Original Research Article

Vibration and Temperature Decreasing Through the Material Damping and Tool Path Strategies Applied for Milling the Difficult-to-machine Materials

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ABSTRACT

The paper is contribution to research of vibration and temperature elimination in machining. It focused on 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℃. 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 Gőring, 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).

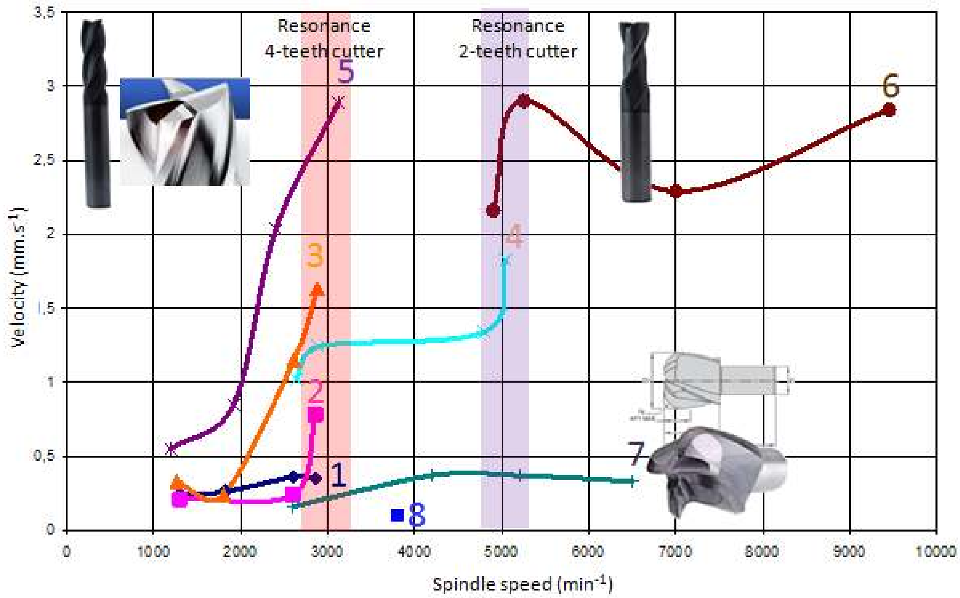

Fig. 1 Spindle speed vs. vibration velocity

If the high speeds (about 3000 and 5000 min^{-1}) are supposed to be used, the resonance appears. The resonance zones could be shifted to higher values in order to eliminate the problem of large vibrations. We propose to use the non-conventional materials for designing machine tools (section 2.2) regarding their natural frequency and damping properties.

2.1 Testing the tool path strategies

2.1.1 Sample shape and material properties

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

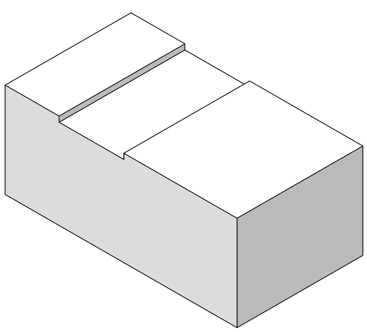

Fig. 2 ~~Fixed sample (left) and its~~ Virtual model with milled groove

The material of sample is heat-resistant steal marked according various technical norms as following: STN (Slovak Technical Standard): 17 134; DIN (German standard): 1.4923, X22CrMoV12-1; EN (European Standard): 10269. It involves carbon C 0.18 – 0.24%, chromium Cr 11.00 – 12.50%, nickel Ni 0.30 – 0.80%, molybdenum Mo 0.80 – 1.20%, vanadium V 0.25 – 0.35%. The typical properties are middle resistance to corrosion, good mechanical, magnetic, welding properties, good forge-ability and medium-hard machinability. The special properties are heat resistance up to 600℃ and maximal hardness up to 590HV.

2.1.2 Machine tool and cutting tool

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

Fig. 3 Vertical machining centre for experiment and detail with sensors

Fig. 3, right, presents detail of vertical machine centre where the accelerometer sensors are placed. Sensor 1 is situated on spindle radialy to spindle axis in perpendicular direction to feed, sensor 2 is on the clamped workpiece in perpendicular direction to feed.

