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Vibration analysis during AZ31 magnesium alloy milling with the use of different toolholder types

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Highlights

- This study explored the stability of the AZ31 magnesium alloy milling process.
- Vibration analysis was performed based on the displacement and acceleration signals.
- The influence of toolholder type and cutting condition on vibration was determined.
- Chatter frequency was detected based on the FFT spectrum.

Abstract

Machining vibrations are an important issue as they occur in all types of machining processes. Due to its negative impact on machining results, this phenomenon is undesirable, and so there have been continuous efforts to find solutions that will minimise it, and thus improve the stability and safety of the machining process. The paper attempts to determine the impact of toolholder type and cutting condition on the vibrations generated while milling an AZ31 magnesium alloy. The tests were performed using the three most common types of toolholders: ER, Shrink Fit and hydraulic. The vibration displacement and acceleration signals were analysed based on parameters such as Peak-to-Peak, Peak, and Root Mean Square. Composite Multiscale Entropy was also applied to check the stability of cutting processes and define the level of signal irregularity. To determine the frequencies of vibrations and to detect chatter vibrations Fast Fourier Transform was performed. This provides information on the stability and enables vibrations to be minimized by avoiding unfavourable cutting conditions.

Keywords

vibration, stability, magnesium alloy, milling.

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1. Introduction

Vibrations are a major issue in any production process. They have a significant influence on the safety of machining processes and on their effects, mainly on the accuracy and surface quality of manufactured machine and device components. Therefore, it is necessary to minimize the vibrations, since their complete elimination is unfortunately not possible. The usual division of vibrations is as follows: free (transient), forced, and self-excited (chatter) vibrations. In the context of machining, chatter vibrations are the most interesting and, at the same time, dangerous type, which can result in specific machining issues. These vibrations exist when there is no effect on the exciting force and are caused directly by the loss of stability by the machine-holder-workpiece-tool (MHWT) system. Among the many reasons for the loss of stability, the two most common are: internal feedback in the mass-dissipation-elastic system (MDE) and machine-holder-workpiece-tool (MHWT) as well as between the parameters of working processes (WP); feedback by so-called regenerative chatter (vibration reproduction) [25, 40].

The main factor that affects vibrations are the machining conditions with which the cutting process is carried out [39, 46]. The increase of technological parameters may significantly change the dynamics of the process and thus the tendency to generate vibrations. As a rule, an improvement in stability is obtained by decreasing technological parameters, but this results in a simultaneous decrease in process efficiency. Therefore, the selection of appropriate parameters that will ensure sufficient machining stability while maintaining satisfactory productivity is extremely important. As a process optimization criterion, indicators such as the quality of the machined surface or the favourable form of chips are also adopted [45, 49]. Stability can also be influenced by the machining tool, more specifically its rigidity, geometry or material [1, 22]. The tool must provide adequate chip evacuation and sufficient sharpness. For this purpose, tools with different shapes of cutting edges and different helix and pitch angles [7, 41]. Important for the stability of the machining can also be the inclination angle of the tool in relation to the material being machined [34]. It has been shown in [13] that also the tool wear rate can have a significant impact on the dynamics of the machining process. The process stability can also be improved by selecting an appropriate toolholder. There

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are currently vibration-reducing holders on the market, but their cost is very high. However, satisfactory results can be obtained by using commonly available holders or by applying coatings to them [5, 42]. The intensity of vibrations also depends strongly on the type of machined components. In the case of thin-walled elements, vibrations can have a critical impact on the deformations, therefore vibration reduction is particularly important here. These types of elements are usually shaped using tools with a long overhang, which additionally intensifies the generated vibrations [15, 44]. An even greater risk of vibration occurs when machining components with curved surfaces where motion interpolation occurs [38]. The machining strategy can also be a way of improving stability. Trochoidal milling, where the cyclic exit of the tool from the workpiece prevents vibration from escalating to high levels, is increasingly being used. However, this is associated with an increase in machining time [3, 26, 43]. The main reasons for the loss of stability during cutting of various construction materials are also [25, 34]: high friction coefficient at the tool-workpiece interface, vibrations in the direction of resistance force F_p may generate vibrations in the direction of main cutting force F_c and vice versa (the phenomenon is also called feedback by so-called displacement), and vibrations causing the variable undeformed chip thickness (so-called external modulation).

Chatter vibrations may also leave characteristic chatter marks [6, 9] on the machined surface. This is mainly the effect of vibrations between the tool and the workpiece. Marks on the machined surface caused by vibrations significantly deteriorate the quality of the manufactured elements, which requires the use of additional finishing operations or re-manufacturing the element [10, 39]. It was also observed in [20] that high waviness and roughness occurred on the machined surface as a result of excessive vibration. There could also be problems in achieving the appropriate accuracy of the machined components. Therefore, in addition to the deterioration in the quality of the machined surface, vibrations can affect the durability and service life, and cause accelerated or even catastrophic wear of the surfaces of tools actively involved in cutting [47, 48]. In addition, the high amplitude of vibrations may pose a risk of damage to toolholders and even entire machining units, and might also be a health hazard (high frequencies and excessive noise). The presence of vibrations is often related to the decrease in efficiency and effectiveness of machining, which means a longer machining time (deterioration or limitation of machining parameters) [15].

There are the following options to improve the stability of machine tools [40]: design changes (adding damping elements, increasing stiffness), adding vibration absorbers to the machine structure, and modifying the external modulation (disturbing the phase coincidence in adjacent tool vibrations). Furthermore, a few methods can be applied to increase the dynamic stiffness and vibration stability of tools: the use of anisotropic mandrels, the use of materials with a high Young's modulus and good damping properties, so-called passive dynamic absorbers with inertial mass, and the use of active vibration control by means of active vibration dampers. Active methods usually minimise vibrations on the basis of recorded frequencies, which also take into account the tooth passing frequency and its multiples. However, they are a natural part of the machining process. However, milling chatter suppression is described in [30], which allows for adaptive vibration suppression, which increases productivity.

It is also possible to classify the vibration elimination methods according to the division in [25]. In-process methods are based on continuous monitoring of the machining process and immediate change of the machining conditions when undesirable vibrations are detected [4, 16, 21]. The methods in this group require the collection of a lot of data about the process being carried out and the development of an advanced algorithms. However, a significant advantage is the high autonomy of the system, without the need for substantial human involvement [17, 18]. Out-of-process methods are much more popular; they involve the selection of parameters based on the stability lobe diagram (SLD). These graphs allow to identify stable machining areas in which vibrations should not occur. Hence, they can be the basis for adjusting the appropriate values of the process parameters, i.e. rotational speed and axial depth of the cut [2]. Unfortunately, SLDs also have some disadvantages, the biggest of which being the static approach to obtaining input data (during the machine "standstill", the so-called static test). This does not take into account important and key "dynamic parameters" of the spindle system, such as spindle system stiffness, thermal expansion and various other factors with a direct effect on the workpiece (mechanical and damping properties, changes in the cross-section of the undeformed chip thickness, structure heterogeneity and material defects, etc.) [19, 23]. Therefore, in addition to theoretical considerations (determining the SLD curve), a particularly important and relevant aspect is the practical verification during milling in dynamic real conditions. The paper [32] also presents an attempt to determine the stable areas based on numerical analysis for the process described by the Duffing method.

The methods and types of chatter damping are also listed in [23], which also describes how to select the damping method depending on the machining conditions (workpiece machinability and stiffness of the MHWT system). Paper [14] also considers the impact of the cutter diameter on the shape of the SLD curves (an increase in diameter may extend the stable machining area; an increase in the number of tool blades significantly increases the useful range of rotational speed n and also the range of applicable cutting speed v_c). Other methods are also used in scientific works on milling process stability. Paper [34] contains a list of these methods, including the chase plane method and Poincare method. It discusses the relationship between the maximum Lyapunov exponent (index 0.61 – non-linear vibration criterion) and the milling parameters (spindle speed and milling depth). The higher a_p is, the more the Lyapunov exponent increases. In [33], an external forcing was applied to control the milling process with the use of Matlab-Simulink (numerical tests based on the Runge-Kutta fourth order method with a variable integration step using a proportional-derivative PD controller – closed loop control). A non-linear model with two degrees of freedom was analysed, including phenomena such as non-linearity, and tool and workpiece susceptibility. Lower vibration values were obtained through optimal selection of the process parameters (based on SLD stability curves), the use of the PD controller, and external forcing. A common method of attempts to avoid vibrations is also the selection of technological parameters based on the prediction [28].

