Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Investigation of Vibration Assisted Machining Impact on Aluminium Surface Quality

Master’s Final Degree Project

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Kaunas, 2019

Kaunas University of Technology
Faculty of Mechanical Engineering and Design

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Mechatronics (6211EX017)

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Declaration of Academic Integrity

I confirm that the final project of mine, Vilmantas Sudaris, on the topic „Investigation of Vibration Assisted Machining Impact on Aluminium Surface Quality“ is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarised from any printed, Internet-based or otherwise recorded sources. All direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by Law) have been paid to anyone for any contribution to this project.

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(name and surname filled in by hand) (signature)

Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Task of the Master's final degree project

Given to the student – Vilmantas Sudaris

1. **Title of the project –**

Investigation of Vibration Assisted Machining Impact on Aluminium Surface Quality

(In English)

Vibrofrezavimo poveikio aliuminio paviršiaus kokybei tyrimas

(In Lithuanian)

2. **Aim and tasks of the project –** The aim of this research is to evaluate the real world application and advantages of vibration-assisted aluminium machining process in comparison to conventional machining process by comparing surface roughness.

Tasks of the project:
1. Analysis of scientific literature sources.
2. Numerical simulation of milling process.
3. Experimental validation of simulation results.
4. Economic impact of ultrasonically assisted milling in relation to conventional milling.

3. **Initial data of the project –**

N/A

4. **Main requirements and conditions –**

Main requirements:
1. Experiments shall be carried out using CNC machines used for serial production.

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Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: ultrasonics, machining, aluminium, surface roughness, vibration-assisted.

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Summary

The aim of this research is to evaluate the real world application and advantages of vibration-assisted aluminium machining process in comparison to conventional machining process by comparing surface roughness in unstable cutting conditions. In order to accomplish this goal, four task were set: 1) to analyze scientific research; 2) to do a numerical simulation of the machining process; 3) to verify the results of the simulation by experiments; 4) to compare conventional machining process to vibration assisted machining process economically.

After the analysis of scientific literature, there was a clear tendency of improved machining results in all areas – tool wear reduction, surface quality improvement, cutting force reduction, etc. However, all of the experimentation was done in stable conditions. Therefore, potential analysis of high frequency excitation effect on surface roughness seemed relevant.

Afterwards, numerical simulation of tool excitation frequency and workpiece frequency response was carried out. After simulation the excitation frequency was selected and potential reduction in vibration amplitudes was evaluated.

Experimental session consists of 4 endmill tests with various levels of deterioration – from new endmill to severely damaged. Each endmill made two cuts – conventional cut and vibration assisted. Afterwards, surface roughness was measured and results compared.

These conclusion were made:

1. After analyzing scientific literature and previously done experimentation the conclusioncan be made that vibration assisted machining currently is very relevant as many different processes are investigated with a lot of potential results (surface finish improvement, tool life extension, etc.). However, all analysis is based on stable cutting conditions.
2. After carrying out the numerical simulation of tool resonant frequency and two step workpiece frequency response analysis, two conclusions can be made: the excitation frequency of the tool should be ~23 kHz (minor adjustments may occur because the tool stickout might variate in small way). Potentialy, the vibration amplitudes at different points can be reduced 0,3 – 50,8 times. This great variation shows that improvement of vibration amplitudes very strongly depend on cutting conditions.
3. After experimentation session, the results show that in all cases the high frequency excitation improved the surface roughness compared to conventional milling. The improvement level depends on the severity of the tool wear. When the tool is new, the surface quality improvement was 13%, but when the tool is blunt and has some slight chipping at the cutting edge, the surface

roughness improvement reaches only 10 – 11%. Finally, severely damaged tool showed only 7 % improvement in surface roughness.

4. On average, the improvement was 10 % therefore the tool life could be extended up to 10 %. This would save companies ~4,5 €/endmill used. Finally, potentionally other unstable cutting conditions could be improved by high frequency excitation of the tool.

Sudaris, Vilmantas. Vibrofrezavimo poveikio aliuminio paviršiaus kokybei tyrimas . Magistro baigiamasis projektas, vadovas/vadovė doc. dr. Vytautas Ostaševičius; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

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Santrauka

Šio tyrimo tikslas yra realaus vibrofrezavimo panaudojimo ir privalumų įvertinimas apdirbant aliuminį lyginant su tradiciniu apdirbimu vertinant paviršiaus šiurkštumą gautą apdirbant nestabiliomis sąlygomis. Šiam tikslui pasiekti buvo iškeltos keturios užduotys: 1) išanalizuoti mokslinę literatūrą šia tema; 2) atlikti proceso skaitinę analizę; 3) eksperimentais patikrinti skaitinės analizės rezultatus; 4) įvertinti ekonominį poveikį naudojant vibrofrezavimą lyginant su tradiciniu apdirbimu.

Atlikus mokslinės literatūros analizę pastebėta tendencija įvairių procesų tyrimuose – įrankio dilimo mažėjimas, paviršiaus kokybės gerėjimas, pjovimo jėgų sumažėjimas ir t.t. Tačiau visi bandymai tyrimuose buvo atlikti stabiliomis apdirimo sąlygomis. Todėl potencialus įrankio aukšto dažnio sužadinimo poveikis paviršiaus kokybei atrodo aktualus.

Atlikus literatūros analizę, buvo atlikta skaitinė analizė reikiamam sužadinimo dažniui nustatyti bei ruošinio atsako į tokį sužadinimo dažnį įvertinti. Po analizės buvo parinktas sužadinimo dažnis bei įvertintas potencialus vibracijų amplitudžių lygio sumažėjimas.

Bandymų serija sudarė 4 pirštinių frezų su skirtingais nusidevėjimo lygiais tyrimas – pradėta nuo nuajos frezos iki stipriai apgadintos. Kiekviena freza atliko du pjūvius – vieną įprastą, kitą su aukšto dažnio sužadinimu. Po to, buvo pamatuotas paviršiaus šiurkštumas ir rezultatai palyginti.

Buvo prieita šių išvadų:

1. Po literatūros analizės nustatyta, kad šiai dienai vibroapdirbimo tema yra aktuali ir atliekami įvairių procesų bandymai rodo daug potencialo (paviršiaus kokybės pagerėjimas, įrankio gyvenimo laiko prailginimas ir t.t.). Tačiau visi bandymai atlikami stabiliomis sąlygomis.

2. Atlikus skaitinę analizę nustatyti įrankio rezonansiniai dažniai bei ruošinio atsakas į žadinimą. Parinktas žadinimo dažnis yra ~23 kHz. Potencialiai vibracijų amplitudes galima sumažinti 0,3 – 50,8 karto. Didelė variacija rodo didelę proceso stabilumo įtaką.

3. Atlikus bandymus, visais atvejais paviršiaus šiurkštumas pagerėjo lyginant su tradiciniu apdirbimu. Gerėjimo lygis priklauso nuo įrankio nudilimo lygio – naujo įrankio šiurkštumas pagerėjo 13 %, tuo tarpu nudilusio ir aptrupėjusio – 10 – 11%. Galiausiai, labiausiai nudilusio įrankio paliktas paviršiaus šiurkštumas pagerėjo 7 % lyginant su tradiciniu apdirbimu.

4. Vidutiniškai paviršius pagerėjo ~10%, tad įrankio gyvenimo laikas gali pailgėti iki 10 %. Tai leistų sutaupyti po 4,5 €/frezą. Galiausiai potencialus pagerėjimas nestabiliomis sąlygomis turėtų pasikartoti esant ir kitokiam apdirbimui, kas leistų taupyti įrangos kaštus.

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Introduction

In modern manufacturing world it is becoming progessively harder to gain the competitive edge over the competition. Companies must reduce production costs and improve quality at the same to keep the clients satisfied. In order to achieve this, continious research, development and investment in both production processes and new technologies has to be ensured. One of the ways to reduce production costs is to reduce number of operation, thus eliminationg costs of additional operations, prolonged storage, logistics and administration. To increase quality investment in new technology is vital. Therefore, technology that offers both increased quality and reduced overhead costs is especially attractive. A good example of such technology is vibration assisted machining. In this paper, vibration assisted machining's (milling) impact on surface quality (surface roughness and geometrical tolerances) will be investigated. The focus is on macromachining process in long part fabrication.

The main hypothesis of the research: the quality (surface roughness and flatness) of machined aluminium suface can be improved by excitation of the cutting tool with periodic high frequency vibrations.

The aim of this research is to evaluate the real world application and advantages of vibration-assisted aluminium machining process in comparison to conventional machining process by comparing surface roughness.

To achieve the aims of this research four main tasks were formulated:

1. Analysis of scientific literature sources.

2. Numerical simulation of milling process.

3. Experimental validation of simulation results.

4. Economic impact of ultrasonically assisted milling in relation to conventional milling.

1. Analysis of previous research and testing method selection

In order to evaluate the research in terms of relevance and novelty, previously done research is analyzed. Beside the relevance and novelty, testing methods will be analyzed in this chapter as well.

1.1. Analysis of the previous research

To understand if the research is important or not, previously done research is analyzed to find is similar topics have been recently researched. The results of such investigations will show if the topic is proven to have potential or it is proven ineffective and not worth pursuing.

The beginning of the more research in this field begins with D. Kumabe [1] in 1979. Many later investigations reference this work. About fifteen years later V.I. Babitsky et al published a series of more extensive research with multiple papers where he investigates vibro-impact systems, ultrasonic cutting and autoresonance [2]. Starting from 1995 such research was quite popular as it showed promising results and a lot of different aspect where experimented with – different cutting processes and material behaviours were tested and changes in surface roughness, tool life, cutting forces and temperatures where observed. However, currently in manufacturing the technology is changing almost evey year – starting with information technologies to modern engineering materials. Advances in information technologies enabled machine manufacturers to build better control systems, which in turn enabled the application of modern manufacturing techniques that required much higher computing capability but could deliver much better results simply by running a smoother operation. Having the ability to better control the process allowed engineers to achieve more precision and accuracy, therefore, better machines can be produced. Finally, adding the advances in material science and processing, new materials and new applications for existing materials are discovered everyday – this gives machine designers new alloys and even new types of materials to work with [3]. As a result, modern fabrication enterprises can use only one computer numerically controlled (CNC) machine to replace the job of multiple machines from 30 years ago and achieve much greater results than previously was expected. For example, CNC machines now can achieve surface roughness that previously could only be achieved by surface grinding. Naturally, such improvements have raised the expectations of machine and industrial designers and the manufacturing processes are being studied constantly and vibration assisted machining is not an exception. The focus in this chapter will be on advances in the more recent research as most of it is based on work published by Babitsky and other scientists' from that time period.

1.1.1. Application in drilling process

Drilling is one of the most popular conventional machining methods [4]. It is mostly used because this machining process has a large material removal rate compared to other machining methods. That is one of the reasons why quite a lot of experimentation is done to analyze vibration assisted machining to improve this process [4-9].

M. Ubartas, et al. carried out a series of experiments to analyze vibration assisted drilling process [9]. In this investigation the cutting force, torque and surface finish were measured and the results were compared with conventional machining results. The results have shown that the surface finish quality has increased up to 25 %, axial force decreased up to 46 % and torque up to 20 % compared to conventional drilling.

These results correlate with other experiments carried out – the advantages of vibration assisted drilling or ultrasonically assisted drilling include reduced drilling torque and reaction force, increased material removal rate, better surface quality, strongly improved chip evacuation, increased accuracy of hole position, surface quality, smaller geometrical and size deviations, reduced burr formation and extended tool life [8, 10]. These advantages can be used directly in the industry as it can directly influence costs – longer tool life means smaller expenses for tooling, material removal rates means increased productivity and better hole accuracy, better surface quality and elimination of burr means that additional deburring and finishing operations are not required.

A very promising application of vibration assisted drilling is the processing of hard to machine and brittle materials [7]. The application of this material group ranges from precision electronics to medical applications and in these fields the quality requirements are very high. Just as in the previously described applications, in the studies of glass plate and bone drilling [7] reduction of cutting forces and thrust was observed. Some level of crack prevention was also observed, however, there are more factors that influence cracking, for example, tooling geometry, so this application stillneeds to be researched more. Significant reduction in machining temperature can also be achieved when using vibration assisted drilling which is a very important factor in medical applications.

To sum up, multiple studies and investigations have showed that vibration assisted drilling has undeniable advantages which include quality, precision, productivity, and costs reduction. Benefits can be observed in various materials, some of which have specific machining limitations ultrasonic tool excitation helps to overcome (brittleness of material or reduced machining temperatures).

1.1.2. Application in turning process

Drilling is a rather simple process where feed force is working in only one direction or axis. There is an additional direction or axis in turning process which has an impact on all major factors of machining quality evaluation – surface finish, geometric tolerances (in case of turning it is mostly roundness, cylindricity and radial run-out and tool life. Application of vibration assisted turning has positive effects on all of the mentioned factors as well as heat reduction. However, some studies show that in some combinations of materials and cutting conditions, vibration assisted turning might increase the temperature in the cutting zone because of increased friction between the tool and the chip, therefore additional research needs to be done in order to have firm understanding. [6, 11-14].

Most researched materials for vibration assisted turning is for aerospace application. It includes materials such as nickel based alloys, stainless steels, titanium alloys, aluminium and composite materials [12, 15 – 18]. As previously mentioned the benefits of vibration assisted turning were observed in cutting aviation grade nickel based alloys. In the same study [12] steel was turned to compare the results achieved on aviation materials - even greater improvements compared to nickel based alloys were observed in steel. A study of vibration assisted turning of Ti-15333 (titanium alloy) [15] showed that there was a maximum reduction 77 % in cutting forces (200 μm depth of cut, 10 m/min cutting velocity). In this study, cutting temperature was measured and higher cutting temperature was observed in vibration assisted turning. However, the average temperature of cutting tool in vibration assisted turning was lower compared to conventional turning which can result in extended tool life. The numerical model showed that vibration assisted turning could have up to five times higher material removal rate compared to conventional turning [15]. During tests in aluminum and composite [16, 18] material improvements in surface quality, reduction in cutting forces and tool wear were observed and it confirms the findings of previously mentioned studies of different materials.

One more important finding from previous studies is that the experimental system to study ultrasonically assisted machining can be assembled using components that are available commercially (with some adaptation and modifications). This potentially is a very serious factor because this means that these systems could be easily introduced to fabrication plants without very high investments – this and the fact that the surface roughness can be decreased by 25 – 40% can be very appealing to the manufacturing companies.

1.1.3. Application in milling process

Investigations done on vibration assisted milling are mostly divided in micro end milling [19, 20, 21] and macro scale machining [22, 23, 24]. The focus of most studies are on surface finish quality [19, 20, 22, 21, 24] because it is a most sensitive factor that represents any variation in machining parameters.

Surface finish quality, as in previously discussed vibration assisted drilling and vibration assisted turning applications, increases when the machining is done with vibration assisted milling process. Investigation of vibration assisted machining of aluminum EN AW 6060 [24] showed up to 44 % reduction of surface roughness. This finding confirms other research results [21] – increment in vibration amplitude or frequency results in higher surface quality. Experimental study [21] was done on hardened tool steel where it was observed that there is a surface finish improvement when high frequency vibrations are introduced to either cutting tool or the workpiece. In Figure 1, the dependency between surface roughness and vibration amplitude as well as surface roughness and frequency can be observed.

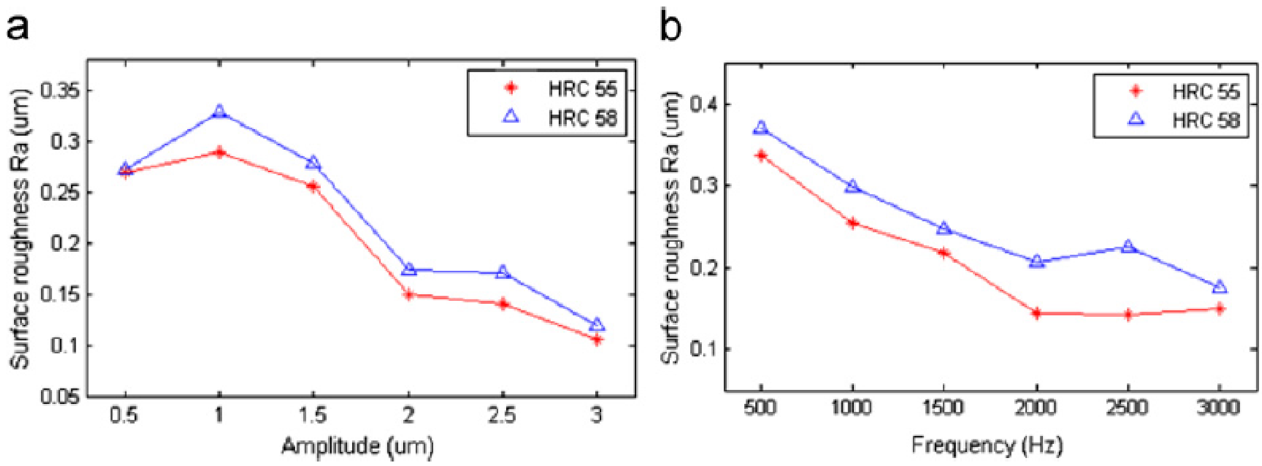

Figure 1. Dependency between surface roughness and: a) amplitude; b) frequency. [21]

In the Figure 1 graph "a" shows that the surface roughness is decreased by increasing the amplitude of the vibrations whereas graph "b" shows how much surface roughness decreases when the vibration frequency is increased.

However, X. H. Shen et al. [19, 20] have concluded that vibration assisted micro end milling process had a negative effect on surface finish on the machined slot floor. They attributed this finding to the elliptical two-dimensional tool trajectory [5, 6]. The test surfaces can be seen in Figure 2:

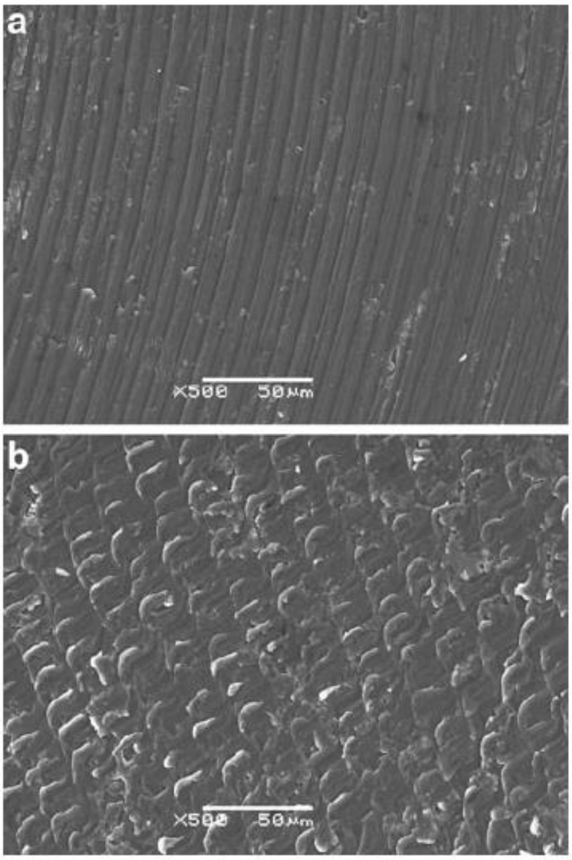

Figure 2. Slot bottom surfaces: a) conventional milling; b) vibration assisted milling. [19]

The surface in Figure 1 b) is much more complex than created after conventional milling (Figure 1 a)) - that results in higher surface roughness. The same study investigated not only surface finish on slot bottom but the surface quality of vertical walls as well. A smoother surface was observed in this case. Therefore, the study concluded that vibration assisted milling had a positive effect on slot vertical walls but had a negative effect on machined slot bottom.

