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micro-milling, impact test, vibration

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CHATTER STABILITY INVESTIGATION IN MICRO-MILLING

The paper presents investigation under chatter stability in micromilling process. To determine the impact of micromilling machine dynamic properties, impulse test of micromilling tool was carried out. Due to high participation of ploughing in micromilling process the regenerative effect in comparison to conventional milling can be reduced or lead to frictional vibration. Series of cutting tests for variable cutting speed, feed per tooth and cutting depth were performed to verify these assumptions. During the tests cutting forces and accelerations, both on machine spindle and workpiece were measured. Performed milling tests show that the vibration occurs at highest depth of cut and at lowest feed rate. This leads to the conclusion that reason of vibration could be friction between tool and workpiece.

1. INTRODUCTION

Vibration occurring in milling and micro-milling process could have impact on the surface quality. Investigation under this phenomena in macro scale was first introduced by Altintas [1] and then made by many other researchers. Model proposed by Altintas is versatile and can be applied in most cases of peripheral milling. Many researchers also made attempts of explaining vibration phenomena in micro-scale milling [2],[3],[4]. However due to ploughing and elastic recovery versatile model of micro-milling dynamics was not created.

Another aspect that is significant in micro-milling process dynamics research is obtaining frequency response function on the tool tip. FRF must be known in order to find the stability lobes of the milling process. Due to very small tool tip dimensions excitation cannot be applied with impulse force hammer directly on the tool tip. In the paper usage of modal synthesis for finding frequency response function on tool tip is proposed.

Milling experiment including dynamics of micro-milling machine was conducted in order to verify the stability lobes in micro-milling process. The experiment also can show if there is a need of creating the new model of finding stable cutting parameters for micro-milling.

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2. IMPACT TEST

Frequency response function can be obtained in many methods. Most common is applying impulse force at tool tip and simultaneous measurement of its displacement. Due to very small tool tip dimensions excitation force cannot be applied directly at micro-milling tool tip. One of the solutions of this problem is synthesis of spindle experimental frequency response function and tool analytical frequency response function with receptance coupling [5],[6].

Approach used in the experiment is also indirect due to very small tool tip dimensions, however only tool excitation cannot be applied at tool tip. Tool response is measured directly at the tool tip with laser vibrometer [7]. This method, based only on experimental data gives better results than synthesis of experimental and analytical data.

Impact test was performed on prototype micro-milling machine which was built Mechatronics Centre of West Pomeranian University of Technology. The milling machine is part of major diagnostic system [8],[9],[10]. *LMS SCADAS III* data acquisition device was used for signals registration. Impulse force hammer *PCB 086E80* was used for tool excitation (Fig. 1a). Tool response was measured with *Polytec PSV-400* Scanning Vibrometer. *LMS TestLab* was used for signal processing and modal synthesis. Tool mounted in micro-milling machine spindle was *Kyocera 2FESM010-025-04* (diameter 1mm).

Due to very small tool tip dimensions excitation cannot be applied directly at tool tip (point 7). Therefore excitation was applied to point 5 of the tool. This point was chosen because it is closest to the tool tip. Tool displacement was measured in points 1-7 (Fig. 1b).