The displacement or acceleration of vibrations is often used in the diagnostics of machines and devices. Vibration measurements are usually made using transducers, tactile sensors (e.g. accelerometers, acceleration measuring instruments) or laser sensors (e.g. laser vibrometers). Due to the relatively high versatility, vibration sensors can be used not only to assess the stability of the machining process, but also for structural health monitoring of machining machines [12]. Measurement of the vibration signal has a number of advantages, including the easy installation of the sensor, the small size of the sensor, and the cost of the sensor itself (lower compared to expensive dynamometers, for example). Vibration measurements allow us to obtain as much information about the course of the process as in the measurement of the total cutting force components (good correlation of vibrations with the force signal). But the main disadvantage is the susceptibility to interference (sensor installation point) [29, 43]. The recorded vibration signals are usually analysed as a function of time, but an analysis as a function of frequency is also possible. This allows to determine the frequencies of vibrations during machining, making it possible to detect chatter vibrations and check the stability in the cutting process [3, 27]. The knowledge of the frequencies at which chatter vibrations occur allows for the selection of the appropriate spindle speed at which the machining can be performed with greater safety [11]. A useful tool for analysing the signals recorded during machining, such as vibrations or cutting forces, is Composite Multiscale Entropy (CMSE) [30, 42]. It defines the irregularity and uncertainty of the obtained signal for a better understanding of the phenomena occurring during the cutting process. Composite Multiscale Entropy was developed on the basis of the previous Multiscale Entropy (MSE), which was affected by some errors. The new algorithm assumes the graining procedure for all data series, not only for the first one, like in the MSE. This solution is to ensure greater accuracy of results, even for high values of the scale factor [36, 37].

The process of aluminium alloy milling and the formation of chatter vibrations during such machining are quite well known and described. Many scientific papers have been devoted to analysing the machinability of popular and frequently used aluminium alloys, including: 2024-T351, 6061-T6, 6063, 7050-T7451, 7075 T6/T7. The machining tools used in this regard are often (3- or 5-axis) milling centres, but in research studies, these are also industrial robots (e.g. Kuka) [24, 46] with special tools for machining (e.g. tungsten carbide end mill of the special protection part under the cutting edge). Still, there is no broader analysis of machinability (including vibration) for magnesium alloys, although we can observe a slow trend of interest in such publications and research. For example [8] during the vibration-assisted micro-milling of AZ31B magnesium alloy is investigated in terms of size effect and material removal mechanism. It is found that vibration frequency has a significant influence on the machining mechanism. However, the presented paper applies to micro-milling, which is difficult to compare with machining processes conducted under typical production conditions. The literature review shows that the number of available research on the machining of magnesium alloys is much lower than in the case of other light metal alloys. Magnesium alloys have quite a wide range of applications, and therefore it is believed that a broader analysis is needed for the phenomena accompanying the machining of this group of materials. Despite the relatively high similarity of aluminium alloys to magnesium alloys, the results of the conducted research, and thus the values of the machinability indexes obtained for this group of materials, cannot be directly translated into magnesium alloys. Therefore, an independent analysis of the phenomena accompanying the milling of these materials is necessary.

Based on the literature review, it is stated that machining vibrations are a significant impediment to the implementation of machining processes on various materials. They lead to the loss of process stability, which may lead to faster or even catastrophic tool wear, as well as damage to the machines on which the machining is carried out. All these factors have a crucial impact on the reliability of production processes, as unexpected machine failure can result in production downtime. An important issue is also the quality and accuracy of the manufactured products, which can be significantly deteriorated as a result of the impact of vibrations. In the case of magnesium alloys, this is particularly important as components for the automotive, aircraft and aerospace industries are produced from them. The manufactured products must therefore meet the highest quality criteria. Due to their lightness, magnesium alloys make it possible to significantly reduce the weight of vehicles, and thus reduce emissions to the environment, and thus fit perfectly into the current ecological trends. For this reason, a further increase in the use of these materials is expected in the coming years.

The main novelty of the research described in the paper is the analysis of process stability during milling of the AZ31 magnesium alloy based on, among others, Composite Multiscale Entropy or Fast Fourier Transform. The number of papers on the analysis of phenomena during the processing of this group of materials is significantly lower than in the case of other construction materials. It is believed that knowledge on their machinability is currently insufficient and should be significantly expanded, especially due to the growing popularity of magnesium alloys in many industries. The main objective of the research was to analyse the vibrations generated during the AZ31 magnesium alloy milling process as widely as possible and to determine the factors that may have a significant impact on their formation. The study attempts to determine whether changing the tooling and machining conditions may prove to be an effective method of minimizing vibrations, without the need for large investments in advanced monitoring systems. The latest publications on the dynamics of machining processes indicate that the problem of vibrations is still a valid issue, despite the ongoing research in this area and the development of new solutions to reduce vibrations. Each step taken to increase the stability of the machining is crucial to improving the safety, efficiency and reliability of the manufacturing processes. The conducted research will provide knowledge about the intensity of vibrations that can be expected in the process of machining the magnesium alloy, and whether it is possible to improve the stability without the need to reduce the efficiency of the process. Another novelty of the paper is the use of Multiscale Composite Entropy for stability assessment as an alternative to commonly used indicators. A Fast Fourier Transform was also used for the analysis, which made it possible to determine the frequency of vibrations and the potential susceptibility of the process to the occurrence of chatter.

2. Materials and Methods

The tests involved an analysis of vibrations occurring during the milling process of AZ31 magnesium alloy, as per the diagram shown in Fig. 1. The cutting process was performed on an AVIA VMC 800HS vertical milling centre, without any cooling agents. It is equipped with an electro-spindle with a maximum rotational speed of 24,000 rpm, sufficient for high-speed machining. Three types of toolholders were used for the test: ER by Seco, Shrink Fit by Seco and hydraulic Tendo E by Schunk. The manufacturers of these holders guarantee a balance quality grade of G2.5 up to a rotational speed of 25,000 rpm, as per ISO 21940-11:2016. However, this is the result declared for the holder itself, without the cutting tool attached. For this reason, the toolholder-tool assembly balance was checked with a Cimart RT610 balancing machine. For the tool mounted in the ER holder, the balance was 7.67 gmm, compared to 7.24 gmm in the hydraulic holder. The Shrink Fit toolholder is the only type of holder that allows to adjust the balance yourself, and therefore its result was 4.27 gmm. It is therefore concluded that in all cases, the holder-tool set was balanced in grade G6.3 up to a rotational speed of 20,000 rpm. The tool used during machining was a 16 mm diameter end mill from Fenes made of solid carbide (VHM). The tool is equipped with two cutting edges and has a helix angle of $\lambda_s = 30°$. The overall length of the tool is 92 mm, while the length of cut is 26 mm. The working part of the tool is covered with TiAlN coating, commonly used for machining light metal alloys such as magnesium and aluminium alloys.

Table 1 shows the experiment plan used for carrying out the test. In addition to the type of holder, the variables included two process parameters: cutting speed v_c and feed per tooth f_z. The cutting speed was changed in the range of 400–1000 m/min, and the main limitation was the maximum rotational speed of the spindle. The feed per tooth was changed in the range of 0.05–0.30 mm/tooth. The ranges of parameters used result mainly from the research carried out so far and the authors' experience in the machining of magnesium alloys. Additionally, the cutting speed was limited due to the spindle speed to which the holders were balanced by the manufacturers. The constant factors were the axial depth of cut $a_p = 6$ mm and the radial depth of cut $a_e = 14$ mm. The generated stability curves were also considered when selecting the machining parameters.

Two vibration parameters were recorded during the cutting process: displacement and acceleration. The machining vibrations were analysed in the Y axis of the machine tool, which is in accordance with the direction of the tool feed movement. The vibration displacement was measured with an optoNCDT LD1605-2 laser sensor by Micro-Epsilon, with a measuring range of 2 mm. The laser beam was aimed at the front wall of the workpiece. Vibration acceleration measurements were recorded using a PCB 352B10 piezoelectric accelerometer by Piezotronics, attached to the front surface of the material. Both vibration sensors were connected to an LMCS SCADAS Mobile data acquisition system coupled with a computer with the Test.Xpress 4A software. Both the displacement and acceleration measurements were recorded at a sampling frequency of 10 kHz.

