Gradus Vol 9, No 1 (2022)
ISSN 2064-8014

VIBRATION BASED CHARACTERIZATION OF TOOL WEARING IN MICRO-MILLING OF CERAMICS DURING WAVEFORM TOOLPATH

László Móricz[1,2] *Zsolt János Viharos*[3,4]

[1] University of Pannonia, Faculty of Engineering, Mechatronic Education and Research Institute, Zalaegerszeg, Hungary, moricz1888@gmail.com
[2] Zalaegerszeg Center of Vocational Training, ZSZC Ganz Ábrahám Technical School
[3] Institute for Computer Science and Control (SZTAKI), Centre of Excellence in Production Informatics and Control, Center of Excellence of the Hungarian Academy of Sciences (HAS), Eötvös Loránd Research Network (ELKH), Budapest, Hungary, viharos.zsolt@sztaki.hu
[4] John von Neumann University, Kecskemét, Hungary

https://doi.org/10.47833/2022.1.ENG.003

Keywords:
Ceramics machining, Rake face wearing, Vibration analysis, Feature selection, Waveform tool path

Article history:

Received	30 November 2021
Revised	10 February 2022
Accepted	20 February 2022

Abstract

The main aim of the paper is to monitor the micro- milling tool wearing process offline, by a microscopic tool measurement on one hand, and using high-frequency vibration measurement online, during the cutting process, on the other. Relations between the rake face wear stages and the measured online and offline parameters were determined applying an own-developed, artificial neural network based feature selection solution. As the main result, the experiment-based research appoints that the measured vibration variable component(s) which characterizes the key, three tool wearing phases, in the same way as the real rake face wearing stages occur, applying the waveform tool path

1 Introduction

Machining of rigid materials with regular cutting edge geometry is one of the main technology 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, 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, however, considering the relative quick wearing process of the cutting tool, this methodology is economically acceptable only by applying an appropriate technological optimisation.

The main aim of the paper is to monitor the micro-milling tool wearing process offline, by a microscopic tool measurement on one hand, and using high-frequency vibration measurement online, during the cutting process, on the other. Three tool path strategies were applied in the experiments (cycloid, chained and waveform), the current paper reports the experimental results using the waveform strategy.

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

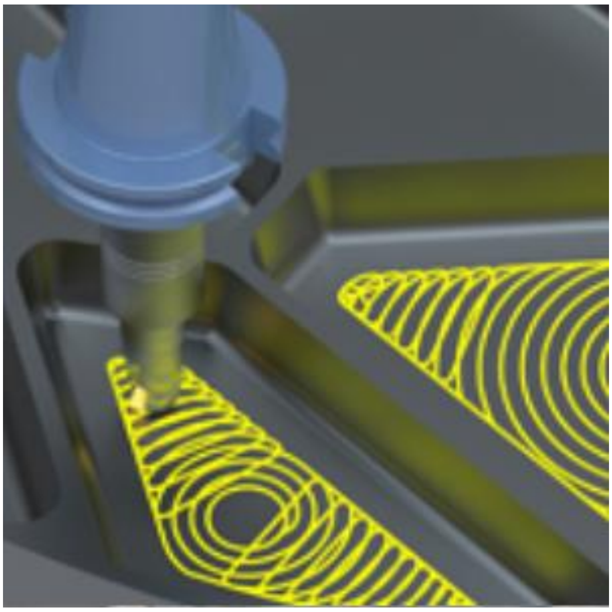

Figure 1: Element of the waveform path [6]

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 [7][8].

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.

The effect of having smaller radial cutting forces increases the stability of the cut, i.e., there is a substantial decrease in the force for pushing the tool to the workpiece and the vibration level decreases as well. While increasing the cutting speed and reducing chip thickness, the heat generated at the cutting point is reduced, so it is possible to increase the cutting depth further. These positively changed milling conditions ensure that the tool and the machine are more wear-resistant, exhibiting a much longer service life, and the machining process thus becomes very effective and desirable in many new applications [9][10][11]. This technology can be applied to produce deep grooves, pockets or high workpiece sides, with high process reliability and long tool life [12][13][14].