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

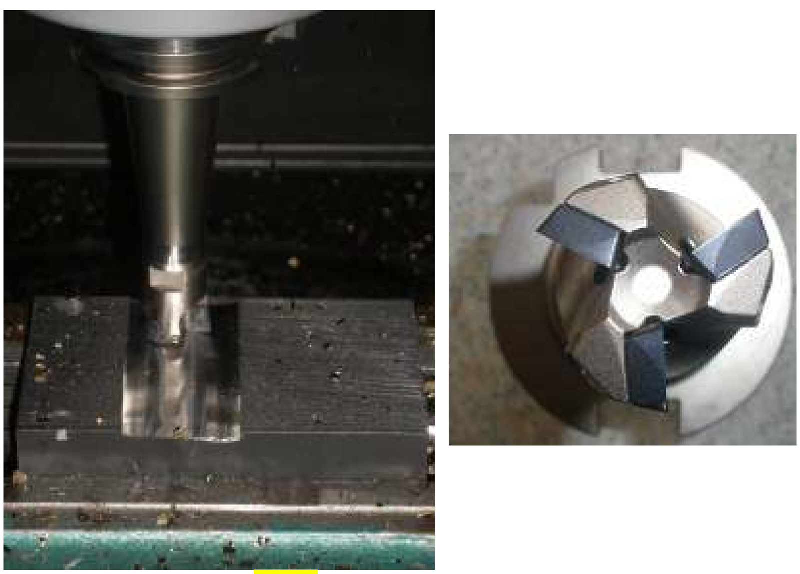

Fig. 4 Milling cutter ~~body~~

2.1.3 Milling tool path strategies

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

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

Tool vibrations were being monitored by NI PXI system and the distribution of temperature in time was being recorded by thermovision camera for each of mentioned tool paths. The coolant was not used because it caused barrier for thermo-measuring. In case of continuous milling the milling cutter is permanently engaged while milling the groove. The engagement of cutter is interrupted for discontinuous milling tool path. In both cases the 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.

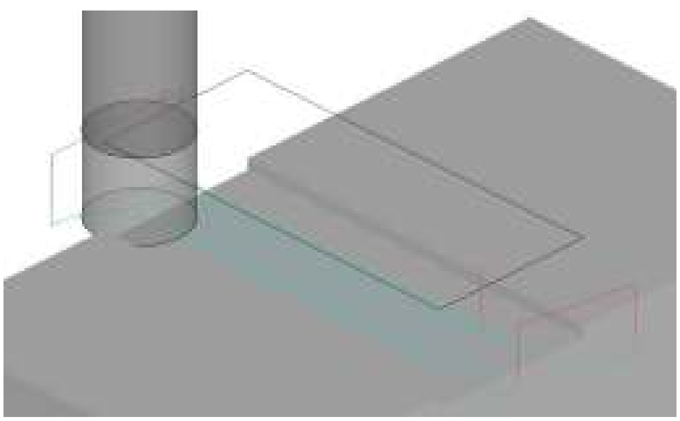

Fig. 5 Trochoidal milling

2.1.4 Results of tool path strategies

The average measured temperatures for trochoidal milling tool paths provide the lowest values, i.e. average tool temperature 62.0℃ and average temperature of machined material 29.1℃. The highest average temperature was measured for discontinuous milling, i.e. average tool temperature 195.7℃ and average temperature of machined material 53.1℃. A continuous tool path generates average tool temperature 157.1℃ and average temperature of machined material 48.1℃. The measured values during milling are illustrated in Fig. 6.

According to 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]

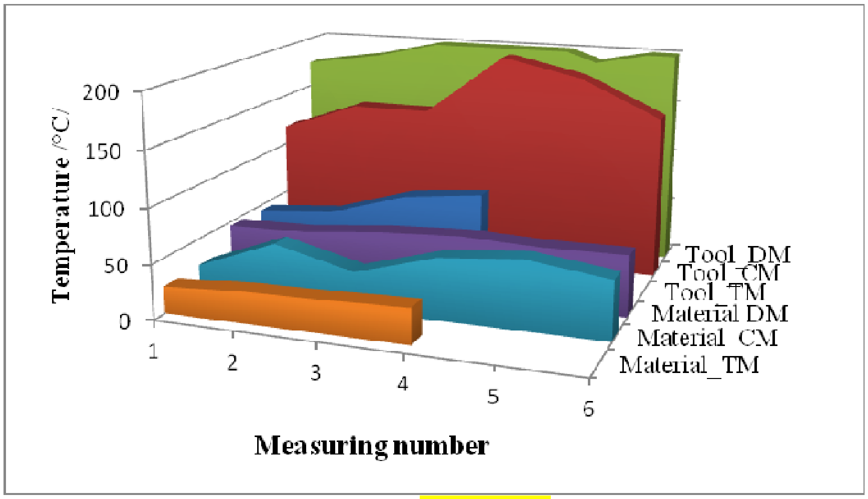

Fig. 6 Measured temperatures of workpiece material and tool

(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.