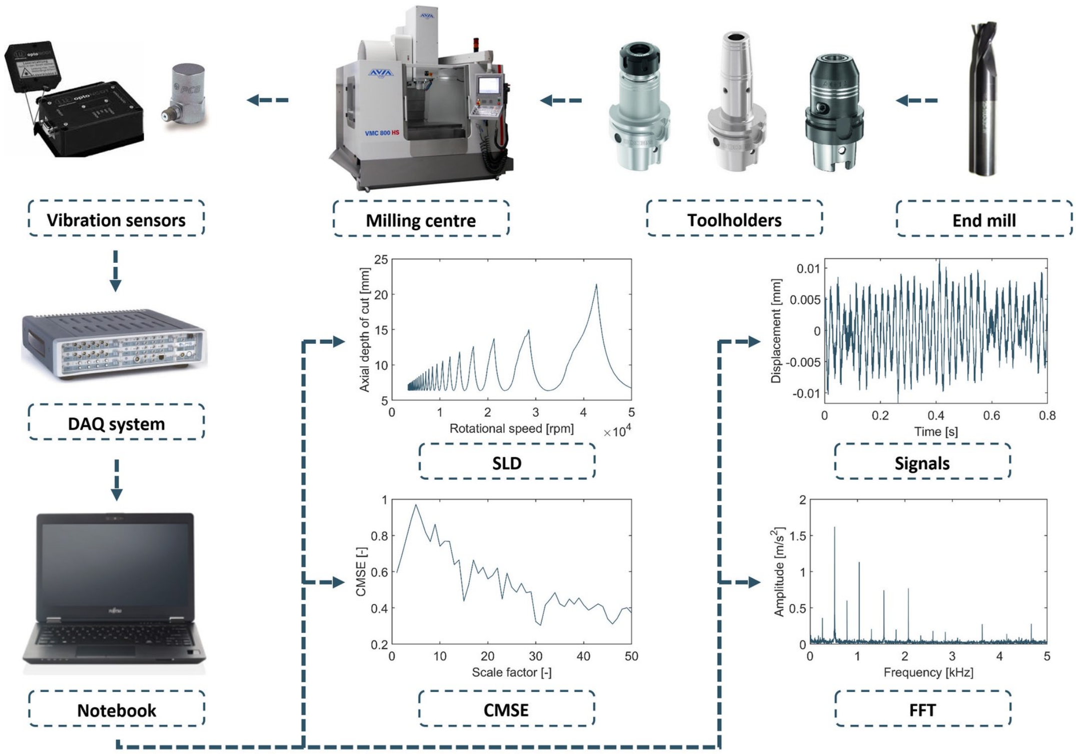

Fig. 1. Scheme of tests

Table 1. Experiment plan

Toolholder type	Cutting speed v_c [m/min]	Feed per tooth f_z [mm/tooth]
ER	400	0.15
	600	
	800	
	1000	
	800	0.05
		0.10
		0.15
		0.20
		0.25
		0.30
Shrink Fit	400	0.15
	600	
	800	
	1000	
	800	0.05
		0.10
		0.15
		0.20
		0.25
		0.30
Hydraulic	400	0.15
	600	
	800	
	1000	
	800	0.05
		0.10
		0.15
		0.20
		0.25
		0.30

The vibration signals recorded during milling were analysed in the full cutting area, i.e. ignoring the tool entry and exit zones. Vibration signals as a function of time were analysed on the basis of three parameters: Peak-to-Peak, Peak, and Root Mean Square (RMS) value. The Peak-to-Peak parameter was defined as the difference between the maximum value and the minimum value, while the Peak parameter was the difference between the maximum value and zero. To avoid distortions caused by single signal spikes, the maximum and minimum values were set as the average of the 10 highest and 10 lowest values, respectively. The RMS parameter values for vibration displacement and acceleration were calculated successively according to Eq. 1 and 2:

$$x_{RMS} = \sqrt{\frac{1}{T}\int_0^T x^2(t)\,dt} \tag{1}$$

$$a_{RMS} = \sqrt{\frac{1}{T}\int_0^T a^2(t)\,dt} \tag{2}$$

where: T – time interval, $x(t)$ – displacement as a function of time, $a(t)$ – acceleration as a function of time.

Composite Multiscale Entropy was calculated according to the standard procedure [31, 36, 37] using the Matlab software. With one-dimensional time series x of total length N, the value of coarse-grained time series $y^{(\tau)}$ was determined for the adopted scale factor τ in accordance with Eq. 3:

$$y_{k,j}^{(\tau)} = \frac{1}{\tau}\sum_{i=(j-1)\tau+k}^{i=j\tau+k-1} x_i, 1 \le j \le N/\tau, 1 \le k \le \tau \tag{3}$$

In the next step, the SampEn sampling entropy was determined to specify the probability that two successive data chains of length m will be similar to each other with tolerance r. Composite Multiscale Entropy is defined as averaging of τ SampEns:

$$MSE\left(x,\tau,m,r\right)=\frac{1}{\tau}\sum_{k=1}^{\tau}SampEn\left(y_k^{(\tau)},m,r\right) \quad (4)$$

The calculations were performed for scale factor $\tau = 50$ and data chain length $m = 2$. Tolerance r was set at 10% of the standard deviation of the original time series.

3. Results

Before starting the milling tests, a modal analysis was carried out to generate SLD for the machined material. The stability curves shown in Fig. 2 were generated for each type of toolholder with mounted cutting tool. The chart also presents the points corresponding to the process parameters applied for the material milling process. The rotational speeds corresponding to the applied cutting speeds were as follows: 7,962; 11,943; 15,924; and 19,904 rpm, while the axial depth of the cut was constant $a_p = 6$ mm.

Based on the curve analysis, it was concluded that the applied depth of the cut is close to the border of the stable area, which should be free of chatter vibrations. However, the stability curves should be used with some caution, because the modal analysis was done in a static system, which may differ significantly from the conditions during the cutting process. Therefore, a more reliable assessment of the process stability is possible only on the basis of experimental tests.

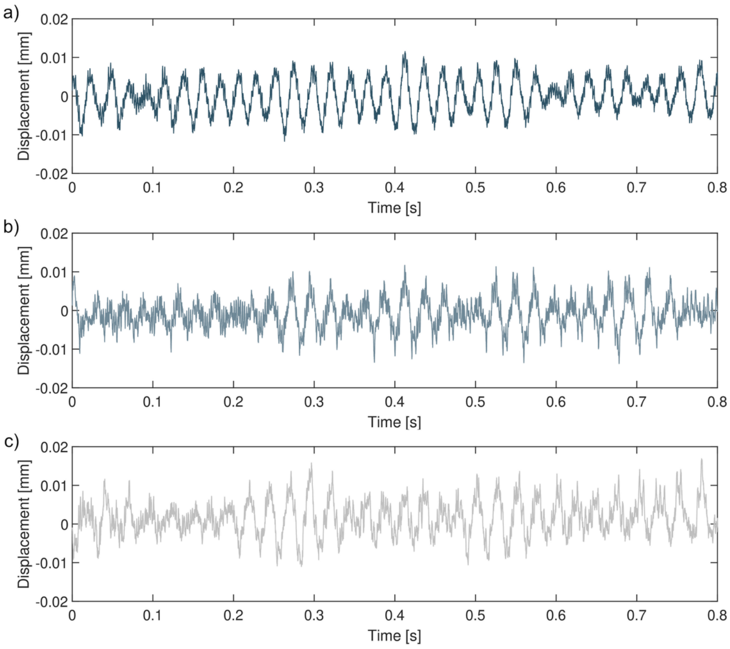

Fig. 3. Time series of vibration displacement obtained during milling with cutting speed v_c = 600 m/min with the use of: a) ER; b) Shrink Fit; c) Hydraulic toolholder

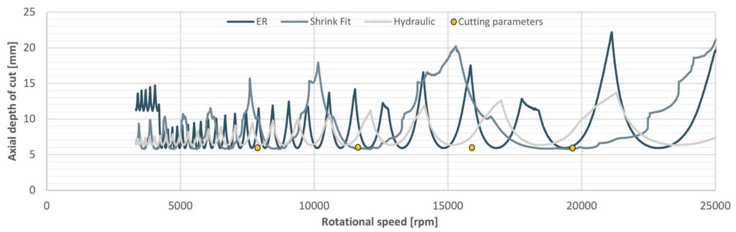

Fig. 2. Stability lobe diagrams for tool clamped in ER, Shrink Fit and Hydraulic toolholders

The values of individual signal parameters recorded at a given cutting speed were similar for different types of toolholders. In general, we could observe a tendency of parameter values to increase as a result of higher cutting speeds. However, at a cutting speed of 1000 m/min, the values of the analysed parameters decreased, which may be connected with entering the HSM (High Speed Milling) area. The exceptions are the results for the tool mounted in the Shrink Fit toolholder, where the value also decreased slightly at cutting speed v_c = 600 m/min. The parameter values were recorded in the following ranges: 0.018–0.045 mm for Peak-to-Peak, 0.009–0.023 for Peak and 0.003–0.011 mm for RMS. The lowest values of the Peak-to-Peak and Peak parameters were obtained in the hydraulic holder at the cutting speeds of 400 m/min and 1000 m/min, and in the ER holder for the

3.1. Vibration displacement analysis

Vibration displacement signals were recorded during milling tests with the use of various types of toolholders and with variable process parameters. Examples of time series fragments for vibration displacement recorded during machining at cutting speed v_c = 600 m/min and with the use of a tool mounted in various holders are shown in Fig. 3.

