# MECHANICAL RESPONSE OF COMPOSITE ON IMPACT LOAD

Zuzana Murčinková

Technical University of Košice, Faculty of Manufacturing Technologies with seat in Prešov,
Bayerova 1, 080 01 Prešov, Slovak Republic

**Abstract**

*The paper deals with mechanical response of conventional homogeneous materials and short and long fiber composites that are excited by impact force. Such type of excitation is typical for dynamic effects in the machine tool performance. The maximum portion of generated vibrations should be damped. The material damping is one of factors improving the damping properties. The paper provides the results of measurements that analyze mainly the natural frequencies, character of Fast Furier Transformation spectrum focusing on damping time of conventional and nonconventional materials, carbon and glass fibers and their different material configuration.*

**Keywords:** *fibre, material damping, vibrometry, frequency range*

## 1. INTRODUCTION

The cutting is a dynamic process that involves the excitation of vibrations. The impact between cutting tool, e.g. milling cutter, and workpiece in cutting, e.g. milling, is one of sources of vibrations resulting in generation of vibrations of acting machine parts and of whole machine tool-cutting tool-workpiece system. The vibrations rise from inappropriate tool, fixing of tool, machine tool construction (clearance), shape and material of workpiece, workpiece fixture etc. The collision between the tool and workpiece activates the free vibration. The forced vibration occurs when time varying external disturbance is applied to the mechanical system, the self-excited vibration affects excitation force resulting from the interaction of all inside factors. The self-excited vibration arises in the system without external periodic influence. (Vasilko 2007, Muhammad et al. 2017)

The impact appears when two or several mass units (either mass particles or bodies) are in contact in very short time interval ($10^{-3}$- $10^{-5}$ seconds), Záhorec & Caban 2002. The impact forces act and disappear over a short period of time (Lankarani & Nikravesh 1994). The relatively large reaction forces (impact forces) arise among bodies. A time interval influences the effect of force on the body. The product of a force by the time interval during which the force acts is called impulse (Warburton 2014.). The impact analysis approaches differ according to assumption of elastic or inelastic bodies, time period of contact, velocity of contact etc. (Lankarani & Nikravesh 1994). The components of technological system machine tool-cutting tool-workpiece are elastic deformable bodies. In case of inelastic impact (a total kinetic energy is less after collision then it was before collision), the kinetic energy lost in impact is transformed to sound energy, to heat energy and to the energy required to deform or fracture a body (Semat & Katz 1958).

Machine tools absorb impact (forces and energy) to avoid damage due to overload. The impact appears either suddenly (inhomogenity of workpiece material) or periodically (irregular workpiece shape, several flute (inserts) milling cutters). At low impact velocities, energy is dissipated in the form of internal damping or heat. If the initial indentation velocity is not negligible compared with the propagation speed of deformation waves across the solid, then permanent indentation is the dominant factor accounting for energy dissipation (Lankarani & Nikravesh 1994). The paper focuses on low-velocity impact and internal material damping.

Despite the fact that the kinetic energy lost in impact is undesirable in most cases of kinematic pairs in mechanisms, the elimination is impossible, but it can be reduced. Resulting from that, to develop more energy-efficient poses machine tools and production systems is a challenge for machine developers. One of the solution for improvement of machine tools behaviour is the use of special material properties of composite materials.

*1.1. Composite materials in machine tools*

Composites provide many advantages over conventionally used materials. The use of composite materials in the construction of production machines begins at the beginning of the 20th century by first applications, using concrete as a representative of particle composites. Due to insufficient capacity of the foundries and steel plants during the 2nd World War, the concrete for machine beds of single-purpose lathes started to be used. In the post-war period, metal materials were returned, and in the 1960s European producers returned to use concrete.

At present, polymer concrete (PC - Polymer Concrete, also referred to as mineral cast iron) and high strength concrete (also called Cement Concrete, HPC - High - Performance Concrete) are mainly used for machine frames and beds by moulding casting or by filling chamber of welded structures. Compared to the steel, they have a lower thermal expansion, with a high compressive strength and excellent damping. Their low tensile strength (lowest for HPC concrete) can be increased by reinforcing the concrete or by creating a pre-stressed structure.

