PhD thesis booklet

University of West Hungary

Sopron

József Cziráki Doctoral School of Wood Science and Technologies

MONITORING AND OPTIMIZING TOOL WEAR DURING MICRO-MILLING OF CERAMICS

PhD thesis booklet

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1. Description of research topic, objectives

The current technological progress of humanity is directly linked to a rapid increase in energy use. Of all the forms of energy used, electricity is one of the most dominant and crucial one in our society. The growing trend in energy demand reflects the fact that gas turbines are very dominant, both in terms of technological sophistication and market role [1][2].

Current trends reveal that the ever-increasing energy consumption worldwide makes the continuous development of turbines inevitable, which means a constant challenge for the current researches as well. To achieve the required efficiency, turbines must be able to operate under even extreme operating conditions, and in this regard, one of the most challenging issues is improving their resistance to high temperatures. Gas turbines operate well above the melting temperature of the turbine blade castings, so a continuous cooling and thermal protection is required. The blades are hollow inside, cooled by the introduced air, which exits from inside the blade through the cooling holes. In addition, the blades of modern turbines are protected by an insulating ceramics layer applied to the surface of the castings [3][4]. The technology used to produce the coating entails that the ceramics coating on the blade requires subsequent surface finishing after application, which accounts for a significant proportion of the total cost of the manufacturing process.

All these well reflect the fact that the application of ceramics is a highly relevant subject, which is why the processing of ceramics is also a subject of special attention, and this doctoral thesis also presents new scientific results in this field.

The detailed objectives of my research are as follows:

1) The primary objective is to explore the effects that impact ceramics cutting, within which I have formulated the following subpoints:
    a) To determine the extent to which these characteristics affect the tool life. In the experiments I do not investigate the development of the achievable surface quality.
    b) A further aim is to explore such a combination of technological parameters where tool life time is expected to be the longest and production time the shortest.
2) In order to optimize the number of experiments, the aim is to develop and carry out a complete factorial design of experiments, which would enable to implement a reliable optimization.
3) Since complex geometry was investigated, an additional objective was to explore the impact of different path strategies on tool life.
4) In all cases, vibrations are generated during deburring. The nature of these vibrations is strongly influenced by the condition (degree of wearing) of the given tool. The aim of the research was to implement an online monitoring procedure to monitor the actual wear condition of the tools based on vibrations, without having to stop the production during the process.
5) In addition to the online monitoring of the accuracy of the tool, a further aim is to determine the actual, momentary state of the tool's particular edges and surfaces of complex geometry, based on the online vibration measurement.

2. Review of Literature

Ceramics are defined by the American Ceramics Society as a group of non-metallic materials that are subjected to heat during their manufacture or use [5][6]. Ceramics are generally characterized by their low density, high melting point and significant heat resistance. They are also characterized by high mechanical hardness and endurance, high compressive and flexural strength, but low tensile strength. They are poor electrical conductors, but have favourable piezoelectric and dielectric properties. The field of application of ceramics is mainly determined by the physical and chemical properties of the material, which are determined by the composition of the primary material and the parameters of its production. Nowadays there are many types of technical ceramics. The different types of technical ceramicss can be divided into 3 main groups, which are the following:

- *silicate ceramics*
- *oxide ceramics (Al_2O_3, BeO, SiO_2, etc.)*
- *non-oxide ceramics (nitrides, carbides, borides, etc.)*

Surface treatment of ceramics are difficult due to their physical properties (high level of hardness, sensitivity to thermal shock, good thermal insulation, sensitivity to dynamic stresses, electrical insulation) [7]. Their processing is basically made difficult by their high hardness, since on the one hand, the surface often cracks and breaks due to the forces generated during chipping, and on the other hand, tool-wear is very intense in such cases.

After reviewing the available national and international literature, I have come to the conclusion that the research directions can be summarized in the following points:

- *Options to increase tool service life relating to milling of different ceramics base materials (exploration of tool wear phases, deburring/smoothing in flexible-brittle range, base material preparation, tool coating, technological process-optimization) [8][9*]
- *Possibilities of surface quality improvement relating to processing different ceramics base materials (achieving crack-free surface via technology optimization, combined technologies) [9]*

Micro-milling

The size below which we talk about micro-cutting has no uniformly accepted definition in the literature [10]. If we want to quantify the concept, we can assume that the structure size and/or the machining range of micro-machining processes is in the micrometre range, i.e. between 1–999 μm [11].

