

Original Research Article**Vibration and Temperature Decreasing Through
the Material Damping and Tool Path Strategies
Applied for Milling the Difficult-to-machine
Materials****ABSTRACT**

The paper is contribution to research of vibration and temperature elimination in machining. It focused to milling the difficult-to-machine materials. The milling is characterized with complex vibrations regarding changing machining forces in milling and the difficult-to-machine materials have properties decreasing their machinability. The paper provides the results of experiments for measuring vibrations and temperature in different milling tool path strategies. Moreover, the results of measuring dynamic response of composite materials are presented. Finally, the paper proposes the techniques for vibration and temperature decreasing through the material damping and tool path strategy applied for milling the difficult-to-machine materials.

Keywords: milling, temperature, tool path, dynamic response, material, damping

1. INTRODUCTION

Regarding the vibrations, the milling process is characterized by more sources of vibrations comparing with turning and other ordinary kinds of machining as drilling and grinding. The more complex vibrations are generated by machining forces that act discontinuously as the milling cutter involves several cutting edges. The cutting force values change itself by variation of chip thickness. In generally, the cutting process involves forced and self-excited vibrations as natural side effect caused by various sources. [8]

In recent period, the scientists develop special materials as composites, super-alloys, tool steels, hardened steels and stainless steels for extreme applications that are harder, more wear, corrosion and fatigue resistant, less heat sensitive, tougher. Mentioned improved properties cause difficulties for manufacturing. For example, high toughness causes large cutting forces on cutting tool edge and moreover larger thermal and contact stress [12, 13]. The super-alloys as heat resistant steel designed for the highest thermal-strength components keep special mechanical properties even for high temperatures over the 750°C. Such materials become difficult-to-machine materials while keeping the conventional or better surface quality and dimensional and geometric accuracy and lower costs of machining.

The machining of difficult-to-machine materials involves solving the problems of negative effects. The main heat flow during milling of conventional steel is transferred into chip but in case of heat resistant materials the heat conductivity is low and temperature become higher,

mainly in cutting tool (insert) that is source of short lifetime, material strengthening, sticking on the cutting edge, high friction, formation of built up edge etc. [12, 13]

There are several options for solution of mentioned problems of temperature and vibrations varying the parameters of basic technological system: machine tool – cutting tool – workpiece that can involve also workpiece fixture and cutting tool holder. In present, new cutters or cutting inserts (so called chatter free) characterized by new geometry and/or holding systems even for long tools have been developing applied to high-feed milling and high cutting speeds in order to decrease vibrations, reduce cutting forces, ensure stiffness and accuracy. The paper is contribution to research of vibration and temperature decrease for milling of difficult-to-machine materials.

2. EXPERIMENTAL DETAILS AND METHODOLOGY

As introduction analyses showed, the milling is characterized by various sources of vibration and there are several strategies of vibration elimination (see more in [4, 6, 7, 10 and 13]). To minimize vibrations the following approaches are possible to use:

- Change of process parameters (speed, feed, depth of cut)
- Modification of cutter geometry,
- Shortening of cutter overhang,
- More rigid workpiece support,
- Tuned dampers,
- Stiffer machines,
- Active milling process control [5, 7].

Modal properties of technological system influence its dynamic behaviour [8, 9]. Very important is the ratio of Young's modulus of elasticity and low density. In case of large ratio, the natural frequency is high and the damping properties are excellent. High natural frequency avoids the resonance in case of high speeds. Fig. 1 shows measuring of vibration velocity while increasing the spindle speed.

At the research beginning, we focused to measure data confirming different dynamic response of technological system to dynamic load. The resonance appeared if frequency of excitation force was the same as natural frequency of machine tool. The individual curves in Fig. 1 are for following cutters of various tool producers:

- 1: 4-teeth roughing cutter, larger lead of screw, Gruma, Ø12,
- 2: 4-teeth roughing cutter, lower lead of screw, Iscar, Ø12,
- 3: 4-teeth ordinary cutter Göring, Ø12,
- 4: 2-teeth cutter Slotworks, Ø 20,
- 5: 3-teeth cutter Slotworks, Ø 25,
- 6: 2-teeth cutter Kienenger, Ø12,
- 7: Toroidal finishing cutter Fruiza, Ø12,
- 8: 4-teeth cutter, Ø 8 (breakage – no curve).

