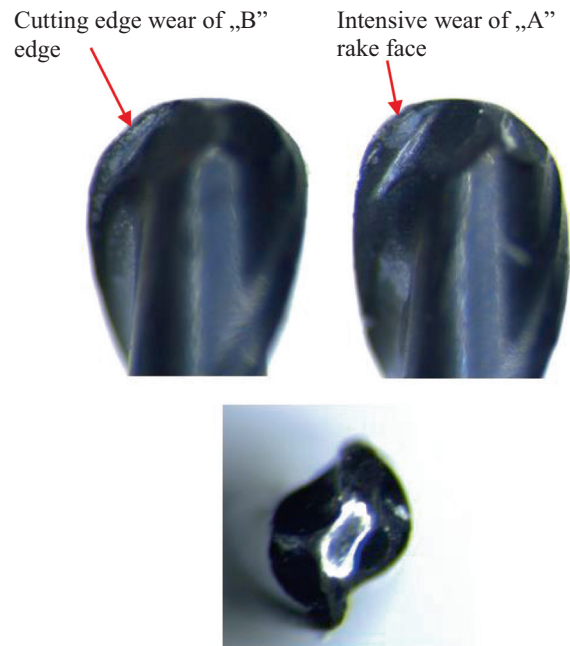


Fig. 11. Tool wear at 40% of the tool life.



Fig. 12. Tool wear at 60% of the tool life.

3. Indirect, off-line tool wear analysis based on microscopic observation

During the cutting process, microscopic images were taken repeatedly after machining a certain number of workpieces in order to monitor in an offline way the wearing evolution of the tool. Measurements were performed using Zeiss Discovery V8 microscope (Figs. 6 and 8) and the authors evaluated the wearing based on the pictures. The tool was applied until its breakage, this cycle of measurements covered the entire tool lifetime resulting in various identified phenomena.

After 20% of the total tool lifetime, an interesting phenomenon was observed. Types of the wear are presented by red marks in Fig. 9. The rake faces of tool began to wear unevenly. The “A” rake face began to wear on bigger surface, but on a smaller cutting edge length. The “B” rake face began to wear and pitting along the longer cutting edge length, but on a relative smaller surface (Fig. 9. and Fig. 10.). Another form of wear was observed on the tool tip.

The second inspection point was defined at the 40% of the complete lifetime. Further asymmetric wear of cutting edge and increasing wear of tool tip can be observed here as well (Fig. 11.).

At 60% of the lifetime, the flank face and geometrical distortion arose and turned to the burn out phase (Fig. 12.).

After the 80% of the lifetime almost the entire tool geometry was worn and burnt, consequently, the tool life was in its final phase (Fig. 13.).

Only the burn effect dominated entering the last 20% of the tool lifetime. This caused tool break in a short time-period (Fig. 14.). The

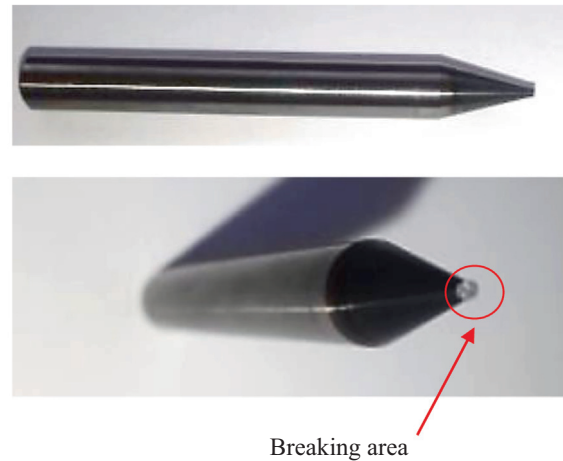


Fig. 14. Tool break at the end of the tool life.

main reason why this happened is, that the “new” wear out geometry of tool was not able to cut the material.

