16th IMEKO TC10 Conference
"Testing, Diagnostics & Inspection as a comprehensive value chain for Quality & Safety"
Berlin, Germany, on September 3-4, 2019

Product quality and cutting tool analysis for micro-milling of ceramics

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Abstract **– Based on their favourable mechanical features, applications of ceramics are continuously spreading in industrial environment. Such a good feature is their resistance against heat shock, so, currently they are applied e.g. as coating material for gas turbines. The main aims of the paper 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.**

Keywords: cutting of ceramics, regular cutting edge geometry, micro-milling, product quality, tool wear

I. INTRODUCTION

Machining of rigid materials with regular cutting edge geometry is one of the main trends in the 21th 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 optimisation, 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 tool wear state serves with information about the actual wearing stage of the tool.

Bian et al. [6] used ultra-miniature diamond coated tools to mill fully sintered ZrO_2. Wear of the tool was described 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.

Romanus et al. [7] analysed the tool wearing process and the resulted surface quality during cutting of also ZrO_2 by diamond and cBN coated milling tools. They observed the same three stages of the wearing.

Bian et al. described experimental results in another publication [8] using WC milling tool coated by different sizes of diamond grains with the aim for analysing the peeling process of the diamond coating. They concluded that when the machining in the classical "X-Y" direction the cutting force is significantly smaller as in the "Z" direction. The reason for that is, 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 identified also that with the increase of the feed per tooth and axial cutting depth the cutting force will grow significantly.

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

a) availability of ultra-miniature tools having appropriate cutting edge geometry to ensure proper compression/tensile stress distribution in the chip zone;

b) appropriate tool stiffness and sufficient wear resistance;

c) identification of suitable cutting parameters to ensure ductile material removal and damage-free machined surfaces. [7]

The main aims of the current paper are - continuing a previous research - 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.

II. FACTORS INFLUENCING THE CUTTING TOOL LIFE

There are plenty of technological parameters that influence the micro-milling of ceramics. However, the literature shows that the most influencing parameters are the following:

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 assignment for the cutting process with regular geometry tool is to keep the cutting in plastic deformation area instead of in brittle area [8].

K. Ueda and his colleagues cut plenty of ceramics materials to find solution for this question, and 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 a parameter combination that can cut in the ductile deformation zone.

The other author of the mentioned publication who conducts some research into the ductile-brittle range in shaping method is Muhammed A, who tried to find what those cutting parameters are, and how they influence the ductile range [9]. It was found that there are critical parameters belonging to the cutting depth and feed values which affects the chip-removal mechanism. These results are summarized in Figure 1.

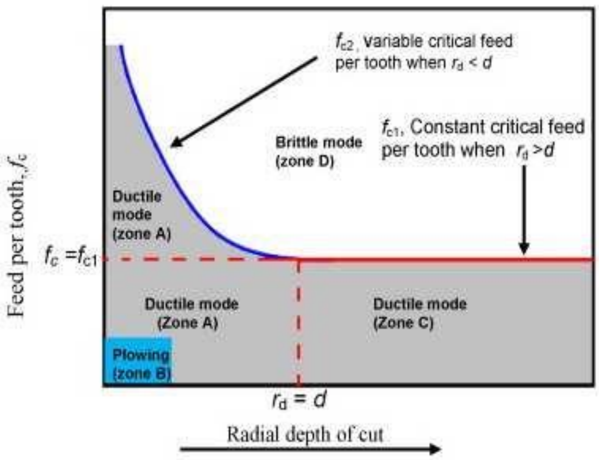


Fig. 1. Critical value of feed-depth to reach the plastic deformation range [9]

During their experiments it was found that there is a critical value of cutting depth and feed, where the analysed material can be shaped in the ductile removal area. Under a certain cutting depth, the value of feed can be increased without the removal of the cutting mechanism from the brittle area. 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 [7][9]. Another important aspect of the mechanism is the tilt angle of the tool [10].