Tool wear is another important factor in machining process – it affect surface quality, accuracy and precision, production costs, etc. Previously mentioned study about vibration assisted micro end milling of hardened tool steel [21] had some promising observations about tool wear. Conventional milling left the tool flanks chipped. In case of vibration assisted micro end milling the tool did not have major signs of wear. Such results indicate that machining with vibration assisted cutting tool reduces its wear by preventing chiping. In addition to reduced tool wear, the burr formation was reduced as well - 18 % burr reduction when using down milling in vibration assisted milling compared to conventional milling [25]. Burr removal in micro endmilling is a complicated task so limiting burr formation is a significant achievement.

Interesting results were observed in cases of plastic vibration assisted milling. In a study investigating high frequency vibration applications for surface milling [24] a plastic PA6 was machined. The results showed no difference in surface quality. Authors have concluded that plastic has vibration absorbing qualities and the vibration assisted milling had no effect to surface quality. Another study about vibration assisted milling of plastic was carried out by E. Uhlmann et al. [23]. The aim of the study was to investigate ultrasonic assisted milling of carbon fiber reinforced plastics. No reduction of cutting forces was observed in their experiments. When machining carbon fiber reinforced plastics an important factor is dust concentration as carbon fiber dust is hazardous. In this case vibration assisted milling outperformed conventional milling – authors concluded that dust concentration reduction was up to 80 %. The vibration assisted milling process showed great results in fiber protrusion when using up milling and workpiece quality was improved regarding fiber pull-out when using down milling.

In addition to previously mentioned benefits of vibration assisted milling – improved surface quality, accuracy, reduced cutting forces, extended tool life, reduced burr formation – the material removal rate is increased and heat generation is reduced [6].

1.2. Selection of research methods

1.2.1. Milling operation

Milling is a mechanical machining process when a tool (i.e. endmill, face mill etc.) is rotating and moving in respect of part that is being machined. During this process, the tool cuts a defined thickness of the material off. Milling is one of the most common and effective machining processes [26].

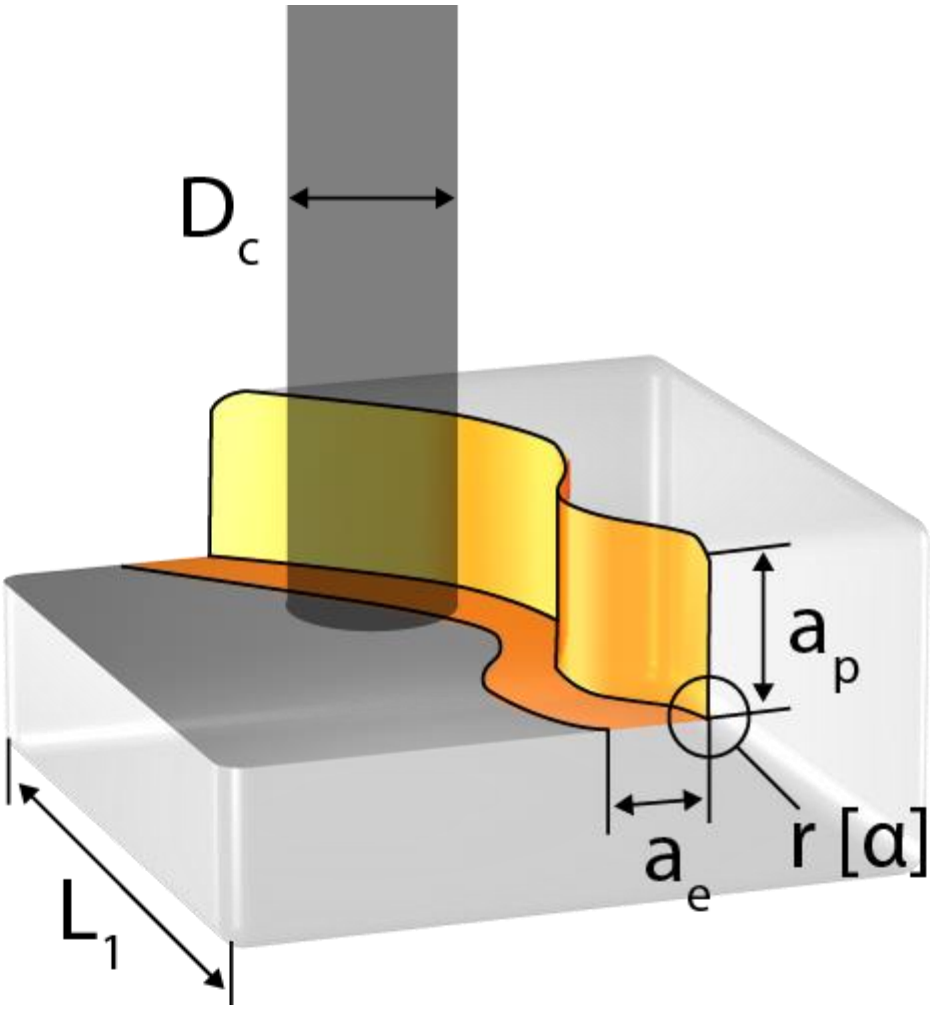

Figure 3. Milling operation parameters [27]

In the Figure 3, some of the main milling parameters are marked:

- D_C – tool diameter, mm

- a_p – depth of cut, mm
- a_e – width of cut, mm

Not marked milling parameters are:

- Feed rate – the speed that the tool moves in relation to part, mm/min
- Spindle speed – the speed at which the tool rotates, rev./min (rpm)
- Number of cutting flutes – number of teeth of the tool.

1.2.2. Vibrations

Modern machining requirements are at all-time high regarding quality and productivity. However, there is always one aspect to consider – unwanted vibration, also known as chatter. According to Wiercigroch et al. [28], chatter, as mentioned before, is unwanted excessive vibrations between the tool and the work piece. Chatter reduces surface quality and that is one of the reasons why simply increasing machining speed results in a poor part quality finish. Another thing is the economical aspect. Chatter strongly accelerates tool wear so increased productivity means increased expenses in this case. The combination of these effects results in shorter machine tool life, safety and milling operation.

When machining speeds increase to 7500 – 45000 rpm, it is considered high-speed machining (higher spindle speeds is called ultrahigh-speed machining) [29]. At higher speeds the dampening or stabilizing effect minimizes. This reason increases the chances to have chatter in the machining process [28]. There are certain limits of stability, more commonly known as stability lobes. At certain higher speeds, there are stability "peaks" where the material removal rate can be increased substantially without increasing chatter. To utilize these spikes of stability, they need to be predicted very accurately [28]. An example of stability lobe diagram can be seen in Figure 4:

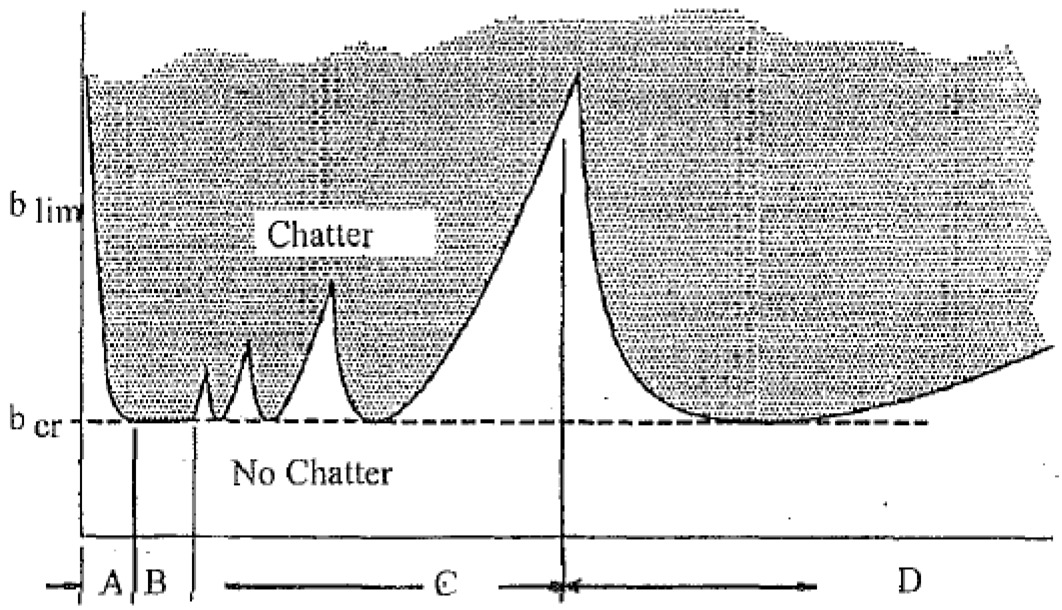

Figure 4. Stability lobe diagram example [29]

The stability lobe diagram depends on every part of the system – machine, tool holder, tool, fixture and work piece. In the example (Figure 4), the lobe diagram was calculated for Ø25 mm two flute endmill. Range A is called a low-speed machining range with machining speeds up to 2300 rpm. Range B is machining speed midrange with spindle speeds of 2300 – 7500 rpm. This range as it is visible from lobe stability diagram has no obvious stability effects. Most stability effects are observed in high-speed machining speed range as mentioned previously in this chapter [29].

1.2.3. Eigenfrequencies and eigenmodes

Eigenfrequencies, also known as natural frequencies, are certain frequencies of a given system at which the system resonates and strongly increases amplitude of the oscillation [30].

When the system is periodically excited and the frequency of excitation matches systems natural frequency (or eigenfrequancy), the vibration amplitude increases drastically and changes the shape of the part. These shapes are called eigenmodes and certain eigenmodes appear at certain eigenfrequencies. When performing an Eigenfrequency analysis, the eigenmodes (vibration shapes) and natural frequencies can be found – not the exact amplitude, because only the material properties, geometry and boundary conditions are evaluated. To know the exact values of vibration amplitude, the excitation frequency and amplitude is needed [30].

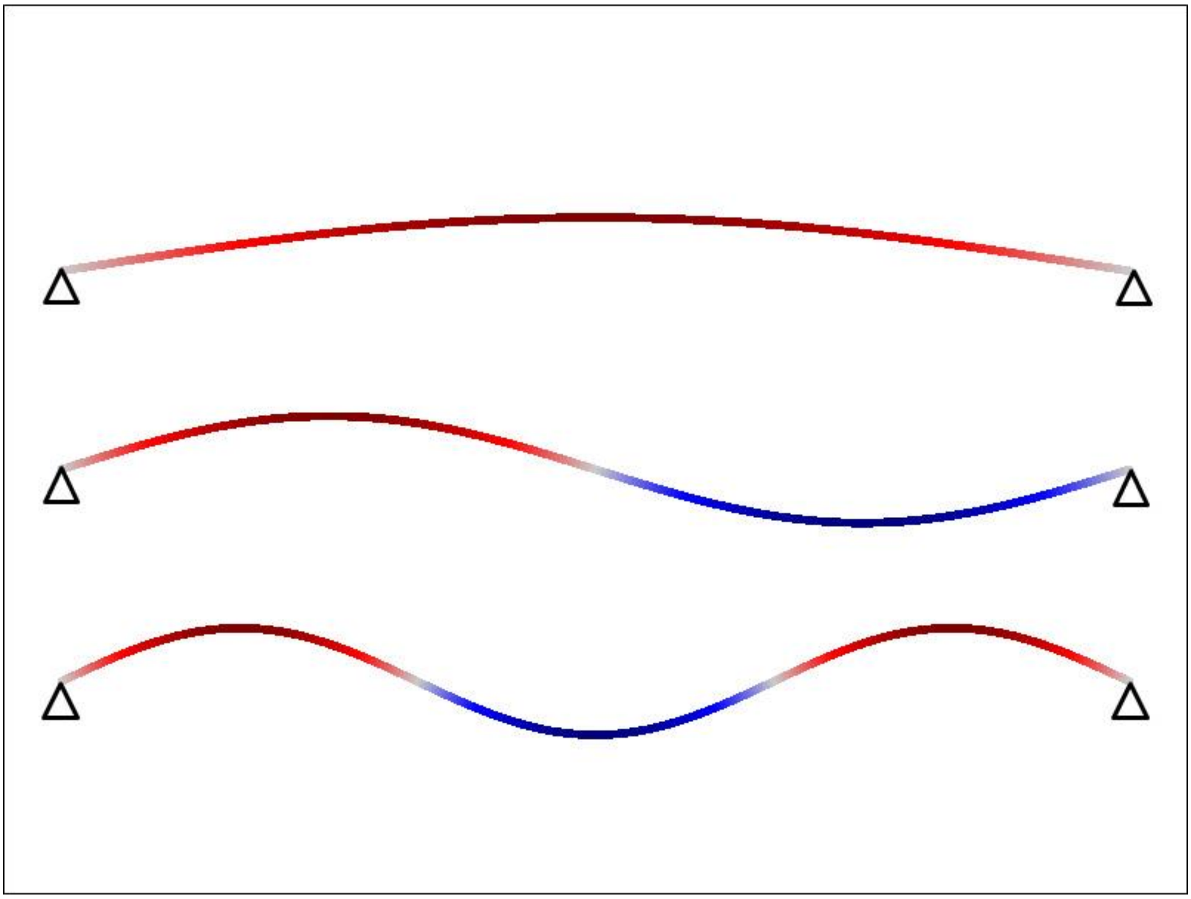

Figure 5. First three eigenmodes of supported beam structured [30]

1.2.4. Vibration types

Vibrations are classified into a few categories.

First of all, there are free vibrations. This type of vibration is only theoretical because in reality it is always dampened. Free vibrations can be described with a mathematical formula:

$$m\ddot{u} + ku = f(t) \tag{1}$$

Here m – mass, $\ddot{u}$ – acceleration (or second derivative of displacement), k – stiffness coefficient, u – displacement.

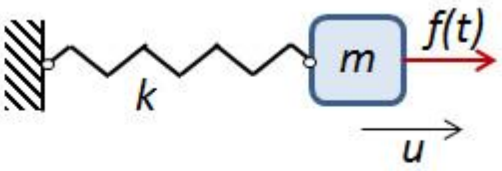

Figure 6. Undamped system [30]

Natural angular frequency ω_0 can be calculated with formula (2):

$$\omega_0 = \sqrt{\frac{k}{m}} \tag{2}$$

Natural angular frequency ω_0 is related to natural frequency f_0 as follows:

$$\omega_0 = 2\pi f_0 \tag{3}$$

In other words, if the mass on the spring would be excited, it would oscillate forever unless external force or damping is introduced. As mentioned before, in reality systems are always damped.

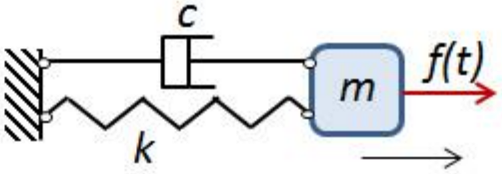

Figure 7. Vibrating system with damping [30]

Damped vibrations can be described with a following equation:

$$m\ddot{u} + c\dot{u} + ku = f(t) \tag{4}$$

Here c – is damping coefficient, $\dot{u}$ – speed (or first derivative of displacement).

If harmonic vibrations are analyzed, harmonic functions are replaced by e^{iwt}. Displacement can be described as $u = \tilde{u}e^{i\omega t}$. Here $\tilde{u}$ is amplitude. Each derivative gives $i\omega$. Then

$$(-\omega^2 m + i\omega c + k)\tilde{u}e^{i\omega t} = 0 \tag{5}$$

When $\tilde{u} \neq 0$ then

$$-\omega^2 + i\omega\frac{c}{m} + \frac{k}{m} = 0 \tag{6}$$

When (2) and

$$\zeta = \frac{c}{2\sqrt{km}} \tag{7}$$

The eigenvalue then is expressed as follows:

$$-\omega^2 + i\omega\frac{c}{m} + \frac{k}{m} = 0 \tag{8}$$

Here, ω_0 – undamped natural angular frequency, ζ – relative damping. Eigenvalues are the solutions to the quadratic equation:

$$\omega_{1,2} = \omega_0(i\zeta \pm \sqrt{(1-\zeta^2)}) \tag{9}$$

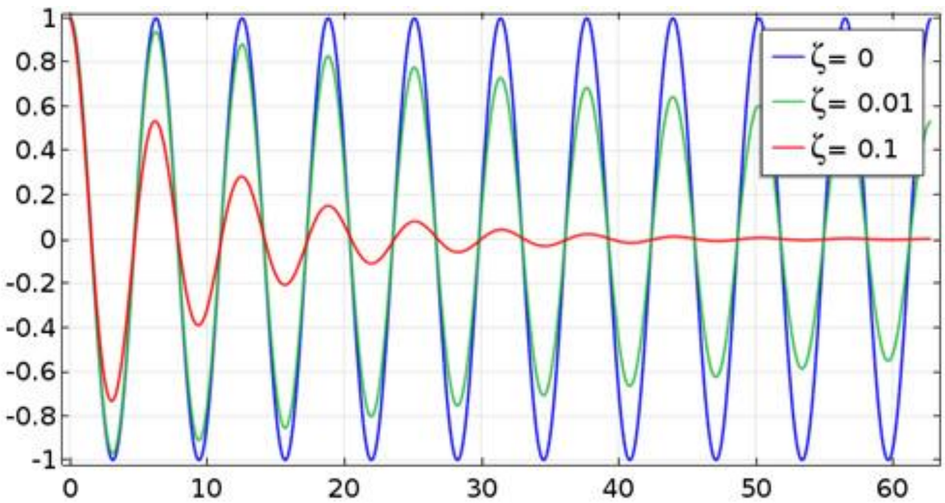

Figure 8. Fading vibrations with different damping coefficients [30]

1.2.5. Machining frequency

In the milling process, excitation frequency depends on spindle and tool. First, the spindle speed – if the spindle rotates faster (more revolutions per minute), the cutting edge of the tool hits the material more often. Following this logic – if the tool hits the material once every rotation then the frequency is:

$$f_t = \frac{n}{60} \tag{10}$$

Here, f_t (measured in Hertz) is tool excitation frequency which in literature is referred as tooth passing frequency [31, 32, 33], n – revolutions per minute (RPM). It is divided by 60 to have revolutions per second instead of revolutions per minute. This expression, however, does not evaluate the parameters of tool – different tools have different number of cutting teeth. So every time the tool rotates, the material is hit number of times equal to the number of cutting teeth on the tool. So the expression is as follows:

$$f_t = \frac{zn}{60} \tag{11}$$

Here, z is number of teeth on a cutting tool.

1.2.6. Vibration assisted cutting

Vibration assisted machining is a machining technology where conventional or advanced machining method is used with small amplitude vibrations in order to achieve better machining results [5, 6]. A small amplitude with high or low frequency can be applied in a few different ways: through cutting tool excitation when a toolpath is directly adjusted or through workpiece excitation when a fixed stock material is vibrated. Another option would be to combine both previously mention methods [43]. Vibration assisted machining can be classified into two main categories: Resonant systems and non-resonant systems. Resonant systems can operate on discrete frequencies greater than 20 kHz with amplitudes up to 6 µm. Non-resonant systems can operate on frequencies from 1 kHz to 40 kHz with amplitudes up to 0,06 mm. [5, 6]. These systems can be categorized according to mode of excitation which is applied to cutting tool or workpiece. They can be categorized to 1 D (one dimentional) and 2 D (two-dimentional) systems. In 1 D system, the vibrations are applied along the rotation axis of the cutting tool. In 2 D system, vibrations cause the tool to move in elliptical trajectory [5, 6].