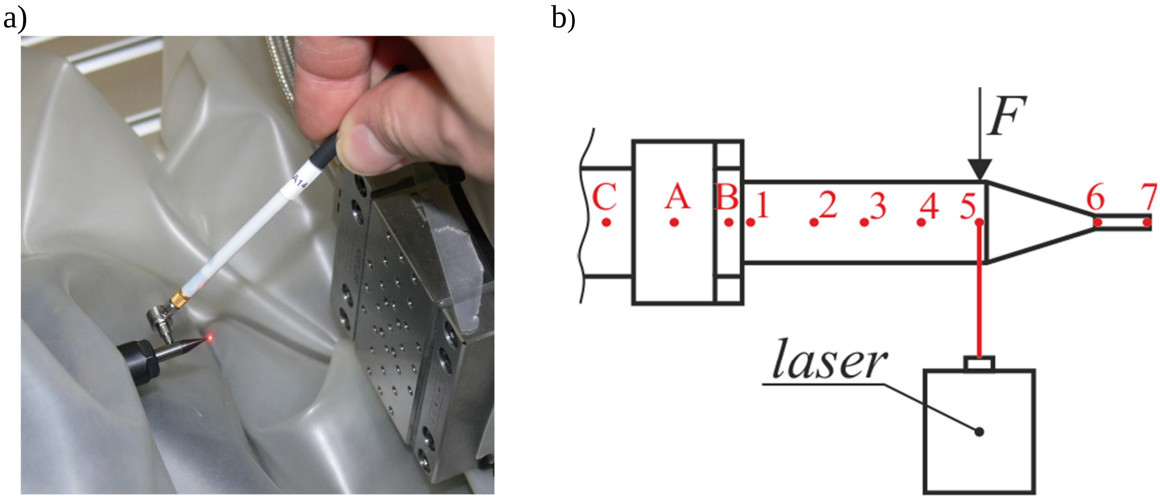


Fig. 1. Tool impact test: a) view of impulse force hammer and tool, b) scheme of measurement points

Modal analysis with LMS PolyMAX algorithm is used for finding the most important vibration modes of the micro-milling tool mounted in the machine spindle. Four vibration modes (Table 1) both in X and Y direction were found.

Table 1. Modal parameters of vibration modes

X		Y	
frequency	**damping**	**frequency**	**damping**
2078	4.12%	2352	6.21%
2737	3.24%	2693	6.24%
4807	2.47%	4776	2.19%
10971	1.32%	11086	1.66%

Modal synthesis of vibration modes shown in tab 1. was used for calculating frequency response function on tool tip (point 7). Frequency response function was calculated with LMS test.lab software. Frequency response function of tool tip for both directions are presented on Fig. 2. These frequency response functions are used for creating stability lobes diagram.

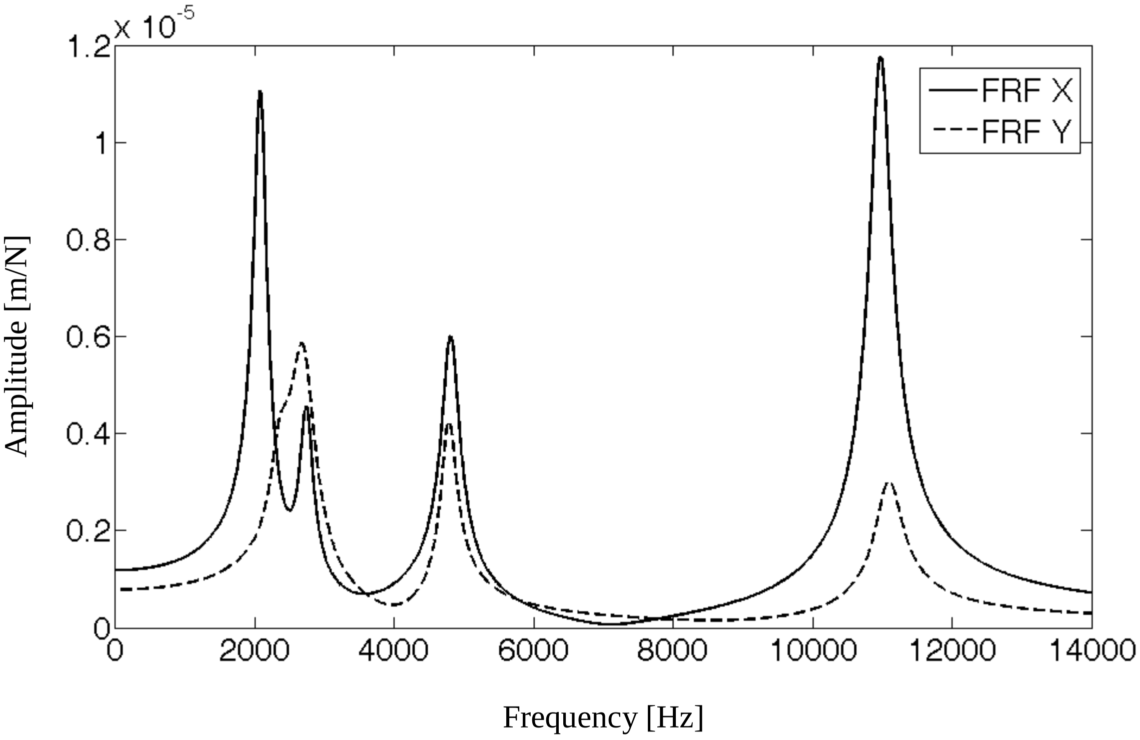


Fig. 2. Synthesized tool tip frequency response functions in X and Y directions

3. STABILITY LOBES

Stability lobes were generated with classic cutting forces model including the regenerative effect [1]. Identified cutting forces coefficients for aluminum alloy are $k_c=6300N/mm^2$ and $k_t=5800N/mm^2$. Stability lobes for aluminum alloy are shown on Fig. 3.