In the previous paper of the authors, the process of tool wearing was investigated by direct and indirect methods in relation to the different CAM (Computer Aided Manufacturing) toolpaths [15][16][18]. These research results concluded that the nature of the volume change of the manufactured pockets can be accurately traced by an "engineering feature" (basic measures calculated on the basis of the measured raw signal values, having engineering meaning) calculated on the basis of the workpiece connected vibration measurement series:

$$\sum \left(sgn(x(i) - \bar{x}) \neq sgn(x(i+1) - \bar{x}) \right) \tag{1}$$

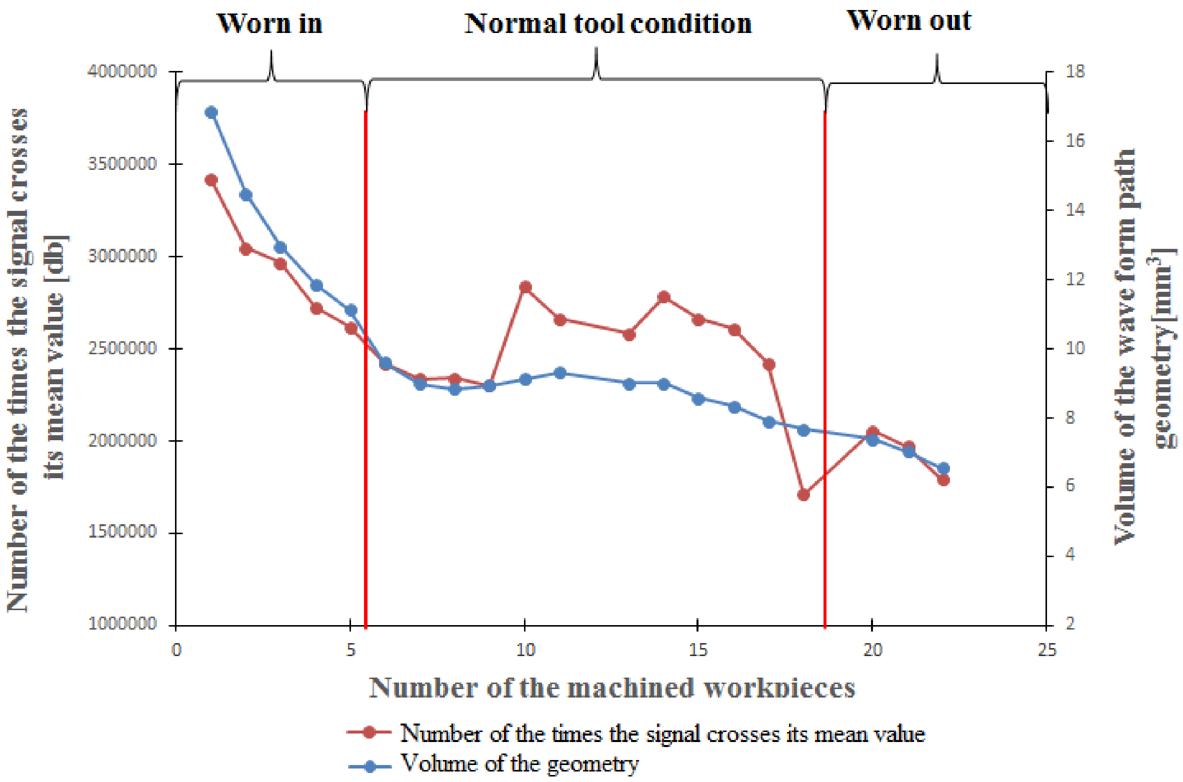

Figure 2: Applying the waveform toolpath, the similar behaviour between the measured vibration signal based, selected engineering feature and the change in the micro-milling tool wear described by the changes in the volume of the machined pockets [16]

Figure 2 shows the almost identical change in the micro-milling tool wear described by the changes in the volume of the machined pockets and the vibration based, calculated variable appointed by the feature selection method [17]. Based on the graph, one can recognize that the two diagrams behave almost identical, consequently, the actual status of the tool lifetime can be well monitored with vibration-based diagnostics method in micro-milling of ceramics. After sufficient number of measurements and experiments, the tool monitoring can be automatized during ceramics micro-milling, and finally, the system could be optimized.