The recorded vibration displacement signals are modulated, without sudden signal spikes. Despite using the same process parameters during milling, the signals differed depending on the type of toolholder used. The recorded signals were analysed on the basis of three basic parameters: Peak-to-Peak, Peak, and Root Mean Square (RMS). The influence of changing the cutting speed and the type of toolholder on the value of the respective parameters is presented in Fig. 4., while Fig. 5. shows the effects of changing the feed per tooth.

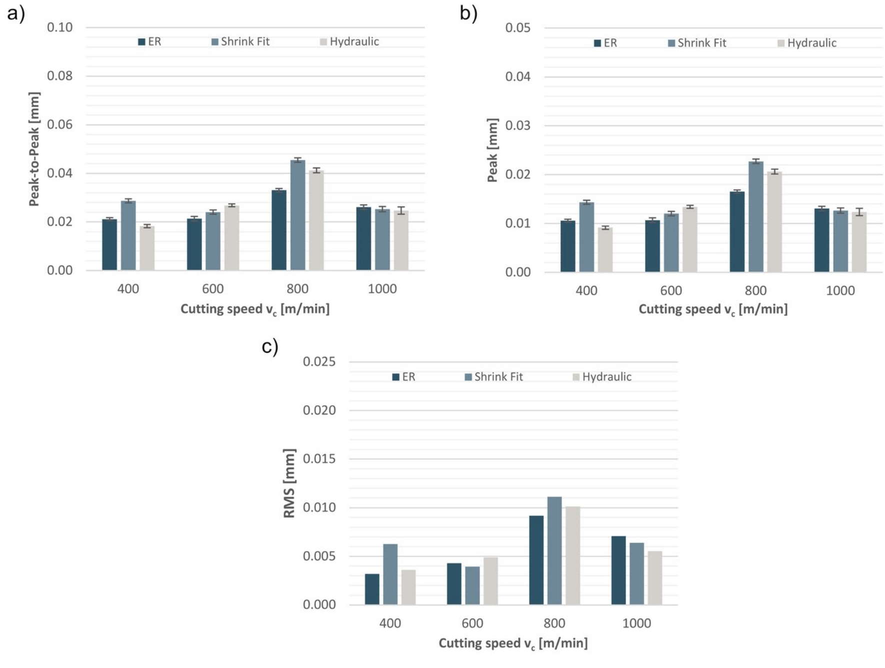

Fig. 4. Effect of cutting speed on: a) Peak-to-Peak value; b) Peak value; c) RMS value of vibration displacement

speed of 600–800 m/min. However, in the case of the RMS parameter, the lowest values were recorded for the ER holder at the cutting speeds of 400 and 800 m/min, for the Shrink Fit holder at the cutting speed of 600 m/min, and for the hydraulic holder at the cutting speed of 1000 m/min. All of the results are also characterised by a small standard deviation, which indicates the absence of considerable individual signal spikes.

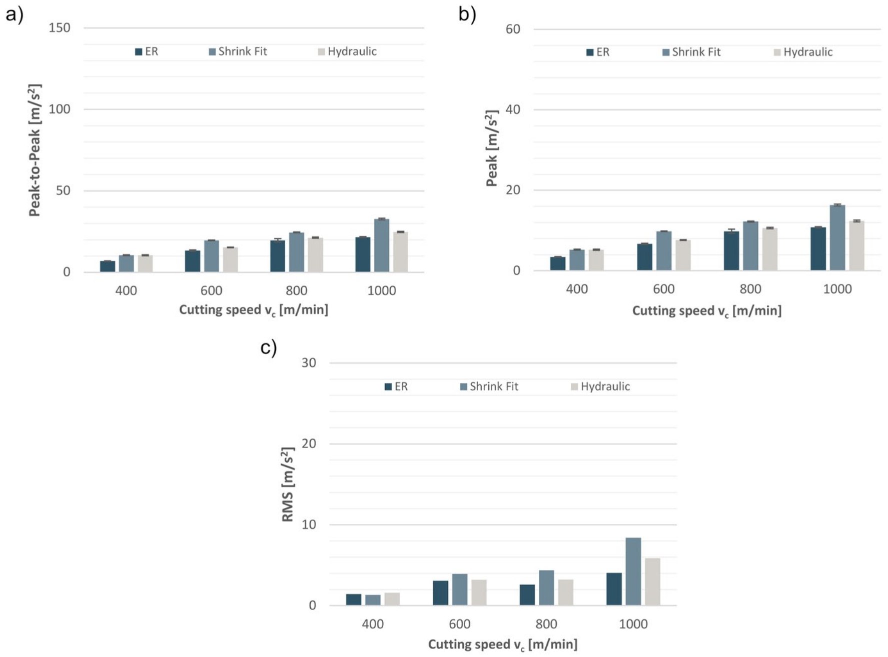

Fig. 5. Effect of feed per tooth on: a) Peak-to-Peak value; b) Peak value; c) RMS value of vibration displacement

Vibration measurements were also carried out during milling tests with variable feed per tooth in the range of f_z = 0.05–0.30 mm/tooth. As a consequence of the change in the feed per tooth, the values of the analysed signal parameters changed indefinitely/irregularly, regardless of the type of toolholder, and remained within the range of 0.019–0.057 mm for Peak-to-Peak, 0.009–0.029 mm for Peak and 0.005–0.012 mm for RMS. The largest change was observed during machining with feed per tooth f_z = 0.30 mm/tooth, where the values increased to 0.082 mm, 0.041 mm and 0.021 mm for Peak-to-Peak, Peak, and RMS, respectively. However, in most cases, the lowest values of the signal parameters were obtained for the tool mounted in the ER holder. Similarly, to changes in the cutting speed, the results were characterised by a small dispersion of values.

3.2. Vibration acceleration analysis

The tests also involved measurements of the vibration acceleration during milling machining with a tool mounted in various types of toolholders and with variable process parameters. Fig. 6 presents examples of time series fragments recorded during machining at cutting speed v_c = 600 m/min.

The vibration acceleration signals recorded during milling with the use of different toolholders have a similar waveform, but differ in values. As in the case of vibration displacement, the obtained signals were analysed on the basis of the following parameters: Peak-to-Peak, Peak, and Root Mean Square (RMS). The values of individual parameters obtained as a result of changes in the cutting speed are shown in Fig. 7, while changes in feed per tooth are presented in Fig. 8.

Increasing the cutting speed resulted in an approximately linear increase in the value of the analysed signal parameters. The obtained values were similar for individual types of toolholders, but the lowest values in the entire range of cutting speed changes were recorded when using the ER holder. The parameter ranges were as follows: Peak-to-Peak – 6.89–32.69 m/s^2, Peak – 3.44–16.35 m/s^2, and RMS – 1.43–8.39 m/s^2. Furthermore, the results showed a small dispersion of values, which demonstrates a high repeatability of the signal.

As in the case of changes in the cutting speed, increasing the feed per tooth resulted in a gradual rise in the values of the analysed parameters. In the feed per tooth range of f_z = 0.05–0.15 mm/tooth, the parameter values increased slightly, while the highest, several-fold increase was observed in the range of f_z = 0.20–0.30 mm/tooth. Regardless of the type of toolholder used, the obtained values remained at a similar level. The values increased from 0.99 to 29.24 m/s^2 for Peak-to-Peak, from 2.97 to 58.30 m/s^2 for Peak and from 0.99 to 29.24 m/s^2 for RMS.

The results obtained during the research show that by changing the technological parameters the dynamics of the milling process can be effectively controlled, both in terms of displacement and vibration acceleration. This is particularly noticeable when changing the feed per tooth, where the values of individual parameters describing vibrations increase several times with increasing feed value. The cutting speed is also a factor influencing the intensity of vibrations, however to a much lesser extent than feed. In order to minimise vibration, it is recommended to carry out machining at low values of technological parameters.