Granite, natural or artificial, can be classified as a particle composite. It is designed for the purpose of carrying components in machine-building, especially for measuring devices and special machine tools (micro-milling machines, very precise grinders). Natural granite is a material without internal stress, which is its main feature, with a low coefficient of length expansion (compared to steel), with high static stiffness and good damping (at the level of grey cast iron).

The most effective reinforcement material is fibre. Fibre composites are materials that have excellent mechanical, thermal and electro-magnetic properties. Fibre composites are mainly suitable for moving parts of machines, for the construction of machine tool spindles, headstocks, bearings, robots or frames of smaller machines. These are dynamically loaded components. Composites allow to increase the operating speeds or to achieve higher moving speeds. The composite massive carry bodies of production machines are unique in the commercial sphere. At present, more applications are applied to ceramic composites or ceramic fibres compared to carbon composites. The advantage of fibre composites is their high strength, low thermal expansion, good damping properties and low specific weight, which predetermines them for highly loaded moving parts of machines. Components have low weight, less moment of inertia while retaining the stiffness. The disadvantage is the very high price, the difficulty of joining with other parts, the low possibility of modification already finished components and the complicated design of the component due to its anisotropic properties.

Hybrid structures are a compromise in the use of conventional and unconventional materials, taking advantage of both. Most common are hybrids:

- Combination of steel weldment/casting and polymer concrete provides the higher damping and higher weight which is useful for unmovable machine tool components,
- A combination of layers of conventional material - a special structure of conventional materials, optionally supplemented with a layer of polymer,
- Aluminium foam (metallic foam, Simančík & Jerz 2008) often used as a combination of steel - Aluminium foam (reinforced aluminium foam).

Except material damping, there are dynamic damping methods. The state of art on the control of machining chatter vibrations, including damping methods related to boring, turning, and milling processes is reviewed in Muhammad et al. 2017.

## 2. MATERIALS AND METHODS

Polytec IVS 400 is the contactless and wear-free measuring equipment. It eliminates the influence of environmental conditions regardless some servo-mechanisms or noise protection to perform the measuring. The vibrometer is based on a phenomenon of Doppler Shift in laser beam to measure e.g. the vibration velocity, amplitude of a moving object etc. The light beam is reflected by moving surface and thus the frequency of light is shifted proportionally to its velocity. The Laser-Doppler vibrometry is

significant by the independence of measured data on reflected light intensity. Hence, the laser vibrometer is suitable for surfaces of low reflectivity.

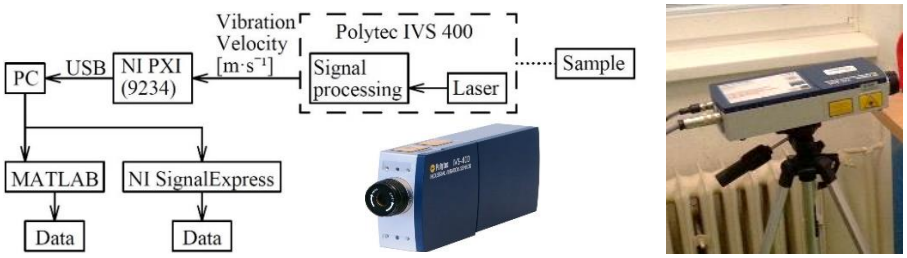


**Fig. 1.** Measuring chain with Polytec IVS 400

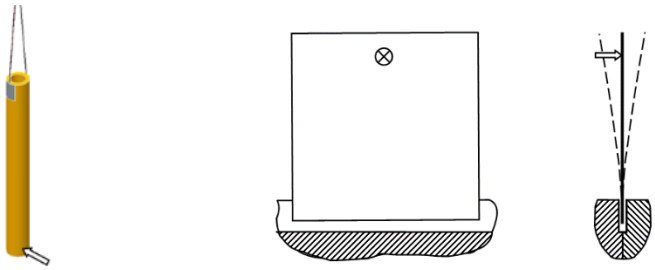

**Fig. 2.** Free and fixed constraints

The specimens are of two shapes: cylindrical and planar. The two constraints are used. The cylindrical specimens are of free constraints (Fig. 2, left) and the planar specimens are fixed at the one side (Fig. 2, right). The specimens are under the low velocity impact in range 1.5-2.5 m/s. There is not one general definition with clear distinction between low and high velocity impact. The many researchers recognize the low velocity impact in case of velocity up to 10 m/s. Other researchers insisted that the upper limit of low-velocity impact vary from 1 to 10 m/s depending on the material properties of target and the mass and stiffness of impactor. More in Shen 2015.