Micro-milling is a precise and flexible technology that can be used to process different types of materials (polymers, ceramics, metals, alloys) and complex 3D geometries at relatively high material removal rates [12]. The kinematics of micro-milling are similar to those of a conventional size milling process; however, it has some unique phenomena and key aspects [12]:

- *The size of the cutting tool can be extremely small, so the length-to-diameter ratio is often quite high. The unfavourable size of the tool – combined with vibration and/or relatively high tool impact – often leads to tool breakage.*

- *The chip thickness is often of the same order of magnitude as the radius of the cutting edge or the grain size of the workpiece material, so the anisotropy, grain size and crystallographic defects of the workpiece also become relevant.*
- *The ratio between burr size and the dimension of the deburred features is higher than usual for conventional chipping operations, so the cost and time requirements of micro-deburring processes have a greater impact on the final cost of the products.*
- *The importance of monitoring and diagnostics of micro-milling processes is reasonably high, as the cutting tool can easily damage the surface of the material (inadequate surface roughness, burr formation, micro-crack formation, etc.), and it can easily break.*

Operating edge angles during micro-cutting

In micro-cutting, the working edge angles change significantly, because the chip thickness is comparable in size to the tool's edge rounding radius or the grain size of the material, and therefore have to cutting with a strongly negative rake angle, as shown in Fig. 1.

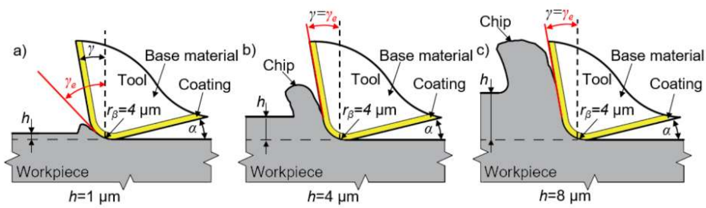

Fig. 1: Different geometrical conditions at micro-milling in the case of different chip thickness values [12]

Cutting forces in micro-milling

In case of macro-milling, the cutting force is much greater than the passive force. In case of micro-milling, the passive force must also be taken into account, as it has a significant impact on the chip removal process. It is important to know and monitor the cutting forces, as they provide information about a number of phenomena, such as chip formation, material removal mechanisms, vibration and tool condition. Since we use slender tools (with high length/diameter ratio), even a small force can cause large tool deformation. Furthermore, the tool's edge geometry changes continuously as the tool wears, so in addition to the forces, the edge geometry also affects all process characteristics.

3. Research methods / Summary of research work

The first step of my research was to assess the effects that may influence tool life time and manufacturing time, as suggested by the literature. These factors and their optimum values are relevant not only in ceramics machining research, but are equally important in industrial practice [13][14]. These effects are summarized in Fig. 2.

The research was designed around the following objective: Make as many pockets as possible with one tool.