The process of vibration assisted cutting is very well illustrated by D.E. Brehl and T.A. Dow:

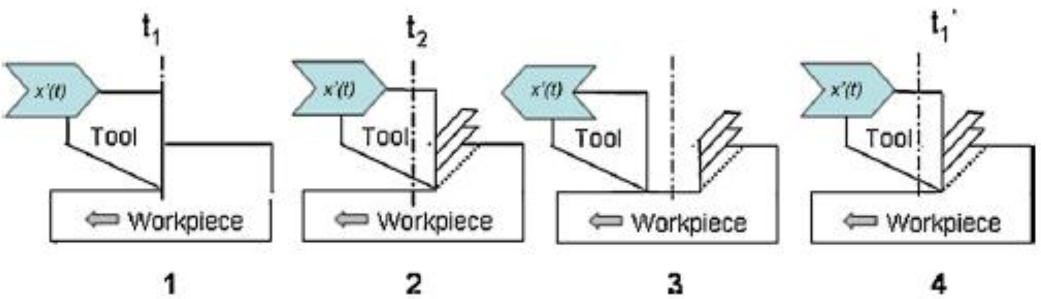

Figure 9. One dimentional vibration assisted machining process. [5, 6]

In the first picture of Figure 1 the tool is about to enter and cut the material. In the second picture the tool has already cut into the material and is about to retract from it because of vibration – that can be seen in the third picture: tool has left the material therefore reducing cutting forces. After that, the tool is pushed back into the material and cuts the material again (fourth picture of Figure 9).

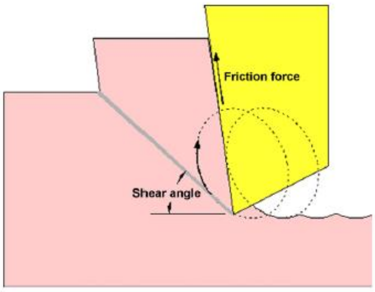

Figure 10. Two-dimensional vibration assisted machining process [5, 6]

In Figure 2 two-dimensional vibration assisted machining process can be observed. Here the vibration adjusts the tool trajectory in two axis. Because either the tool or workpiece moves in a direction of the cutting feed, oscillation in two axis creates an elliptical toolpath as previously mentioned. One more factor can be clearly seen in Figure 10 – the depth of cut. The reduction of cutting forces is based on the tool removing the pressure from the tool, which is pushing against the material, or sometimes the tool leaves the material completely. In order to achieve that the vertical amplitude of the vibration has to exceed the depth of cut. Two-dimensional vibration assisted machining system tend to be used in precision machining applications with depths of cut from around 1 μm and up to 50 μm. One dimensional vibration assisted machining systems, however, are used in precision machining as well as in traditional machining operations with depths of cut up to 0,5 mm. [5, 6].

1.2.7. Vibration sensing with accelerometers

There are two types of vibration sensors – contact and non-contact. Most popular contact type vibration sensors are accelerometers. Accelerometers are attached to vibrating part and then they convert mechanical energy into electrical energy. There are several types of accelerometers are used for vibration measurement [34].

Capacitive MEMS accelerometers. These micro-electro-mechanical systems are very cheap and they are very small in size. That makes them very popular to use in smart phones. In spite of their low cost and size, they lack accuracy in high frequencies. That makes them unfit for industrial application but very suitable for health tracking applications as consumes very little power [34]. Nevertheless, according a study by Huang et al. [33] the new developments in micro-electro-mechanical systems' accelerometer technology shows that it possible to use MEMS accelerometers for milling process monitoring application. In that study, Huang et al. have compared the piezoelectric accelerometer with MEMS accelerometer and the experimental results have shown that both MEMS and piezoelectric accelerometers have registered the same frequency that matched the tooth passing frequency.

Piezoresistive accelerometers. These vibrations sensors utilize variations of resistance in strain gauges. Their main advantage is a very wide bandwidth. That is used to measure high frequency events. Another advantage is that they begin sensing from 0 Hz, which is needed to evaluate velocity and displacement. However, piezoresistive vibration sensors have some drawbacks. First of all, because of their wide range, the accuracy suffers greatly. Secondly, temperature needs to be considered before using this type of sensor as it has an impact on the readings. Finally, piezoresistive accelerometers are more expensive than their micro-electro-mechanical counterparts [34].

In the modern day industry, most utilized sensor type is piezoelectric accelerometers. This accelerometer type is the most universal and adaptable sensor – there are options of these sensors to measure everything: high and low frequencies, vibrations and shock tests. Piezoelectric sensor use lead zirconate titante – PZT for short – to generate electric signals when they are deformed. Their biggest drawback is that these sensors only generate signal when they are being deformed – this means that only active changes can be sensed. So they cannot be used to identify gravity vector or absolute position (only change in the position) [34].

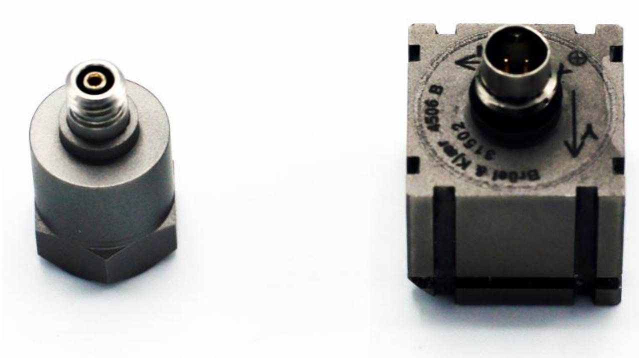

Figure 11. Accelerometers: single axis (left) and triaxial (right) [34]

1.2.8. Vibration sensing with strain gauge

Strain gauge is another contact vibration sensor. This type of sensor is a thin film with conductive grid. This film with the grid is attached to a part or structure that is being measured. When the measured object is deformed (plastic deformation, vibrations or similar) the grid is deformed and the resistance changes. Using this method, stress, strain, force, pressure can be measured. [34, 35].

Strain gauge has many advantages. Firstly, it is very accurate. Because of its size and shape, it can be attached on almost any surface. Its application is very universal – it can measure static and dynamic loads. Because they are very light and thin, they can be attached without any interruption to a functioning mechanism. Besides, compared to other sensor types, they are quite simple, so the price is relatively small. The biggest drawbacks are that they are difficult to install correctly and the signal they are generating is quite weak. Because of that expensive equipment is needed to gather the data [34].

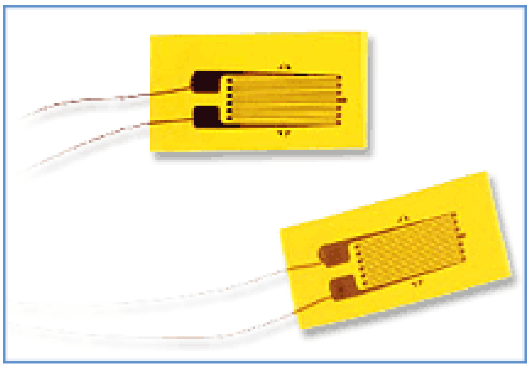

Figure 12. Strain gauge [35]

1.2.9. Vibration sensing with microphone

There are vibration sensors that allows to measure vibrations. One of the most popular and efficient non-contact sensors is microphone. This type of sensor is low cost and it can detect high frequency waves [34]. Microphones do not have certain limitations that other – contact – sensors have. For instance, sensors that have contact with the object that is being measured, at some frequency resonate and that distorts the data. If sensor is moved further away from the vibration source, lack of sensitivity can be observed. Some constructions of contact sensors are limited to only one direction and position. To use the microphone correctly it needs to be placed with enough distance from the source so the source could be considered as a point [36].

There are a few drawback from using microphones. First, if there is a similar frequency and amplitude sound – it can be detected as a real signal. So background noise has a lot of influence on the final result. Another thing, the microphone control system has to be trained in order to detect patterns. Finally, microphones can detect sound in the range of 100 Hz to 13 kHz.

2. Numerical simulation of workpiece frequency response

To evaluate the surface quality after machining we need to evaluate the vibration effects on the workpiece. In order to do this, eigenfrequency and frequency response analysis are done.

2.1. Natural frequencies of the tool and workpiece

2.1.1. Natural frequencies of the tool

In order to have effective tool vibration, the tool has to be excited at its resonant frequency. This way vibration amplitude will become high enough to impact cutting conditions. To determine what frequency to look for, natural frequency analysis is needed. Analysed tool and tool holder geometry is shown in Figure 11:

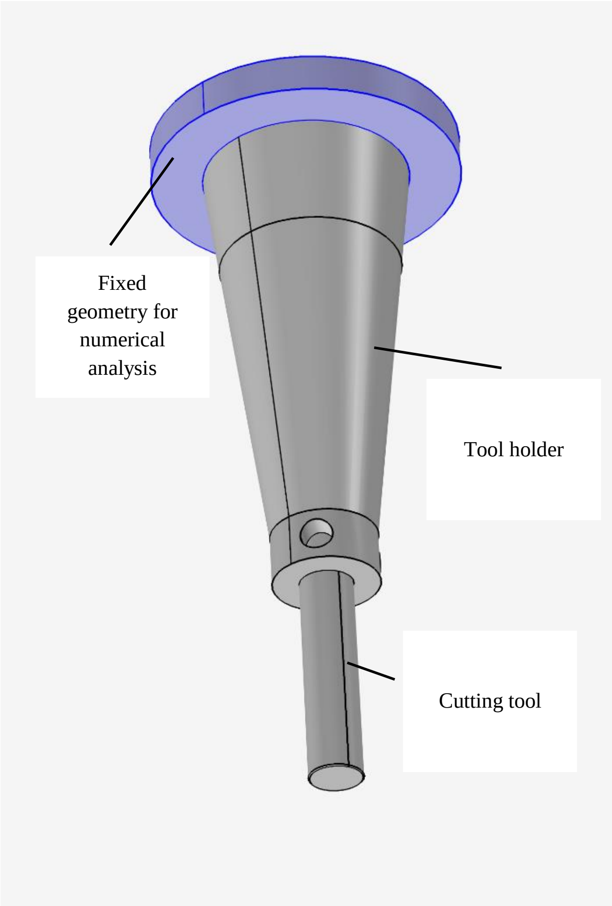

Figure 13 . Analyzed tool and holder geometry

In Figure 11, boundary conditions are marked in blue – blue geometry is fixed. At experimentation stage, displayed geometry will by assembled with a collet tool holder and inserted in CNC machining centre‘s spindle. Geometry marked in blue will be pressed by a collet nut. The cutting tool will be clamped in the tool holder with 3 DIN 912 screws. The results of this analysis are shown in Figure 12:

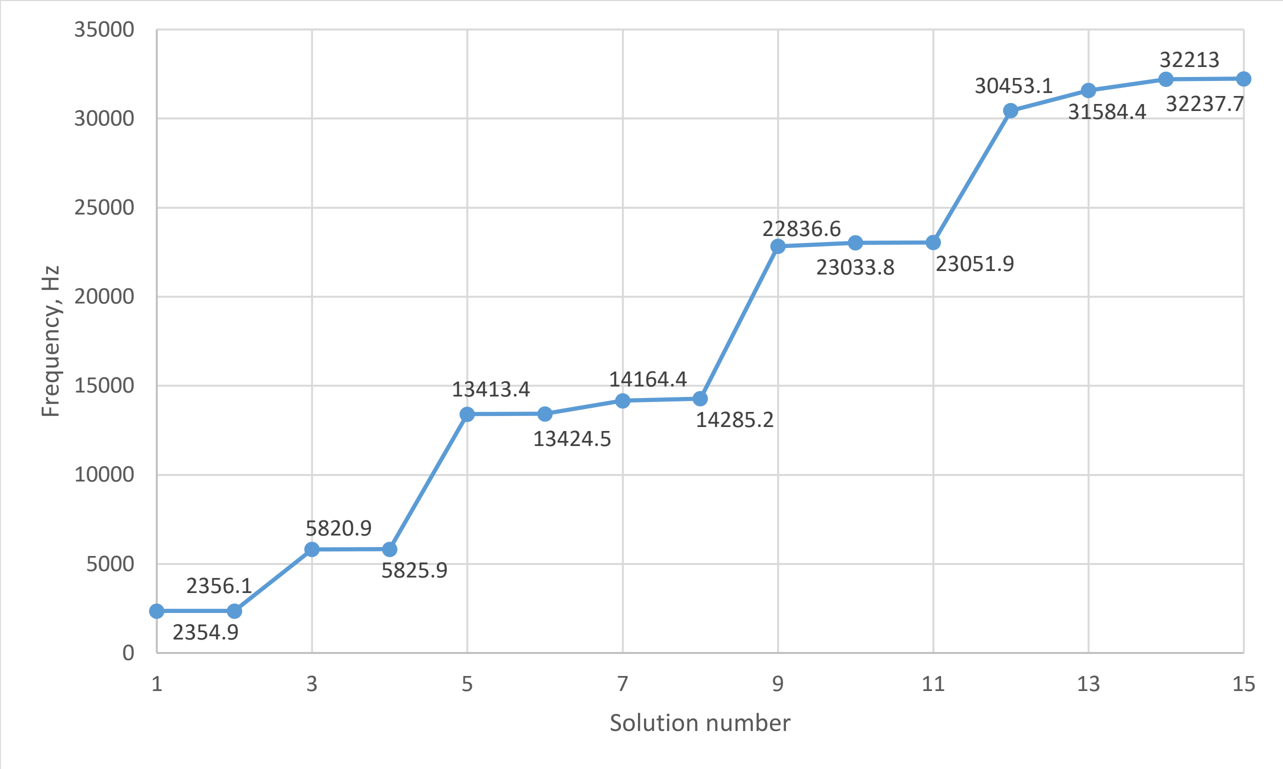

Figure 14. Resonant frequencies of the tool and tool holder

The results show that analyzed system tends to resonate around 5 groups of frequencies: ~2.3 kHz, ~5.8 kHz, 13.4 – 14.2 kHz, 23 kHz and over 30 kHz. In reality these resonant frequencies might not be precisely what was calculated, however, at the experimental stage, this data provides a starting point (frequency might be a slightly different because of the simplification of the simulation model – collet nut, cutting tool fixturing screws are removed for simplicity). These results will also help to identify what frequency to use for tool excitation after the frequency response analysis of the workpiece.

2.1.2. Natural frequencies of the workpiece

This analysis show at what frequencies material of certain geometry that is fixed in a known way tends to resonate with excitation frequency. These frequencies should be avoided because vibration amplitude drastically increases when it resonates with excitation – if such thing happens, cutting condition become extremely unstable which leads to very poor surface quality and potentially damaged cutting tool. If the vibrations become very high – there is a risk to damage tool holder, fixture, workpiece or even machining center. In Figure 13, boundary conditions of the workpiece is shown:

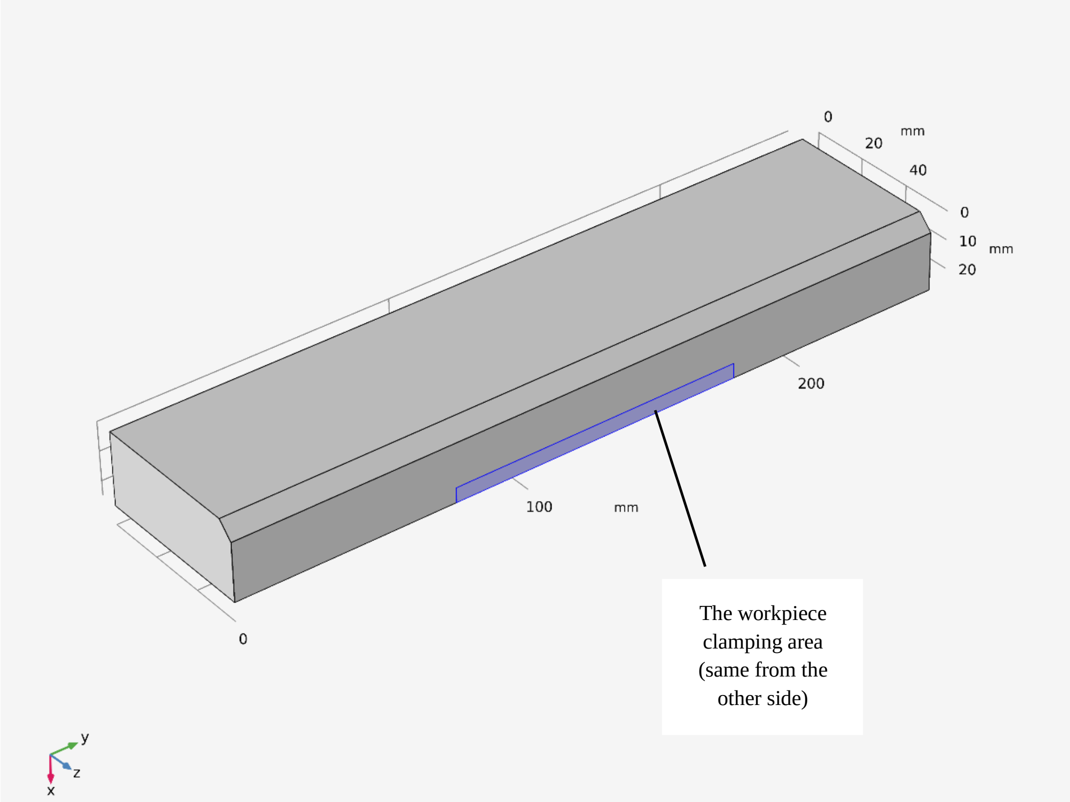

Figure 15. Workpiece geometry and fixturing

In Figure 13 aluminum EN AW 6082 250x58.6x25 mm workpiece is shown. The workpiece is clamped in the middle by a standard vise (100 mm width). After simulation, calculated natural frequencies are shown in Figure 14:

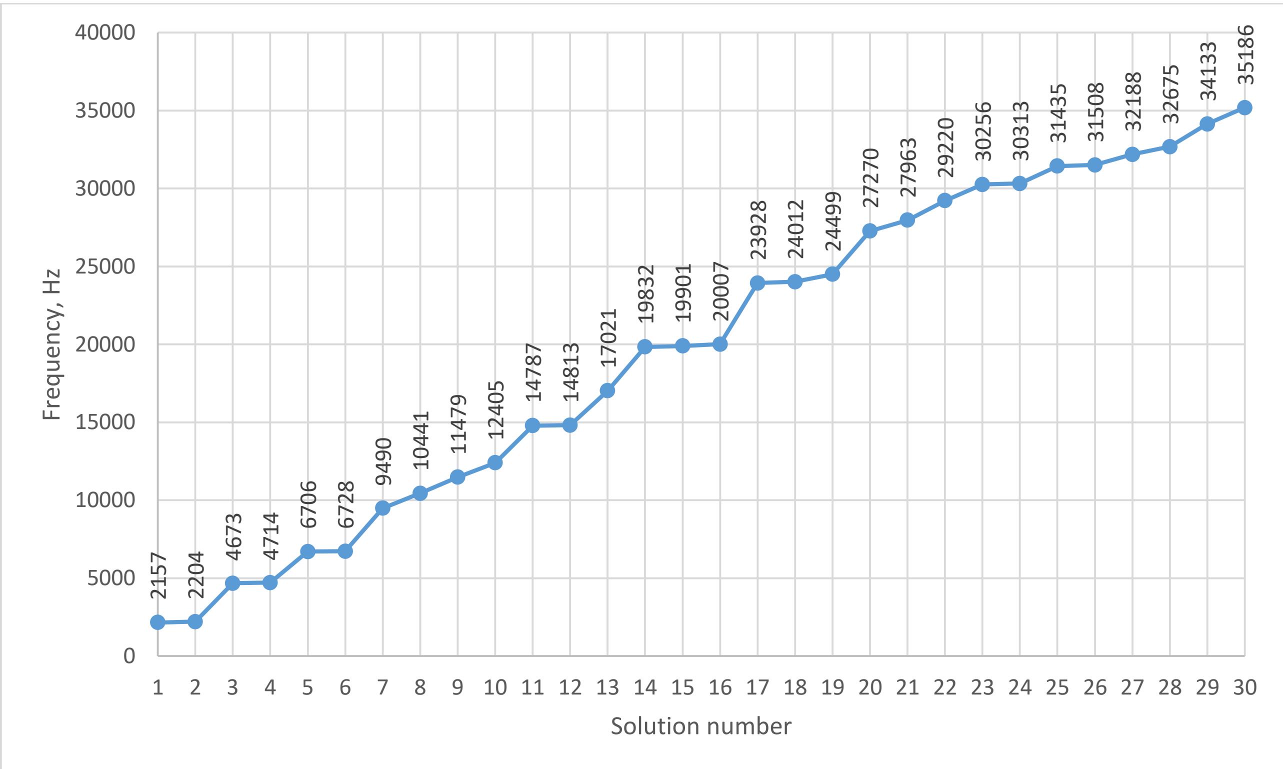

Figure 16. Resonant frequencies of the workpiece

Frequencies in Figure 14 show at what excitation frequency the workpiece will resonate. In this case, contrary to tool and tool holder analysis, these resonant frequencies should be avoided. However, not all frequencies affect the workpiece in the same way. Figure 15 shows mode shapes:

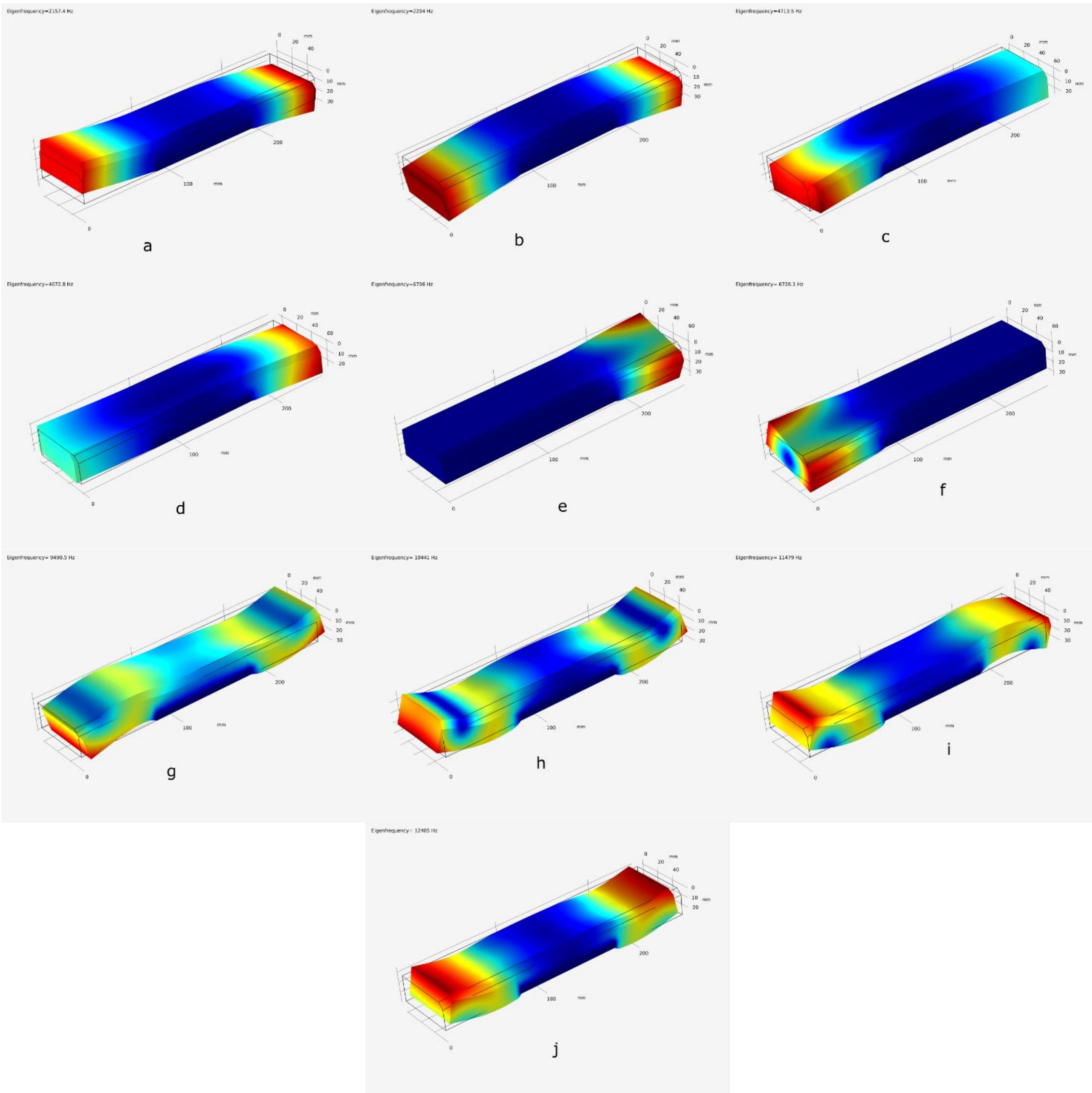

Figure 17. First ten vibration mode shapes of the workpiece

At different resonant frequencies, workpiece takes a different shape – it is shown in Figure 15, where first 10 mode shapes are given as an example. This means that at different resonant frequencies displacement amplitudes are peaking in different directions. With next step can be carried out – workpiece frequency response analysis. It will show how the workpiece will respond to load and excitation and in which direction the vibration amplitude will peak. Combined with resonant frequencies of the tool and tool holder, tool excitation frequency will be chosen by avoididng amplitude peaks at workpiece.

2.2. Frequency response simulation

In a cutting operation the workpiece is continiously excited by the cutting tool. This creates a low frequency excitation which generates displacement. To find out if displacement can be reduced by providing high frequency excitation, workpiece response to different frequencies needs to be investigated. This study will be done in a few steps: cutting force calculation, cutting frequency calculation and frequency response analysis using Comsol Mulitphysics 5.4.

2.2.1. Cutting forces

Calculation of the following milling forces are based on formulas from [3, 40, 41].

$$f_z = \frac{v_f}{N \cdot n} = \frac{300}{2 \cdot 4000} = 0.0375\, mm \tag{12}$$

f_z – feed per tooth, mm

v_f – feed, mm/min

N – number of cutting teeth

n – spindle speed, rpm

$$A = a_p \cdot f_z = 1 \cdot 0.0375 = 0.0375\, mm^2 \tag{13}$$

A – Crossection area cut by a tooth, mm^2

a_p – depth of cut, mm

f_z – feed per tooth, mm

$$h = f_z = 0.0375\, mm \tag{14}$$

h – chip thickness, mm

f_z – feed per tooth, mm

$$F_c = 1.2 \cdot A \cdot k_c \cdot C = 1.2 \cdot 0.0375 \cdot 2150 \cdot 1.2 = 116.1\, N \tag{15}$$

F_c – Cutting force, N

k_c – specific cutting force, N/mm^2. k_c = 2150 N/mm^2

C – coefficient of correction. C = 1.2

$$F_r \approx 0.9 F_c = 104.5\, N \tag{16}$$

F_r – radial milling force, N

$$F_p \approx 0.4 F_c = 46.5\, N \tag{17}$$

F_p – axial milling force, N

2.2.2. Cutting frequency

Cutting frequency is calculated using formula (11) from section 1.4.5:

$$f_t = \frac{zn}{60} = \frac{2 \cdot 4000}{60} = 133.3\ Hz$$

2.2.3. Workpiece frequency response

The frequency response is calculated at four points in the workpiece – 0 mm, 62.5 mm, 187.5 mm, 250 mm. The displacements are calculated in two directions – feed axis (or X axis) and tool axis (or Z axis).

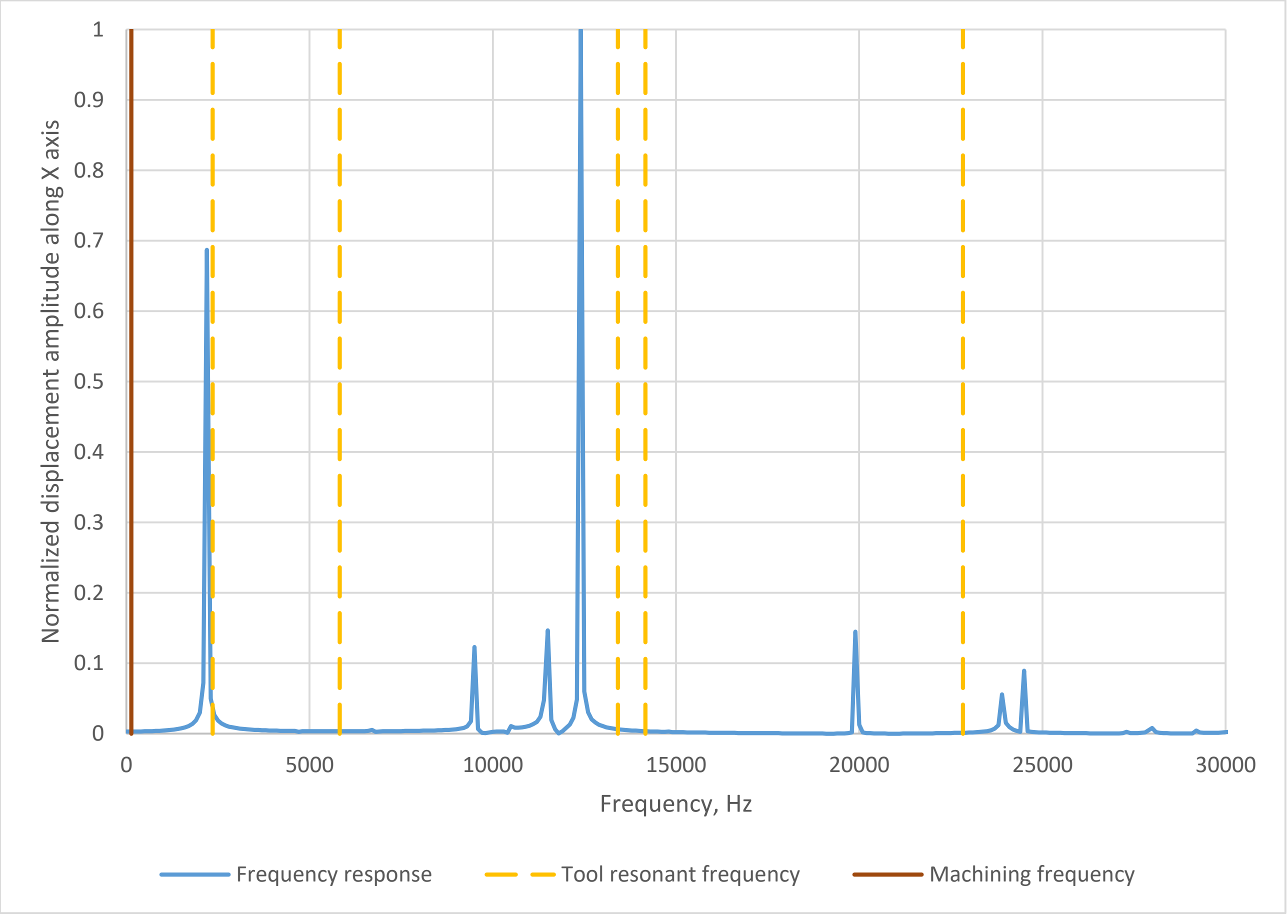

Figure 18. Normalized displacement X amplitude response to harmonic load at 0 mm

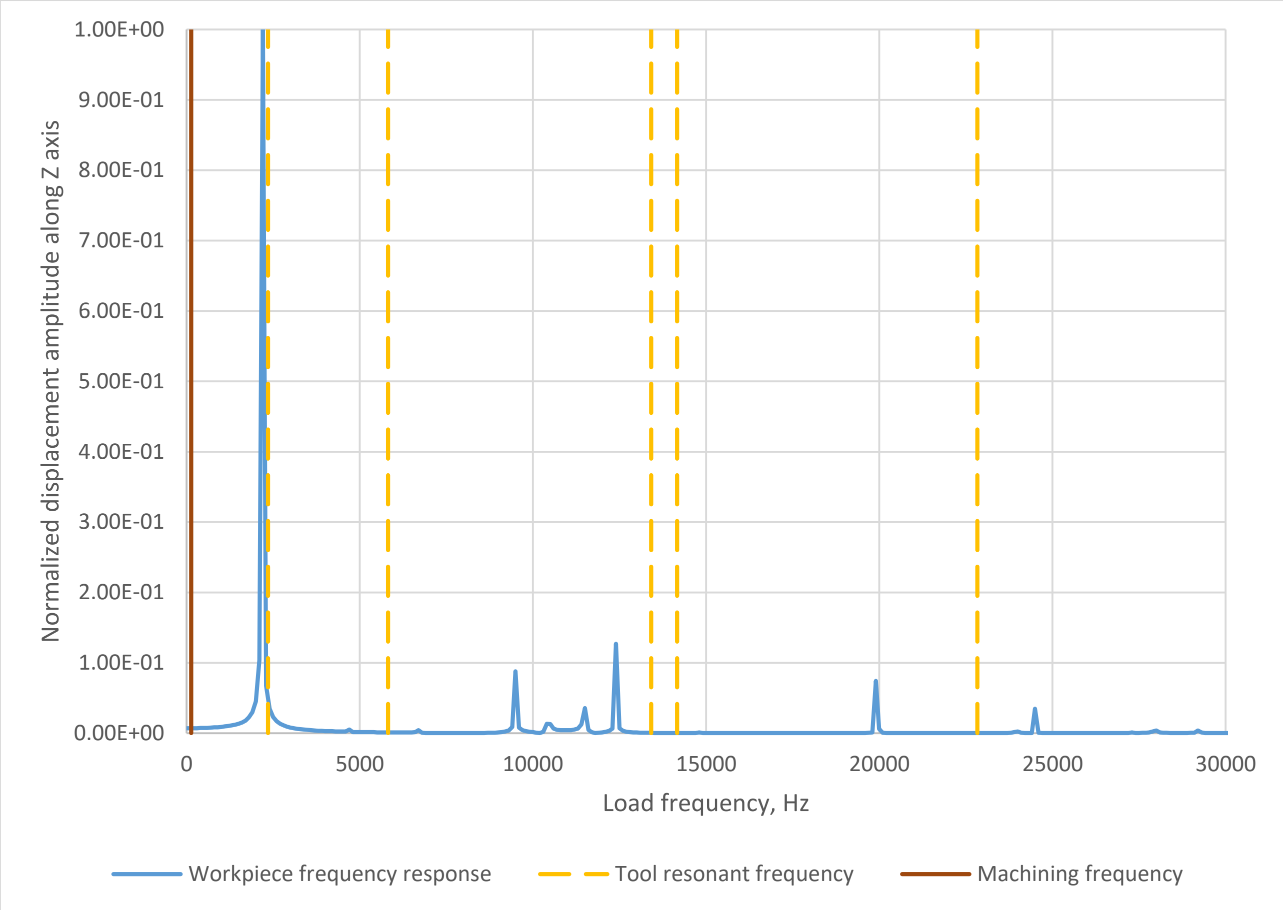

Figure 19. Normalized displacement Z amplitude response to harmonic load at 0 mm

Figures 16 and 17 show a graph that consists of several data series. First of all, the blue solid line represents frequency response from the workpiece. Figure 16 is for displacement amplitude field's X component and Figure 17 is for the Z component. The peaks in the amplitude occur at resonant frequencies and should be avoided – resonant frequencies increase vibrations and in turn, increases the surface roughness.

Resonant frequencies of the cutting tool are indicated in Figure 16 and Figure 17 by orange dashed line. The goal is to select the correct excitation frequency – it should be a resonant frequency for the tool, however, all the peaks should be avoided to keep vibration amplitudes as little as possible.

Evaluating the results of the calculation when load is at the begining of the workpiece (point 0 mm), two options seem available ~14 kHz and ~23 kHz. But before selecting the final tool excitation frequency, all four points of interest should be evaluated.

In the point 0 mm load case the potential decrease in the vibration amplitude can be evaluated. In Figure 16 and Figure 17, solid brown line indicates low frequency machining vibration generated by the cutting tool flutes. This frequency is 133,3 Hz. In case of amplitudes in Z axis, which is of more importance because it has a higher impact on surface finish, at 14 kHz workpiece excitation the amplitudes are ~46.6 times lower when compared to machining frequency without excitation. At 23 kHz the amplitudes are ~50.8 times lower. Therefore, from this calculation, 23 kHz tool excitation is prefered.

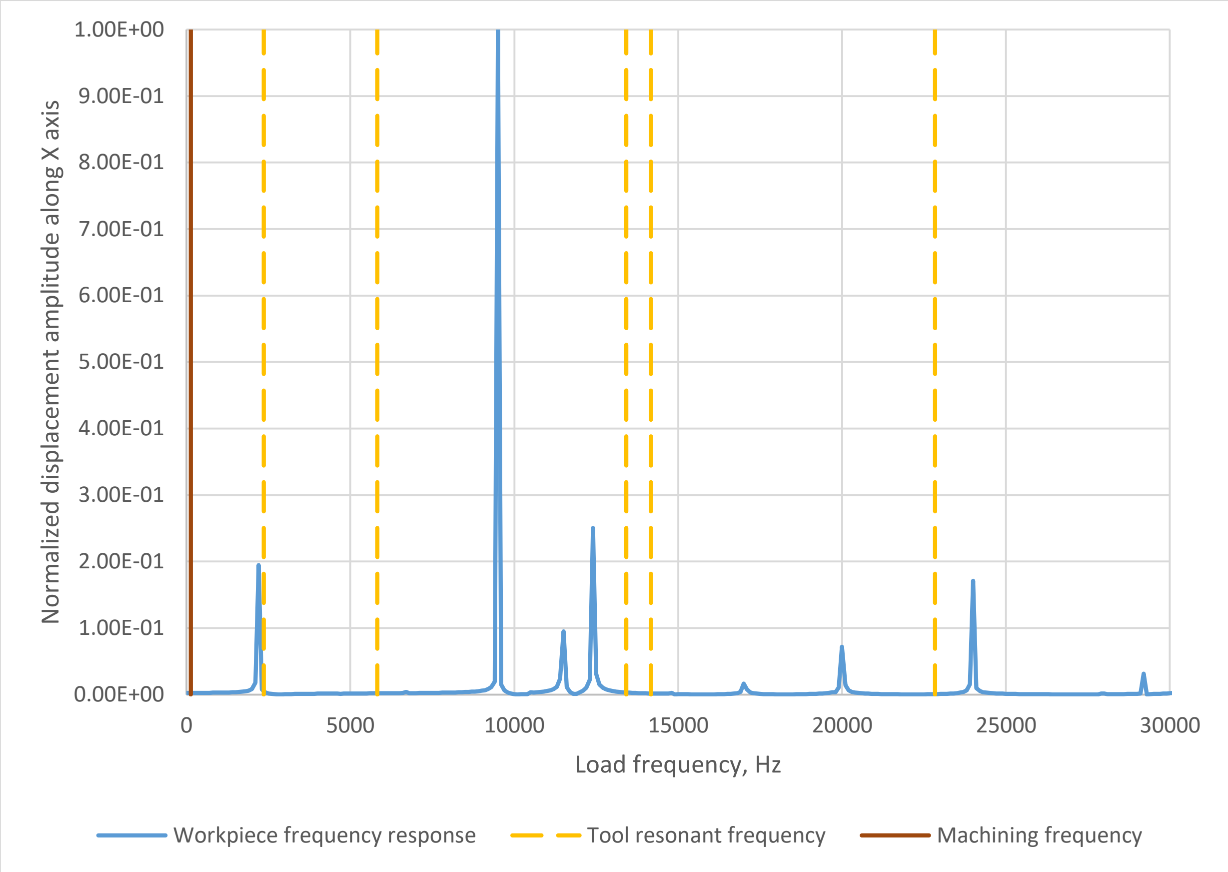

Figure 20. Normalized displacement X amplitude response to harmonic load at 62.5 mm