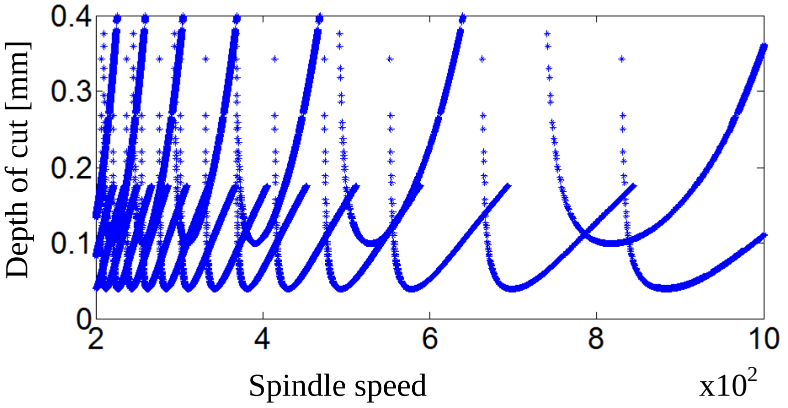


Fig. 3. Stability lobe diagram for aluminum alloy

Identified cutting forces coefficients for C45 steel alloy are k_c=3500N/mm^2 and k_t=3200N/mm^2. Stability lobes for C45 steel are shown on Fig. 4.

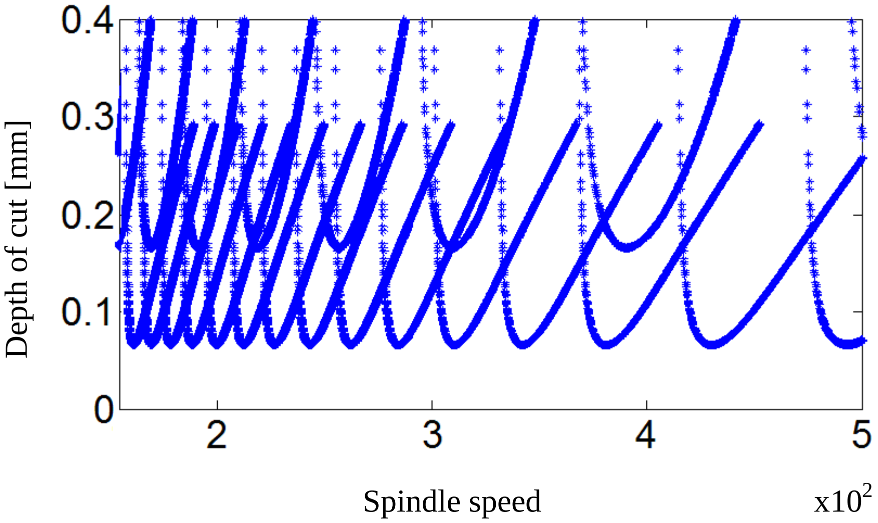


Fig. 4. Stability lobe diagram for C45 steel

Due to a lot of ploughing in micro-milling process, especially when milling elastic material like aluminum alloy, cutting forces coefficients are higher for lower feed rates and for elastic materials.

4. MILLING EXPERIMENT

Milling experiments were performed on experimental micro-milling machine. The machine was equipped with three-axial *Kistler 9256C1* dynamometer. Three axial accelerometer *PCB piezotronics* 356A01 was mounted near machine spindle (Fig. 5a). Three one axial *PCB piezotronics 352B10* accelerometers were mounted both on spindle and workpiece (Fig. 5a, 5b).