The aims of the paper are – continuing a previous research of the authors [16] – to concentrate only on one kind of diagnostics of rake face wearing of the micro-milling tool angles in machining of ceramics and to determine the relationships between the related cutting vibration and the rake face wear of the tool. Finally, the two rake faces can be diagnosed separately and individually.

2 Design of the experiments

The machined ceramics is a multilayer oxide ceramics coating. The machined pockets were made in ceramic coating. During the geometric evaluation of the pockets were measured: length, width, depth of the machined geometries.

Micro-milling tools were applied for the cutting experiments on ceramics (Figure 3). Such tools, which have zero or negative rake angles, should be chosen for cutting the given kind of brittle materials. The TiAlN coated ball end milling tool cutting tool has 1 [mm] diameter. The milling tool had 2 cutting edges. The applied technology parameters are summarized in Table 1.

Table1. Applied technological parameters

Axial cutting depth [μm]	*Radial cutting depth [μm]*	*Feed rate [mm/min]*	*Cutting speed [m/min]*
30	30	300	78,5

Because of the micron cutting depth and the small tool diameter, it is important to check whether the parameter set used belongs to the class of micromachining. There are many definitions of this in the literature, but in general we are talking about micro-machining when the milling tool diameter is less than 1 [mm] or the cutting structure is less than 1 [mm] [19] that were satisfied in the given experiments.

The vibration signals were recorded using a piezoelectric accelerometer. The vibration measurement of ceramics milling was established with a sampling frequency of 100 kHz in one direction.

3 Rake face wear of the cutting tool

The tool was applied until its breakage, this cycle of measurements covered the entire tool lifetime resulting in various identified phenomena. Measurements were performed using Zeiss Discovery V8 microscope and based on the taken pictures the authors evaluated the wearing.
Asymmetrical wear of the cutting edges was observed during tool lifetime. This phenomenon was also observed in the previous research of the authors, too, where also the waveform strategy was investigated in cutting of ceramics material [10].

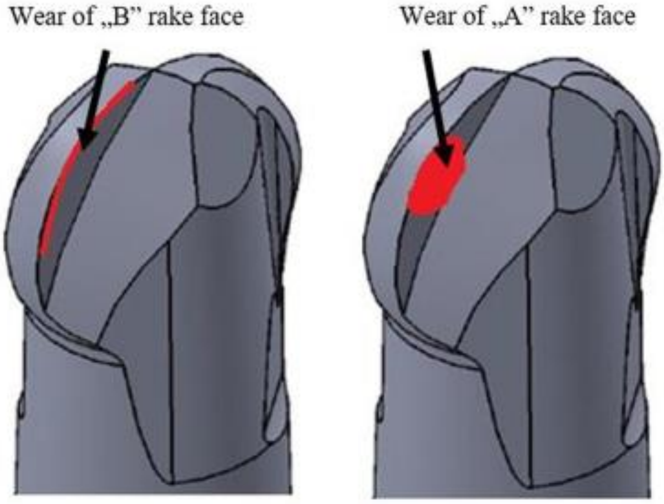

Figure 3: Micro-milling tool geometry in 3D view and the most important wearing places at the early tool life period. The „A" rake face began to wear on bigger surface, but on a smaller cutting edge length. The „B" rake face began to wear and pitting along the longer cutting edge length, but on a relative smaller surface

During the experiments, it was not possible to take microscopic photos after every machining, thus, these were taken after every 5th pocket. Based on these measurements, the different rake face stages of the micro ball mill can be determined, as at the first checkpoint in Figure 4. It was observed that while one of the rake faces began to wear along the cutting edge, the other one showed extensive surface wear. Up to the 3rd checkpoint, this difference was continuous, but the extent of the difference decreased. At the 4th checkpoint the tool edges have become equally unusable.