4. Indirect, off-line tool wear analysis measuring the produced workpiece geometry

The wearing process was supervised in two ways. The first one was the indirect measurement of the resulted workpiece geometry

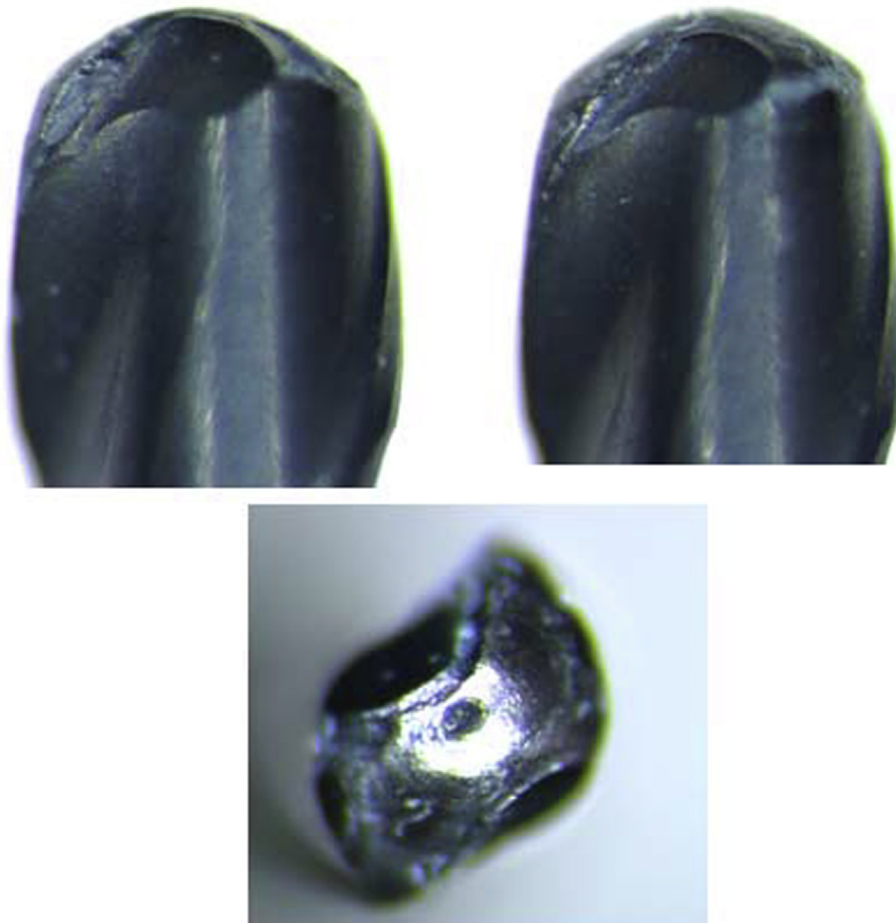


Fig. 13. Tool wear at 80% of the tool life.

[9], so, three, machined (macro-) geometrical features (width, length, depth) were measured (shown as Y axes in Fig. 15, while the horizontal axes represents the number of machining cycles).

As typical Taylor curves, the measured tool wear curve differentiates three stages, as shown in Fig. 15. Period "A" is the initial stage, here the wearing develops rapidly (worn-in). Period "B" is the uniform wear stage; here the wearing is a linear process of time/cycles (normal condition). At this stage, approximately the same wearing level of the tool is observed at equal intervals. In the third stage denoted by "C" stage, the tool wear develops again rapidly and results in tool failure, mainly in break (wear-out). The reason for this effect is that the cutting ability of the tool deteriorates, and the friction surface increases and becomes uneven.

It is proven that with this kind of introduced indirect measurements, the three classical stages in the tool life can be differentiated, consequently, all machining cases can be labelled with the actual state of the tool (worn-in, normal, wear-out). Later on, it can be

used in further researches for finding the best indication for the tool statuses based on on-line monitoring measurements, like vibration, as it is described in the next paragraphs.

Moreover, these workpiece-based indications were fully compliant with the results of another, off-line, microscope based analysis.

5. Direct, on-line tool wear analysis using vibration measurements

Beyond the two off-line analysis (performed by microscope and based on the produced workpiece geometry), an on-line supervision was established for monitoring the tool wearing evolution. 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.