*2.1. Measuring 1 – cylindrical specimens*

The impact force is applied in radial direction (bending), twice per each specimen (two perpendicular directions). The shape of tested specimens is cylindrical with centric hole (pipes) of outer diameter $D$=12mm, inner diameter $d$=8mm and length $L$=110mm.

The specimens are different for their material and microstructure. The specimens are made of carbon steel, aluminium alloy (duralumin), glass ($SiO_2$), corundum (oxide ceramics $Al_2O_3$) and C/SiC composite (ceramics matrix with carbon short fibres), (Fig. 3). Material properties of C/SiC$_\perp$ specimen are directional.

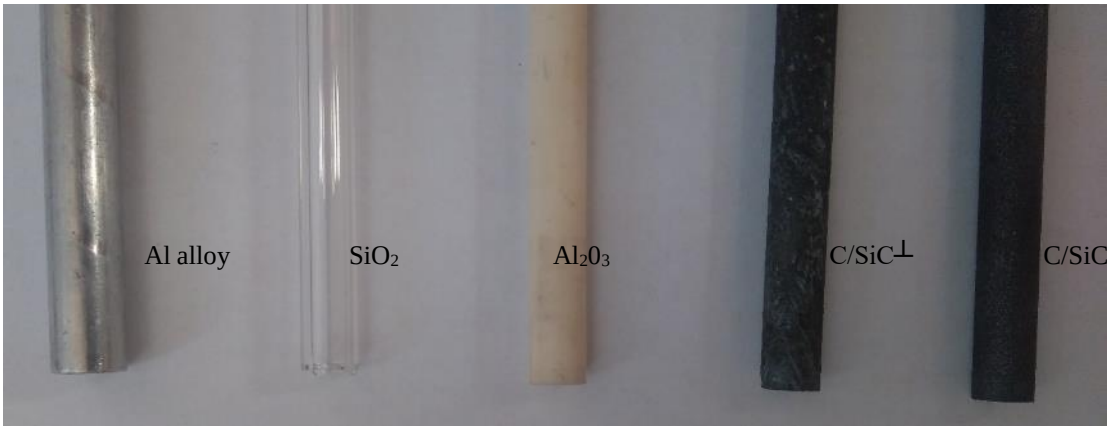


**Fig. 3.** Cylindrical specimens

The steel and aluminium alloy represent conventional materials. Glass ($SiO_2$) is representative of amorphous, isotropic, solid and brittle material in metastable state. Two specimens are made of ceramics composite C/SiC. SiC (carborundum) belongs to technical non-oxide ceramics branch. SiC are infiltrated by short carbon fibre that improving the mechanical and thermal properties of SiC. Short-fibre composite C/SiC comprises short carbon fibres with length of 3 to 6 mm of 12k thickness (1k=1000 filaments). The C/SiC and C/SiC⊥ specimens have different orientation of fibres in volume. The C/SiC specimen has randomly distributed fibres so the material can be considered to be isotropic. The C/SiC⊥ specimen involves the short fibres with preferred orientation perpendicular to pipe axis. The material properties C/SiC⊥ specimen can be recognized as orthotropic.