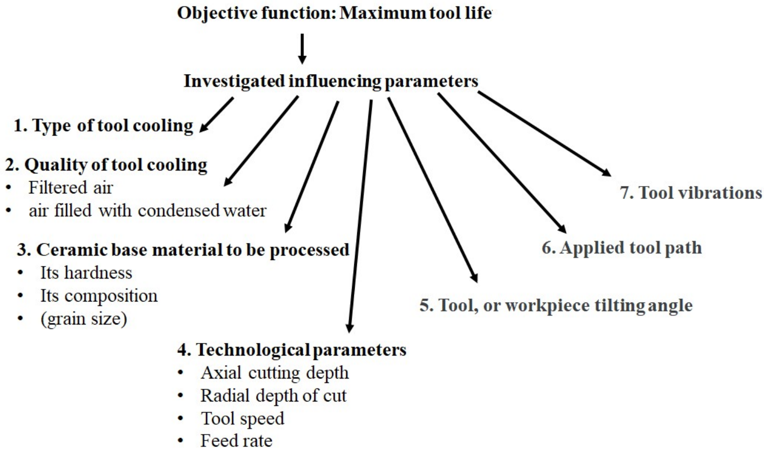

Fig. 2: Factors affecting tool life

In addition to the cutting parameter settings, another technological feature that is important to analyse in the experiments is the different tool-path strategies that can be generated by CAM softwares. The influence of different tool-paths on the tool during oxide ceramics cutting has not been investigated in the literature. Therefore, several tool-path strategies offered by EdgeCam and most commonly used in industrial applications were analyzed. The first, initial strategy (reference track) was the chained tool-path. This strategy is a straight cutting strategy composed of purely straight-line sections, with curved sections present only where the geometry of the production absolutely requires and justifies it. In addition, both the cycloid tool-path with intermediate cycloid cutting depths and the waveform path were analyzed.

Tool-wear monitoring, based on vibration signals

One of the causes of tool-wear during micro-cutting is the vibration generated during cutting. Based on the research in literature, it can be stated that – in addition to the previous analyses – it is important to investigate the vibrations generated during the cutting process as well, since this is a rather under-researched area in the field of ceramics cutting. However, it is known to be a common diagnostic method for monitoring tool-wear [15][16][17].

As the tool wears, its edge geometry changes. This results in a change in the size of the contact surface area between the workpiece and the tool, due to which the amplitude of the vibrations vary continuously. For this reason, the process can probably be well-monitored by vibration-diagnostic methods.

Measurement, data collection

For the vibration measurement a TE-CONNECTIVITY-type accelerometer sensor was used. The measuring device is used to measure the electrical output signal in mV, corresponding to the actual momentary amplitude value of the vibration acceleration. The signals from the amplifier were recorded using a myRIO-1900-type portable Reconfigurable Input/Output (RIO) device.

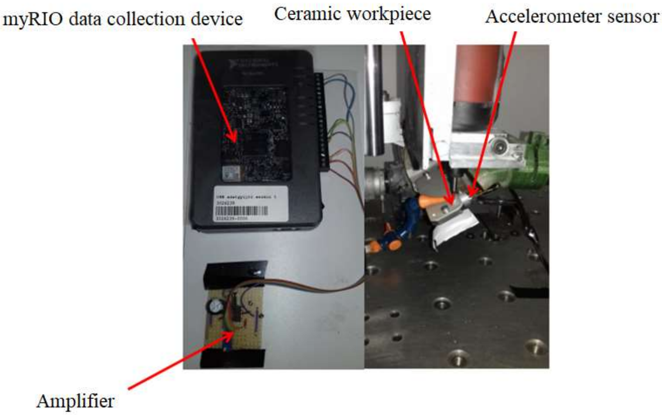

Fig. 3: Consturction of measuring system

The data collected during the experiments were processed in MATLAB software, and the Adaptive, Hybrid Feature Selection algorithm [18] used to evaluate the feature selection method was also run in MATLAB.

4. Presentation of thesis

The effect of the technological parameters on the tool life was investigated with a factorial experimental design, with the following parameter values:

Table 1 Design of experiment

Depth of cut ,(a_p)[mm]	0.05,0.3
Radial depth of cut (a_e)[mm]	0.05,0.3
Number of revolutions (n) [1/min]	10000,25000
Feedrate (v_f) [mm/min]	300,600
Milling strategy	Cycloid toolpath

During cutting, when evaluating the factorial experiment, it is practical and common to consider the effect of the cutting depths as a function of the chip area.

The chip area is a continuously variable value, but for calculations it is sufficient to use is approximated in the form of a (b · h) product. Where "b" is the radial cutting depth and "h" is the axial cutting depth. Both the calculations and experimental results showed that the (a_p:0.3–a_e:0.05) *(axial cutting depth-radial cutting depth)* combination is not the same as the (a_p:0.05–a_e:0.3) combination, even though their product is the same. Therefore, transformation is needed. For this reason, instead of the (b · h product, the ($h^{n+1} \cdot b^{n-1}$) product is used, where the index n can vary between 0 and 1. The effect of the chip area on production time – as revealed by the research results – is shown in Fig. 4.