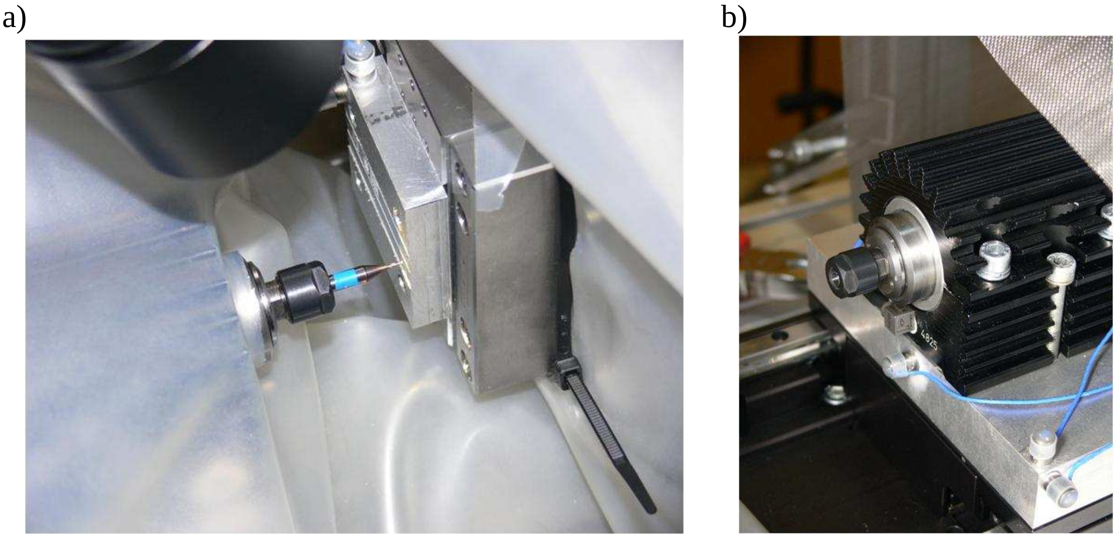

a) b)

Fig. 5. Micro-milling machine: a) workpiece and accelerometers attached to the workpiece, b) machine spindle and accelerometers attached to the spindle

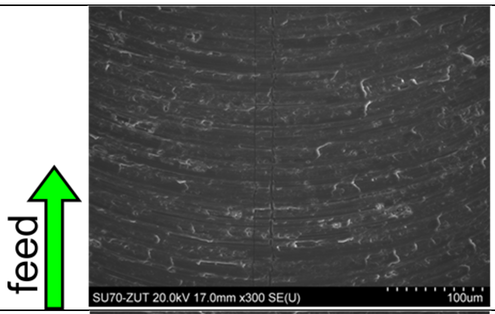
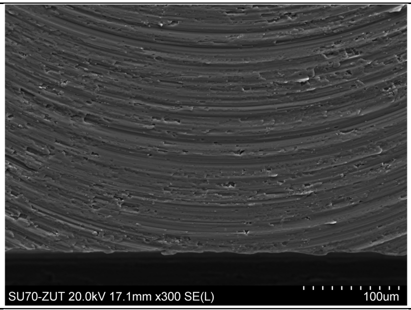
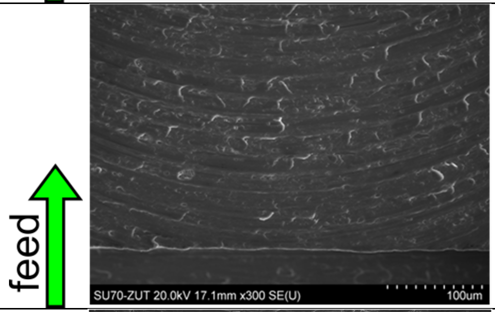
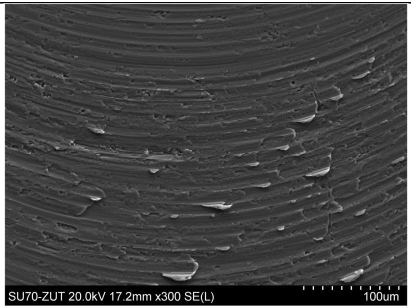
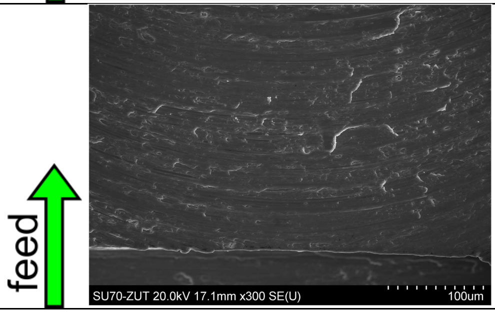
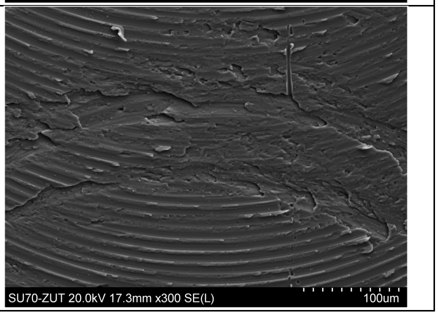
Cutting experiment was performed for aluminum alloy and C45 steel. *Kyocera 2FESM010-025-04* (diameter 1 mm) tool was used for aluminum alloy and C45 steel milling. For both materials wide range of cutting parameters was used in case to obtain vibration.