*2.2. Measuring 2 – planar specimens*

The measurement was performed on six square laminate specimens, size 115x115x0,9 mm, each of which is composed of three layers of carbon or glass fibre twill fabrics in matrix (Fig. 2). The carbon and glass fibre laminate specimens are numbered as 1, 2, 3 and 4, 5, 6, respectively. The orientation of individual layers is different (Table 1) to be able to analyse the influence of that orientation. The carbon fabric is twill weave labelled as 200g/m$^2$, twill 2/2 and glass fabric 280g/m$^2$, twill 2/2, respectively. The three layers are in mixture of epoxy resin (EPIKOTETM Resin MGS® LR 285) and fixative (EPIKURETM Couring Agent MGS® LH286) of mutual ratio 10:4.

| **Number of specimen** | **1, 4** | | | **2, 5** | | | **3, 6** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Layer** | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| **Fibre orientation** | # | # | # | X | X | X | # | X | # |

Note: # - parallel to the edges of the specimen, X - diagonal fibre orientation (45°)

**Table 1.** Specimen layup description

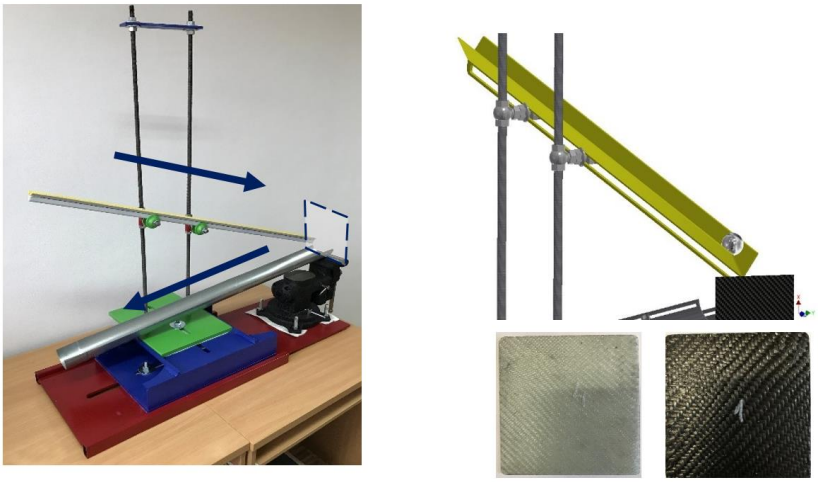

**Fig. 3.** Measuring stand and planar specimens – measuring 2 (Murčinková & Halapi 2018)

The proposed design of the measuring stand (Fig. 3) defines a position-adjustable measuring stand for composite materials – natural frequencies, shapes and damping factors. The stand is designed to be able to make measurement of various shapes and sizes of the specimens - flat specimens up to about 700 mm either height or width and cylindrical shapes up to a diameter of 125mm. In generally, it is possible to measure any shape of the specimen that can be clamped in the measuring stand. The stand is of almost rigid construction but with the ability to adjust the various positions needed for measurement purposes. Fig. 3 shows the snapshot of impact of ball into specimen.

## 3. RESULTS AND DISCUSSION

### *3.1. Measuring 1*

Figs. 4 and 5 summarize the results of measuring 2. The materials on the horizontal axis are arranged in same order (from aluminium alloy to standard steel). We can compare the individual properties as natural frequency vs. damping time vs. specific modulus of elasticity ($E/\rho$; Young modulus of elasticity/specific density). Making the evaluation of the best material properties according to criteria for machine tools, we can make the following statement: The best properties among evaluated materials are of the short fibre composites. The evaluated properties are: high natural frequency, short damping time and large specific modulus of elasticity. Although the C/SiC material is of third natural frequency, it is of the shortest damping time and of the largest specific modulus of elasticity. Other materials are about the same properties considering the all mentioned three factors together.