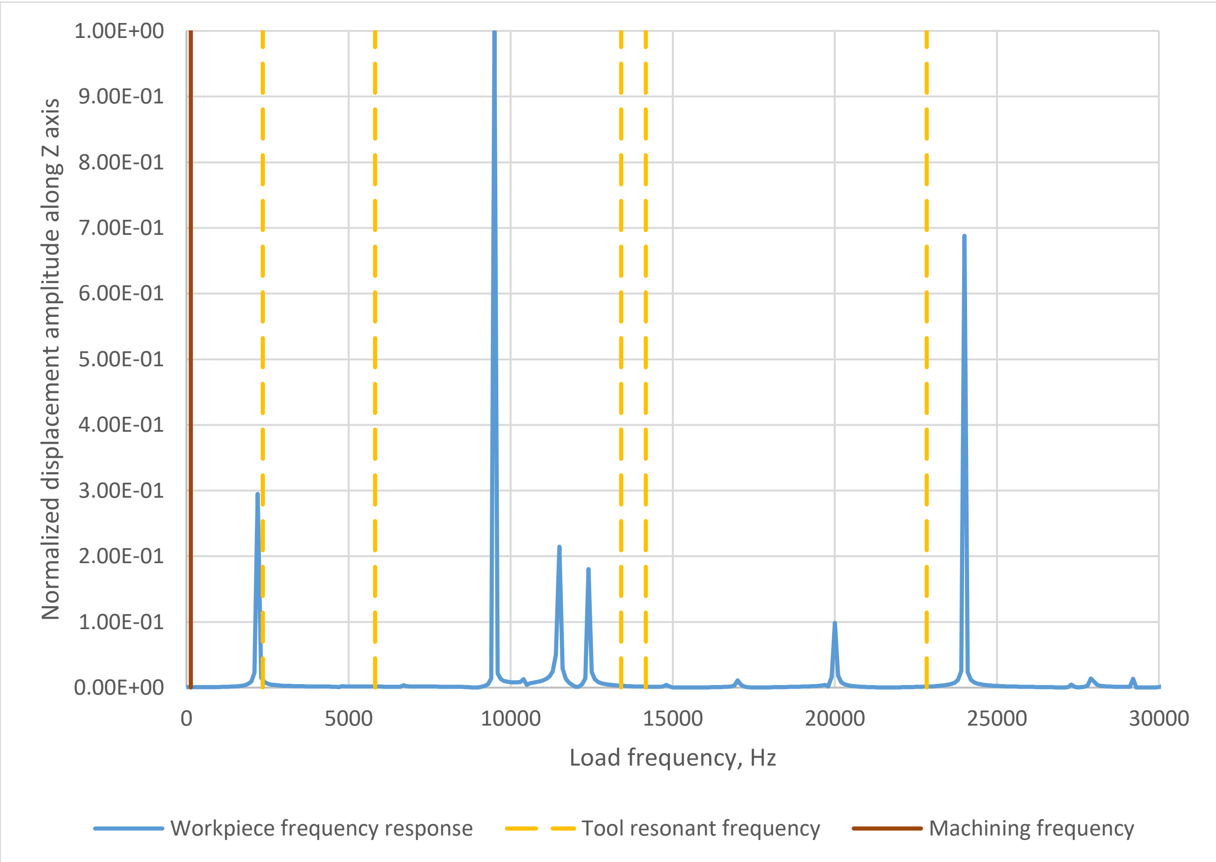

Figure 21. Normalized displacement Z amplitude response to harmonic load at 62.5 mm

Figure 18 and Figure 19 show frequency response of the workpiece when the load is at point 62.5 mm. Figure 18 represents vibration amplitude field's X component relation to load frequency. Figure 19 represents vibration amplitude field's Z component relation to load frequency. The same frequency selection applies as it was in the first load position. And in this case as well ~14 kHz and ~23 kHz seem most promising, however, amplitude at cutting frequency is not high as well. Mostly it is due to the fact that this point is at the vise clamping area which provide additional stability, therefore, reducing vibrations.

In case of amplitudes in Z axis, at both 14 kHz and 23 kHz workpiece excitation the amplitudes are ~0.3 times lower when compared to machining frequency without excitation. This provides a similar yet small improvement, therefore, for this point it is not so important which excitation frequency would be used. However, vibration amplitudes in X direction show a potential 3,3 times improvement at 23 kHz compared to 1,4 times improvement at 14 kHz. This means that even if in Z direction the amplitudes are similar, reduced vibration amplitudes in X direction suggest that 23 kHz excitation is preferred for this point as well.

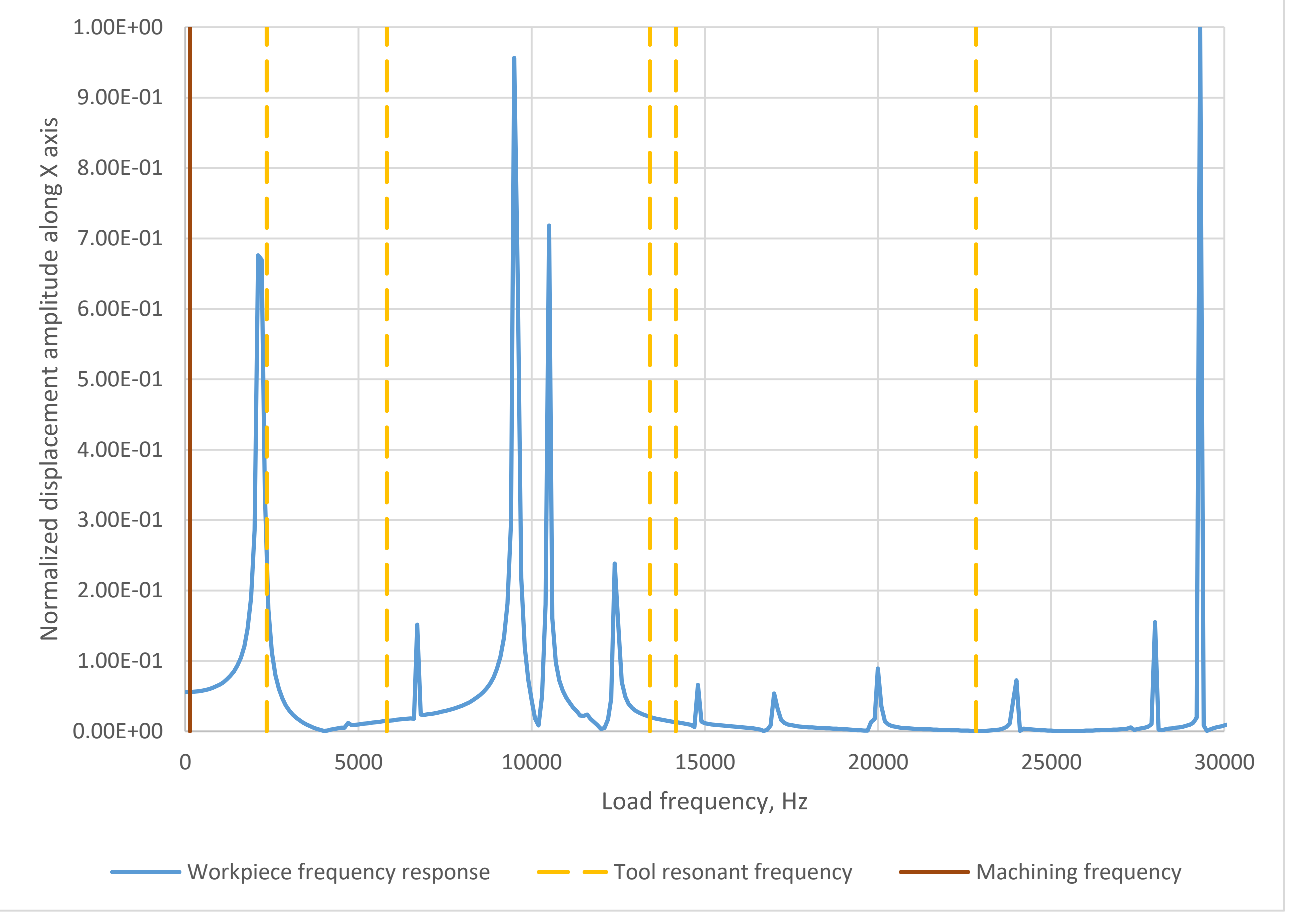

Figure 22. Normalized displacement X amplitude response to harmonic load at 187.5 mm

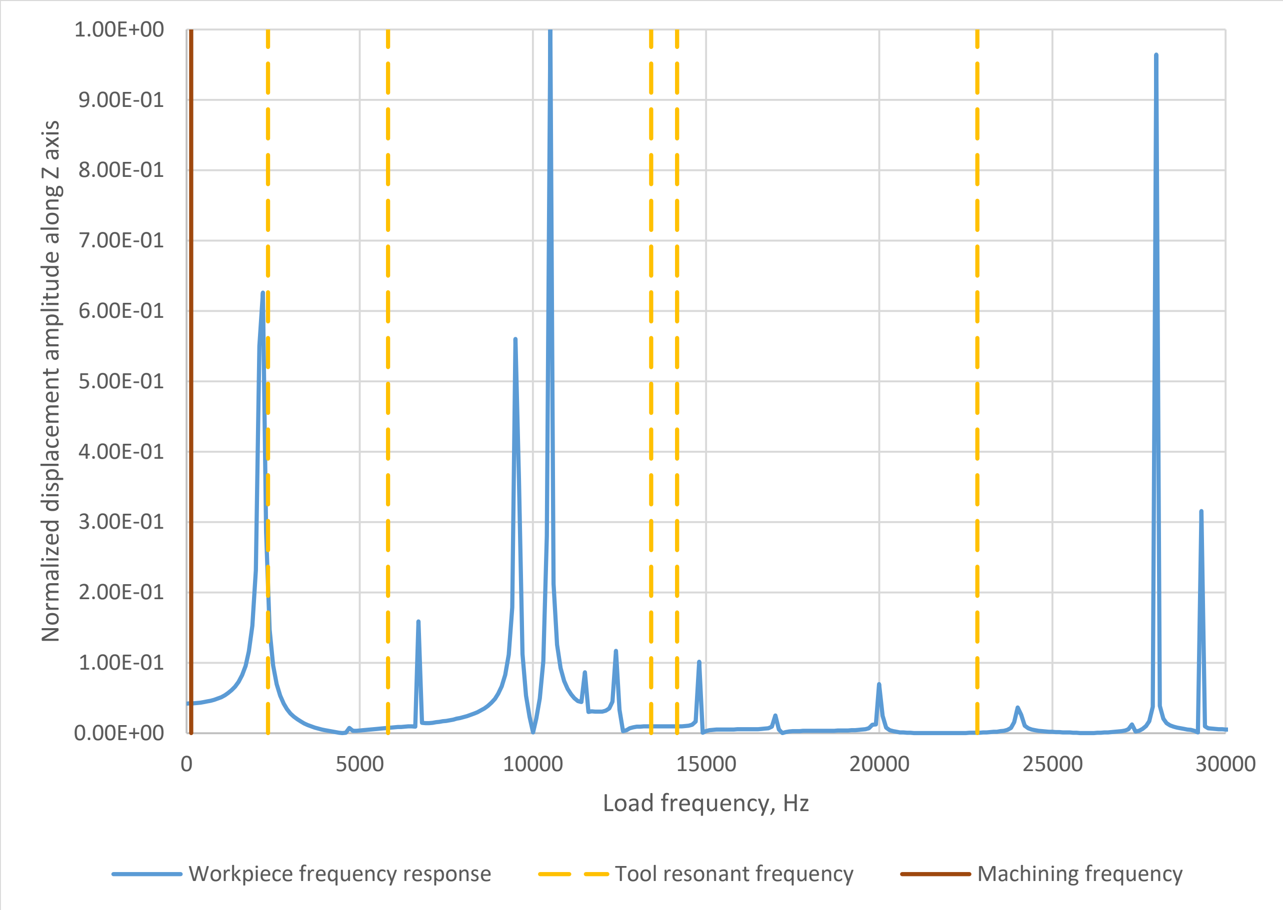

Figure 23. Normalized displacement Z amplitude response to harmonic load at 187.5 mm

Figure 20 and Figure 21 show frequency response of the workpiece when the load is at point 187.5 mm. Figure 20 represents vibration amplitude field‘s X component relation to load frequency. Figure 21 represents vibration amplitude field‘s Z component relation to load frequency. At this point the workpiece is a lot more easily excited to a resonant level – the number of peaks compared to previously analyzed load cases is significantly bigger. And according to the graph, amplitudes at ~14 kHz excitation are a lot higher compared to amplitudes at ~23 kHz. Another observation is that at cutting frequency vibrations are a lot more powerful than compared to previous load cases. This could be a result of endmill leaving the more stable area of the clamp, to unsuported part of workpiece.

In case of amplitudes in Z axis, only amplitude imporovement at ~23 kHz will be evaluated as it is obvious that ~14 kHz (or other) excitation cannot provide such promising results. Compared to cutting tool machining frequency, excitation offer ~41,8 times improvement at ~23 kHz. For comparison at ~14 kHz the improvement is only 4,5 times.

In case of amplitudes in X axis, the vibration amplitude improvement at ~23 kHz excitation frequency is ~100 times higher compared to ~14 kHz excitation frequency.

Results of the calculation when the load is at this point strongly suggests the use of ~23 kHz excitation frequency for good results.

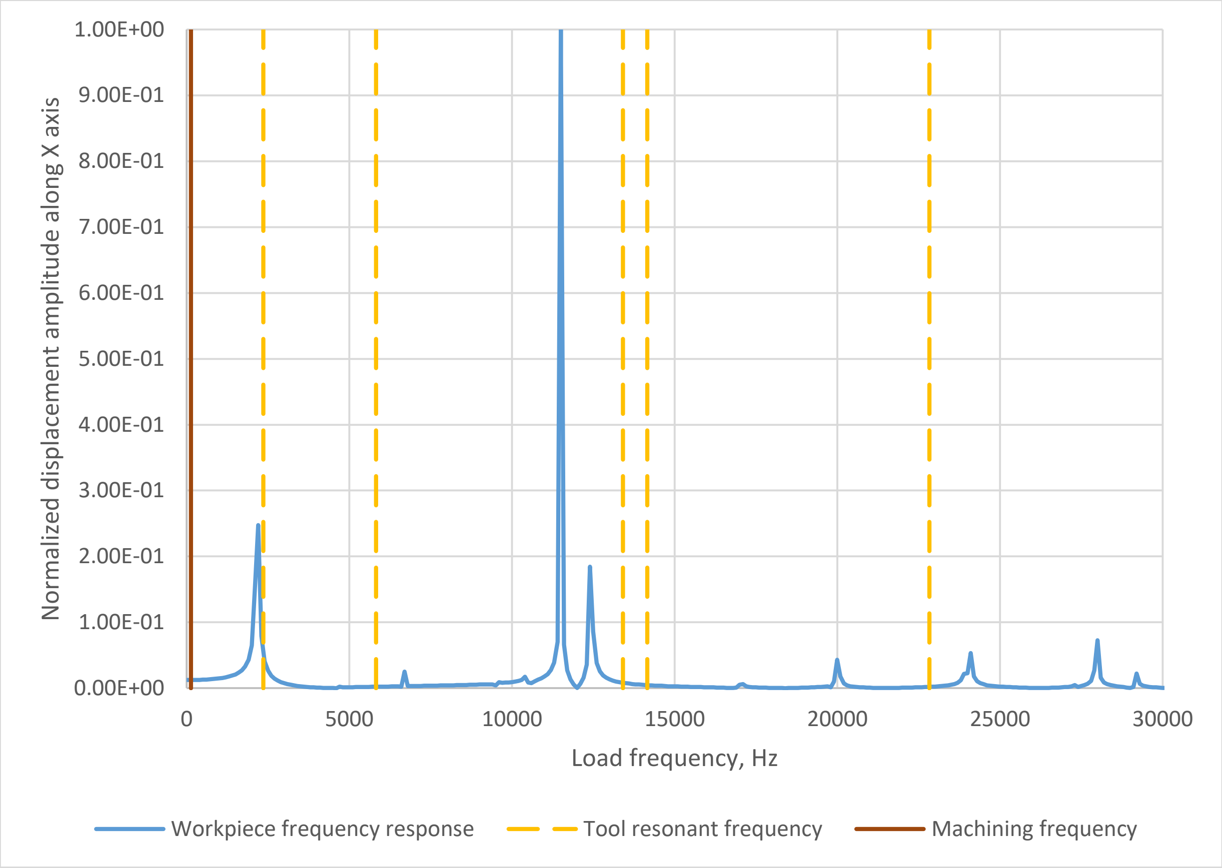

Figure 24. Normalized displacement X amplitude response to harmonic load at 250 mm

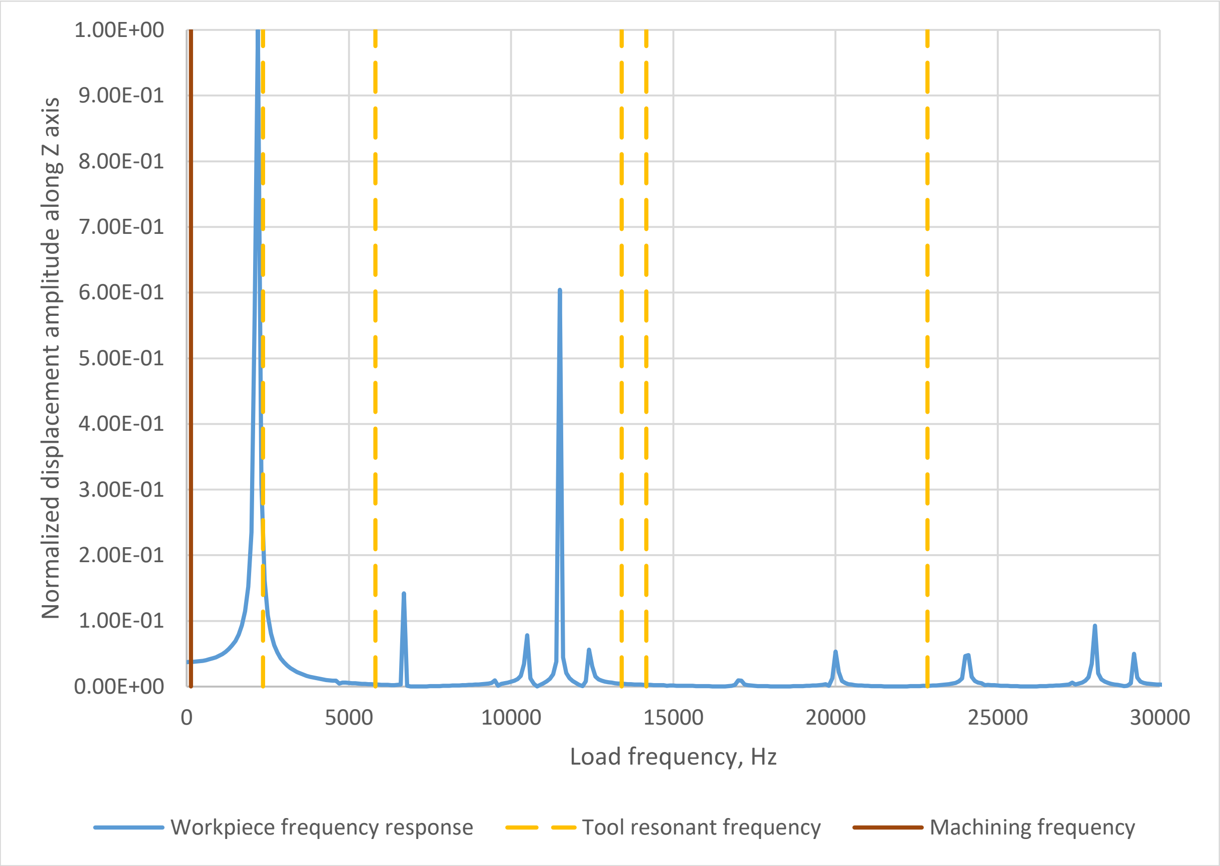

Figure 25. Normalized displacement Z amplitude response to harmonic load at 250 mm

Finally, Figure 22 and Figure 23 show frequency response of the workpiece when the load is at point 250 mm. Figure 22 represents vibration amplitude field‘s X component relation to load frequency. Figure 23 represents vibration amplitude field‘s Z component relation to load frequency. At this point the vibration amplitudes are similar to the first load case – when the load was at point 0 mm. In this case, the cuttig tool is about to leave the workpiece. Once again, after visual evaluation of the graphs, ~14 kHz and ~23 kHz excitation seem most promising improvement and at similar level. The difference from the first load case is that at low frequency machining vibrations are more powerful.