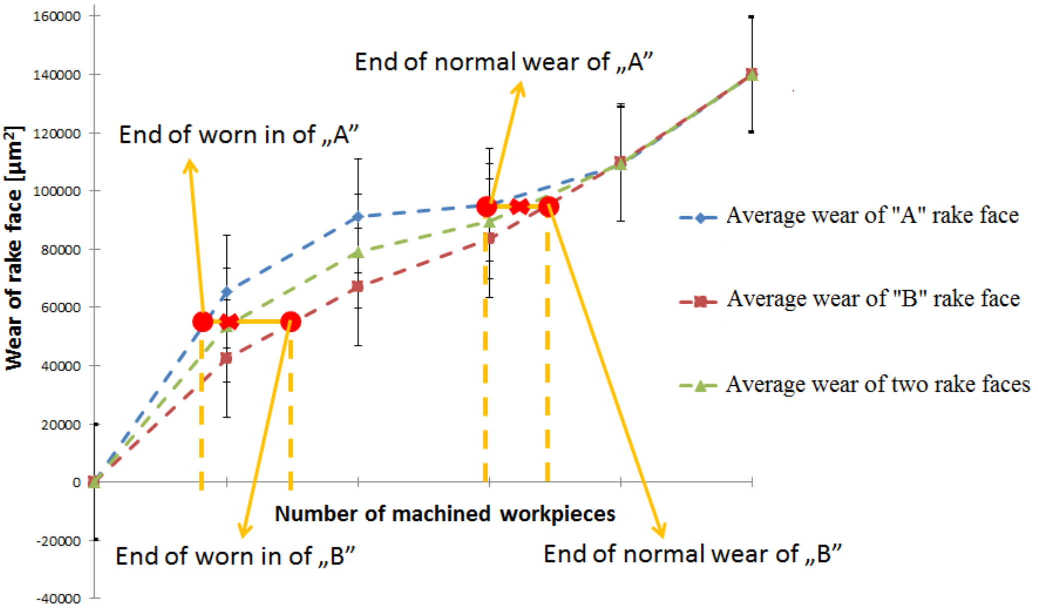

Figure 4: Different behaviour of "A" and "B" wear of rake faces during waveform toolpath micro-milling of ceramics

After determining the wear curves, it was necessary to find the boundary points where the worn-in and the linear wear stages of the cutting edges ended (followed by the and worn-out stage until the break) as specified by the Taylor curve. When determining the threshold values, the volume change of the pockets and the material chipping of the edges of the pockets were also taken into account. Having defined these thresholds, the rake face wear stages can be differentiated for each machining along the entire tool lifetime, Consequently, the individual micro-cutting machining were ordered to these three, different classes (worn-in, normal, wear-out). After these classes and their machining members have been defined, the next step was to apply the feature selection method (FS) developed by some of the authors [17]. It was applied to find the most descriptive statistical/engineering features for distinguishing the three different stages of the tool life. Additionally, the frequency values of the vibration signal where also analysed to separate the classes of the Taylor curve from each other (as feature selection in frequency domain).

4 Vibration diagnostics using feature selection method

The "A" and "B" rake faces mirror different wearing progress, consequently, they are analysed separately.

4.1 Analysis of "Engineering Feature" for the "A" Rake Face

Analysing the „A" rake face (Figure 5), as result, the algorithm identified that the standard deviation of the vibration signal calculated at each workpiece can differentiate the three stages of the rake face tool wear, even if the individual measurements represent non-linearity.