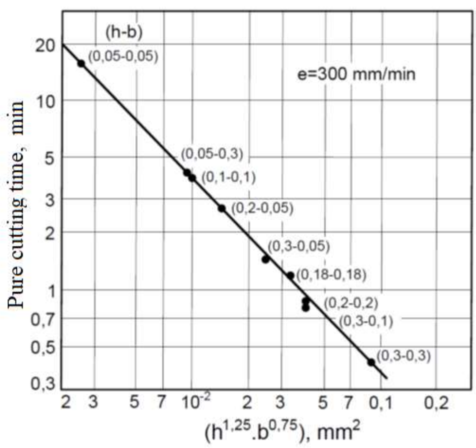

Fig. 4: The clear cutting time as a function of the theoretical chip cross-section, for feed speed: vf=300 [mm/min]

The direction tangent of the curve is -1.06, that is, it does not differ much from inverse proportionality. The correlation obtained from the evaluation of the experiment served as the basis for the 1st thesis.

Thesis 1:

The general relation of the manufacturing time of a cooling channel of trapezoidal cross-section on the oxide ceramics coating of a gas turbine blade is given for geometry, but for arbitrary cutting parameters it can be written as the following formula, in which the exact calculation of the radial and axial cutting depths via a special functional transformation plays an important role:

$$T_{forg} = \frac{8.3}{v_f} \cdot (h^{1.25} \cdot b^{0.75})^{-1.06}$$

Ahol:

- *T_{forg} - clear cutting time for making a piece, depending on the cutting parameters* *(min)*
- *b- chip width* (mm)
- *h- chip thickness* (mm)
- *v_f- feed rate* (mm/min)

Clear cutting time can be specified for cutting out the cooling channel formula was given in general form:

I gave the equation in the following form:

$$T_1 = \frac{2 \cdot (L_1 - s + B_K - s) + [(B_K - 2s)/[b \cdot (L_1 - s)]}{v_f}$$

Where:

- *T_1: Machining time of a pocket based on the geometric parameters of the pocket*
- *B_K- indicates medium width in the first milling layer (B_1- largest width, B_2- smallest width*
- *L_1: Pocket length*
- *s: the effective diameter of the tool as a function of the axial cutting depth ap*
- *b: radial cutting depth „a_e”*

My publications supporting this thesis: [19][21][23]

The next step in the evaluation was to determine what impact the components (non-divisible to further segments) of the variables describing the milling process may have on cutting tool life. So feed per minute has been corrected to feed per tooth. The such-directed effect of the parameters is shown in Fig. 5:

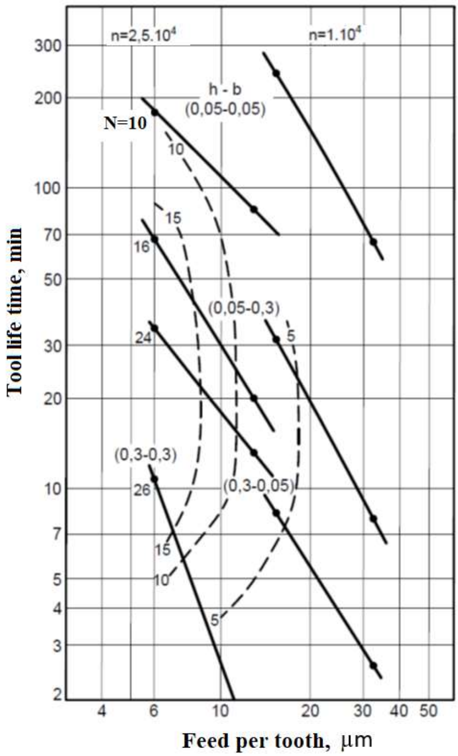

Fig. 5: Curves of tool life as a function of feed per tooth

Two points on a line show the change in effect of two different feeds per tooth for a given axial-radial cutting depth combination. For small cutting depths (0.05–0.05), the decrease in rpm increases the tool life; this behaviour approximately follows the Taylor-equation. For the larger cutting depth combinations, the effect of the rpm is reduced, and for the usable combinations (0.3–0.3 and 0.3–0.05) the effect is negligible (since the lines of action are parallel to each other). The main variable is the value of the feed per tooth. The depth combination number in the denominator ensures the validity of the equation. The results provide the basis of thesis 2.