3.3. Composite Multiscale Entropy (CMSE) analysis

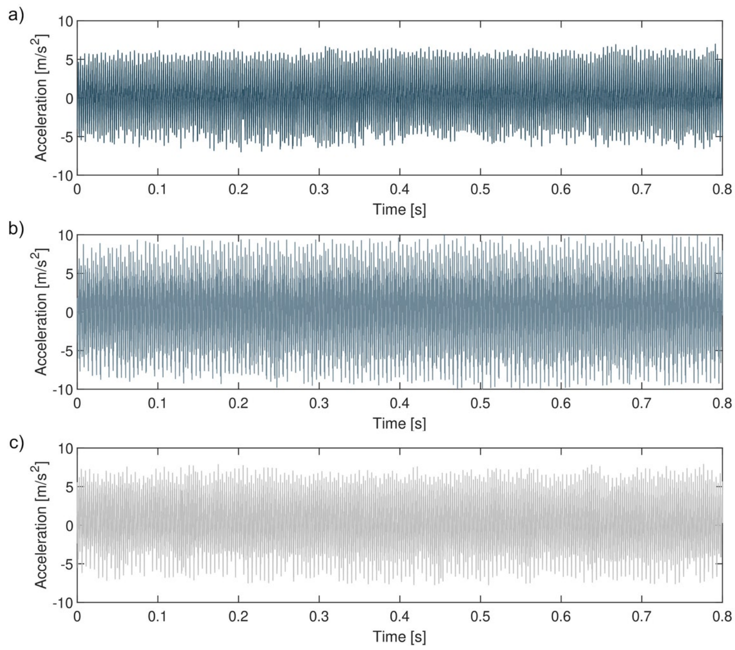

Fig. 6. Time series of vibration acceleration obtained during milling with cutting speed v_c=600 m/min with the use of: a) ER; b) Shrink Fit; c) Hydraulic toolholder

The analysis of the recorded vibration displacement and acceleration signals was also based on Composite Multiscale Entropy (CMSE). It is an indicator that determines the signal entropy, which can be successfully used for analysing the stability of machining processes. The procedure for determining CMSE was carried out for the scale factor of 50, but the greatest changes occurred in the range of τ = 0–20, and

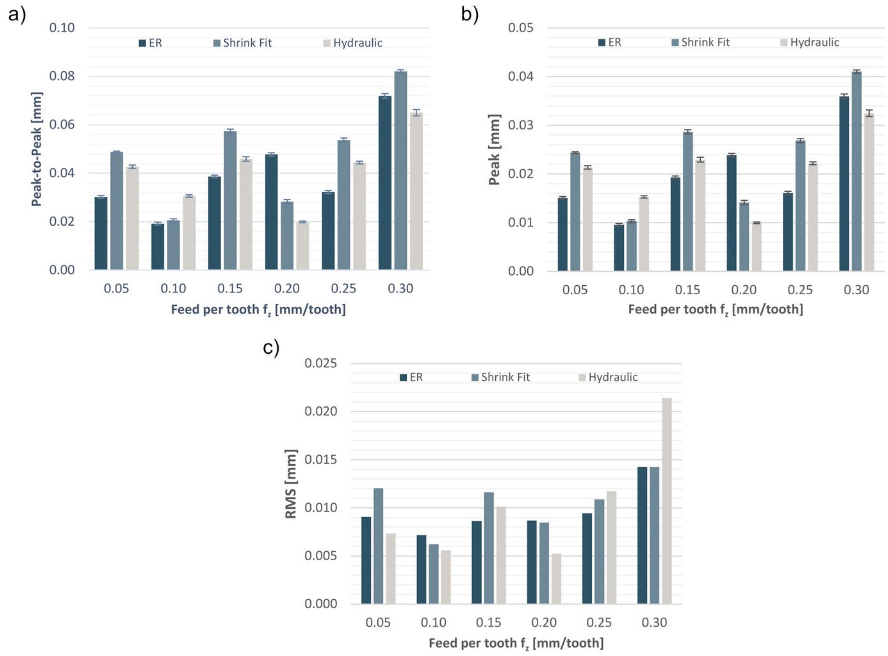

Fig. 7. Effect of cutting speed on: a) Peak-to-Peak value; b) Peak value; c) RMS value of vibration acceleration

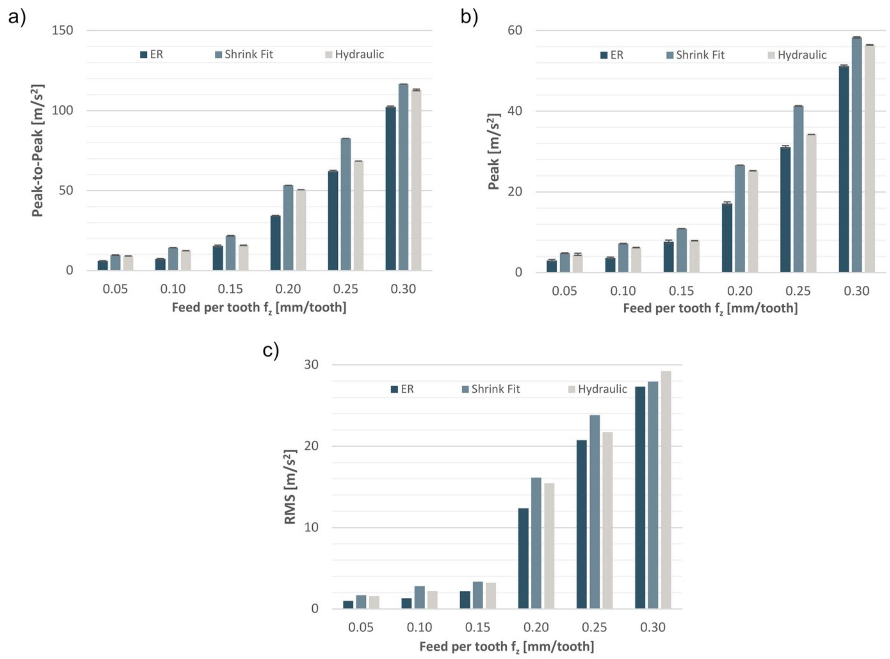

Fig. 8. Effect of feed per tooth on: a) Peak-to-Peak value; b) Peak value; c) RMS value of vibration acceleration

therefore it was decided to limit the scope of the graphs to this area. The CMSE waveform for the vibration displacement signal obtained for the tool mounted in different toolholders during machining with variable process parameters is shown in Fig. 9. A similar analysis was also conducted for the vibration acceleration signals, the results of which are presented in Fig. 10.

The entropy waveforms for the vibration displacement signals recorded during milling with the extreme cutting speed values of v_c = 400 m/min and v_c = 1000 m/min are noticeably different. When machining is done at the lowest cutting speed, the entropy value initially increases, but then stabilises at a scale factor of approx. 14. In the case of signals for cutting speed v_c = 1000 m/min, the value of entropy in the range of τ = 0–10 remains constant, and then drops, which indicates an increase in the stability of the machining process. The nature of entropy waveforms was similar for different types of toolholders, however, at both cutting speeds the lowest entropy values were obtained for the tool mounted in the ER holder, and the highest for the tool in the hydraulic holder.

During machining with variable feed per tooth, the entropy waveforms are very similar regardless of the type of toolholder and change in feed per tooth. In the initial range of the scale factor, a slight increase in entropy can be observed, however, it is much lower than during a change in the cutting speed. The obtained waveforms are very gentle, without clear fluctuations in values, which shows the high stability of the machining processes.