In case of amplitudes in Z axis, amplitude improvement at ~14 kHz is ~13 times whereas at 23 kHz it is almost double - ~23.7 times compared to cutting vibration amplitudes with no excitation.

In case of amplitudes in X axis, situation is very similar when comparing improvement at 14 kHz and at 23 kHz. The difference is that the overall level of improvement is much lower because the cut is more stable without any excitation. The improvement of vibration amplitude level at ~14 kHz is ~2,5 times and ~5,3 times at ~23 kHz.

Results of the calculation when the load is at this point strongly suggests the use of ~23 kHz excitation frequency just as in most cases previously.

2.3. Conclusions

After carrying out the numerical simulation of tool resonant frequency and two step workpiece frequency response analysis, two conclusions can be made:

- The excitation frequency of the tool should be ~23 kHz.
- Potentialy, the vibration amplitudes at different points can be reduced 0,3 – 50,8 times. This great variation shows that improvement of vibration amplitudes very strongly depend on cutting conditions.

3. Experimental study of the high frequency excitation of the cutting tool in unstable cutting conditions

An experiment was carried out to investigate the effects of vibration assisted milling on the aluminium surface quality. Four endmills with different level and severity of wear will be used – starting from new endmill, then two worn out endmills with some minor damage to the cutting edge and, finally, severely damaged endmill that has a large part of cutting geometry torn away. The worn out endmills are taken out of production process so the way they deteriorate is not simulated – it is a representation of a real aluminium machining situation. These endmills should create unstable conditions in the machining process and the aim is to compensate for this unstability with high frequency excitation of the cutting tool.

The hypothesis of this experiment is that high frequency excitation of the cutting tool can improve the surface roughness of the machined groove floor.

3.1. Experiment setup scheme

The experiment was conducted using the following experiment scheme:

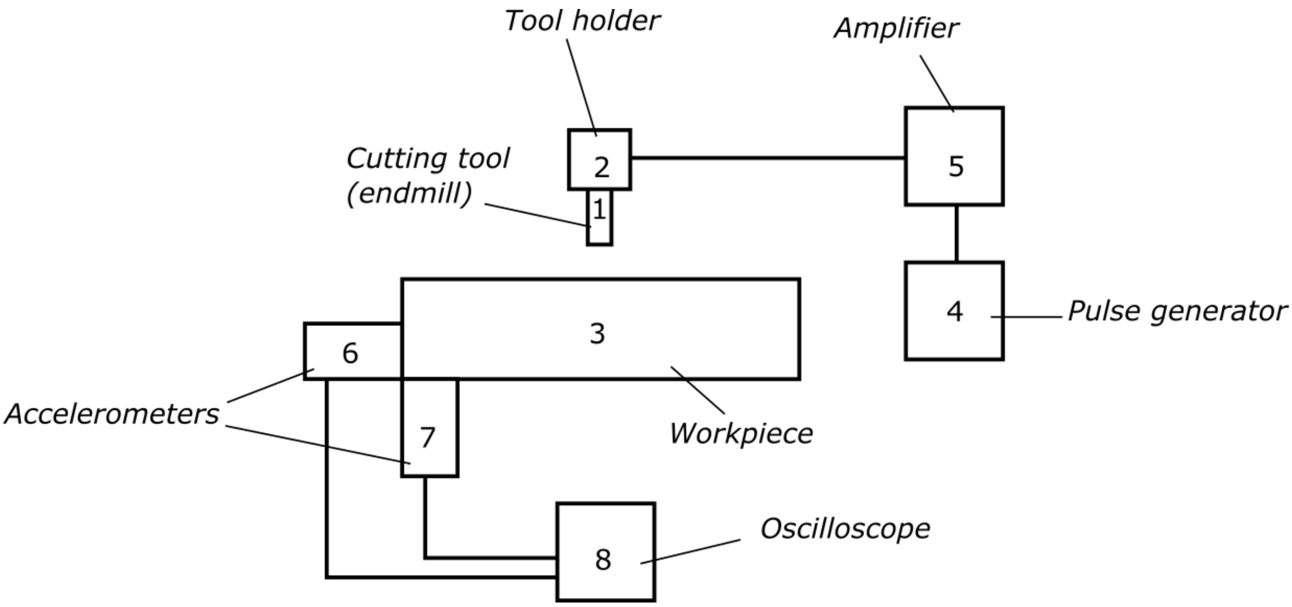

Figure 26. Experiment setup scheme

Workpiece *3* is fixed in standard vise. Piezoelectric accelerometers *6* and *7* are attached to the workpiece *3* to monitor vibrations that workpiece responds to excitation. Piezoelectric accelerometer *6* is used to measure vibrations in the feed axis (or X axis) and accelerometer *7* is used to measure vibration in the axis perpendicular to feed axis that is colinear with tool axis (or Z axis). Both accelerometers send signals to oscilloscope *8* which is used to display and save data for further processing.

The cutting tool (in this case it is as endmill) *1* is fixed in a tool holder *2*. The tool holder is fixed in a CNC machine spindle. The ultrasonic vibrations to excite the cutting tool *1* is generated by a pulse generator *4*. The generated ultrasonic pulse is amplified *5* and sent through tool holder *2* to the cutting tool *1*.

3.2. Experiment setup

The experiment setup was built accoding to experiment setup scheme from section 3.2:

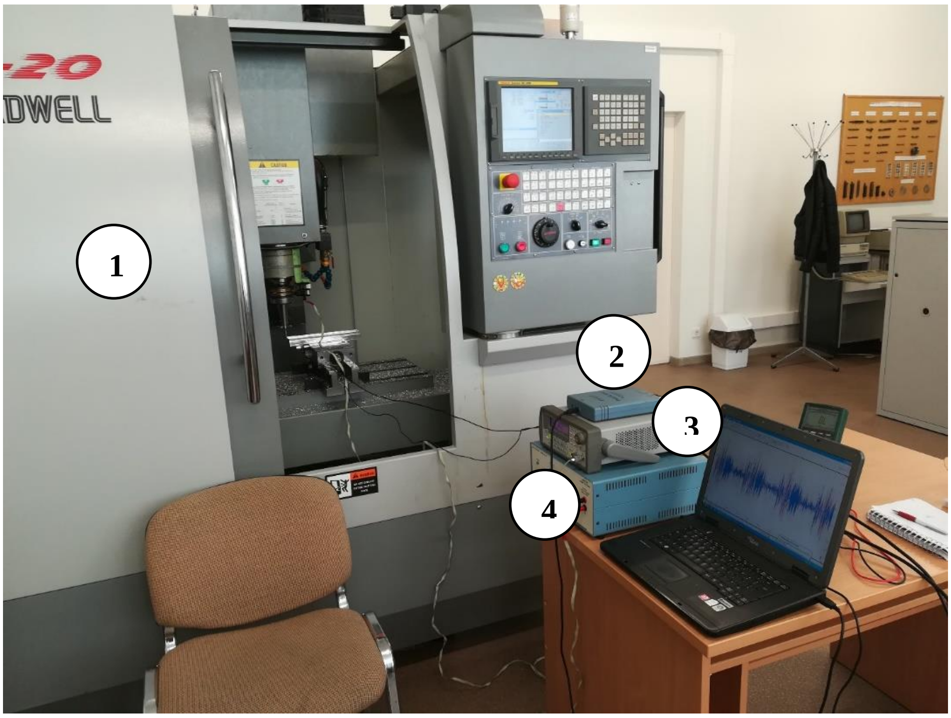

Figure 27. Experiment setup (I): 1 – Leadwell V-20 CNC machinng center [37], 2 – Picoscope oscilloscope, 3 – Arbitrary waveform generator Agilent 33220A, 20MHz [38], 4 –Linear amplifier Piezo Systems model EPA-104 [39].

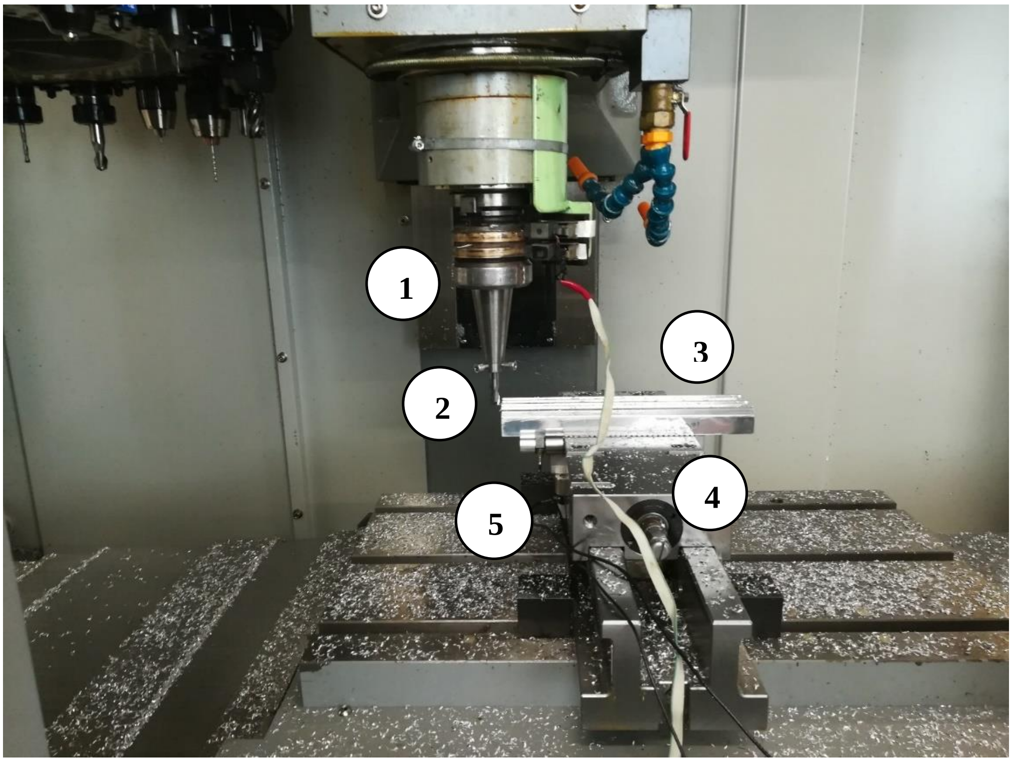

Figure 28. Experiment setup (II): 1 – tool holder with piezoelectric elements, 2 - Endmill, YG Alu-Power, E5930100 Ø10, Z2, 3 - Workpiece - 250x58,6x25 mm EN AW 6082 aluminium bar, 4 – Mechanical vise, 5 – piezoelectric accelerometers KD35

In Figure 25 and Figure 26, the implementation of experiment setup scheme is shown. Main parameters of the CNC machining center:

Table 1. CNC machining center specifications [37]

Parameter	Value
Power, kW	5,5 / 7,4
Spindle speed, RPM	80 – 8000
Max torque, Nm	35

The endmill that is used for the experimentation is Ø10 mm 2 flute endmill with R0,2 radii on the cutting edge.

Data from oscilloscope was gathered and saved to a computer that was running PicoScope 6 software.

The machine is controled with a Fanuc controller and for the experiment the code from Figure 27 was running.

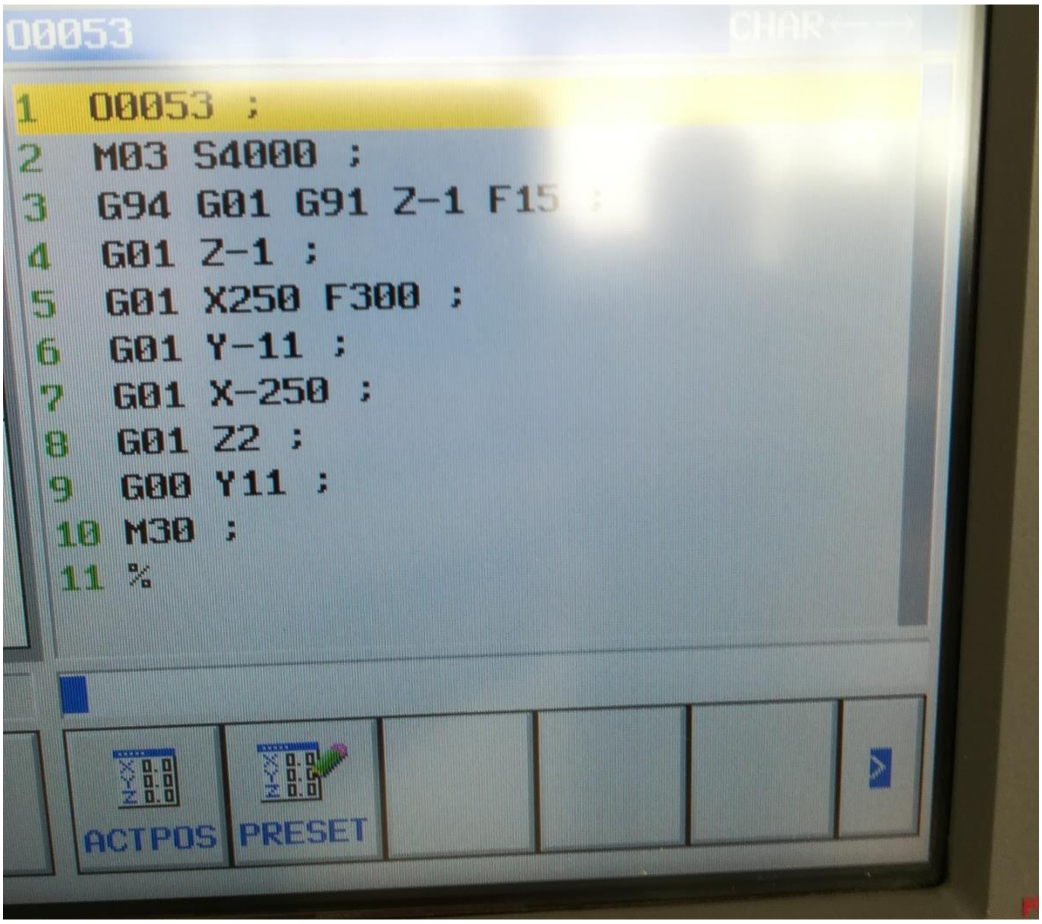

Figure 29. Experiment CNC program

Main parameters can be obtained for the CNC program and they are presented in Table 2. The machined geometry is defined in the program – the cutting tool machined a straight groove through the length of the workpiece, then turned around and machine the whole way back.

Table 2. Cutting parameters

Parameter	Value
Cutting speed, m/min	125,7
Spindle speed, RPM	4000
Feed, mm/min	300
Depth of cut, mm	1
Width of cut, mm	10

Even though separately the CNC machining center and the endmill can be used with much more aggresive cutting parameters, more conservative cutting parameters were selected because the the tools that were used in the experiment are considered worn out by the CNC machining company's evaluation. This fact does not ensure stable cutting conditions which increases the risk to damage the equipment used in this experiment.

3.3. Endmills

Four endmills with different levels of wear were tested. As mentioned in the previous chapters, these endmills were used in production until their performance was not satisfactory anymore – some of these cutting tools have simply blunt edge, some have blunt and chiped edge and some have big parts of the cutting geometry torn away. Figures 28 to 31 show pictures of the endmills' end cutting edge, peripheral cutting edge and end cutting geometry under a microscope.

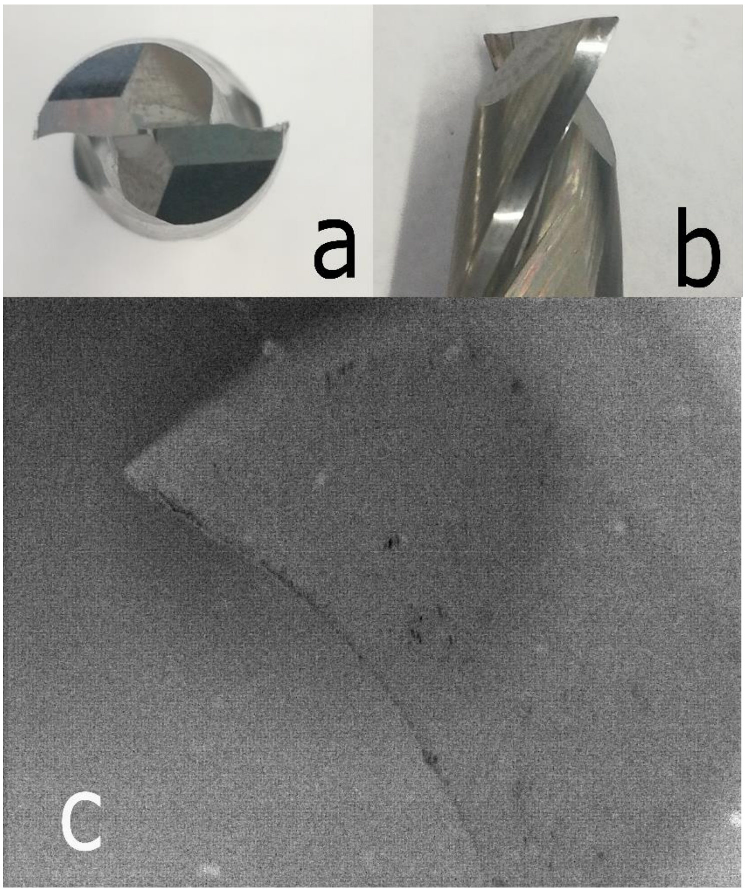

Figure 30. Endmill 0: new endmill. a – end cutting edge, b – peripheral cutting edge, c – cutting geomtery under 2,5X zoom

In Figure 28, the first tested endmill is shown. This endmill is brand new (therefore it is appropriately named endmill 0) and its first cuts were done during the tests. In pictures (a) and (b) undamaged end cutting edge and peripheral cutting edge are shown. Picture (c) is taken under a microscope and it is clear that there is no damage to the cutting edge and there are no changes to the radial rake angle. This endmill's performance might be impacted by the conservative cutting conditions.