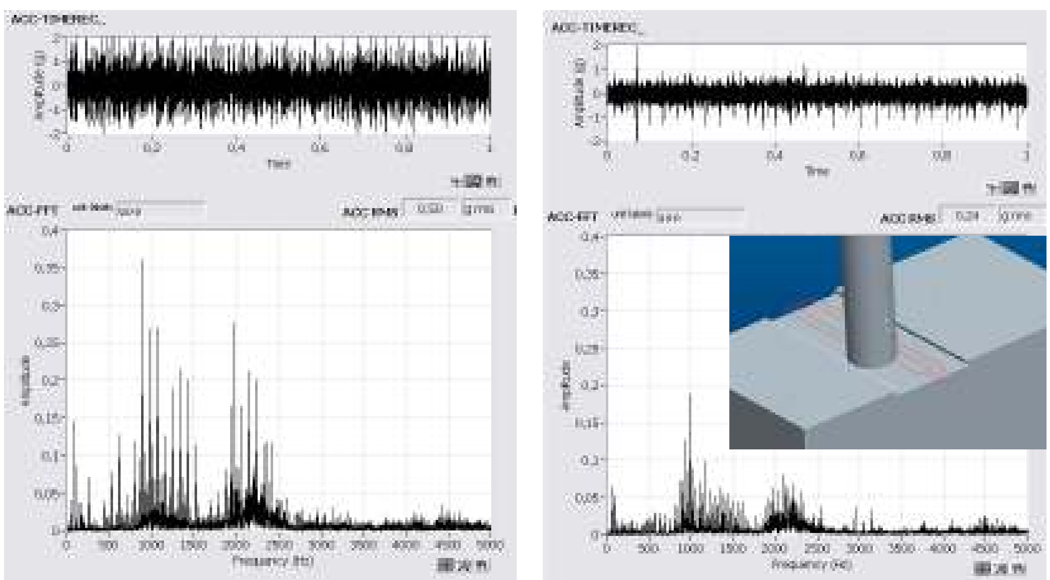

Fig. 7 Continuous tool path: vibration signal of workpiece (left) and spindle

The results of measurement for discontinuous milling (Fig. 8) show slightly rise of the maximal vibration amplitude of workpiece, vibrations of spindle are similar. As regards trochoidal milling (Figs. 5 and 9) the workpiece vibrations were larger but spindle vibrations became lower comparing with continuous tool path. Very important fact for vibrations values is number and geometry of cutting wedges that was found in other realized experiments. The obtained roughness of the machined surface is lower than that of the continuous milling.