Aluminum alloy:
- rotational speed: 70 000, 80 000, 90 000RPM, (v_c=220, 251,282m/min)
- feed: 12, 10, 8, 6μm/tooth,
- depth of cut: 20, 40, 60μm.

C45 steel:
- rotational speed: 15 000, 30 000, 45 000RPM, (v_c=47, 94, 141m/min)
- feed: 10, 7, 4, 2μm/tooth,
- depth of cut: 10, 25, 40μm.

All combinations of above parameters were used during experiment: 36 runs were made for both aluminum alloy and C45 steel. High rotational speeds were used to avoid process damping, which could occur for cutting speed less than 47m/min. [11]. Wide range of feed and depth of cut were used to increase possibility of vibration during experiment. SEM photographs of milled aluminum surfaces are shown in Table 2. There can be seen extractions in the workpiece material and traces of smearing. Quality of the surface decreases when depth of cut increases. For all cutting parameters there can be seen elastic recovery impact on surfaces. When elastic recovery occurs trace can be left not only by leading blade that mainly removes material from workpiece and forms chip, but it can be also left by returning blade that should not mill. Traces left by tool teeth without and with elastic recovery phenomena are shown in Fig. 6.

Table 2. SEM photographs of surfaces *machined at 60 000* RPM for aluminum alloy

ap [μm]	10μm/tooth	6μm/tooth
20		
40		
60		

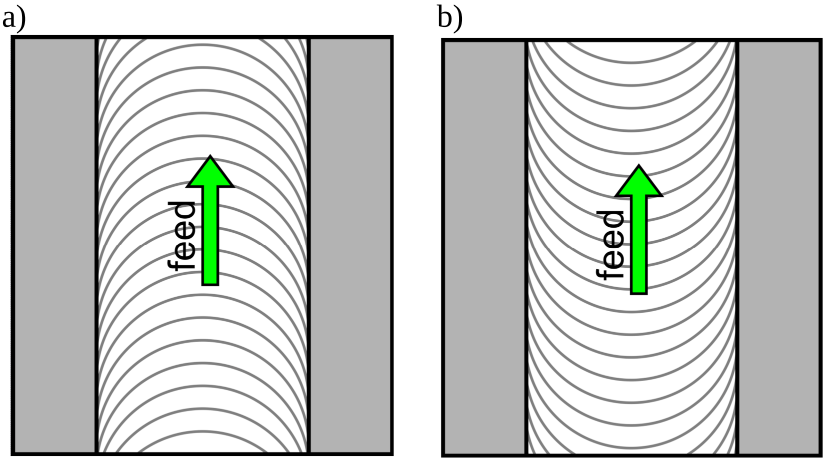


Fig. 6. Traces in milling left by tool teeth: a) without elastic recovery, b) with elastic recovery

Profiles of surfaces from Table 2. are shown on Fig. 7. There can be seen similarity between surfaces photographs and their profiles.