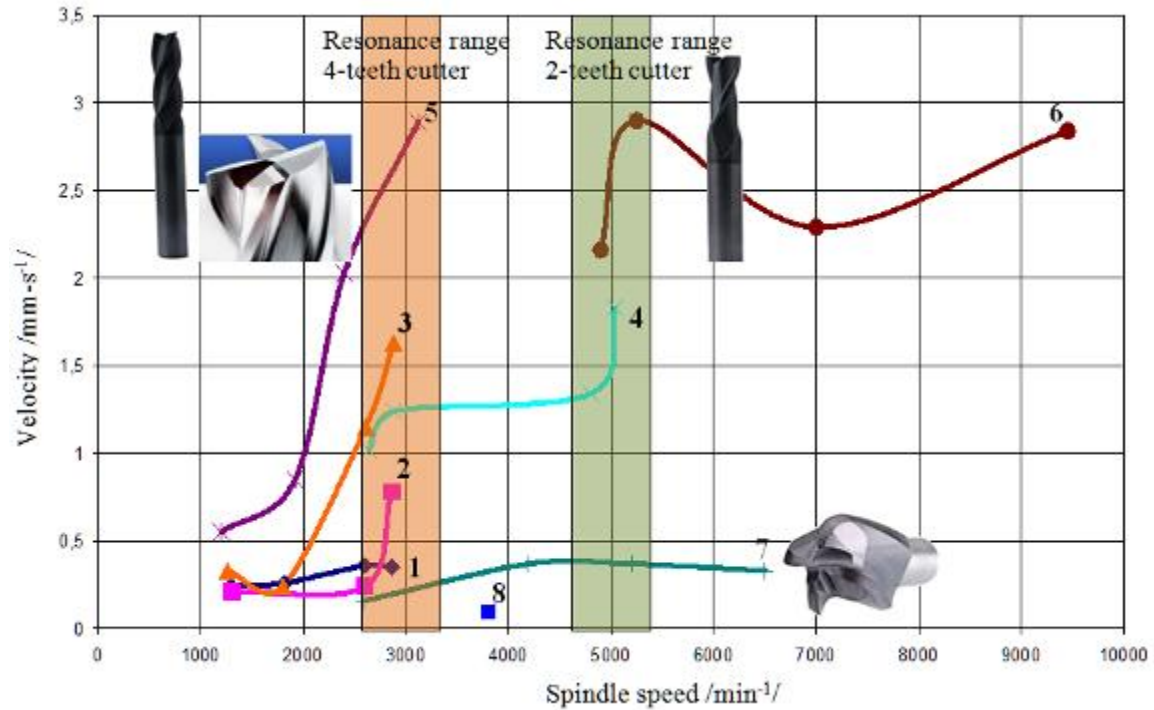


Fig. 1 Spindle speed vs. vibration velocity

If the high speeds are supposed to be used, the resonance zones have to be shifted to higher values. We propose to use the non-conventional materials for designing machine tools (section 2.2) regarding damping properties.

2.1 Testing the tool path strategies

2.1.1 Sample shape and material properties

The tested sample has block shape of dimensions: width 70mm, length 129mm, high 53mm. Fig. 2 shows the sample used for experiment and its 3D CAD model with milled groove.