For the vibration acceleration signals recorded during machining at variable cutting speed, the entropy value decreases throughout the analysed range of scale factor τ = 0–20, which proves the process stabilisation. Despite that, some spikes in value can be observed in the waveform. For both the higher and the lower cutting speeds, the

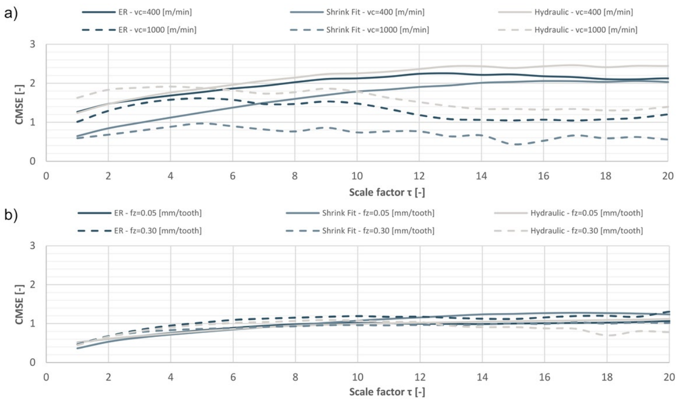

Fig. 9. CMSE for vibration displacement signals obtained during milling with different: a) cutting speed; b) feed per tooth

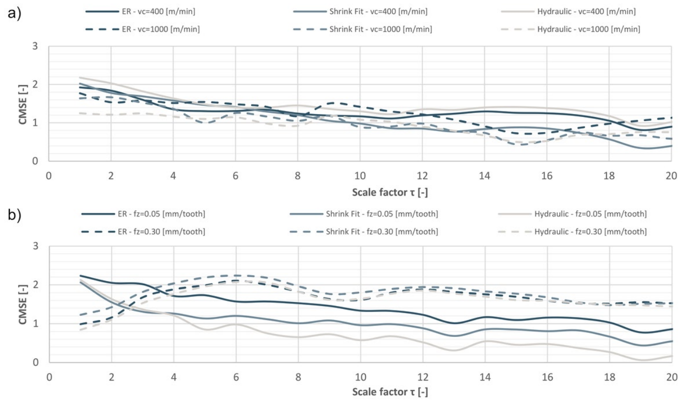

Fig. 10. CMSE for vibration acceleration signals obtained during milling with different: a) cutting speed; b) feed per tooth

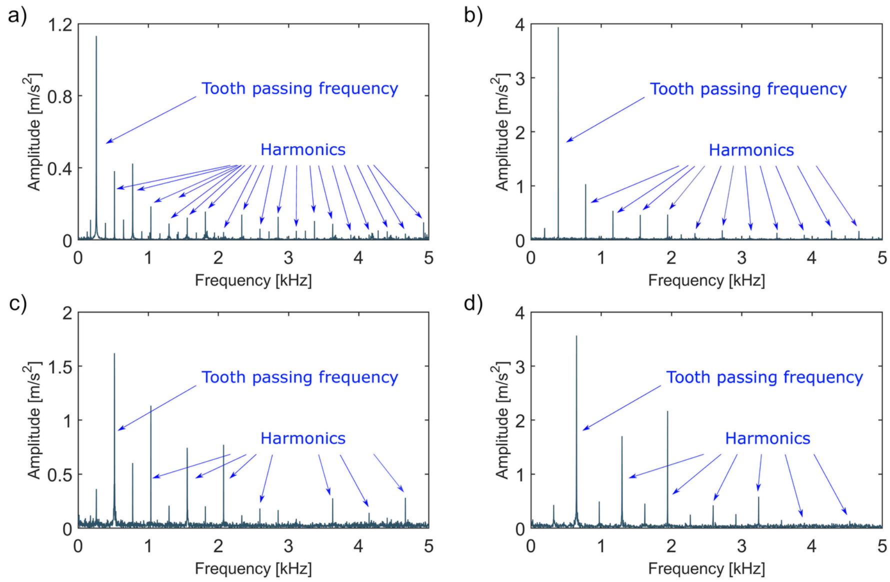

Fig. 11. FFT spectrum of vibration acceleration signals obtained during milling with ER toolholder and different cutting speed: a) v_c = 400 m/min; b) v_c = 600 m/min; c) v_c = 800 m/min; d) v_c = 1000 m/min

entropy values remained at a similar level for all toolholders used. However, at cutting speed v_c = 1000 m/min, the lowest entropy value in the final range of the scale factor was obtained for the tool in the Shrink Fit holder. At cutting speed v_c = 400 m/min, the waveforms intersected in many values of the scale factor, so it is difficult to indicate the signal with the most favourable waveform.

The change in feed per tooth resulted in greater changes in entropy. For feed per tooth f_z = 0.05 mm/tooth, the entropy values decreased throughout the range of the scale factor, while for the highest feed per tooth, the entropy initially increased, and decreased only in the range of τ = 6–20. In the case of the lowest feed per tooth, the entropy waveforms are similar, but the lowest level of signal irregularity was found for the hydraulic holder, while the ER holder was characterised by the most irregular signal. The signals obtained for individual toolholders during machining with the highest feed per tooth f_z = 0.30 mm/tooth had very similar waveforms and entropy values.

Composite Multiscale Entropy analysis has shown that the recorded vibration signals are characterised by a low level of disorder. This applies to both displacement and acceleration signals, for which low entropy values were obtained. The vibration acceleration signals were characterised by a higher level of order, due to decreasing entropy values with increasing scale factor. In the case of vibration displacement signals, an increase in entropy could be observed, however, it eventually stabilised at a low level. On this basis, it is concluded that the vibration occurring during milling were not intense and the machining process was stable.

3.4. Fast Fourier Transform (FFT) analysis

The obtained vibration acceleration signals were also subjected to Fast Fourier Transform to analyse the waveforms as a function of frequency. This type of analysis allows us to distinguish the individual vibration frequencies that make up the recorded signal. It is one of the methods to detect self-excited vibrations during machining processes. The FFT spectrum of vibration acceleration signals obtained during milling with different cutting speed v_c is shown in Fig. 11–13, while the results for variable feed per tooth f_z are presented in Fig. 14–16.

Analysis of the signals recorded during machining using the ER holder (Fig. 11) at variable cutting speed demonstrated that the highest peaks occurred for tooth passing frequencies. For the analysed cutting speeds of 400, 600, 800 and 1000 m/min, these frequencies were 265, 398, 531 and 663 Hz, respectively. In addition to them, the spectrum also includes frequency components corresponding to harmonic vibrations. These are multiplications of the tooth passing frequency. In most cases, these peaks decrease with increasing frequency, and there are no other large peaks, which indicates a fairly high stability of the milling process.

In the frequency domain analysis for signals obtained during milling with the use of the Shrink Fit toolholder (Fig. 12), the situation was a bit different. The highest peaks were again obtained for the tooth passing frequency, with the exception of cutting speed v_c = 1000 m/min. However, the value of harmonic vibrations remained constant, instead of decreasing. During machining at cutting speed v_c = 600 m/min, peaks were observed for the frequencies of 1750 and 2138 Hz,

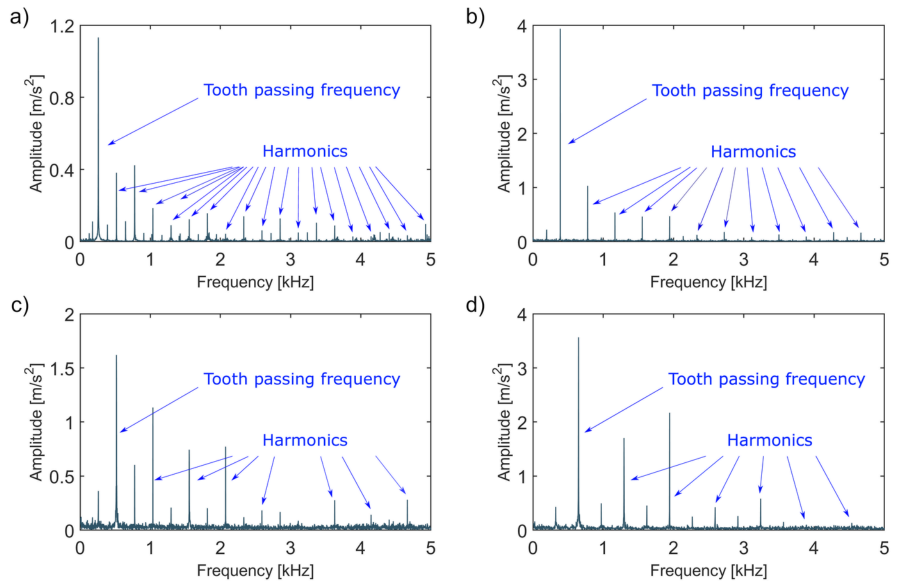

Fig. 12. FFT spectrum of vibration acceleration signals obtained during milling with shrink fit toolholder and different cutting speed: a) v_c = 400 m/min; b) v_c = 600 m/min; c) v_c = 800 m/min; d) v_c = 1000 m/min