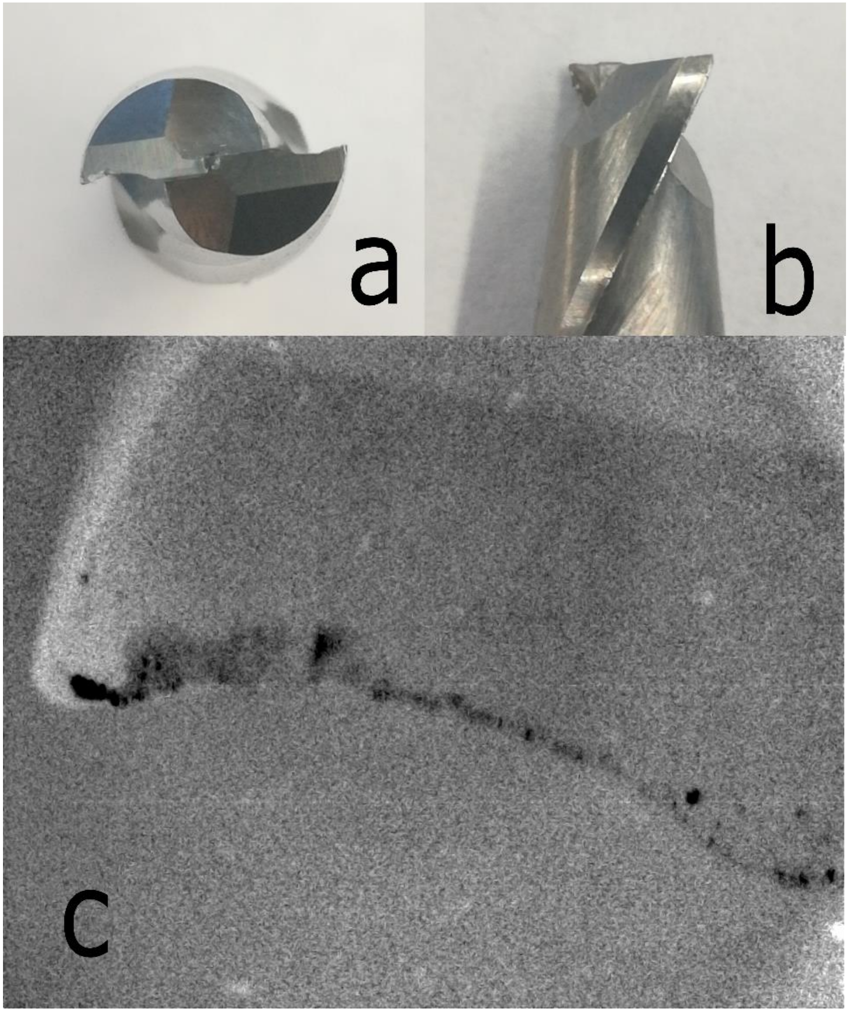

Figure 31. Endmill 1: a – end cutting edge, b – peripheral cutting edge, c cutting geometry 2,5X zoom

Endmill in Figure 29 is the second cutting tool that was used in the experiment. Just as in the previous figure, pictures (a) and (b) shows end and peripheral cutting edges. And picture (c) shows cutting geometry under a microscope. Some deformation of the cutting edge can be seen in picture (a) in comparison to endmill 0 from Figure 28. The cutting edge under the microscope – picture (c) – shows that the cutting edge is not only blunt (compared to endmill 0) but it is also chiped – there is a piece of cutting tool material missing on the left side of the picture. The picture taken with the microscope is inverted (negative) so the black spots indicate the cutting edge – thinner line means sharper mill. So this clearly shows that this endmill is worn out compared to endmill 0. Peripheral cutting edge (picture (b)) is blunter compared to endmill 0. Finally, the dark black spot on the left side of the picture means that the radial rake angle is changed, which have some impact on the surface roughness.

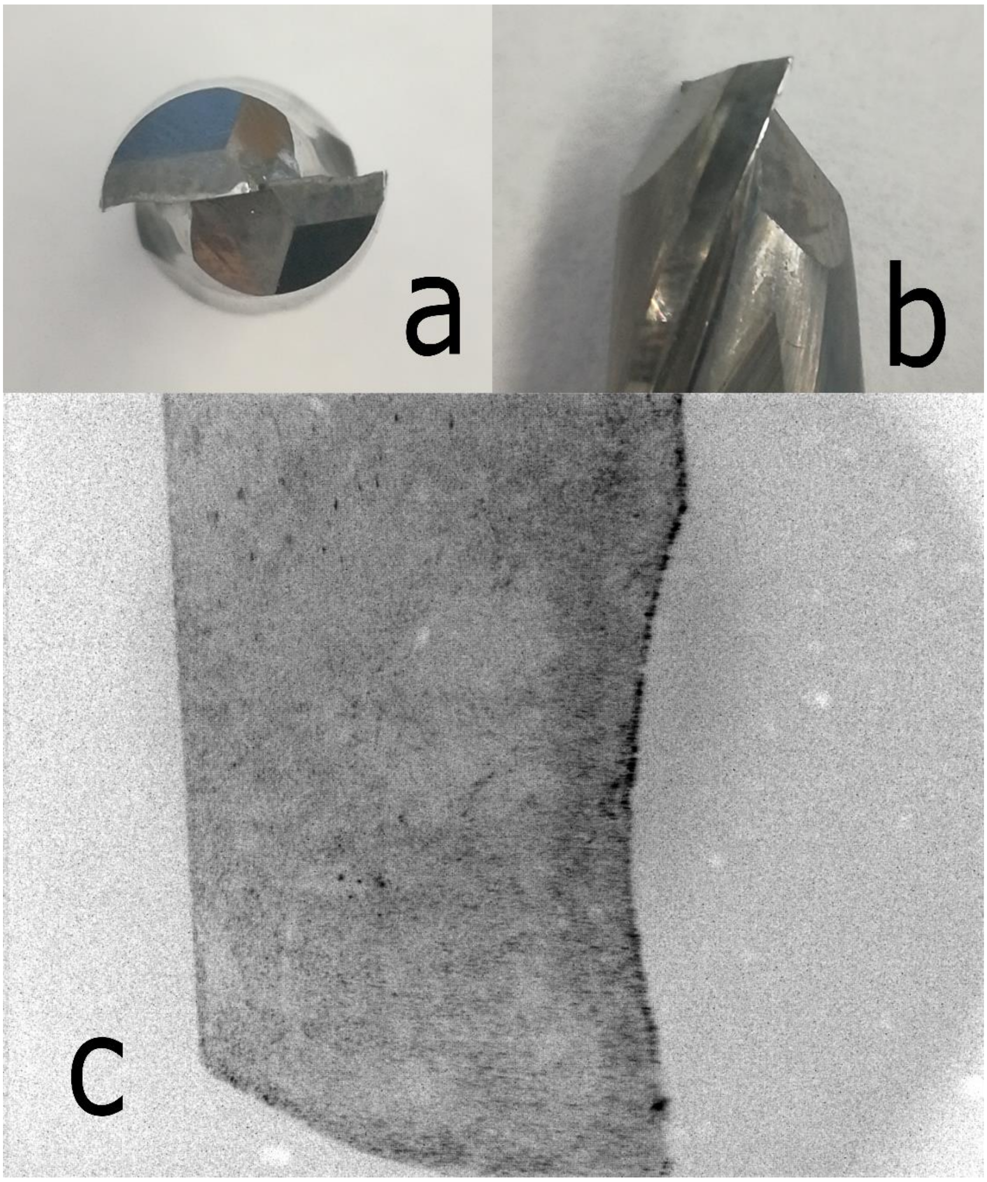

Figure 32. Endmill 2: a – end cutting edge, b – peripheral cutting edge, c cutting geometry 2,5X zoom

Endmill in Figure 30 is the third cutting tool that was used in the experiment. Once again, as in the previous figures, pictures (a) and (b) shows end and peripheral cutting edges. And picture (c) shows cutting geometry under a microscope. Cutting tool in Figure 30, also known as endmill 2, looks better than endmill 1 from Figure 29. The end cutting edge is not chiped as it was on endmill 1. The picture taken with the microscope is inverted (negative) so the black spots indicate the cutting edge – thinner line means sharper mill, and in this case the edge looks more worn compared to endmill 0 (Figure 28). Picture (a) and picture (b) do not show any major damage to neither end cutting edge nor peripheral cutting edge. This places this cutting tool between endmill 0 and endmill 1 in regards of severity of tool wear.

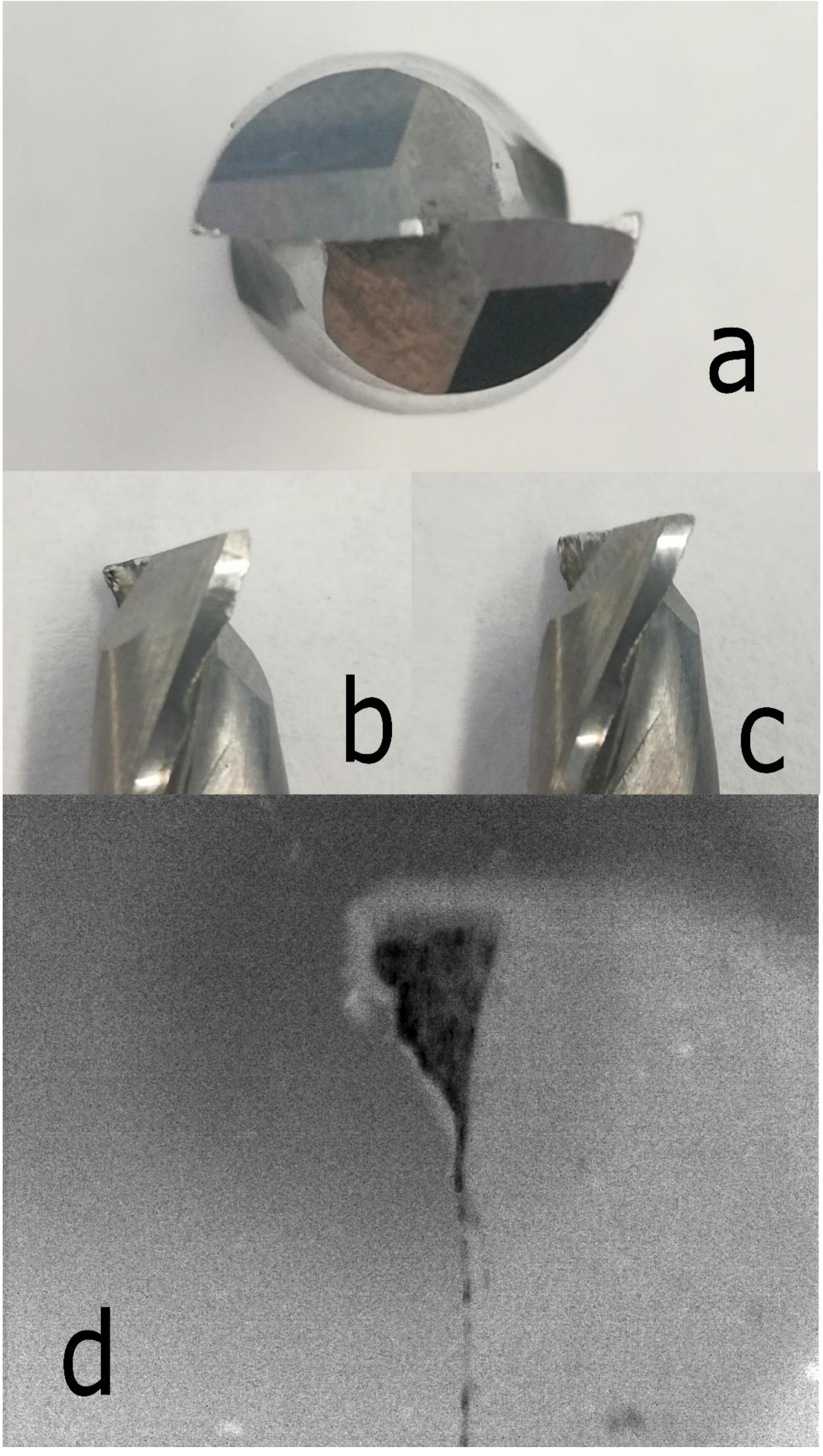

Figure 33. Endmill 3: a – end cutting edge, b, c – peripheral cutting edge, c cutting geometry 2,5X zoom

Endmill 3, shown in Figure 31, is the most severly damaged cutting tool in this experiment. Pictures (a) and (d) show a damaged end cutting edge with large parts of the cutting edge missing. This strongly affects the cutting geometry including radial rake angle. In pictures (b) and (c), damaged peripheral cutting edge is shown. This cutting tool has most damage compared to all tested endmills.

3.4. Results of the experiment

Sourface roughness is the parameter that is most sensitive to changes in any cutting condition – speeds and feeds, tool load, tool wear, variation in materials, etc. That is why this parameter was chosen to represent the results of the experiment.

Even though the vibrations were measured as well, the chosen placement of the piezoelectric accelerometers caused incomplete data – as the workpiece was made from alumunium, the accelerometers could not have been attached easily to the workpiece itself. Instead, it was fixed to the vise with the hopes that the vibration would not dissipate until they are registered by accelerometers. That is why only surfcace roughness was analyzed in order to confirm the hypothesis.

3.4.1. Measurement setup

The surface roughness was measured with Mitutoyo SJ-201. The experimental setup is illustrated in Figure 32:

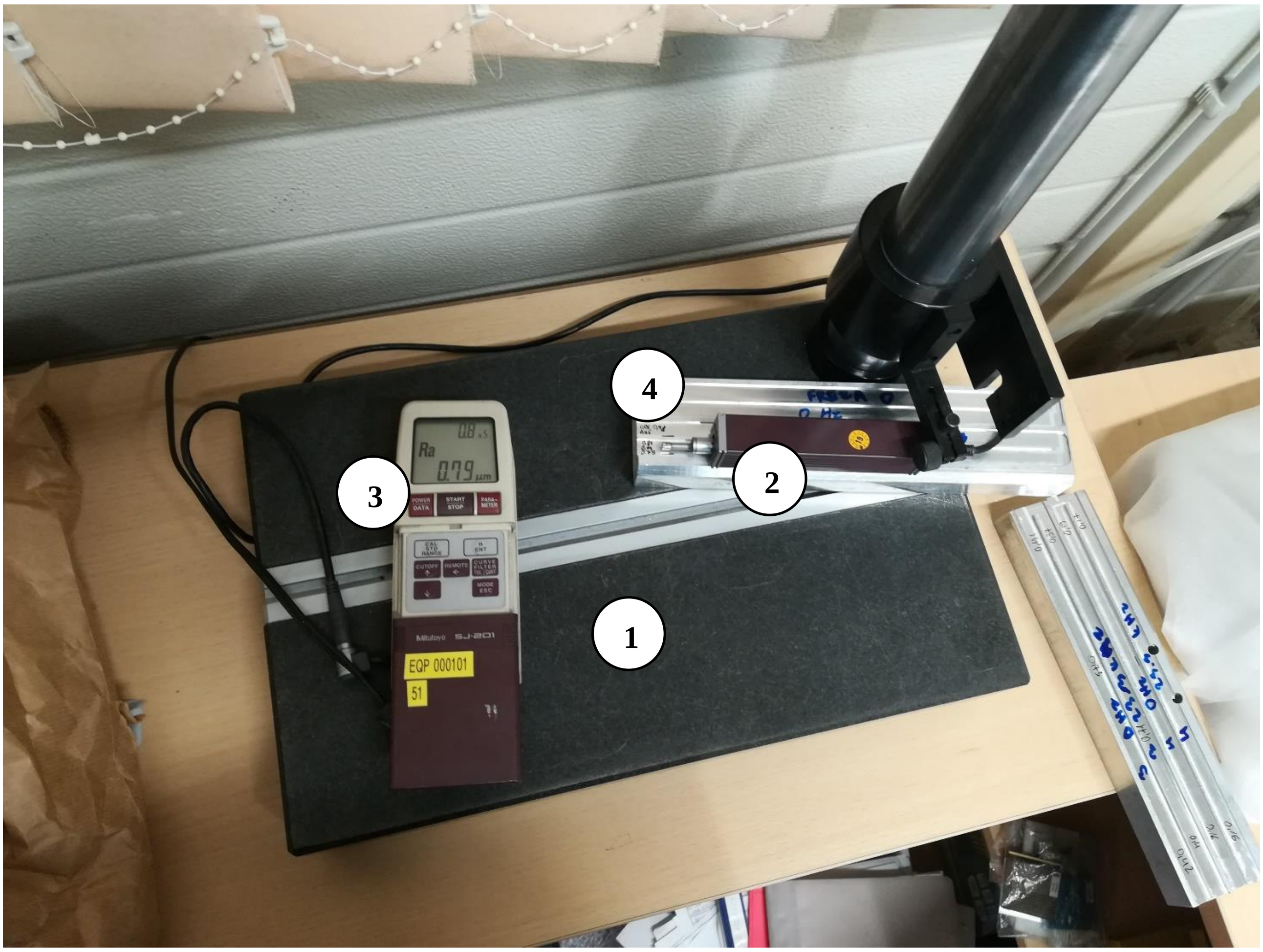

Figure 34. Surface measurement setup: 1 – granite plate, 2 – measurement probe, 3 – processing unit, 4 – workpiece.

Surface roughness was measured by the probe *2* in 5 0,8 mm distances. Then the average of the measurements were assesed and displayed on the screen of the processing unit.

3.4.2. Measurement results

After the measurement of the surface roughness of all of the endmills, the results were gathered and graphs were drawn. Figure 33 to Figure 36 shows the surface roughness of the groove‘s floor that was machined on the workpiece. It these figure it is separated by endmills.

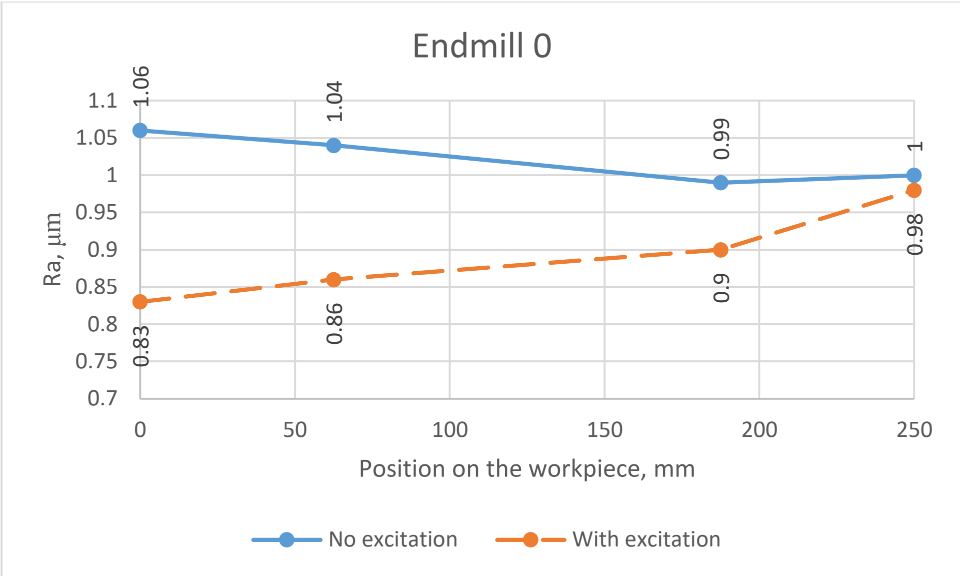

Figure 35. Surface roughness after machining with endmill 0

In Figure 33, the comparison between conventional cut and ultrasonically asssited cut with endmill - a new tool. First of all, the improvement of surface roughness was observed at all measured points when the excitation was applied. The goal of monitoring a cut with a new endmill was to establish a reference point for more damaged endmills. After evaluating the average surface roughness across the workpiece the result was Ra 1,02 µm without excitation and Ra 0,89 µm with excitation. This means that applying tool excitation increased the surface quality of the workpiece by 13%.