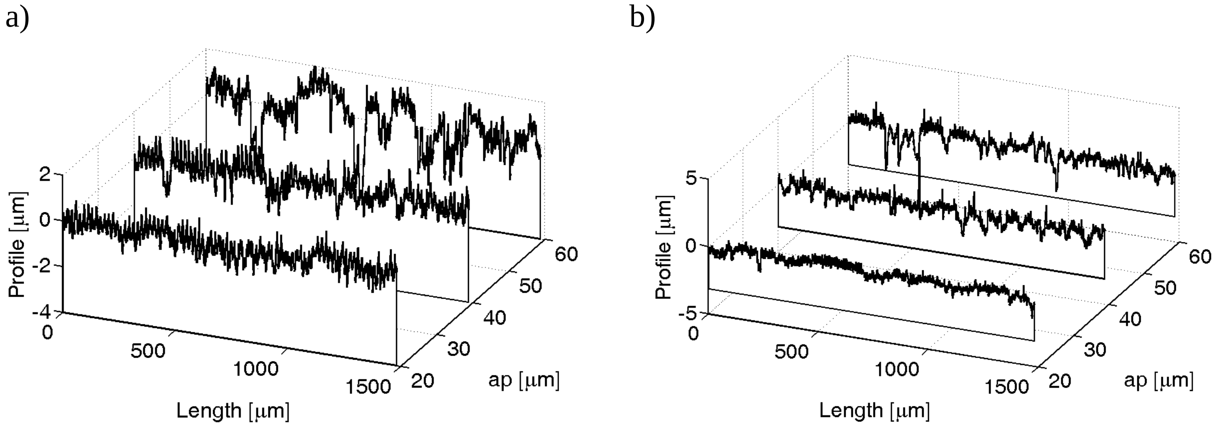
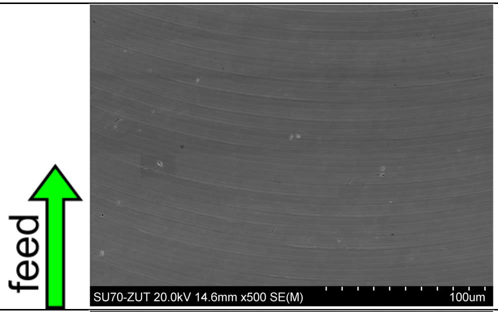
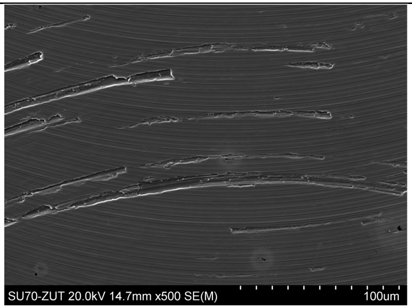
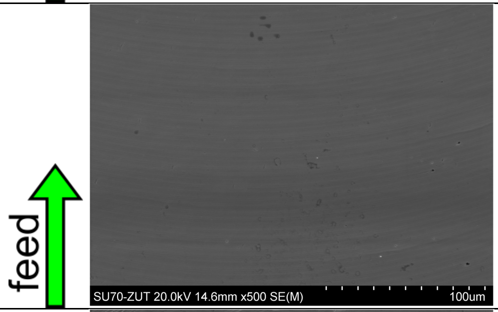
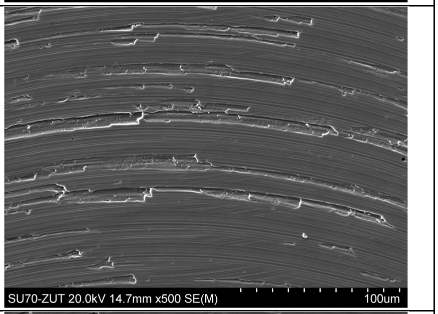
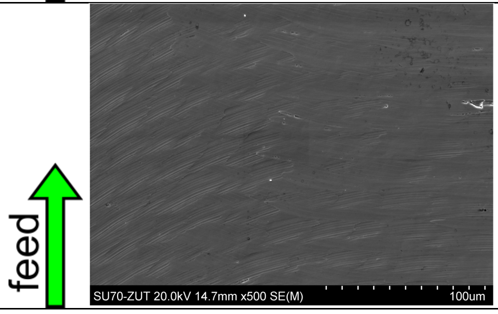
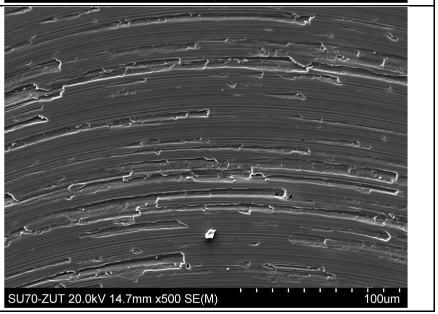


Fig. 7. Aluminum surfaces profiles for variable depth of cut (ap) at: a) feed 10µm/tooth, 60 000RPM, b)feed 6µm/tooth, 60 000 RPM

Table 3. SEM photographs of surfaces machined at 30 000 RPM for C45 steel

ap [µm]	2µm/tooth	10µm/tooth
10		
25		
40		

SEM photographs of milled C45 steel surfaces are shown in Table 3. There can be seen extractions in the workpiece material for highest feed rate. Quality of the surface machined with maximum feed also decreases when depth of cut increases. For the largest depth of cut (40μm) and lowest feed rate (2μm/tooth) on the surface can be noticed traces of vibration. For all cutting parameters there can be seen elastic recovery impact on surfaces. Profiles of surfaces from Table 3. are shown on Fig. 8. There can be seen similarity between surfaces photographs and their profiles. There is no noticeable difference between profile when vibration occurred and other profiles.