Thesis 2:

By micro-cutting oxide ceramics material “based on a cycloi tool-path strategy, using a specially edged, TiAlN-coated tool (1 [mm] diameter)”, I determined the correlation describing the tool life in the function of the technological process variables. The range of validity of the correlation: (fz: feed per tooth = 6–30 [µm], n: rpm = 10000–25000 [1/min], ap: axial cutting depth = 0.05–0.3 [mm], ae: radial cutting depth = 0.05–0.3 [mm]), according to which the decisive variable is the feed per tooth.

The effect of rpm varies, but with rationally usable parameters, its effect is negligible. This can be exploited to reduce the amount of feed per tooth.

The tool life in minutes can be given in the following form:

$$T_{él} = \frac{13.1}{(h^{1.25} \cdot b^{0.75})} \cdot f_z^{-1.53} \text{(min)}$$

The relation for the number of pockets that can be made can be given in the following form:

$$N = \frac{T_{él}}{T_{forg}} = \frac{1.58 \cdot v_f \cdot (h^{1.25} \cdot b^{0.75})^{0.06}}{f_z^{1.53}} \text{(db)}$$

Where:

- f_z*: feed per tooth* *(mm/fog)*
- *b- chip width* *(mm)*
- *h- chip thickness* *(mm)*
- v_f*- feed rate* *(mm/min)*

The effect of the speed is not constant, but with rationally usable parameters, its effect is negligible. This can be used to reduce the feed per tooth.

My publications supporting this thesis: [19],[21],[23]

Due to the unconventional tool geometry (large cutting angle, small clearance angle), with the longitudinal wear of the tool the cutting conditions change, too (the surfaces between the edges also start to friction), resulting in a degradation of the clean chip removal process, and an increase in the axial friction force. Friction losses due to wear result in a noticeable reduction in vibration amplitude. The results provide the basis of thesis 3.

Thesis 3:

During the cutting of the studied oxide ceramics material, the wear of the TiAlN-coated spherical cutter tool (1 [mm] diameter) does not follow the regular pattern due to its special (small-sized) design (e.g. small cog cavity, etc.). The range of validity of the results: ***(f_z: feed per tooth = 6–30 [µm], n: rpm = 10000–25000 [1/min], a_p: axial cutting depth = 0.05–0.3 [mm], a_e: radial cutting depth = 0.05–0.3 [mm])***

Due to the large cutting angle and small clearance angle, after a certain degree of wear of the tool the surfaces between the edges also start to friction, resulting in an increase in the feeding force, frictional work, and frictional attenuation.

My publications supporting this thesis: [19],[31]

By measuring the longitudinal wear of the tool, it is possible to determine the extent to which the deviation of the measured pocket from the nominal size at each test point is affected by tool-wear and by path-error caused by cutting forces. The results provide the basis of thesis 4.

Thesis 4:

The *"tested range"* during cutting of oxide ceramics material with a TiAlN-coated spherical cutting tool (1 [mm] diameter) was: *(f_z: feed per tooth = 6–30 [μm], n: rpm = 10000–25000 [1/min], a_p: axial cutting depth = 0.05–0.3 [mm], a_e: radial cutting depth = 0.05–0.3 [mm])*. I found a correlation between tool-wear and the accuracy of the size of the cut pockets.

Accuracy is affected not only by direct wear, but also by path-errors caused by increased feed forces *(in both axial and radial direction)*. I have presented the latter's contribution to the resultant inaccuracy. I ascertained that for all of the path-strategies studied *(waveform, cycloid, chained)*, 90–95% of the reduction in pocket size – both in the "X" and "Y" direction *(pocket width and pocket length, respectively)* – is due to tool deformation. In the "Z" direction *(*pocket *depth)*, 20–30% of the reduction in pocket size is due to tool-wear, whereas 70–80% of the phenomenon is due to deformation caused by feed force.

My publications supporting this thesis: [22], [23], [26]

The average frequency for each pocket produced was determined by testing the vibrations generated during chipping. This frequency variation coincides with the variation in the volume of the pockets with high accuracy, as shown in the 6-8 figures.