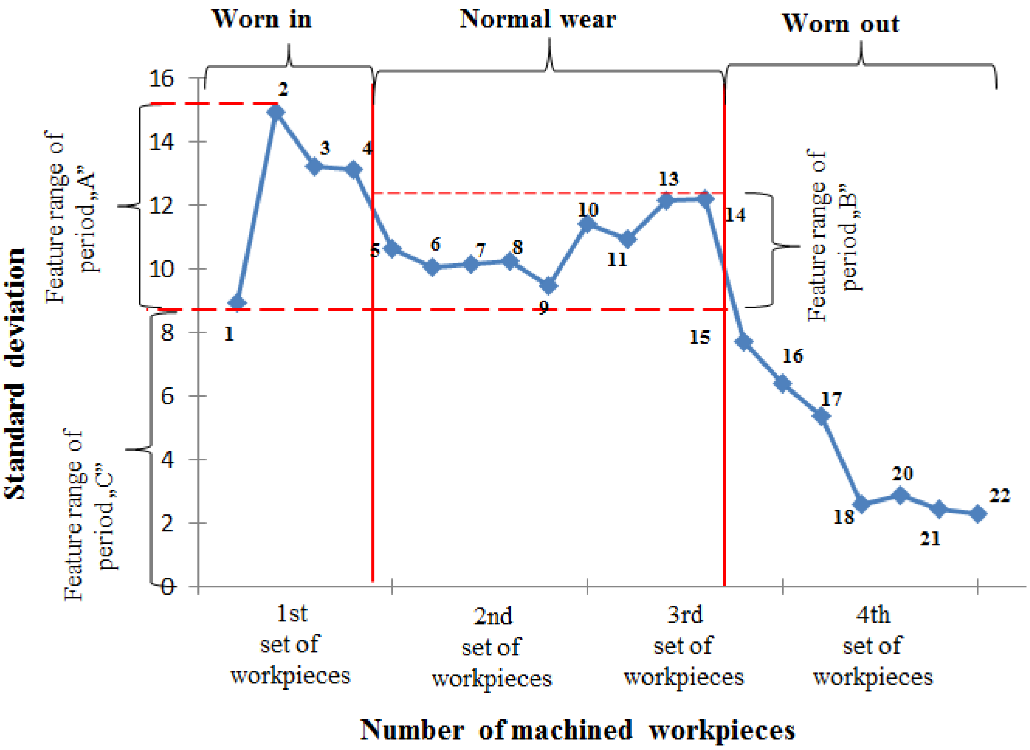

Figure 5: Mean values as a function of the manufactured workpieces by analysing the "A" rake face

Based on the Taylor curves, the worn in phase of "A" rake face ends at 4th pocket, while the normal wear range ends at 14th pocket.

4.2 Analysis of "Engineering Feature" for the "B" Rake Face

Analysing the „B" rake face, as result, the FS algorithm identified that the standard deviation calculated at each workpiece can differentiate the three stages of the tool wear. The "B" rake face enters in the normal wear range at the 9th pocket where a breaking point is observed. The cutting tool enters the worn-out range at the 18th pocket, where another jump is observed at the data set values, like at the "A" rake face represented in Figure 5. Figure 6 and 7 mirror that vibration frequencies where the separation of the worn-in, normal and wear-out stages are on the highest level.

4.3 Analysis of Frequency Feature for the "A" Rake Face

The use of above described statistical/engineering feature-based selection can be extended to monitor the wear of a complex tool angle system.

Thus, the previously applied method was extended by the frequency feature selection (FFS) method. Using FFS, the characteristic frequencies of the signal can be determined in which the rake face wear stages change.

According to FFS calculations, the separation of the wear ranges at the "A" rake face occurs around 6727 Hz. The results, as separated frequency domain amplitude curves, are shown in Figure 6.