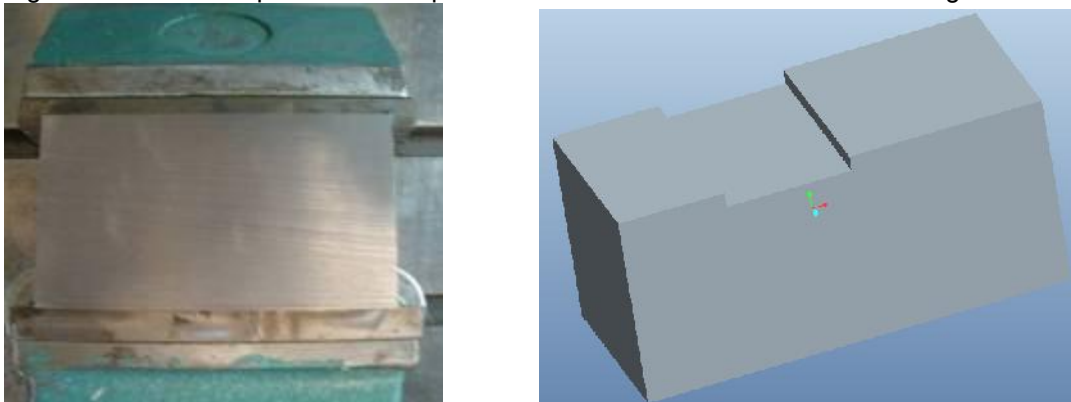


Fig. 2 Fixed sample (left) and its virtual model with milled groove

The material of sample is heat-resistant steel marked according various technical norms as following: STN: 17 134, DIN: 1.4923, X22CrMoV12-1, EN: 10269. It involves carbon C 0.18

97 – 0.24%, chromium Cr 11.00 – 12.50%, nickel Ni 0.30 – 0.80%, molybdenum Mo 0.80 –
 98 1.20%, vanadium V 0.25 – 0.35%. The typical properties are middle resistance to corrosion,
 99 good mechanical, magnetic, welding properties, good forge-ability and medium-hard
 100 machinability. The special properties are heat resistance up to 600°C and maximal hardness
 101 up to 590HV.

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103 **2.1.2 Machine tool and cutting tool**

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105 The milling process of heat-resistant chromium-molybdenum steel was made by the vertical
 106 machining centre VMC 650S CNC of series PINNACLE (Fig. 3).

107



108

109 **Fig. 3 Vertical machining centre for experiment**

110 The high-speed and high-feed face milling cutter of 18 mm in diameter with three coated
 111 cutting inserts was used. The coating is M40 PVST, the cutting inserts are of squared shape.
 112 Milling cutter body is showed in Fig. 4. The cutting insert is designed specifically for
 113 machining of stainless steel and high-temperature alloys as well as for universal use.

114



115

116 **Fig. 4 Milling cutter body**

117 **2.1.3 Milling tool path strategies**

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119 The milling process was realised by three different tool path strategies:

- 120 - continuous tool path (Fig. 7),
- 121 - discontinuous tool path (Fig. 8),
- 122 - trochoidal tool path (Fig. 5).

123 Tool vibrations were being monitored by NI PXI system and distribution of temperature in
 124 time was being recorded by thermovision camera for each of mentioned tool paths. In case
 125 of continuous milling the milling cutter is permanently engaged while milling the groove. The
 126 engagement of cutter is interrupted for discontinuous milling tool path. In both cases the
 127 motion of tool is linear.

In generally, a trochoidal tool path is defined as the combination of a uniform circular motion with a uniform linear motion. Trochoidal tool path was developed for milling of grooves and pockets by high-speeds and high removal of material. It allows creating wider grooves than the cutter diameter what enable to use one tool. Due to the fact that the small values of radial engagement are used the end mills with a small and/or variable pitch mill can be used and thus the feed speed and cutting speed can be increased. [1]

The simulations of presented continuous and discontinuous milling tool paths were made also in CAD/CAM system Creo Parametric. As the mentioned system does not support trochoidal milling, the CAM system NCG CAM was used. Technological conditions of milling process were proposed the same form three tool path strategies regarding the tool material and milling type. The used postprocessor is for control system FANUC.