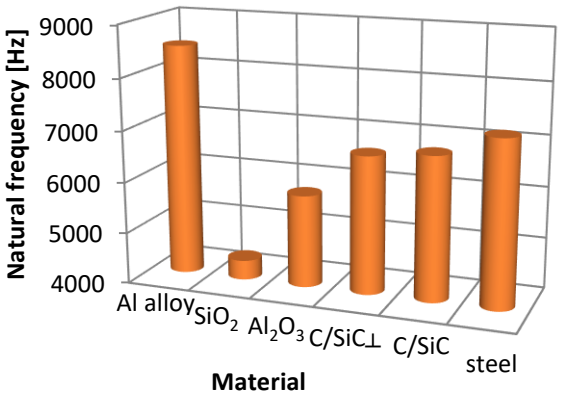


**Fig. 4.** Natural frequency (first) – cylindrical specimens

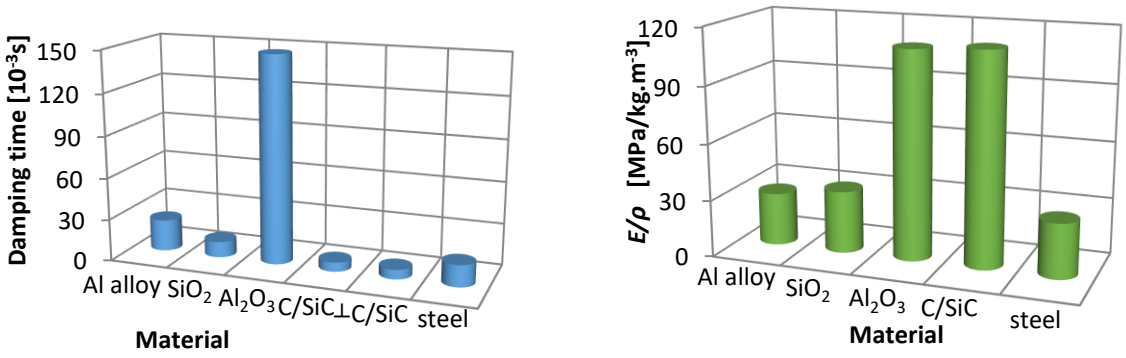


**Fig. 5.** Damping time and specific modulus of elasticity

Fig. 6 shows typical shape of narrow and wide frequency zone of dynamic response. The dominant natural frequency is not evident for aluminium alloy, C/SiC and C/SiC⊥ specimens. Such property is very suitable for preventing the resonance comparing with steel, $SiO_2$ and $Al_2O_3$ specimens that have narrow frequency zone with one dominant natural frequency. $Al_2O_3$ specimen has several times longer damping time comparing with others. If the non-damped $Al_2O_3$ specimen (or component) would be excited by dynamic force, the vibrations would be larger. One can see that damping time is very short in case of composite material specimens. Such materials are very appropriate for designing the components intended for dynamic load with variable exciting frequencies.

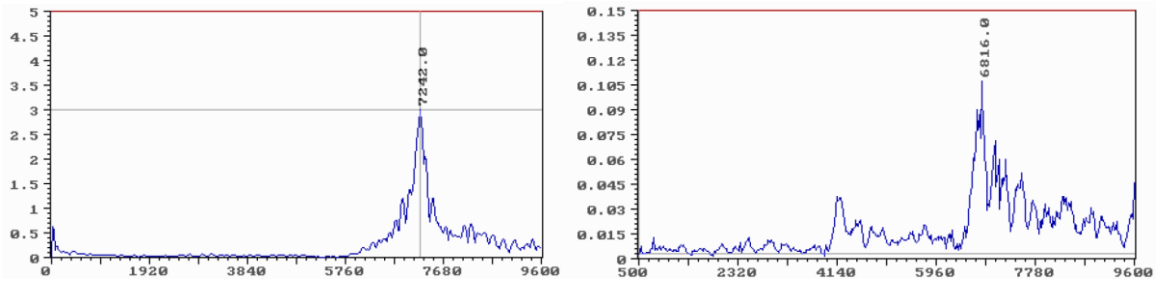


**Fig. 6.** FFT spectrum (dependence of frequency and magnitude vibration velocity) of standard steel (up) and short fibre composite C/SiC (down), measuring 1

*3.2. Measuring 2*

The plate specimens are of different material configuration (Tab. 1 and Fig. 3) and different material of fibres. The 1st natural frequency is higher in case of carbon fibre laminate for all impact forces (F1 – F4), but the 2nd natural frequency is larger for glass fibre laminate (Fig. 7).