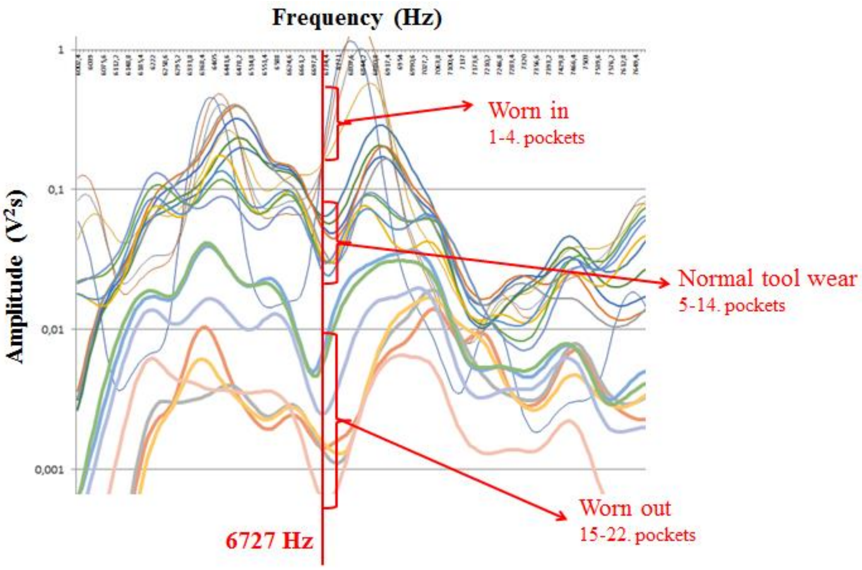

Figure 6: Separation of the sharp (thin curves), normal (middle sized curves) and worn (thick curves) tool at 6727 Hz by analysing the "A" rake face.

Based on Figure 6, the tool life stages are well separable. Furthermore, as the tool wear increases, the amplitude decreases. This is probably due to the continuous decrease in the contact area between the tool and the workpiece. This phenomenon was also observed in the vibration data measured during the application of the trochoidal toolpath [18].

4.4 Analysis of Frequency Feature for the "B" Rake Face

In the case of "B" rake face, the separation of the three stages of the Taylor curve is observed around 44 847 Hz (Figure 7) as separated frequency domain amplitude curves.

At the "B" rake face, the values of the amplitudes in the worn-in range are high and waving (Figure 8), in the normal wear range the values suddenly fall, and then fall further in the worn-out range.

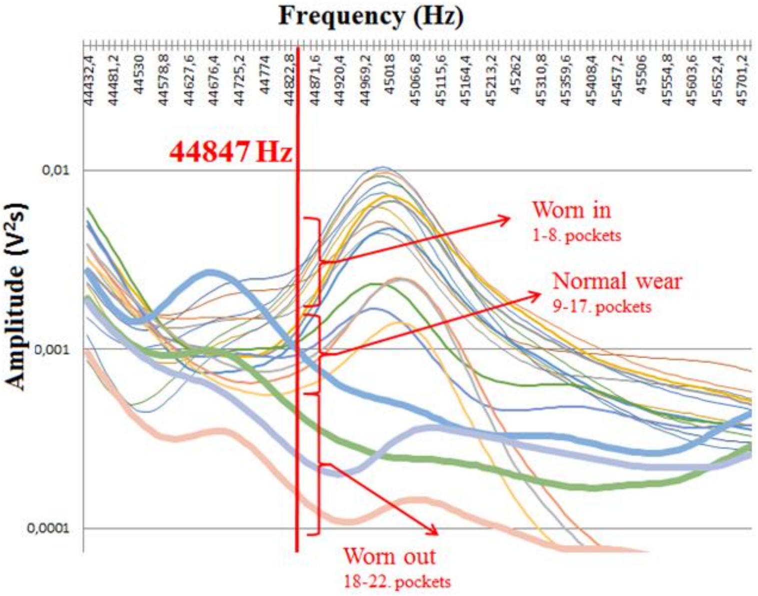

Figure 7: Separation of the sharp (thin curves), normal (middle sized curves) and worn (thick curves) tool at 44.847 kHz by analysing the "B" rake face.

The experiments mirrored asymmetric wearing of the "A" and "B" rake faces that is represented in the frequency analysis in Figure 6 and 7 because the most characteristic separations are on really different vibration levels.