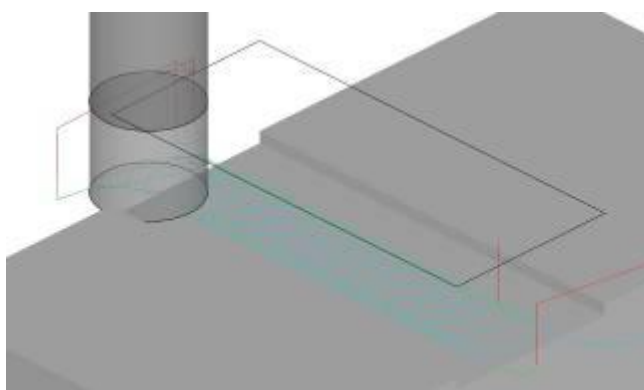


Fig. 5 Trochoidal milling

2.1.4 Results of tool path strategies

Average measured temperatures for trochoidal milling tool paths provide the lowest values_ average tool temperature 62.0°C, average temperature of machined material 29.1°C. The highest average temperature was measured for discontinuous milling: average tool temperature 195.7°C, average temperature of machined material 53.1°C. A continuous tool path generates average tool temperature 157.1°C, average temperature of machined material 48.1°C. The measured values during milling are in Fig. 6.

Regarding the measured values of the temperatures the trochoidal milling is evaluated as the most appropriate. We use the advantage of the selected type of milling tool due to the possibility to set the same cut depth for all tool paths. Trochoidal milling can be used for different types of milling up to a depth of cut of 10 mm in the full angle of cutter. The maximum possible depth of cut of milling processes is strongly limited by unstable vibrations between tool and workpiece. [9]

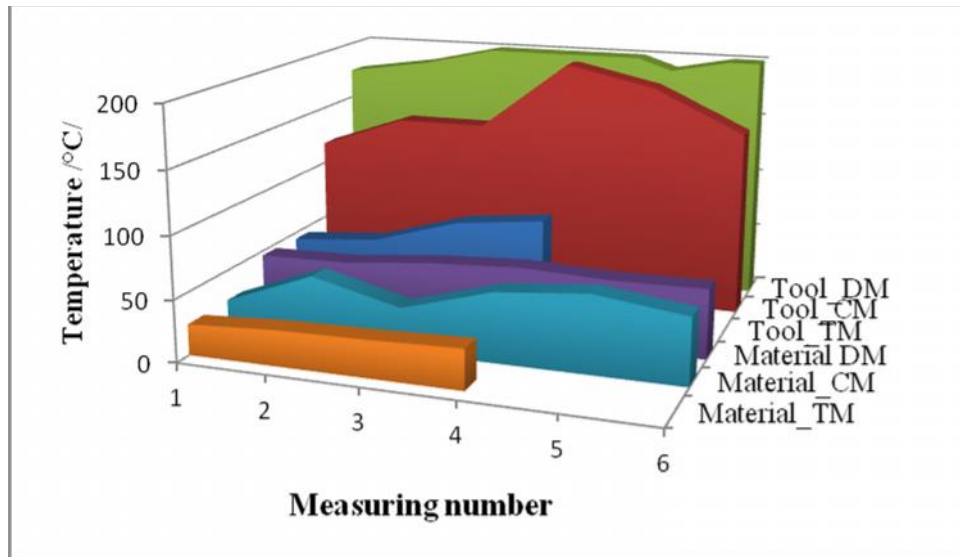


Fig. 6 Measured temperatures of material and tool
(DM – discontinuous milling, CM – continuous, TM – trochoidal milling)

Vibrodiagnostics results for continuous tool path show the stabile vibrodiagnostics signal (Fig. 7) and in case of correct technological conditions settings the high machined surface quality and long tool lifetime can be achieved.