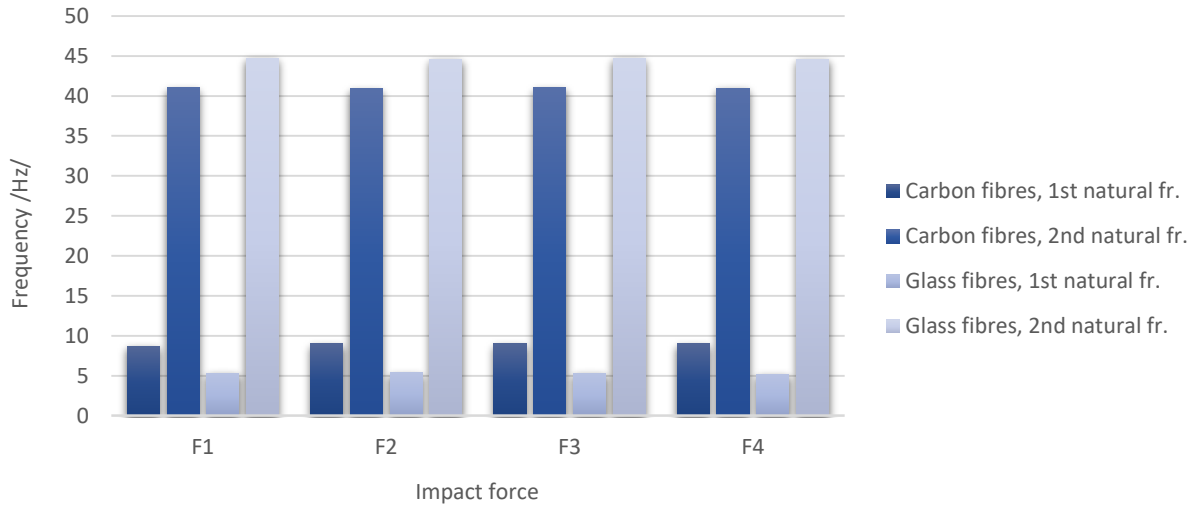


**Fig. 7.** Natural frequencies – plate specimens

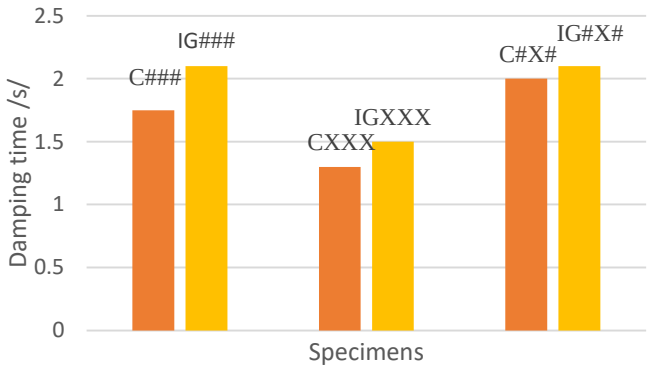


**Fig. 8.** Damping time for individual specimens excited by same impact force and comparison of damping time of carbon and glass fibres

The damping time of carbon laminate fibers is shorter comparing to glass fibers while the weight is lower. The longest damping time is for specimens numbered 3 (2 s) and 6 (2,3 s) that have configuration #X#. The shortest damping time is for specimens numbered 2 (1,3 s) and 5 (1,5 s) that have configuration XXX.

We can make statement that the material configuration influencing more damping time as natural frequency.

## 4. CONCLUSIONS

The study of various types of the fibre (long and short) composites focusing on impact load showed the specific and useful properties of fibre composites for dynamic load. Fibre reinforcement is beneficial for dynamic performance. We suppose that the relatively large surface of interfaces of short fibres and matrix contributes to damping properties. Despite the fact that fibres are stiff, the effects on fibre-matrix interface are the source of fine damping and energy dissipation.

Evaluating and observing the results, we can make statement that dynamic response of homogenous (homogeneity is the idealization) and non-homogeneous (composite) materials is different. The natural frequency zone (in FFT spectrum) of layered laminate and steel is characterized by one sharp peak

comparing to several peaks of short fibre composite and aluminium alloy that form the wide frequency range without sharp peak of significant frequency. Such materials are appropriate for dynamic performance as in machine tools working conditions.

We confirm that macroscale dynamic properties (mainly material damping) of fibre composites can be modified by microscale inner structure. It provides the options to control macroscale dynamic properties through the microscale material configuration.

## ACKNOWLEDGMENTS

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