In [19], 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 [20]. In this case, the reason for such a decrease is that the combined effect of several tool wear types have important influence on the interactions of cutting parameters and tool-workpiece-chip relations, so, the situation is usually not as "simple" as in the previous case.

In the reported research, vibration measurement of ceramics milling was established with a sampling frequency of 100 kHz measuring in one direction. Fig. 16 represents two vibration measurements, the upper one with the sharp tool and the lower one with a worn tool.

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

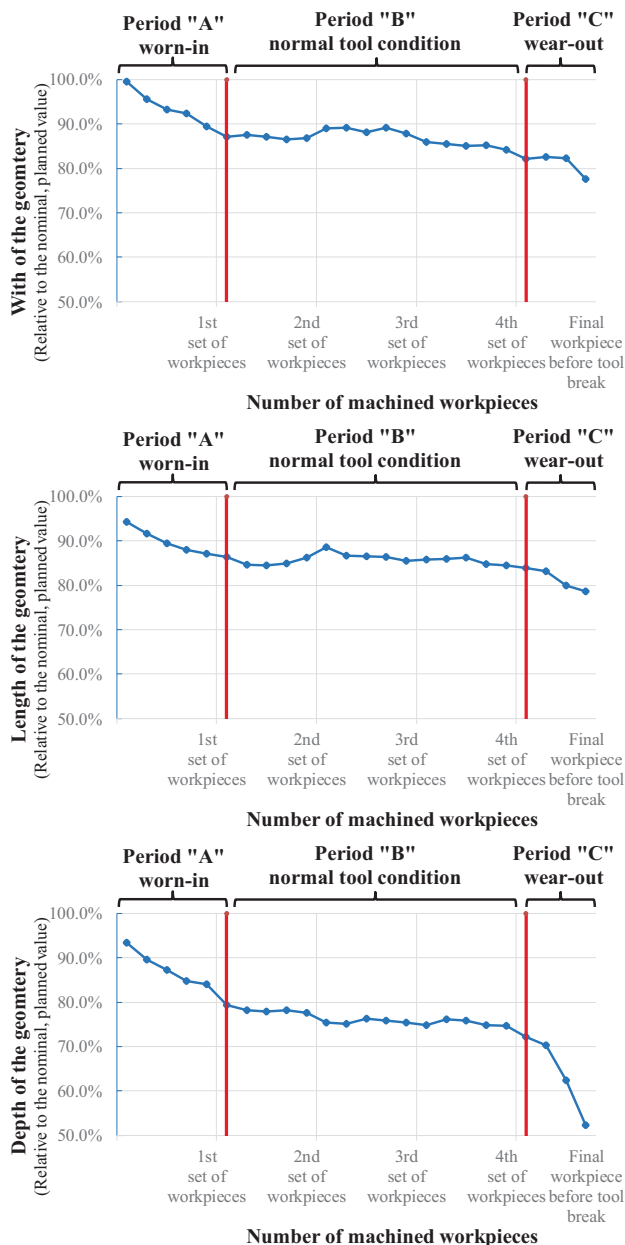


Fig. 15. Changes in the Width, Length, and Depth of the machined workpieces – resulting in typical Taylor curves.