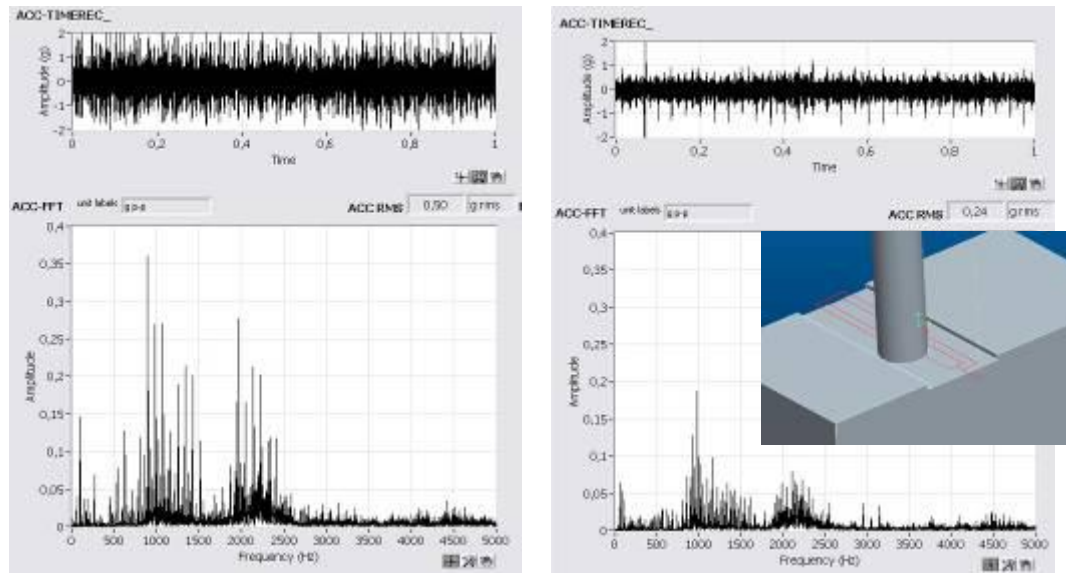


Fig. 7 Continuous tool path: vibration signal of workpiece (left) and spindle

The results of measurement for discontinuous milling (Fig. 8) show slightly rise of the vibration signal of workpiece, vibrations of spindle are similar. As regards trochoidal milling (Figs. 5 and 9) the workpiece vibrations were larger but spindle vibrations were lower comparing with continuous tool path. Very important fact is number and geometry of wedges. The obtained quality of the machined surface is lower than that of the continuous milling.