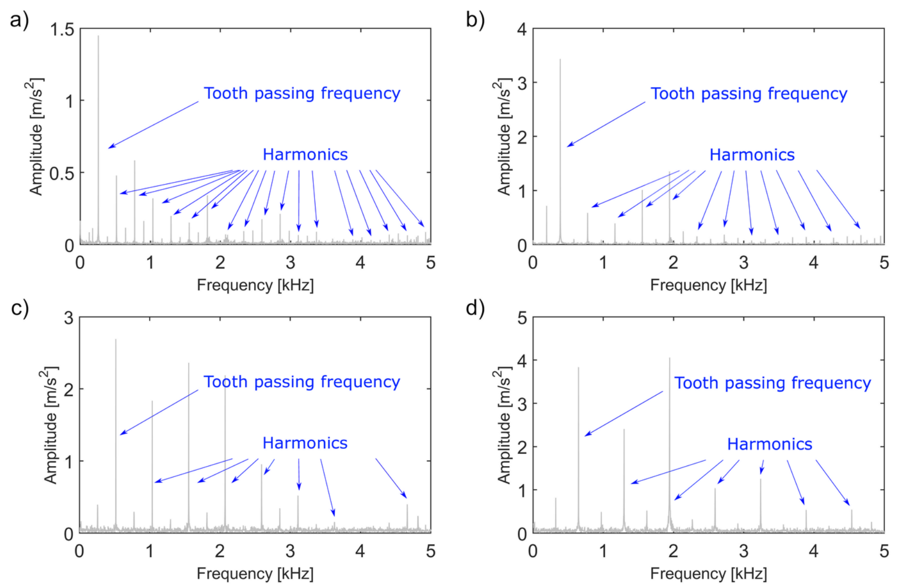

Fig. 13. FFT spectrum of vibration acceleration signals obtained during milling with hydraulic toolholder and different cutting speed: a) v_c = 400 m/min; b) v_c = 600 m/min; c) v_c = 800 m/min; d) v_c = 1000 m/min

which are not harmonic vibrations. So it is supposed that chatter occurred here. In the case of the spectrum for cutting speed v_c = 800 m/min, the harmonic vibration values increased for the frequencies of 1593 and 2124 Hz, which may mean susceptibility to chatter vibrations. The FFT analysis for the highest cutting speed showed that the harmonic vibration frequency of 1989 Hz was dominant. It is much higher than the peak for the tooth passing frequency, which suggests the occurrence of chatter vibration.

The FFT analysis for signals obtained during machining with a tool mounted in the hydraulic holder (Fig. 13) showed that tooth passing frequencies were dominant. For cutting speed v_c = 400 m/min, the harmonic vibrations gradually decreased with the increasing frequency. In the case of v_c = 600 m/min, there was a slight increase in harmonic vibrations at the frequencies of 1592 and 1990 Hz. A much greater increase was recorded at the frequencies of 1593 and 2124 Hz during machining at cutting speed v_c = 800 m/min, similar to the Shrink Fit toolholder. On the spectrum for cutting speed v_c = 1000 m/min, the highest peak occurred for the 2nd harmonic at the frequency of 1989 Hz, which indicated instabilities in the process.

The FFT analysis was also conducted for the vibration acceleration signals obtained during machining with the feed per tooth changed in the range of 0.05–0.30 mm/tooth. Since the change in the feed per blade did not affect the spindle's rotational speed, the tooth passing frequency of 531 Hz was the same in all cases. As can be seen in Fig. 14, during milling with a tool mounted in the ER holder with low feed per tooth values of f_z = 0.05–0.15 mm/tooth, the highest peaks occurred for the 2nd harmonics at a frequency of 1593 Hz, while the subsequent harmonic vibrations decayed. During machining with higher feed per tooth f_z = 0.20–0.30 mm/tooth, the tooth passing frequency was dominant, while the amplitude value increased with the increasing feed value. The height of the peaks of the harmonic vibrations was small, and their number was low.

During milling with a tool in the Shrink Fit toolholder (Fig. 15) at low values of feed per tooth f_z = 0.05–0.10 mm/tooth, the highest amplitudes were observed for the harmonic vibrations, similar to the use of the ER holder. High peaks with a value similar to the tooth passing frequency also occurred at 1814 Hz, suggesting chatter. With feed f_z = 0.15 mm/tooth, the highest amplitude values occurred for the tooth

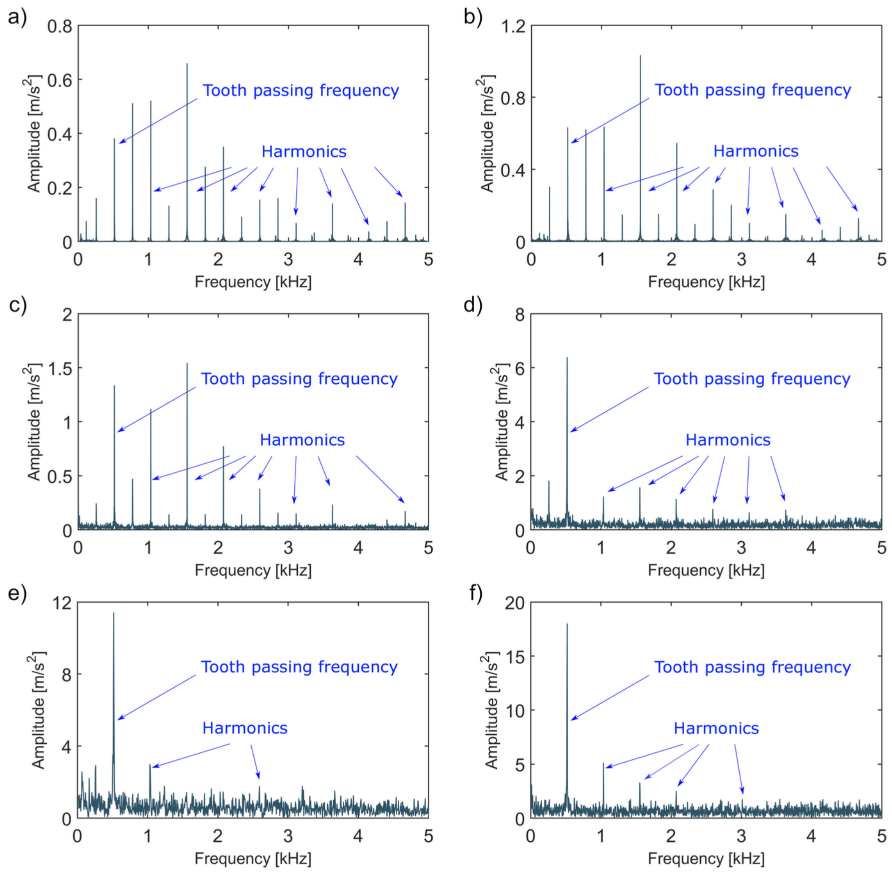

Fig. 14. FFT spectrum of vibration acceleration signals obtained during milling with ER toolholder and different feed per tooth: a) f_z = 0.05 mm/tooth; b) f_z = 0.10 mm/tooth; c) f_z = 0.15 mm/tooth; d) f_z = 0.20 mm/tooth; e) f_z = 0.25 mm/tooth; f) f_z = 0.30 mm/tooth