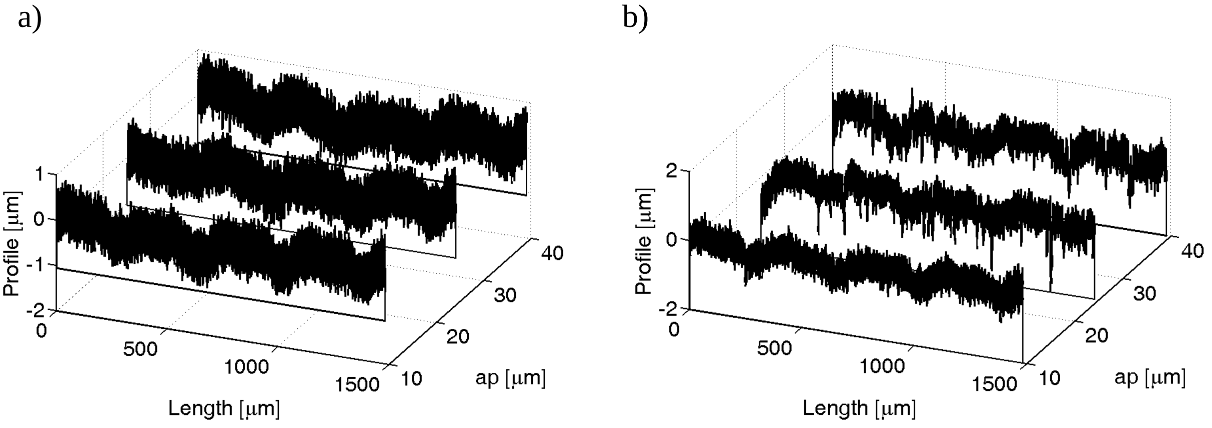


Fig. 8. C45 steel surfaces profiles for variable depth of cut (ap) at: a) feed 2μm/tooth, 30 000RPM
b) feed 10μm/tooth, 30 000RPM

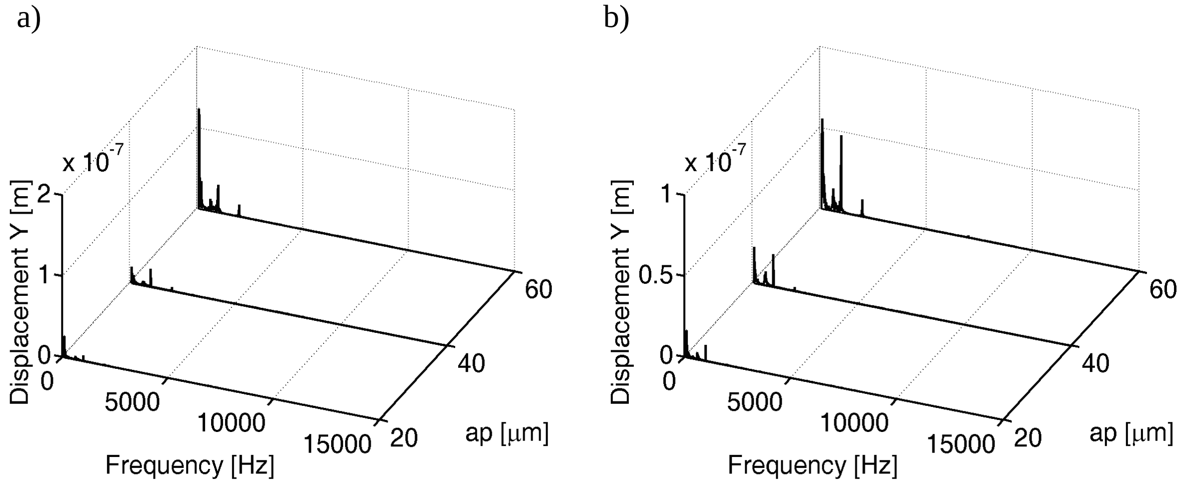


Fig. 9. Fast Fourier transform of displacement signals of aluminum alloy: a) 60 000 RPM, 10μm/tooth; b) 60 000RPM, 6μm/tooth