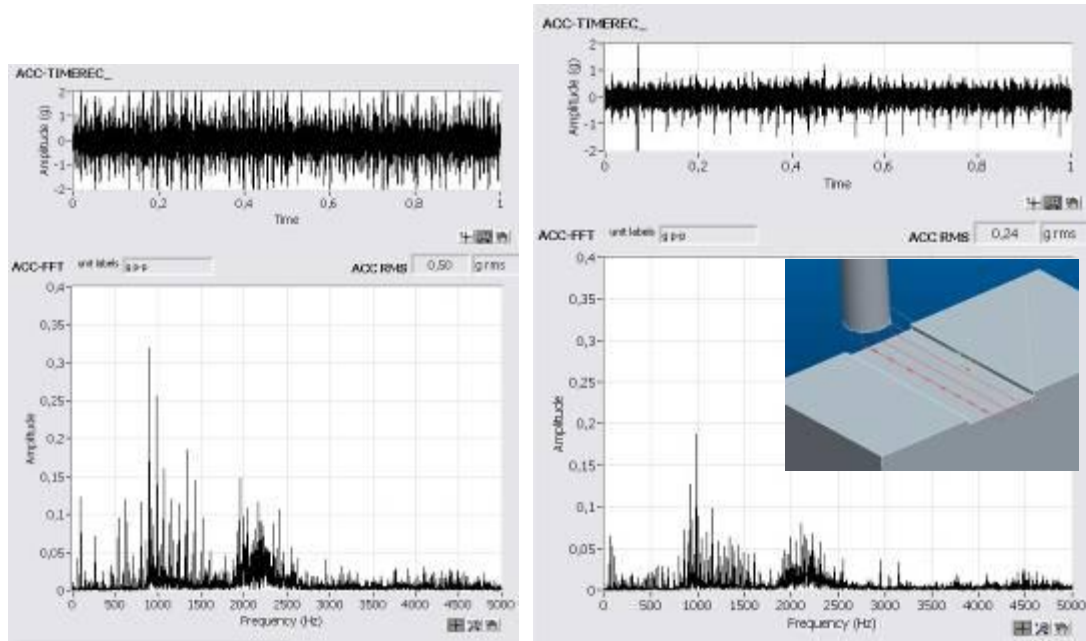


Fig. 8 Discontinuous tool path: vibration signal of workpiece (left) and spindle

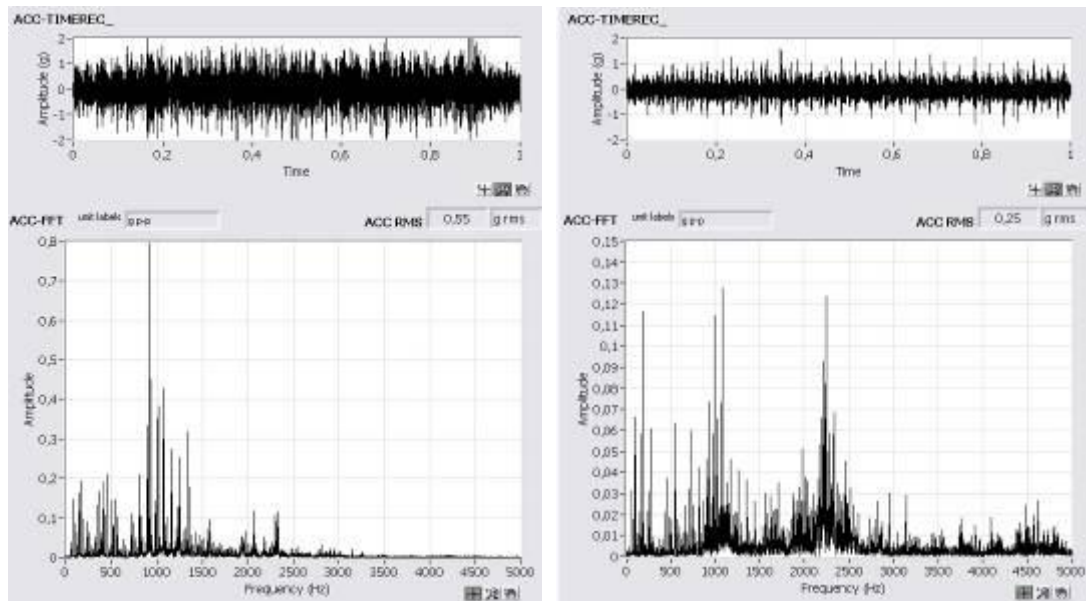


Fig. 9 Trochoidal tool path: vibration signal of workpiece (left) and spindle

2.2 Testing the material damping and results

Moreover, machine tools as one part of technological system start to use materials as fibre composites, particular composites (polymer concrete), natural or artificial granite, ceramics, hybrids, sandwich and special structures (honeycomb, aluminium etc.) to achieve higher stiffness and lower natural frequency. Mentioned new, non-conventional, materials of machine tools are seldom used for commercial conventional usage and the special cutting tools are not always available for economic reason. This is a motive why the presented