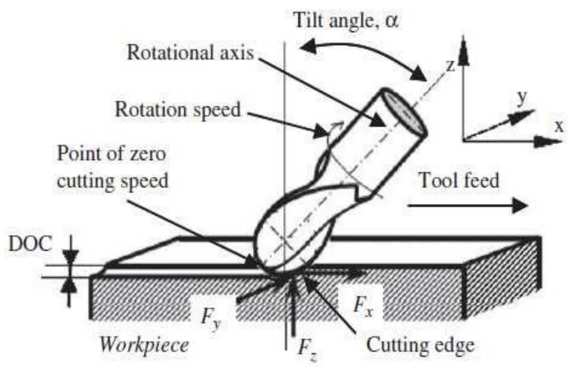


Fig. 2. Tilted milling tool [10]

This parameter is highly important in cutting with ball milling tool, as the cutting speed depends on the tilt angle. The scientific literature represents that the optimal tilt angle is between 40-60° that depends mainly on the ceramics' material [10].

A combined technology is a further interesting method for enhancing the lifetime of a cutting tool: Toru et al. [11] combined the conventional cutting technology with laser technology. J. Feng et al. [12] performed machining with irregular cutting tool geometry while they made conclusions on the cutting tool's wear based on cutting force and vibration measurements. Xiaohong and his colleagues [13] preformed 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 researches 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 [14]. The results served with a quasi (linear) optimal technology concerning the maximisation of material removal speed; however, the analysis of the wearing process is an open issue, because a novel indirect measurement could be applied before [15]. The current paper goes beyond the previously applied methods, because the complete wearing behaviour of the tool is described.

III. EXPERIMENTS WITH MACHINING USING SMALL PITCH ANGLES

Micro-milling tools were applied for the ceramics cutting experiments.

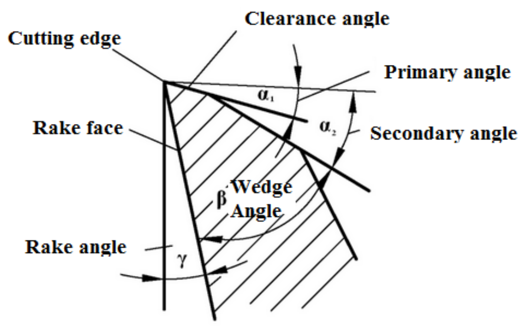


Fig.3. Tool geometry and angles

According to the available literature, the cutting edge and the flank edge (Fig. 3.) are loaded on the highest level during such machining [7][8].

Parameters of the milling machine

The basis of 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. 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 do machining on ceramic materials, too.

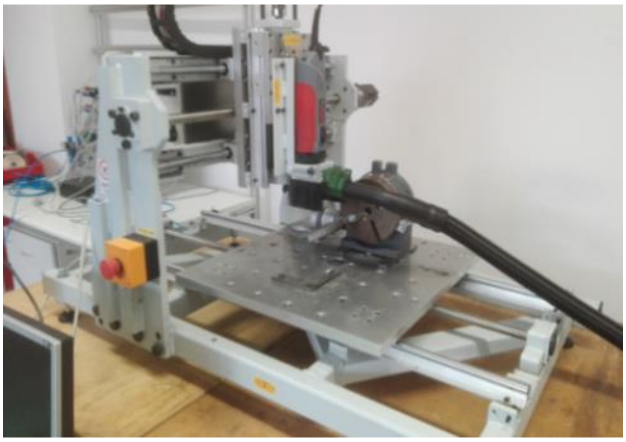


Fig.4. The applied three axis cutting machine

Parameters of the laboratory milling machine:

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

Tool path

The path which was used during the experiments was created using the of EdgeCam software. A very small part of the tool path is presented in Fig. 5. representing mainly of linear movements and machining along circle slices having various radiuses.