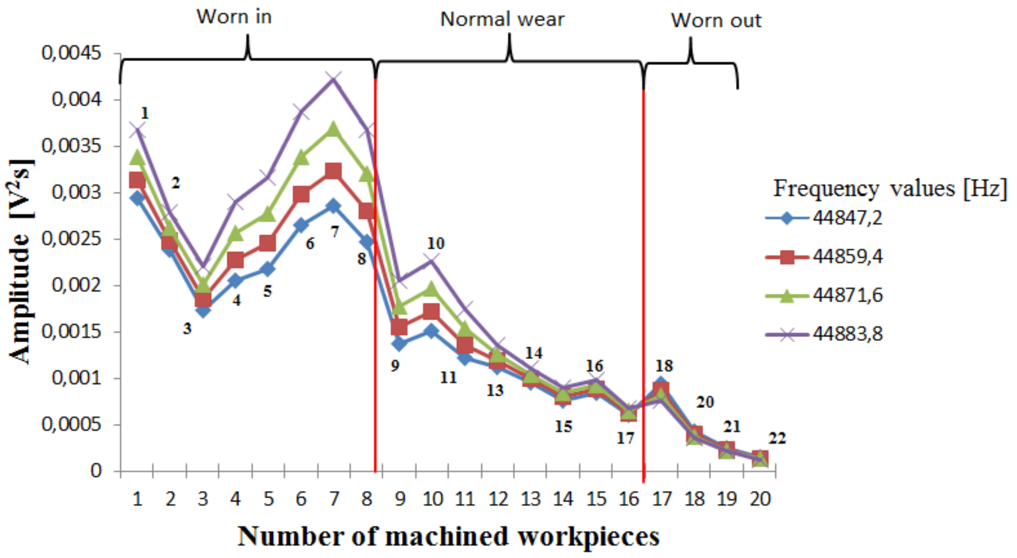

Figure 8: Amplitude value change in relation to the tool wear stages at 44.847 kHz by analysing the "B" rake face. The tool wearing stages were determined according to the preliminary tool microscopic measurements and separation as highlighted in Figure 4.

5 Conclusion

The preliminary research results of the authors [7][15][18] mirrored that the wear of the micro-milling tool in machining ceramics can be well monitored by considering the volume of the formed pockets.

The purpose was to find a relationship between the wear of cutting-edge angles and the vibrations signals.

During the tests, it was found that the cutting edges and the tool faces show asymmetric wear when using a waveform toolpath.

Examining the statistical/engineering vibration signal features resulted that the change in the mean values and the number of the times the signal crosses the mean value of the measured signal successfully describes the complex wearing course for each cutting edges. Additionally, analysing the signal vibration in the frequency domain resulted that the amplitudes at 6.7 and 44.84 kHz represents the complete separation of the worn-in, normal and wear out stages of the "A" and "B" rake faces, respectively. Finally, the two rake faces can be diagnosed separately and individually.

All these results represent the really complex and diverse tool wearing behaviour of micro-milling tools, considering the different cutting edges.

Acknowledgment

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 digitalization" (https://inext.science/).

References

[1] Peter, J.: Modern gas turbine systems, High Efficiency, Low Emission, Fuel Flexible Power Generation, Woodhead Publishing Series in Energy, 2013, Vol. 20, pp. 8-38., ISBN: 9781845697280

[2] Móricz, L; Viharos, Zs. J.: Trends on applications and feature improvements of ceramics, Manufacturing 2015 Conference, Budapest University of Technology and Economics, Vol. 15, No., 2, 2015, pp. 93-98

[3] Xian, W.; Kai, Z.; Li, Z.; Shen, J.; Li, L.: Hybrid micro-milling assisted with laser oxidation based on the hardness reduction that caused by cemented carbide oxidation, Ceramics International, 2021, Available online, DOI: https://doi.org/10.1016/j.ceramint.2021.09.057

[4] Zeng, J.; Thomas Kim, J.: An erosion model for abrasive waterjet milling of polycrystalline ceramics, Wear, Vol. 199, Issue 2, 1996, pp. 275-282, DOI: https://doi.org/10.1016/0043-1648(95)06721-3

[5] Xia, H.; Zhao, G.; Mao, P.; Hao, X.; Li, L.; He, N.: Improved machinability of TiB2–TiC ceramic composites via laser-induced oxidation assisted micro-milling, Ceramics International, Vol. 47, Issue 8, 2021, 11514-11525, DOI: https://doi.org/10.1016/j.ceramint.2020.12.280

[6] Hexagon Manufacturing Intelligence, https://www.edgecam.com/edgecam-waveform, 2021

[7] Móricz, L.; Viharos, Zs. J.; Németh, A.; Szépligeti, A.: Efficient Ceramics Manufacturing through Tool Path and Machining Parameter Optimisation, 15th IMEKO TC10 Workshop on Technical Diagnostics, Budapest, Hungary, June 6-7., 2017, pp. 143-148.