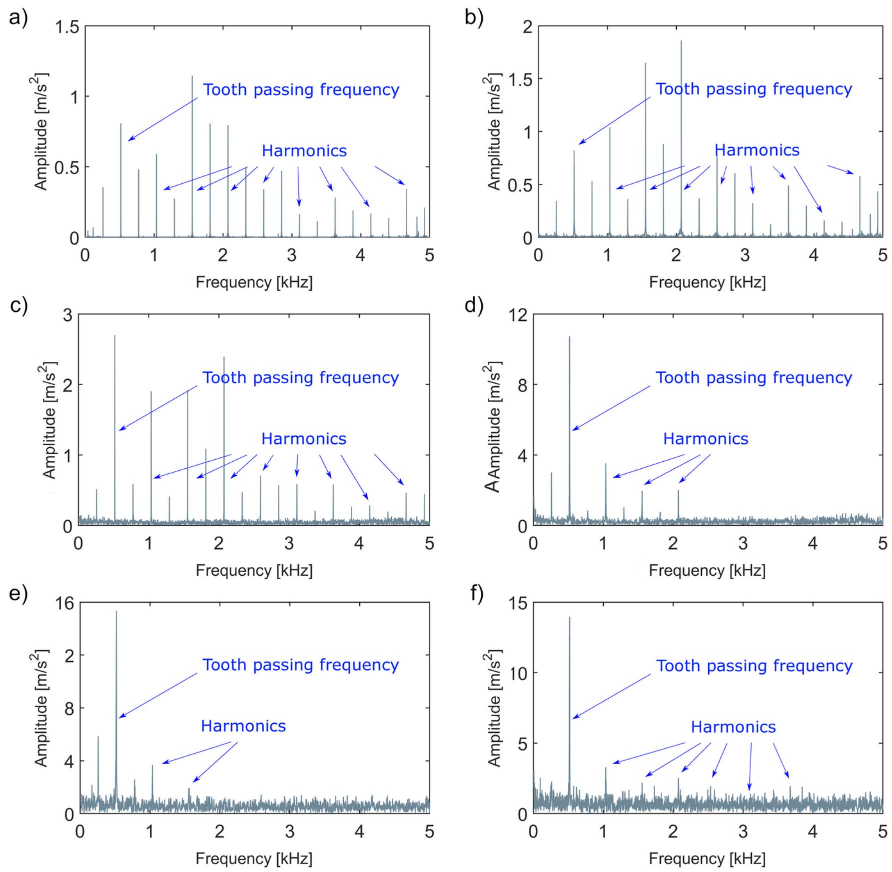

Fig. 15. FFT spectrum of vibration acceleration signals obtained during milling with shrink fit toolholder and different feed per tooth: a) f_z = 0.05 mm/tooth; b) f_z = 0.10 mm/tooth; c) f_z = 0.15 mm/tooth; d) f_z = 0.20 mm/tooth; e) f_z = 0.25 mm/tooth; f) f_z = 0.30 mm/tooth

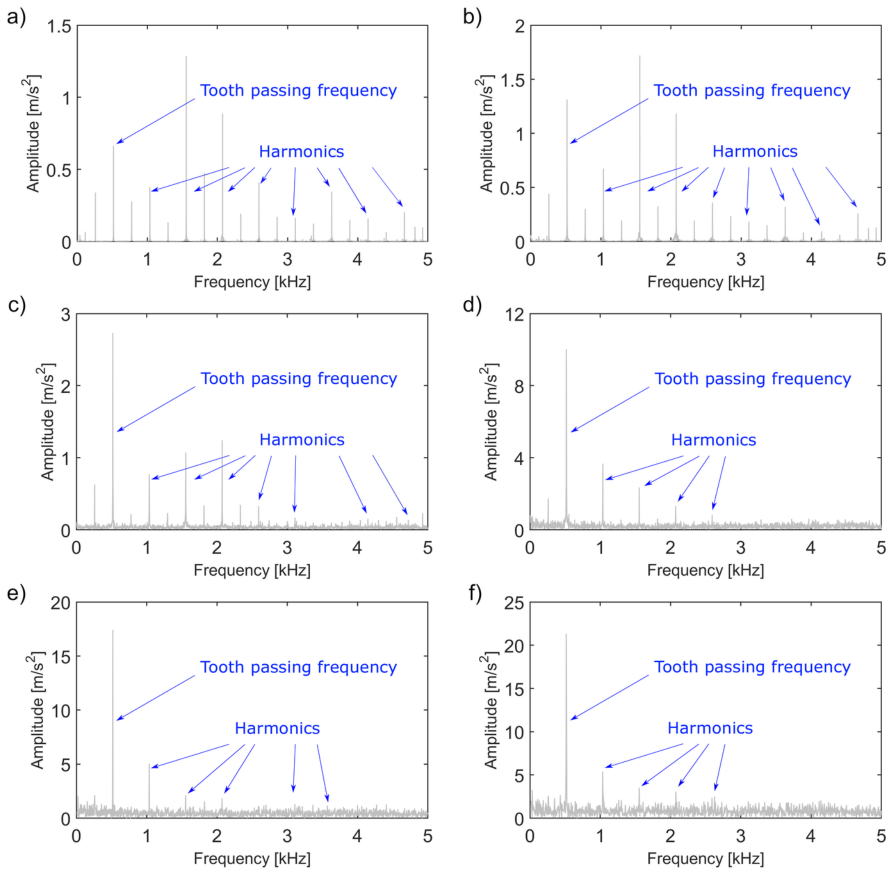

Fig. 16. FFT spectrum of vibration acceleration signals obtained during milling with hydraulic toolholder and different feed per tooth: a) f_z = 0.05 mm/tooth; b) f_z = 0.10 mm/tooth; c) f_z = 0.15 mm/tooth; d) f_z = 0.20 mm/tooth; e) f_z = 0.25 mm/tooth; f) f_z = 0.30 mm/tooth

passing frequency, but the harmonic vibrations were equally high. High peaks for the tooth passing frequency, increasing with the feed per tooth, occurred at high values of feed f_z = 0.20–0.30 mm/tooth. This was accompanied by low amplitudes of the harmonic vibrations, which decayed.

The frequency domain analysis of signals recorded during machining with the hydraulic holder (Fig. 16) showed that at low values of feed per tooth f_z = 0.05–0.10 mm/tooth, the highest peaks occurred for the 2nd harmonics, as in the case of the other two holders. In the range of feed per tooth f_z = 0.15–0.30 mm/tooth, tooth passing frequencies are dominant, while their amplitude increases for higher feed values. We could also observe the decay of harmonic vibrations. Regardless of the type of toolholder used, it was found that as the feed per tooth increased, the number of peaks other than the tooth passing frequency and its multiplication also decreased. With higher feed per tooth values, the floor noise value also increases, but it does not hinder the detection of high peaks.

The analysis of vibration signals as a function of frequency showed that the signal is dominated by vibrations at the tooth passing frequencies and its harmonics, which are multiples of the fundamental component. On the obtained FFT spectrum, no clear peaks resulting from chatter vibrations were observed. A few small peaks appear mainly during machining with the highest cutting speed and low feed per tooth. However, they are relatively small and therefore it can be concluded that the process is quite robust against chatter vibration. High machining stability is therefore ensured over a wide range of technological parameters.

4. Conclusions

The paper presents and discusses the influence of the type of toolholder and basic process parameters on vibrations during the milling process of AZ31 magnesium alloy. Based on the analyses, we have formulated the following main conclusions:

1. Changes in process parameters such as cutting speed and feed per tooth have a significant impact on the vibrations generated during milling. This applies to both displacement and acceleration of vibrations. Increasing the cutting speed results in an approximately linear increase in the value of the analysed vibration parameters. However, the greatest increase in vibrations is caused by changes in the feed per tooth, which is particularly noticeable for vibration acceleration.
2. The type of toolholder also has an impact on the value of the generated machining vibrations, but to a much lesser extent than a change in the process parameters. Due to the similar values of the analysed parameters obtained for individual machining conditions, it is not possible to clearly indicate the toolholder that is best for reducing vibrations.
3. Composite Multiscale Entropy can be successfully used for analysing the vibration displacement and acceleration signals. The analysis showed that the recorded time series are characterised by a relatively low level of signal irregularity. The vibration acceleration signals were characterised by lower uncertainty, and their entropy value decreased for higher values of the scale factor.
4. The FFT spectrum is dominated by tooth passing frequencies and their multiples, which are harmonic vibrations. This indicates the high stability of machining processes. However, when performing milling at the highest cutting speed and low feed per tooth, the process shows susceptibility to chatter vibration.

In conclusion, the milling process of the AZ31 magnesium alloy can be performed with relatively high stability. However, this requires the selection of an appropriate configuration of technological parameters. In a wide range of machining condition, the milling process carried out did not show a clear tendency to generate chatter vibrations. It is therefore concluded that the milling of the magnesium alloy can be conducted in a safe manner with respect to machining vibrations. Despite the different design of the tool holders, the conducted research did not show any significant differences in the obtained results. Therefore, the stability of the cutting process can be maintained regardless of the type of tool holder used. It has been found that the main factor enabling the control of machining vibrations are technological parameters - cutting speed and feed per tooth. The obtained results of the parameters describing the vibrations, as well as the FFT analysis showed that in order to reduce the vibrations, the AZ31 magnesium alloy is preferably processed with the lowest possible values of technological parameters. Various methods of vibration signal analysis used in the study showed that each of these methods can be used to assess the stability of the process. The choice of method depends largely on the type of information the researcher wants to obtain, because each of these methods provides different information about the vibration signal. Despite the relatively large use of AZ31 magnesium alloy in various industries, the available knowledge on the processing of this material alloy is quite limited. Therefore, the conducted research provided valuable information on the dynamics of the milling process of this material. The obtained results indicate that the machining of AZ31 alloy is more stable than in the case of the most popular magnesium alloy AZ91D. This may be related to the higher plasticity of this alloy, which contributes to better vibration damping capacity.

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