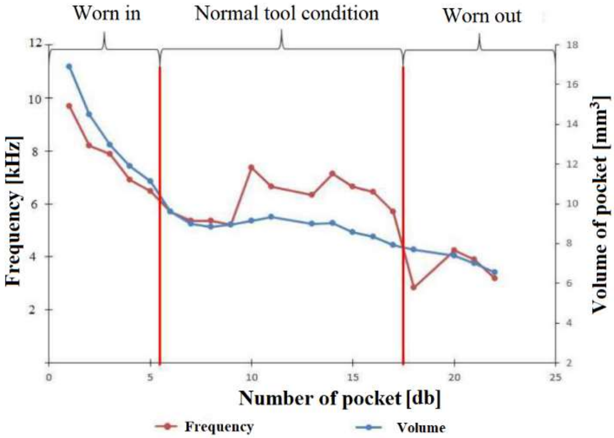

Fig. 6: Volume change of pockets and evaluation of the statistical function obtained with the Adaptive Hybrid Feature Selection method for waveform tool path

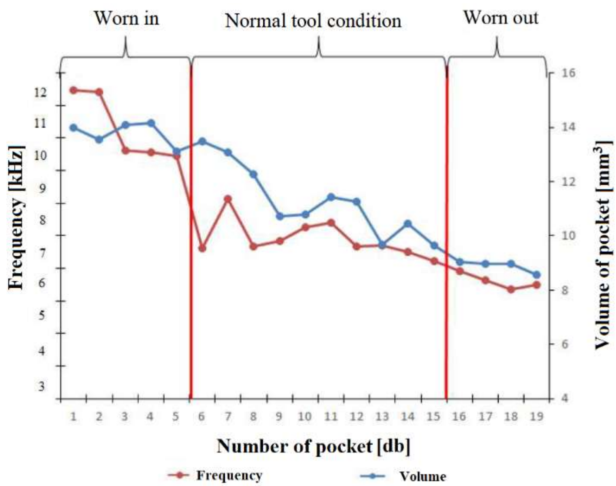

Fig. 7: Volume change of pockets and evaluation of the statistical function obtained with the Adaptive Hybrid Feature Selection method for a cycloid toolpath

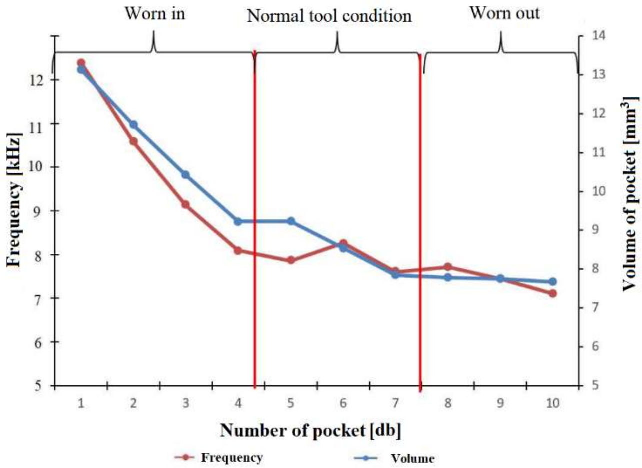

Fig. 8: Volume change of pockets and evaluation of the statistical function obtained with the Adaptive Hybrid Feature Selection method for a chained toolpath

The new scientific results related to the manufactured geometric size change and vibration change were summarized in the 5th thesis.

Thesis 5:

The *"tested range"* during cutting of oxide ceramics material with a TiAlN-coated spherical cutter tool (1 [mm] diameter) was: *(f_z: feed per tooth = 6–30 [µm], n: rpm = 10000–25000 [1/min], a_p: axial cutting depth = 0.05–0.3 [mm], a_e: radial cutting depth = 0.05–0.3 [mm])*. I have defined standard frequency characteristics for monitoring tool-wear in practice. I ascertained that the standard functions for different cutting path strategies *(waveform, cycloid, chained)* are similar, and therefore they can be transformed into each other as a function of the number of producible pockets. This means that each stages of the wearing process are similar to each other, regardless of the path strategy.

My publications supporting this thesis: [25], [27], [28], [29]

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