[8] Shao, W.; Li, Y.; Liu, C.; Hao, X.: Tool path generation method for five-axis flank milling of corner by considering dynamic characteristics of machine tool, Elsevier, Intelligent Manufacturing in the Knowledge Economy, 9., 2016, pp. 155-160. DOI: https://doi.org/10.1016/j.procir.2016.10.046

[9] Šajgalík, M.; Kušnerová, M.; Harni, M.; Valí, J.; Czán, A.; Czánová, T.; Drbúl, M.; Borzan, M.; Kmec, J.: Analysis and Prediction of the Machining Force Depending on the Parameters of Trochoidal Milling of Hardened Steel, Applied Sciences, Vol. 10, No. 5, 2020, paper ID: 1788, DOI: https://doi.org/10.3390/app10051788

[10] Santhakumar, J.; Mohammed Iqbal, U.: Parametric Optimization of Trochoidal Step on Surface Roughness and Dish Angle in End Milling of AISID3 Steel Using Precise Measurements, Materials, Vol. 12, 2019, paper ID: 1335, DOI: https://doi.org/10.3390/ma12081335

[11] Amaro, P.; Ferreira, P.; Simoes, F.: Tool wear analysis during duplex stainless steel trochoidal milling, AIP Conf. Proc. 2018, 1960, paper ID: 070001

[12] Xu, K.; Wu, B.; Li, Z.; Tang, K.: Time-E_cient Trochoidal Tool Path Generation for Milling Arbitrary Curved Slots, J. Manuf. Sci. Eng., Vol. 141., Nr. 3., 2019, paper ID: 031008, https://doi.org/10.1115/1.4042052

[13] Pleta, A.; Ulutan, D.; Mears, L.: Investigation of Trochoidal Milling in Nickel-Based Superalloy Inconel 738 and Comparison with End Milling, In ASME 2014 International Manufacturing Science and Engineering Conference Collocated with the JSME 2014, Proceedings of the International Conference on Materials and Processing and the 42nd North American Manufacturing Research Conference, Detroit, MI, USA, 9–13 June 2014; American Society of Mechanical Engineers: New York, NY, USA, Vol. 2, paper ID: MSEC2014-4151, V002T02A058, 2014., DOI: https://doi.org/10.1115/MSEC2014-4151

[14] Bettine, F.; Ameddah, H.; Manna, H. R.: A Neural Network Approach for Predicting Kinematic Errors Solutions for Trochoidal Machining in the Matsuura MX-330 Five-Axis Machine, FME Trans. 2018, Vol. 46, 2018, pp. 453–462, DOI: https://doi.org/10.5937/fmet1804453B

[15] Móricz, L.; Viharos, Zs. J.; Németh, A.; Szépligeti, A.; Büki, M.: Off-line geometrical and microscopic & on-line vibration based cutting tool wear analysis for micro-milling of ceramics, Measurement, Vol. 163., 2020, paper ID: 108025, https://doi.org/10.1016/j.measurement.2020.108025

[16] Móricz, L.; Viharos, Zs. J.; Büki, M.: Effect of CAM Path Strategies on Tool Life in Ceramics Micro-Cutting, 17th IMEKO TC 10 and EUROLAB Virtual Conference: “Global Trends in Testing, Diagnostics & Inspection for 2030”, October 20-22., 2020., ISBN: 978-92-990084-6-1, 2020, pp. 92-98.

[17] Viharos, Zs. J.; Kis, K. B.; Fodor, Á.; Büki, M.: Adaptive, Hybrid Feature Selection (AHFS), Pattern Recognition, Vol. 116., 2021, Paper ID: 107932, https://doi.org/10.1016/j.patcog.2021.107932

[18] Móricz, L.; Viharos, Zs. J.: Vibration based characterization of tool wearing in micro-milling of ceramics, Measurement: Sensors, 18, December 2021, Paper ID: 100174, https://doi.org/10.1016/j.measen.2021.100174

[19] M. J. Vasile, C. R. Friedrich, B. Kikkeri és R. Elhannon, „Micrometerscale Machining: Tool fabrication and Initial results,” Precision Engineering, 1996 No 19, pp. 180-186, https://doi.org/10.1016/S0141-6359(96)00024-4