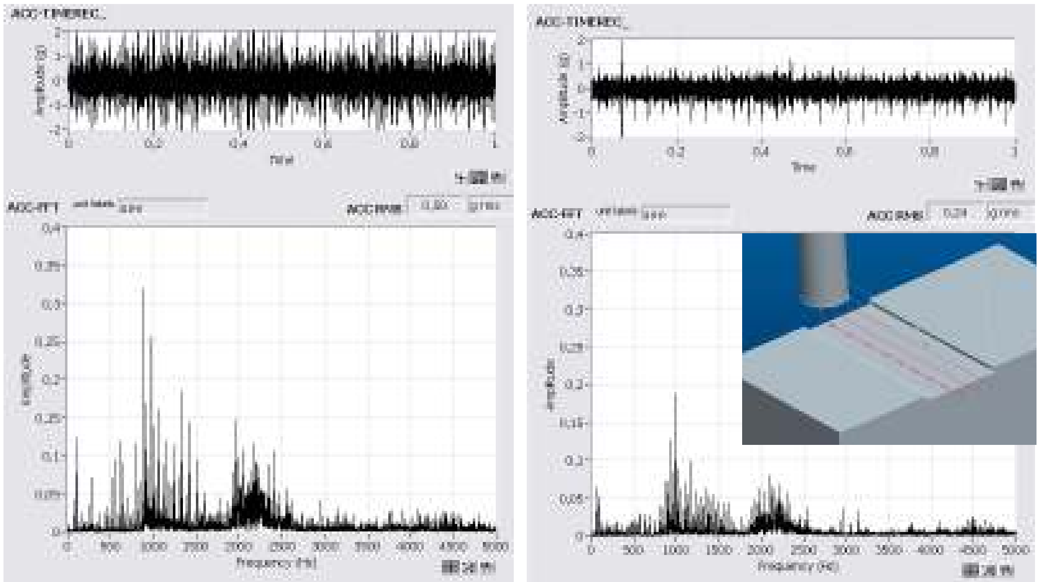

Fig. 8 Discontinuous tool path: vibration signal of workpiece (left) and spindle

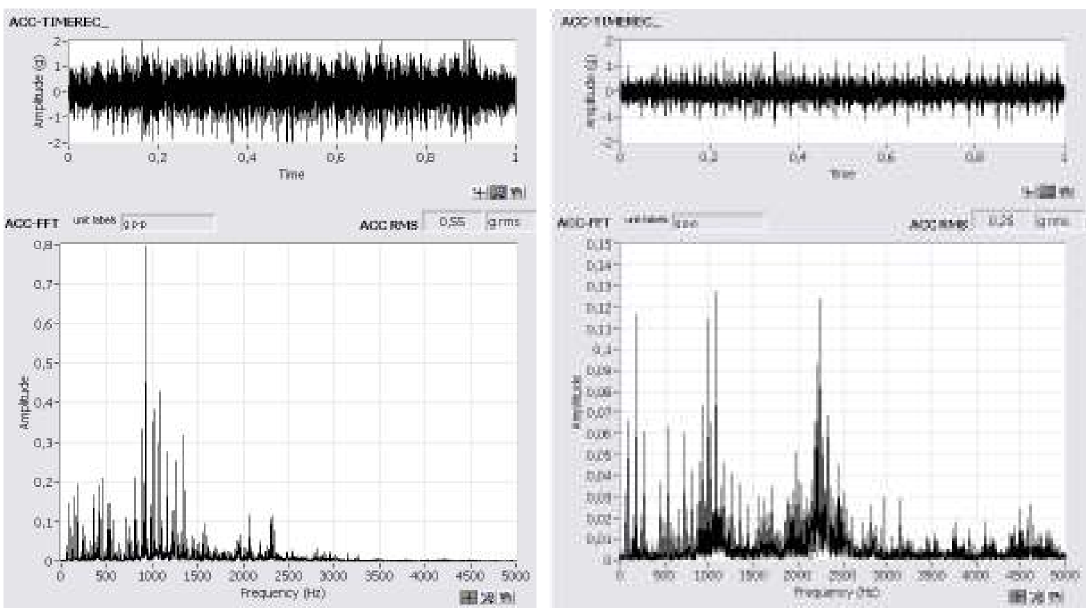

Fig. 9 Trochoidal tool path: vibration signal of workpiece (left) and spindle

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

2.2.1 Details of measurement

Fig. 10 shows the individual members of measuring chain: 1 – sample, 2 - bump hammer, 3 – microphone, 4 – analyser of dynamic signals (measuring card NI PXI 4472B, A/D convertor and 5 – PC with software PXI LabView. The samples shape is hollow tube with outer diameter 12 mm, ~~and~~ thickness of wall 2 mm and length 110 mm. The sample is freely hanging. The force about equal value is applied manually by bump hammer. The acoustic response of materially different samples is recorded by microphone and analysed. There is more precision measuring using fixture of both sample ends and accelerometer but we did not use it.