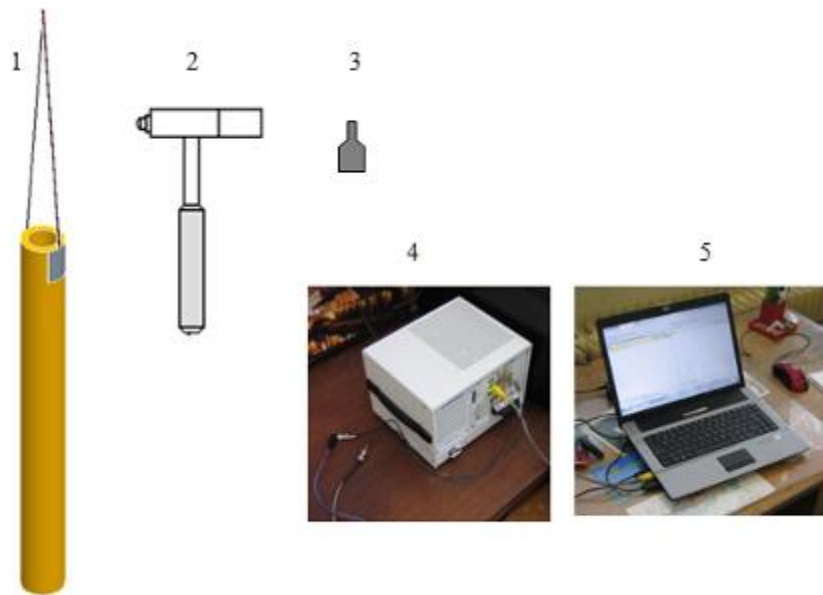
190 paper deals with parameters as tool path, modal properties, vibrations and temperature for
191 machining of difficult-to-machine materials.

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193 **2.2.1 Details of measurement**

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195 Fig. 10 shows the individual members of measuring chain: 1 – sample, 2 - bump hammer, 3
196 – microphone, 4 – analyser of dynamic signals (measuring card NI PXI 4472B, A/D
197 convertor and 5 – PC with software PXI LabView. The sample shape is hollow tube with
198 outer diameter 12mm and thickness of wall 2mm. The sample is freely hanging. The force of
199 bump is approximately same. The acoustic response of materially different samples is
200 recorded by microphone and analysed. There is more precision measuring using fixture of
201 both sample ends and accelerometer but we did not use it.



202

203 **Fig. 10 Members of measurement chain**

204

205 *1 – sample, 2 - bump hammer, 3 – microphone, 4 – analyser of dynamic signals, 5 - PC*

206 Natural frequency and damping time were measures by bump test for various materials:
207 aluminium, glass, steel and short fibre composite (with random and preferred fibre
208 orientation). SiC (carborundum) belongs to technical ceramics branch. SiC are infiltrated by
209 short carbon fibres that improving the mechanical and thermal properties of SiC. Some
210 material properties are following: density 2.65 g/cm^3 , Young's modulus 250-350 GPa,
211 bending strength: min. 160-200 MPa. Composite SiC comprises short carbon fibres with
212 length of 3 to 6 mm of 12k thickness (1k=1000filaments). The short fibres can be distributed
213 randomly in volume so the material is considered to be isotropic or with preferred orientation
214 (material properties are orthotropic) in volume. Fig. 11 presents amplitudes of natural
215 frequencies (up) and damping time for sample with best results - ceramics composite with
216 carbon fibres C/SiC. Fibre orientation did not influence the results considerably.