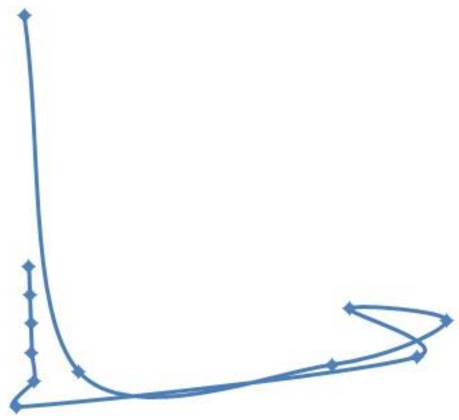


Fig.5. One simple, small part of the generated tool path

The applied cycloid form is a special milling technology where the milling tool is going along an arc, avoiding sharp changes in the direction.

The wearing-out process

The optimum cutting conditions determined in previous research [13] were applied in the current analysis, while the tool wear was measured by microscope in predefined intervals. These microscope measurements are presented in the next figures, representing the wearing-out process (Fig. 6-9.). From the previous experiments the approximate lifetime of the tool was also identified. Using this information, the specific stages of the tool lifetime are known.

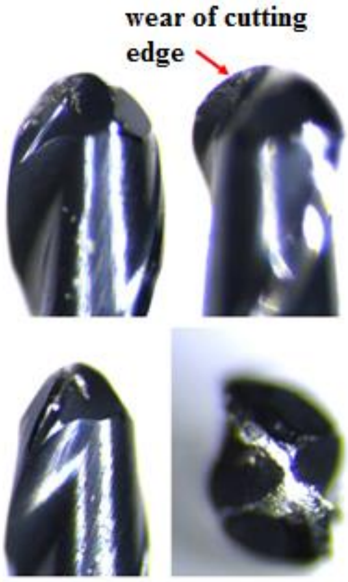


Fig. 6. Tool wear at 20% of the tool life

The first inspection point was defined for the 20. percent of the complete lifetime. The first wear form was observed on the cutting edge.

Fig. 7. Tool wear at 40% of the tool life

The second inspection point was defined for the 40 percent of the complete lifetime, the Fig. 7. shows the wearing of chisel edge and an early wear of flank.

Fig. 8. Tool wear at 60% of the tool life

Strong flank wear was observed at 60 percent of the lifetime and the first burning-out with geometrical distortion arose.

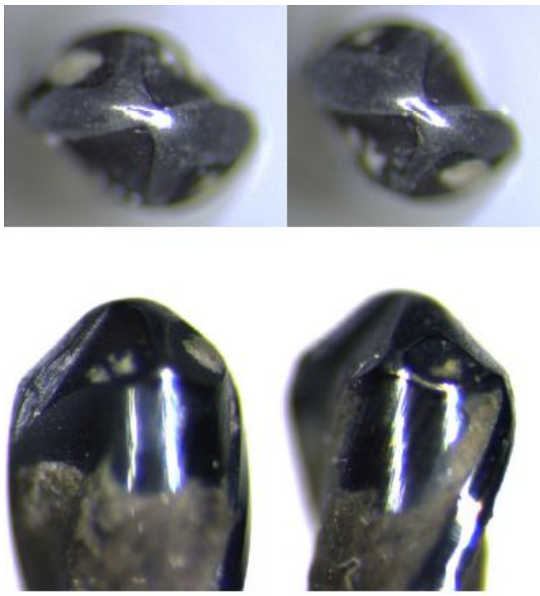


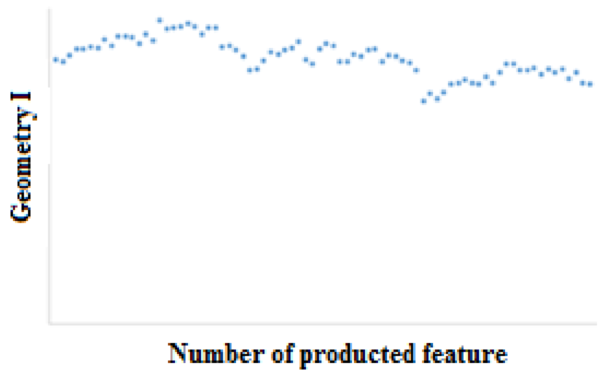
Fig. 9. Tool wear at the end of the tool life

Through the optimisation of the technological parameters more than 40% increase in the cutting tool life was achieved. On the final point the chisel edge was fully wearing out, and the tool geometry was strongly distorted, as shown in Fig. 9. Consequently, there were no sense to continue these experiments.