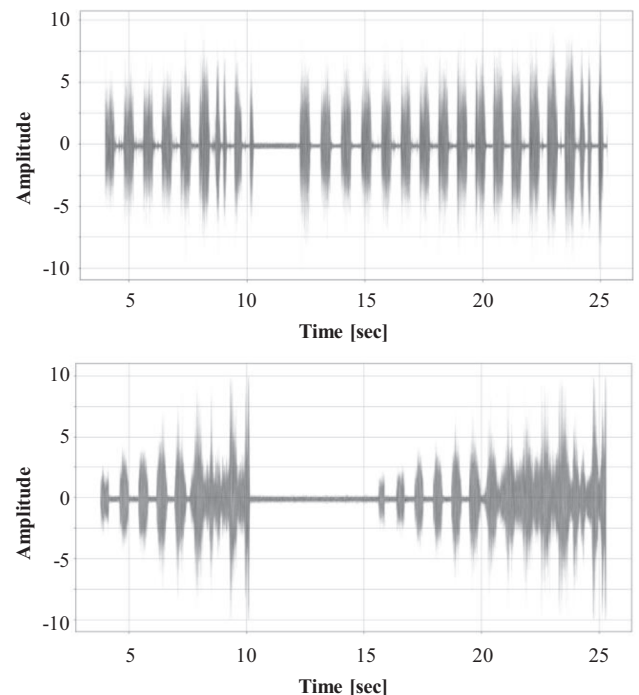


Fig. 16. Measured vibration amplitudes, the upper one with the sharp tool up and the bottom with a worn tool.

resulted also in a shift of the dominant frequencies into higher frequency ranges.

Ahmad et al. found similar results [21], they reported that in metal milling, when the flank wear increased, then, the vibration amplitude decreased. Furthermore, they found that the increasing cutting speed caused further decrease in the amplitude. Mu and Xu also examined the wearing method of milling tool [22] with similar results.

Having measured the vibration with such high frequency it is possible to calculate a great variety of signal description features. So, instead of analysing over millions of individual measured values, as time series of the vibration amplitudes (Fig. 16), a number of 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

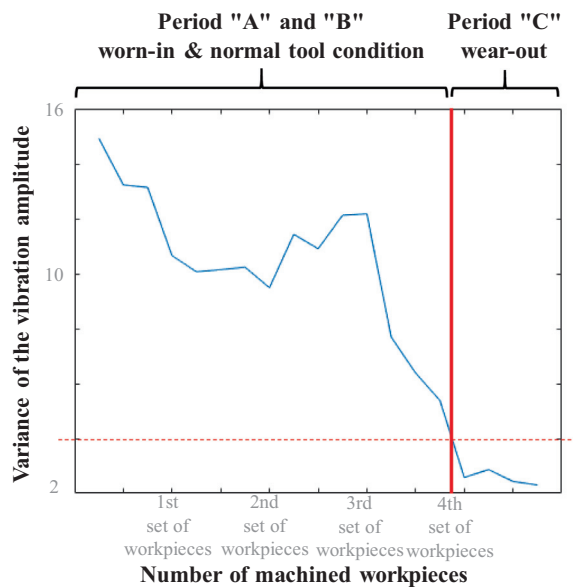


Fig. 17. Changes in the vibration standard deviation of the machined workpieces (left: starting with a sharp tool, right: fully worn-out tool).

experiments the same tool is used, until its break. Feature selection was applied to find the most descriptive features for distinguishing two different stages of the tool life (usable (incorporating worn-in & normal) and wear-out). The (still unpublished) feature selection solution – developed by one of the authors – was applied; it combines the best state-of-the-art feature selection techniques and serves with a superior solution over them [18]. This method is called Adaptive, Hybrid Feature Selectin (AHFS); it uses a set of feature selection methods as heuristics and makes selection about the best features using a related artificial neural network model. In the current case, it selects those calculated features that most distinguish the usable tool life period from the wear-out stage.

As result, the algorithm identified that alone the standard deviation value of the vibration signal calculated at each workpiece can differentiate the two stages of the tool wear; moreover, the decrease in the standard deviation mirrors the increased wearing evolution of the tool (Fig. 17).

The reason for the correlation that was found between the decrease in the standard deviation and in the decrease of the vibration amplitude values could be the following: as the contact surface of the tool reduces thus the vibration amplitudes also decrease and the amplitude deviations from the average amplitude as well [20,21].

Since only one feature was enough for the separation of the two tool statuses, it is obvious that a concrete threshold value (dotted line in Fig. 17) of the standard deviation parameter can be defined to appoint and supervise the transition of the cutting tool from usable (worn-in & normal) to wear-out statuses.