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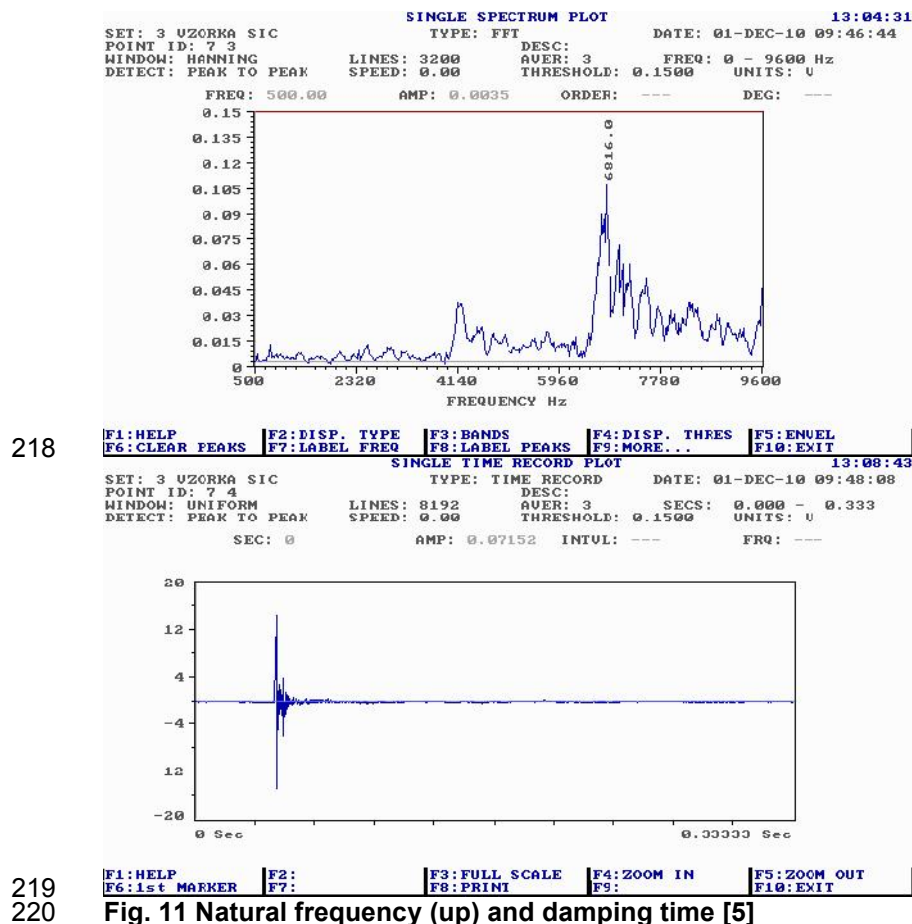


Fig. 11 Natural frequency (up) and damping time [5]

Moreover, Fig. 11 shows large frequency zone of dynamic response of C/SiC. The dominant natural frequency is not evident. Materials without dominant natural frequency (large frequency range) are very appropriate for designing the components intended for dynamic load with variable exciting frequencies. Such property is very suitable for preventing the resonance. One can see that damping time is very short (comparing for example with steel).

3 DISCUSSION AND CONCLUSIONS

The requirements for accuracy (dimensional, geometric, roughness etc.) and state and quality of machined workpieces made from difficult-to-machine materials are the same comparing with conventional steel/materials. The paper presents the experiments and show possible strategies to improve the milling of difficult-to-machine materials.

We compared three different milling tool path strategies in presented experiment, continuous, discontinuous and trochoidal, and found advantages and disadvantage each of them. The continuous milling is characterized by increasing of temperature on the cutting edge that caused its early wearing and dulling, vibrations are low and thus the machined surface quality is high. The discontinuous milling is useful due to better chip removal from cutting edge and thus longer cutter (insert) lifetime. The disadvantage is the discontinuity itself regarding vibration increase and lower surface quality. Trochoidal milling is intended for various shape features up to 10-15mm of depth in normal operation. Small cut depth is not suitable due to longer milling time. Presented experiment remained the same technological

conditions even for trochoidal milling. Trochoidal milling provided higher vibrations of the workpiece, lower spindle vibrations and decreasing of temperature that is very important fact for heat resistant materials. The temperature decrease is the main profit of trochoidal milling of difficult-to-machine materials. The important benefit is decrease of spindle vibrations. The increase of vibration of workpiece can be solved by improved fixture of workpiece for example based on composite.

As the technological system is loaded by dynamic loads, its response can be changed by various approaches. The paper presents results of the analysis of resonance for chosen machine tool and provides the results of bump test applied on different materials. The option for preventing the resonance and use high speed milling is to make natural frequency of milling machine high through the use of composite materials with very good modal properties that change the dynamic response of machine tool.

The future research will be focused on tool path interpolation that has major influence on the milling process implementation and applying the fibre composite components in order to eliminate vibrations and increase the natural frequency of milling machine.

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