In the current paper only the cutting tool wearing forms were examined together with the specification in which section of tool lifetime they appear. To give nominal, directly measured values for tool degradation will be one of the next steps in the research.

Analysis of the cutting tool wear process based on geometrical changes of the machined workpiece

The wearing process can be followed also by indirect measurements of the resulted workpiece geometry, see the related details in paper [14]. Two machined geometrical features (Geometry I. and II.) were measured (Y axes), represented in Fig. 10., while the horizontal axes represents the number of machining cycles.



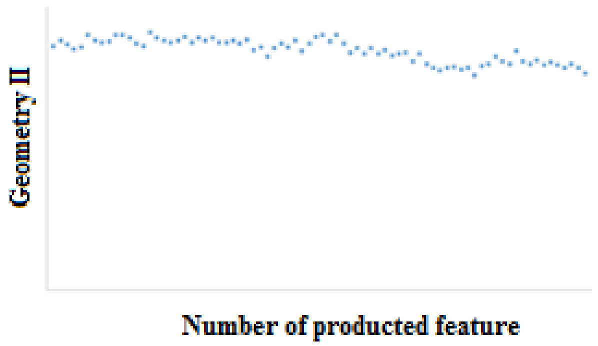


Fig 10. Changes in the Geometry I. and II. of the machined features

Fig 10. mirrors some repeated errors based on the measurements (increasing parts in the y values), however these are in relation to the uncertain behaviour of the workpiece re-positioning after the separated microscope measurements of the tool wearing. Consequently, it can be eliminated. Finally, the tool wearing trends were identified, since the wearing process started at the tool's chisel edge.

IV. RESULTS AND DISCUSSIONS

Based on the experiments the wear of the tool can be described in four stages:

1. Cutting edge and rake face early delamination.
2. Wearing of the chisel edge, flank face early delamination.
3. Strong flank face and chisel edge wearing.
4. Wear-out of the complete geometry.

The length of the stages can be influenced by technological optimisation:

- One of the most influencing factors is the cutting speed. Under a critical value consequent tool breakage was observed within a very short time period.
- Fast wearing of the cutting tool was observed when selecting an inappropriate value for the tilt angle. In this case the same wearing stages can be identified as described above, but much quicker.
- Comparing the wearing forms of the cutting tool and the geometrical changes of the machined workpiece, it was found that the wearing of chisel edge has the strongest influence on geometrical measures.

Further research directions

Research directions for the close future can be also formulated:

- Deeper insight into the relations between tool wearing and technological parameters.
- Optimisation of technological parameters to eliminate the negative effect of the chisel edge.
- Measurement method for nominal values of the factors of tool degradation.
- Monitoring and diagnostics of the cutting tool using vibration sensors and advanced data analysis.

V. 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.

During the reported research, by optimising the technological parameters, more than 40% increase in the cutting tool life was achieved At the experiments the wearing progress was analysed in parallel to the changes in the machined workpiece geometry and it was identified that the tool wearing is the key factor influencing the resulted workpiece accuracy and quality. Scientific progress has been reached in three fields:

- Increase in the cutting tool life by more than 30%.
- Monitoring and diagnostics on the cutting tool

wear directly and indirectly, and comparison of them.

- Analysis of the cutting tool also after the damage and wear-out of the tool coating.

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

VI. ACKNOWLEDGMENTS

First of all, thanks have to be expressed to the AQ Anton Kft., 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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