During the data collection, time-dependent vibration amplitudes were recorded, the distribution in their signal energy values at different frequencies were determined by the PSD (Power Spectral Density) function [23]. This classical PSD method is applicable to analyse such signals where the signal is dependent on several unknown variables. The PSD describes how the energy of a signal or a time series is distributed over frequency. The results of measurements are represented in Fig. 18. It mirrors that the amplitude value of the whole spectrum has a decreasing trend from the sharp tool to worn tool. The reason for this is the decreasing contact area between the workpiece and the cutting tool as explained at the standard deviation analysis.

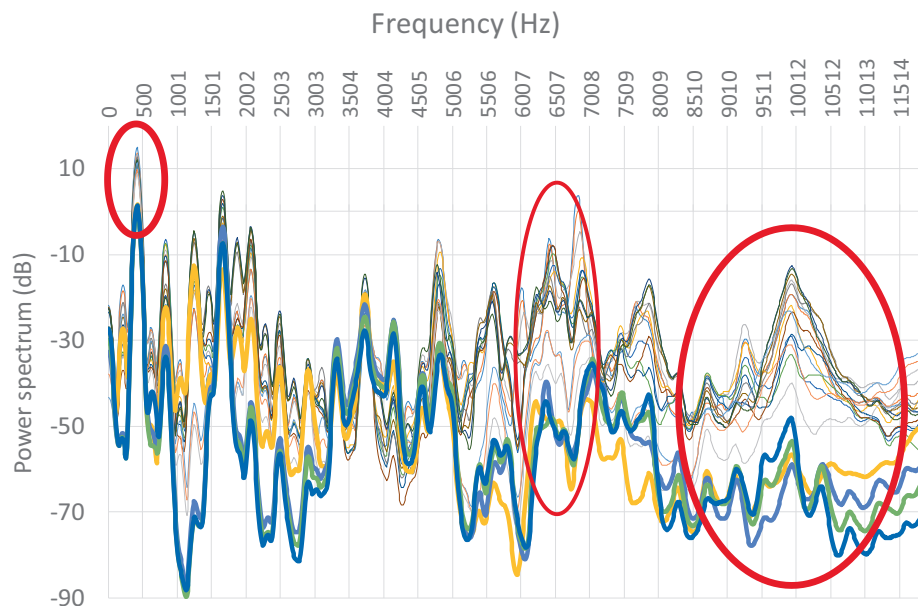


Fig. 18. Separation of the sharp (thin curves) and worn (thick curves) tool according to the various vibration frequencies.

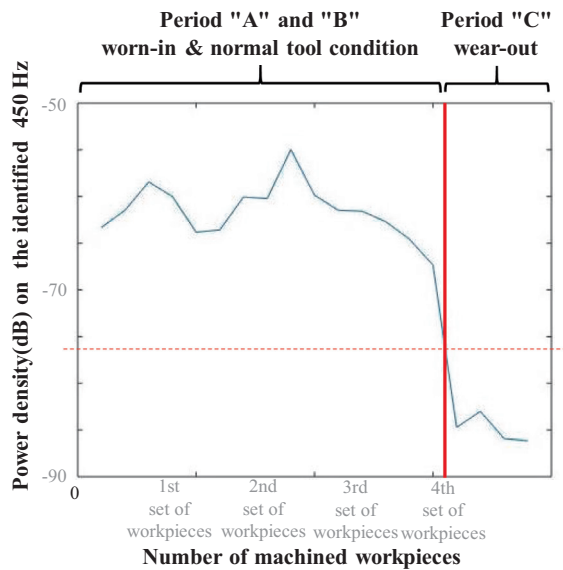


Fig. 19. Changes in the power density signal at the most indicative frequency (450 Hz) with respect to the number wear-out progress represented by the order of the machined workpieces (left: starting with a sharp tool, right: fully worn-out tool).