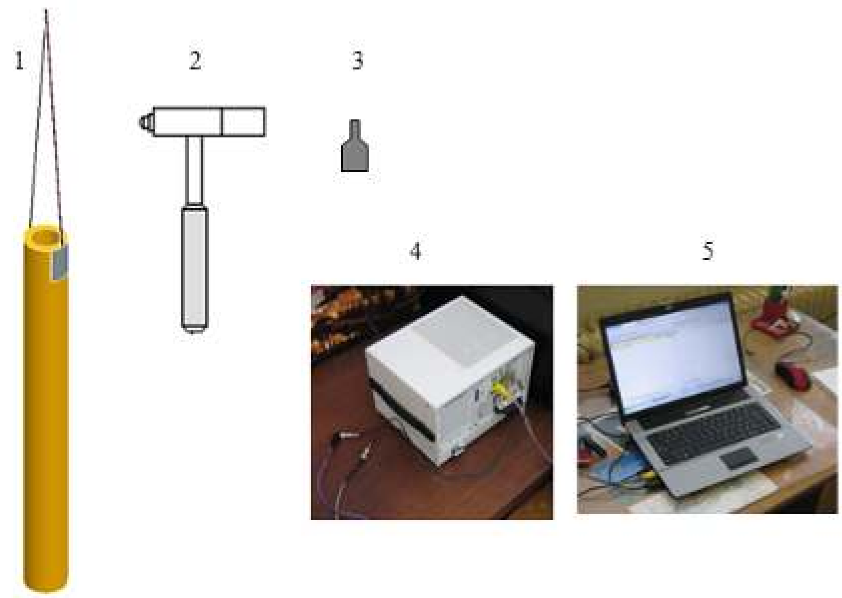

Fig. 10 Members of measurement chain

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

Natural frequency and damping time were measures by bump test for various materials: aluminium, glass, steel and two short fibre composites C/SiC (with random and preferred fibre orientation).

The sample C/SiC was made by external foreign producer. The sample is a composite ceramic produced by infiltrating a carbon greenbody with high purity liquid silicon at high temperatures (above 1600 °C), leading to the reaction of the Si with the C to form carbon-fiber reinforced SiC. SiC (carborundum) belongs to technical ceramics branch. Short carbon fibres improve the mechanical and thermal properties of SiC. Some C/SiC material properties are following: density 2.65 g/cm^3, Young's modulus 250-350 GPa, bending strength: min. 160-200 MPa. The short carbon fibres are of length 3 to 6 mm of 12 k thickness (1k=1000 filaments). The short fibres are distributed either randomly in volume so the material is considered to be isotropic or with preferred orientation (material properties are orthotropic) in volume.

Fig. 11 presents amplitudes of natural frequencies (up) and damping time for sample with best results, i.e. ceramic composite reinforced by carbon fibres C/SiC. The results showed the fibre orientation does not have in this case significant impact. Moreover, Fig. 11 shows large frequency zone of C/SiC dynamic response. The dominant natural frequency is not evident. Materials without dominant natural frequency, i.e. with 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).

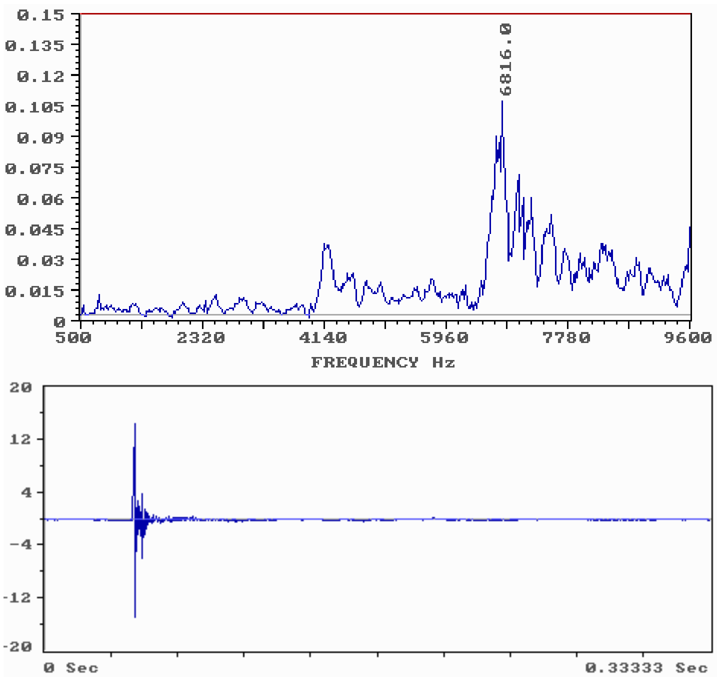

Fig. 11 Natural frequency (up) and damping time [6]

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 according to temperature and vibration criterion. The continuous milling is characterized by three-times larger temperature on the cutting tool 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 in time of tool impact engaging into workpiece 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, but lower spindle vibrations and lower 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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