Signal used for further analysis were acceleration signals. Cutting forces due to own dynamometer vibration [12] are not reliable above 4kHz and can be useful only after signal processing [13]. Expected vibration frequency is about 11kHz, which is much above dynamometer own vibrational frequency. Moreover impact tests performed on tool and dynamometer shown that tool and machine spindle are weakest points in the micro-milling machine dynamics [7],[12]. Acceleration signal in Y (cross feed) direction was chosen for further analysis. Firstly acceleration signal was double integrated to obtain displacement signal. Then fast Fourier transform was used to transform displacement signal into a frequency domain.

Fast Fourier transform of displacement signals for aluminum alloy are shown on Fig. 9. FFT plots on Fig. 9. corresponds with surface profiles shown on Fig. 7. There can be seen only frequencies which are harmonics of tool teeth immersion frequency.

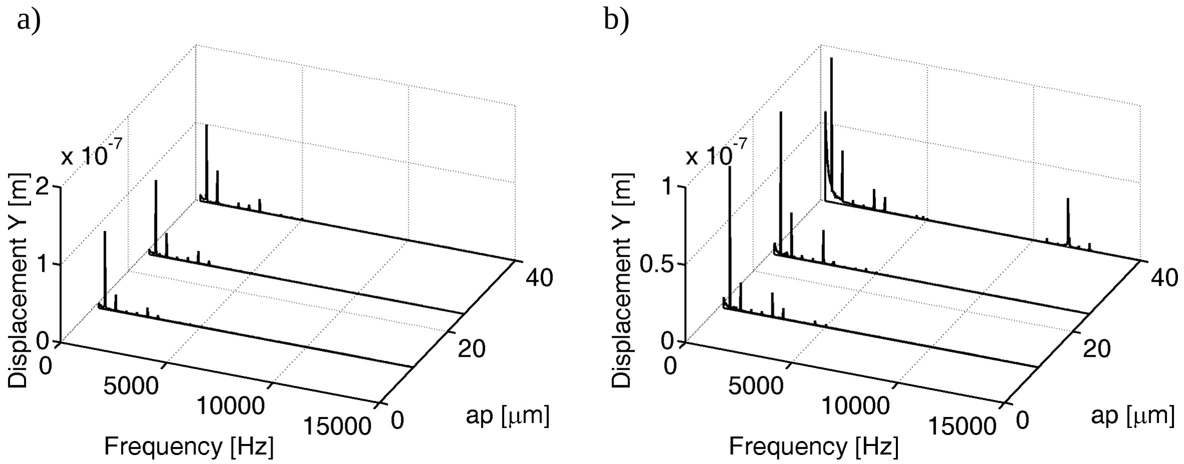


Fig. 10. Fast Fourier transform of displacement signals: a) 30 000RPM, 10μm/tooth; b) 30 000RPM, 2μm/tooth

Fast Fourier transform of displacement signals for C45 steel are shown on Fig. 10. FFT plots on Fig. 10. corresponds with surface profiles shown on Fig. 8. For the highest feed rate (Fig. 10a) there can be seen only frequencies which are harmonics of tool teeth immersion frequency. For lowest feed rate and highest depth of cut there can be seen additional amplitude peak at about 11kHz.

5. SUMMARY

Cutting parameters have significant impact on milled surface quality. Milling experiment of aluminum alloy showed that in process is a lot of smearing and some extractions of material can occur. C45 steel has good surface quality for low feed rates. For higher feed rates also can be noticed extractions of the workpiece material. In both materials elastic recovery phenomena has impact on direction of traces left by tool teeth.

Vibration occurred for lowest feed rate and highest depth of cut during milling of C45 steel. Higher feed rate should result with higher cutting forces which increases probability of regenerative vibration. The research showed that for higher feed rate vibration do not occur. Moreover cutting parameters for machining when vibration occurred were different than expected from the stability lobes. That leads to the conclusion that for cutting parameters used in experiment regenerative effect do not have impact on vibration occurring in micro-milling process. Probably the source of the vibration is friction between tool and workpiece. This assumption requires further research.

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