(At least) three different ranges of frequencies were identified by the feature selection method that can be used to differentiate between usable and wear-out tool wear statuses. The most applicable frequency is around 450 Hz, the largest gaps are to be found in this range between the two stages to be differentiated. Is it a relative narrow frequency range, while between 8500 and 11 000 Hz a much broader range for differentiation can be found, but here, the gap is smaller. A third range is between 6000 and 7000 Hz, however, the distances between the amplitudes of the two classes is relative small. It is also represented that with the evolution of the tool wearing, the vibration amplitudes decrease as well.

The Fig. 19 presents the power density values of the vibration measurements at the most indicative 450 Hz frequency along the comprehensive cutting progress using one tool starting as a sharp one on the left side, with continuous wearing in the direction to the right and having the wear-out statuses on the right side. This figure represents clearly and in a simple way the easy separation (see the dotted line as threshold in Fig. 19.) of the usable (worn-in & normal) tool from the wear-out statuses based on vibration analysis.

These experiments and analyses represent that the monitoring and identification of the worn-out status of ceramics micro-milling can be realised based on vibration measurement using either by the supervision of the measured vibration deviation itself (calculation of its standard deviation) or by its frequency analysis (at the identified indicative frequency(es)) as well.

6. Conclusions

Based on their favourable mechanical features, applications of ceramics are continuously spreading in industrial environment, however, there are many open issues in their machining, e.g. in cutting them with regular tool geometry. The paper introduced two off-line and one on-line method to supervise the milling tool wear evolution during machining of ceramic workpieces:

- The first off-line method is based on microscopic pictures about the tool with human/expert evaluation, applied for identifying the various tool-wear types at different stages of the wearing process.

- The second off-line supervision method is an indirect, off-line tool wear analysis measuring the changes in produced workpiece geometry.
- The third method is an on-line tool wear monitoring solution with high-frequency vibration measurement and analysis, exploiting also the labelling results of the off-line, workpiece geometry-based supervision.

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.

Feature selection algorithm was applied to find the most descriptive features calculated on the vibration measurements for distinguishing two different stages of the tool life (usable (worn-in & normal) and wear-out):

- As a result, the algorithm identified that alone the standard deviation value of the vibration signals calculated at each workpiece can differentiate the two stages of the tool wear, moreover, the decrease in the standard deviation mirrors the increased wearing evolution of the tool. It was identified that (two) concrete threshold values of the standard deviation parameter can be defined to appoint and supervise the transition of the cutting tool from usable (worn-in & normal) to wear-out statuses.
- During the data collection, time-dependent vibration amplitudes were recorded, the distribution of the performance values at different frequencies were determined by the PSD (Power Spectral Density) function. Analyses represent that the monitoring and identification of the worn-out status of ceramics micro-milling can be realised also by its frequency analysis (at the identified indicative frequency(es)) as well.
- Both of the identified, vibration-based supervision indicators (standard deviation and frequency analysis on 450 Hz) resulted in clear and robust separation of the usable (worn-in & normal) and wear-out tools: in Figs. 17. and 19., the values of the indicators (vertical axis) of the usable tools are (left) in the high-value range, but the values of the indicators of the final four machinings with worn-out tools are far from them in the low-value range. *It means that the proposed approach is robust enough against possible deviations in the precisions (e.g. measurement, set-up, material, etc.), even if a detailed analysis of the uncertainties were not performed.*

The reported research allows to improve and stabilise the cutting of ceramics significantly, applying micro-milling with regular tool geometry.

CRedit authorship contribution statement

László Mórícz: Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Zsolt J. Viharos:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration,

Funding acquisition. **András Németh**: Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **András Szépligeti**: Validation, Investigation, Resources, Data curation. **Máté Büki**: Software, Formal analysis, Data curation, Writing - review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

First of all, thanks have to be expressed to the AQ Anton Kft. at Zalaegerszeg, Hungary, serving with materials, equipment, challenges, experts any many other resources enabling and supporting the research. The research in this paper was partly supported by the European Commission through the H2020 project EPIC (<https://www.centre-epic.eu/>) under grant No. 739592 and by the Hungarian ED_18-2-2018-0006 grant on a "Research on prime exploitation of the potential provided by the industrial digitalisation".

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