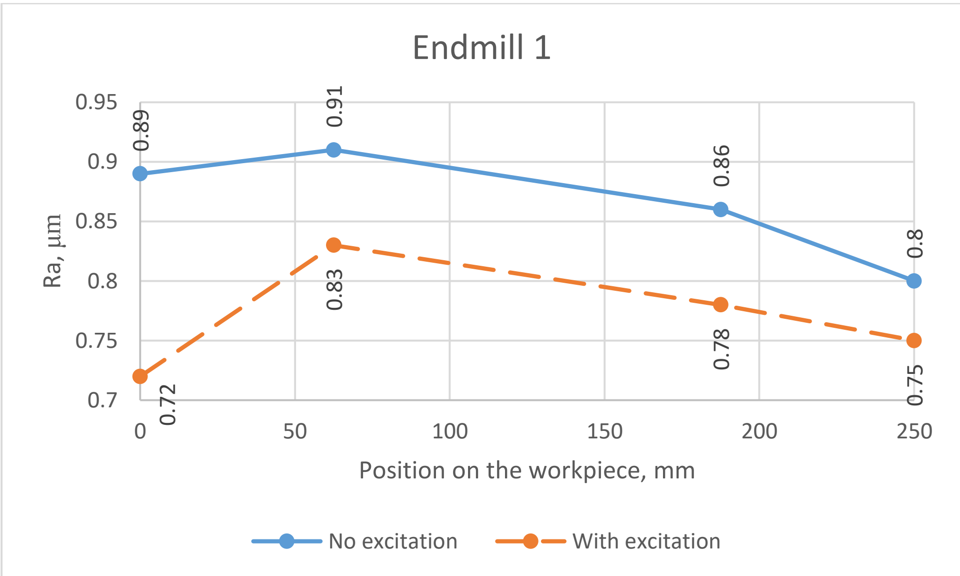

Figure 36. Surface roughness after machining with endmill 1

The second cut was done with endmill 1 which had a blunt cutting edge and some chipping on the cutting edge. The results of this cut are shown in Figure 34. Once again, the cutting tool excitation with high frequency vibrations improved the surface finish compared to conventional milling at all points of the workpiece. Again after calculating the overall surface roughness of the workpiece it was Ra 0,87 µm without excitation and Ra 0,77 µm with excitation. This means there was 11% improvement of the surface roughness. Very interesting observation has to made here – the surface roughnes is quite a lot higher at the endmil 0 compared to endmill 1. This means that a damaged endmill created a better surface quality than a new endmill.

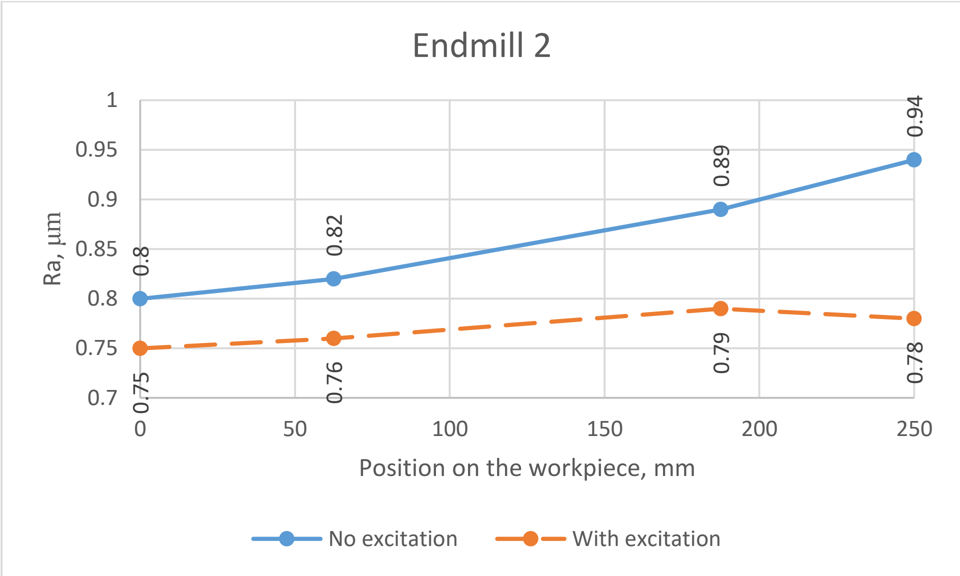

Figure 37. Surface roughness after machining with endmill 2

The third cut was done with endmill 2 which had a blunt cutting edge. Even though endmill 1 had some chipping on the cutting edge, the state of the endmill wear was quite similar to endmill 1. The results of this cut are shown in Figure 35. After this cut, once again, the improvement at all points of the workpiece was observed. After calculating the overall surface roughness of the workpiece it was Ra 0,86 µm without excitation and Ra 0,77 µm with excitation. This means there was 10% improvement of the surface roughness. These results confirm that the endmill 1 and endmill 2 were at similar stage – both the surface roughness values (before excitation and after excitation) are close to each other. This shows that the improvement level is also similar. The surfce roughness is significantly better with worn out endmill compared to endmill 0 – a brand new endmill. However, just as for endmill 1, the overall surface roughness improvement level is lower when the conventional cut and ultrasonically assisted cut are compared. Endmill 0 had overall surface roughness improvment of 13% whereas endmill 1 and endmill 2 had an 11% and 10% improvemets respectably.

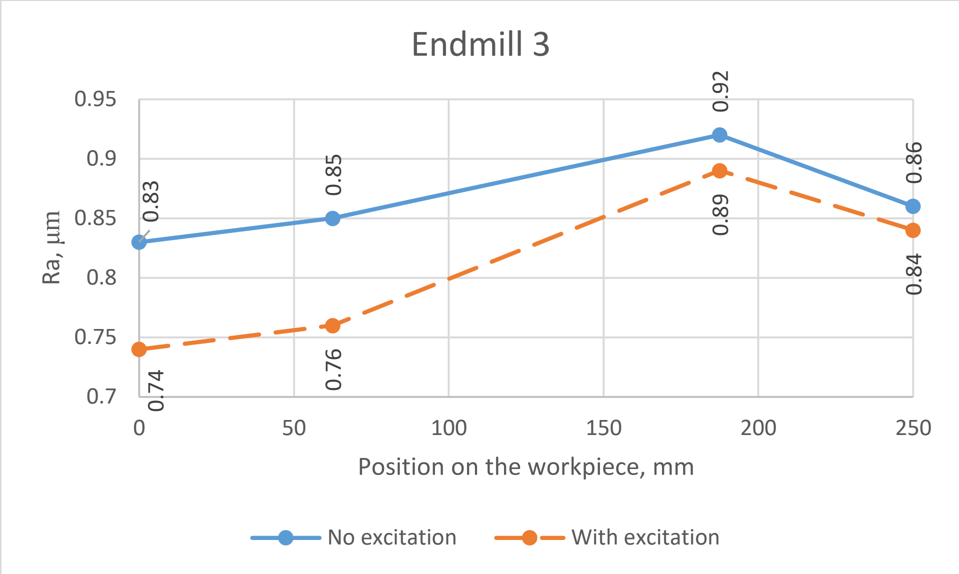

Figure 38. Surface roughness after machining with endmill 3

Finally, the fourth and final cut was done with the most severily damaged endmill 3. The outcome was the same as in previous cases. The surface roughness as improved when high frequency excitation was introduced to the cutting tool compared to conventional milling. And this improvement was continious through all of the measured points of the workpiece. The overall surface roughness without excitation was Ra 0,87 µm. After tool excitation the surface quality improved to the point of Ra 0,81 µm. So this means there is only 7 % improvement in surface quality after machining with this endmill. These results show once again that the surface even with a strongly damaged tool remains better than the surface after machining with a brand new endmill 0. However, the level of increase in surface quality is reduced to 7 %.

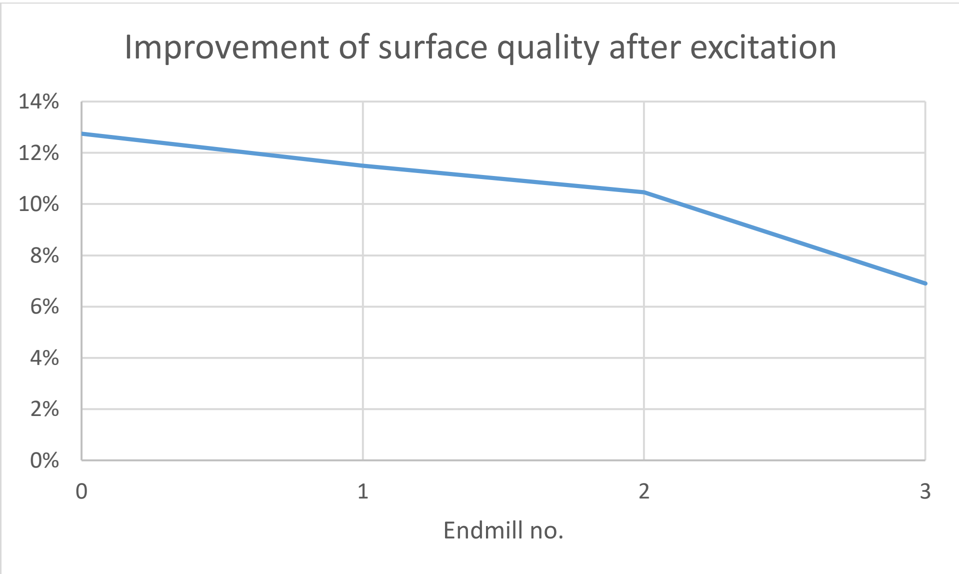

Figure 39. Overall improvement of the surface roughness by endmill number

In the Figure 39, a graph of overall improvement level is presented. As mentioned above, the level of improvement was decreasing with the severity of the wear of an endmill.

3.5. Discussion

Interesting observation is that a new tool had worse surface quality compared to worn and damaged endmills. There are a few possibilities why such results were obtained. First of all, cutting speed of aluminium with the tested endmill should be around 250 m/min – in this experiment, the cutting speed was 125,7 m/min. Such decrease in spindle speed could have had an impact on the new endmills performance. And more conservative cutting parameters prevented the damaged endmills to behave more violently. That is why their all surface roughness was at almost the same level. And the fact that the improvement after tool excitation was smaller with more severily damaged tool indicates that there were higher vibration levels which limited the surface roughness improvement.

Another possibility is the change in radial rake angle. A recent study [42] in China found that changes in rake angle (to either positive or negative side) resulted in surface quality changes. These changes were very different – devation in the angle either improved or made the surface finish worse. This strongly depended on the angle of the radial rake angle which was sligtly changed because of the tool wear the experiment. The changes in radial rake angle are showed in the pictures that are enhanced with a microscope. However, the changes in this angle are not even but the surface quality is similar.

Finally, for some time now, toolmakers use a special cutting chip geometry to increase the surface finish. The Wiper series cutting chip uses a bigger surface to leave a better surface roughness. Comparison between traditional chip and Wiper is shown in Figure 40:

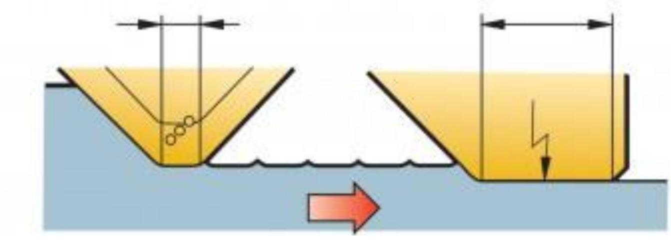

Figure 40. Wiper series chip compared to conventional cutting chip [44]

As shown in Figure 40, the bigger cutting surface provide a better surface finish, whch might be the case with the more worn endmills – the geometry of the cutting teeth changes and the surface quality improves but because there is more rubbing with the surface, the rate of improvement after ultrasonic excitation is introduced is smaller with the severity of the endmill wear.

3.6. Economical comparison to conventional milling

The new endmill that was used in the experiment cost around 45 €/pc. This means that the tools can actually be used even longer – even after the endmills are worn out. This means that companies that produces one-off or very sall series can use their tools much longer – just the excitation of the cutting tool is needed. On average, the improvement in surface finish is about 10 %. So considering that, the endmills should last 10% longer. In this case, it saves 4,5 € for every endmill used.

In case of companies that produce higher volumes, machining until the endmill breaks is usually more expensive than regular tool change. However, such companies tend to produce their own equipment, where using tools that are not suitable for serial production is a great way to reduce costs and improve quality.

Finally, this experimentation shows that there are potentional opportunities to improve unstable cutting conditions – for example, not rigid workpiece. This would allow to save fixture making costs.

3.7. Recommendations for further research

First of all, deeper analysis can be carried out to investigate what are the actual reasons behind the worse surface roughness of a new endmill compared to worn out endmills.

This investigation was carried out to study high frequency excitation effects on surface quality in unstable conditions. Unstable conditions were simulated using worn out cutting tools. Further research could be done by creating these conditions in a different way, for example, not rigid workpiece. After that the result correlation should be evaluated.

Secondly, simultaneously with previously described experiment another investigation was carried out – Ph.D student P. Karpavičius et al tested the wireless vibration energy harvester and it showed promise for cutting condition monitoring.

Finally, as both monitoring and excitation of the tool is using similar equipment based on piezo ceramics, application of combination between the two could be investigated. This would allow to monitor cutting condition to the point it would require help from high frequency excitation. This would allow to conserve costs and improve quality when needed.

Conclusions

1. After analyzing scientific literature and previously done experimentation the conclusioncan be made that vibration assisted machining currently is very relevant as many different processes are investigated with a lot of potential results (surface finish improvement, tool life extension, etc.). However, all analysis is based on stable cutting conditions.
2. After carrying out the numerical simulation of tool resonant frequency and two step workpiece frequency response analysis, two conclusions can be made: the excitation frequency of the tool should be ~23 kHz (minor adjustments may occur because the tool stickout might variate in small way). Potentialy, the vibration amplitudes at different points can be reduced 0,3 – 50,8 times. This great variation shows that improvement of vibration amplitudes very strongly depend on cutting conditions.
3. After experimentation session, the results show that in all cases the high frequency excitation improved the surface roughness compared to conventional milling. The improvement level depends on the severity of the tool wear. When the tool is new, the surface quality improvement was 13%, but when the tool is blunt and has some slight chipping at the cutting edge, the surface roughness improvement reaches only 10 – 11%. Finally, severely damaged tool showed only 7 % improvement in surface roughness.
4. On average, the improvement was 10 % therefore the tool life could be extended up to 10 %. This would save companies ~4,5 €/endmill used. Finally, potentionally other unstable cutting conditions could be improved by high frequency excitation of the tool.

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Appendices

Appendix 1. Endmill documentation

ALU-POWER END MILLS

E5930 SERIES

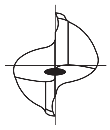
PLAIN SHANK
GLATTER ZYLINDERSCHAFT

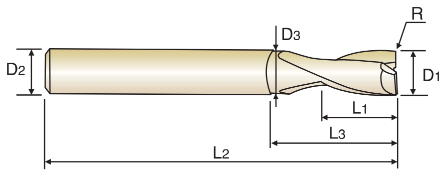
CARBIDE, 2 FLUTE 25° HELIX CORNER RADIUS with NECK

VOLLHARTMETALL, 2 SCHNEIDEN 25° RECHTSSPIRALE ECKENRADIUS mit ABGESETZTEM SCHAFTTETL

- Designed for the machining aluminum and aluminum alloys, non-ferrous materials
- Mirror surface - Excellent surface finishes
- Increased tool life and higher cutting accuracy
- Maximum-metal removal rate
- Superior chip evacuation
- Corner Radius for avoiding the chipping

- Entwickelt für die Bearbeitung von Aluminium, Aluminiumlegierungen, NE-Metalle
- Spiegel-Oberfläche - Hervorragendes Oberflächenfinishing.
- Verbesserte Standzeiten und höhere Fräsgenauigkeit.
- Maximale Zerspanungsleistung.
- Überlegene Spanabfuhr
- Eckradien verhindern Schneidkantenausbrüche





P.976

Unit : mm

EDP No.	Corner Radius R	Mill Diameter D_1	Shank Diameter D_2	Length of Cut L_1	Length Below Shank L_3	Overall Length L_2	Neck Diameter D_3
E5930020	R0.2	**2.0**	3	3	6	40	1.9
E5930030	R0.2	**3.0**	3	4	8	40	2.9
E5930040	R0.2	**4.0**	4	5	12	50	3.8
E5930050	R0.2	**5.0**	5	8	14	50	4.8
E5930060	R0.2	**6.0**	6	8	18	65	5.7
E5930080	R0.2	**8.0**	8	10	22	70	7.7
E5930100	R0.2	**10.0**	10	14	28	80	9.7
E5930120	R0.2	**12.0**	12	16	35	90	11.5
E5930160	R0.2	**16.0**	16	20	40	90	15.5
E5930200	R0.2	**20.0**	20	25	50	100	19.5

- TiN, TiCN-COATING & TiAIN-COATING are available on your request.

Mill Dia. Tolerance(mm)	Shank Dia. Tolerance
0~−0.03	h6

◎ : Excellent ○ : Good

Carbon Steels	Alloy Steels	Prehardened Steels	Hardened Steels		High Hardened Steels	Copper	Graphite	Cast Iron	Aluminum	Stainless Steels	Titanium	Inconel	Acrylic	CFRP
~HB225	HB225~325	HRc30~40	HRc40~45	HRc45~55	HRc55~70									
									◎					

HSS
CBN END MILLS
i-Xmill END MILLS
i-HS mill END MILLS
X5070 END MILLS
4G MILL END MILLS
X-SPEED ROUGHER END MILLS
X-POWER END MILLS
JET-POWER END MILLS
TN MILL END MILLS
V7 Mill END MILLS
ALU-POWER END MILLS
CRX S END MILLS
D-POWER GRAPHITE END MILLS
D-POWER CFRP END MILLS
ROUTERS
K-2 CARBIDE END MILLS
GENERAL CARBIDE END MILLS
TANK-POWER END MILLS
GENERAL HSS END MILLS
MILLING CUTTERS
TECHNICAL DATA

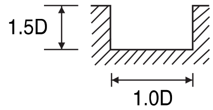
ALU-POWER END MILLS

RECOMMENDED CUTTING CONDITIONS
EMPFOHLENE SCHNEIDKONDITIONEN

CARBIDE, 1 FLUTE
VOLLHARTMETALL, 1 SCHNEIDEN

E5E47 SERIES

MATERIAL	ACRYLIC				ALUMINUM ALUMINUM ALLOY			
DIAMETER	RPM	FEED	Vc	Fz	RPM	FEED	Vc	Fz
2.0	32000	2200	200	0.069	23000	1500	145	0.065
3.0	25000	2400	235	0.096	18000	1700	170	0.094
4.0	20000	2400	250	0.120	15000	1800	190	0.120
5.0	15000	2200	235	0.147	12000	1800	190	0.150
6.0	13500	2300	255	0.170	10000	1800	190	0.180
8.0	10000	2400	250	0.240	7800	1900	195	0.244
10.0	8000	2400	250	0.300	6000	2000	190	0.333
12.0	6700	2300	255	0.343	5000	2200	190	0.440

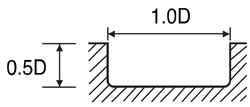


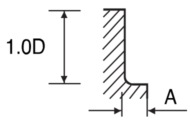
RPM = rev./min.
FEED = mm/min.
Vc = m/min.
fz = mm/t

CARBIDE, 2FLUTE 25° HELIX CORNER RADIUS with NECK
VOLLHARTMETALL, 2 SCHNEIDEN 25˚ RECHTSSPIRALE ECKENRADIUS mit ABGESETZTEM SCHAFTTETL

E5930 SERIES

MATERIAL	ALUMINUM ALUMINUM ALLOY							
DIAMETER	RPM	FEED	Vc	Fz	RPM	FEED	Vc	Fz
2.0	10400	460	65	0.022	10400	810	65	0.039
3.0	10400	720	100	0.035	10400	960	100	0.046
4.0	10400	960	130	0.046	10400	1120	130	0.054
5.0	10400	1040	165	0.050	10400	1360	165	0.065
6.0	10400	1200	195	0.058	10400	1600	195	0.077
8.0	8000	1440	200	0.090	8000	1840	200	0.115
10.0	8000	1760	250	0.110	8000	2160	250	0.135
12.0	8000	2160	300	0.135	8000	2720	300	0.170
16.0	6400	2000	320	0.156	6400	2480	320	0.194
20.0	4000	1600	250	0.200	4000	2000	250	0.250





A : Ø2 ~Ø10 = 0.25×D
Ø12 ~ Ø20 = 0.5×D

RPM = rev./min.
FEED = mm/min.
Vc = m/min.
fz = mm/t