

Andrzej WEREMCZUK
Marek BOROWIEC
Michał RUDZIK
Rafał RUSINEK

STABLE AND UNSTABLE MILLING PROCESS FOR NICKEL SUPERALLOY AS OBSERVED BY RECURRENCE PLOTS AND MULTISCALE ENTROPY

STABILNY I NIESTABILNY PROCES FREZOWANIA SUPER STOPU NIKLU OBSERWOWANY Z WYKORZYSTANIEM WYKRESÓW REKURENCYJNYCH I ENTROPII WIELOSKALOWEJ

This paper discusses the stability of high-speed machining processes. The problem of harmful vibrations can usually be detected based on measured signal forces. Nevertheless, the chatter effect may be unrevealed and hence some alternative approaches of signal monitoring must be taken to detect it. In the discussed case of machining, process stability is determined by means of stability diagrams. The measured milling force components are investigated by various signal analysis methods. In addition to this, the analysis also uses recurrence plots, recurrence quantifications, composite multi-scale-entropy and as well the statistical approach. Results obtained by the different methods are presented and discussed.

Keywords: machining, recurrence plot, entropy, chatter.

W niniejszym artykule omówiono stabilność procesu obróbki szybkościowej. Problem szkodliwych drgań zwykle może zostać wykryty na podstawie sygnału mierzonych sił. Niemniej jednak drgania samowzbudne mogą nie ujawnić się w sposób wyraźny, a niekiedy do ich wykrycia potrzebne jest alternatywne podejście do monitorowania sygnału. W przedstawionym procesie obróbki stabilność procesu oszacowano za pomocą wykresów stabilności. Zmierzone siły frezowania badano różnymi metodami analizy sygnału. W analizie wykorzystano wykresy rekurencyjne, wskaźniki rekurencyjne, entropię wieloskalową, a także podejście statystyczne. Przedstawiono wyniki różnych metod i omówiono ich porównanie.

Słowa kluczowe: obróbka skrawaniem, wykresy rekurencyjne, entropia, drgania samowzbudne.

1. Introduction

Nickel alloys are often used in different branches of industry, from medical to aerospace industries. Nickel-based alloys are known to have very good strength and temperature resistance, therefore they are called superalloys. Due to their strength properties, superalloys are very difficult to machine. Additionally, the cutting of these materials can generate harmful vibrations during machining. This poses a serious problem for engineers. Undesired relative vibrations between the tool and the workpiece may deteriorate the quality of machined surfaces or even damage the machine tool and the workpiece. As a result, the cutting forces that depend on the tool geometry, material properties, feed rate and cutting speed can have a large amplitude, which leads to faster tool wear. These vibrations of the tool are known as chatter [39, 40]. In order to use the full capacity of a new fast machine and to achieve a potentially high material removal rate together with the desired surface quality, optimum machining parameters are necessary. The fundamental parameters which may improve efficiency of the cutting process include cutting depth and velocity. Usually, the selection of cutting depth and spindle rotational speed is made via Stability Lobes Diagram (SLD) which can be applied in high-speed machining (HSM) processes to optimize the maximum depth of cut at the highest available spindle speed. When the cutting depth exceeds the critical value, chatter vibrations can occur at some

spindle speed, whereas if the cutting depth is below the critical value, the process is stable regardless of the spindle speed. Generally, in practice, the selection of optimal speed and depth of cut is difficult. Classical SLDs can be obtained by modal analysis of the tool-spindle system; nevertheless, in many research papers the milling process is first modelled and then the numerical results are used to determine SLD (for example [11, 15]). An alternative solution is to calculate stability lobes directly from delay-differential equations [22]. However, only a few papers report complete experimental verification of these stability lobes [24]. The literature reports numerous analytical, numerical and experimental methods for cutting stability prediction. For instance, Altintas and Budak [2] describe an analytical method for predicting milling stability lobes based on a mean of the Fourier series of dynamic milling coefficients. This method is fast but cannot predict additional stability regions and period doubling bifurcation for a low radial depth of cut [8]. To overcome this problem, a multi-frequency solution of chatter stability was developed by Budak and Altintas [3] and then extended by Merdol and Altintas [3, 27]. One of the most popular numerical methods for chatter prediction is the Finite Element Method (FEM) [1, 10, 23, 38]. Bayly et al. [4] propose the use of a temporal finite element analysis for milling and interrupted turning [13]. Moreover, Voronov [38] and especially Adetoro et al. [1] propose an improved model of the classical milling process. This new

model takes into account the well-known model and combines it with considerations about the nonlinearity of cutting force coefficients and the axial immersion angle as a function of the axial depth of cut. The model is validated and the theoretical findings show a very good agreement with the experimental results [1]. Although experimental findings are very often compared with FEM results [13], the problem of experimental signal analysis remains an open question. Various methods of signal analysis are applied to recognize chatter vibrations in cutting operations, including multifractal and wavelet approaches [18], multiscale entropy [20], Hilbert Huang transform [32, 19], recurrence analysis [33, 31], flicker-noise spectroscopy [21] and audio signal analysis [38]. In [7] the delay space reconstruction method is applied to show that the workpiece motion is characterized by fractal geometry. The auto-bispectra suggest a quadratic phase coupling among the spectral peaks associated with the cutter frequency. Finally, the authors propose a mechanics-based model with impact to explain the obtained results. Their predictions agree well with the experimental observations. Other researchers have noticed that the dynamic behaviour of the tool-workpiece system depends on the tool position in the workpiece. This phenomenon and the problem of the influence of several modes on stability lobes is discussed in [37]. On the other hand, modal interaction can affect surface roughness, particularly in the milling of thin-walled structures [34].

Numerical analysis of the cutting process is also useful for stability analysis. However, the models of cutting processes are described by delay differential equations, which may pose some problems in numerical calculations. To accelerate the integration procedure and overcome the difficulties, semi- or full-discretization methods for predicting milling stability are proposed in several papers. The semi-discretization method developed by Insuperger and Stepan is an efficient numerical technique for stability analysis of linear delayed systems. Nonetheless, Ding et al. [8] propose a more effective full-discretization method for prediction of milling stability. Insuperger [12] proposes the so-called act-and-wait concept for continuous-time control systems with feedback delay.

In the literature one can find a number of publications with practical approach to the problem of cutting efficiency. Wojciechowski et al. [42] propose a method ensuring the reduction of forces and the improvement of efficiency in the finish ball end milling of hardened 55NiCrMoV6 steel. The primary objective of the paper is optimal selection of milling parameters (cutting speed and surface inclination angle), as this will ensure minimal cutting force values and increased process efficiency at the same time. From a practical point of view, surface roughness is very often analysed. Roughness depends on different factors including feed direction, axial and radial run-out errors, and cutting tool geometry. In the paper [45] an algorithm considering the effects of static and dynamic factors on surface roughness is proposed. A new approach to surface roughness parameters estimation during finish cylindrical end milling is presented in [41]. The proposed model takes account of the influence of cutting parameters, the tool's static runout and dynamic phenomena related to instantaneous tool deflection.

An interesting contribution to the problem is a numerical and experimental study of the dynamics of flank milling operations at low cutting rates presented in [28]. The paper focuses on both the properties of cutting vibratory phenomena and their impact on the roughness of the machined surface. The study is based on a one-degree-of-freedom model of a mechanical machining system. The system consists of a rigid cutter and a flexible workpiece. The cutting force model is based on a regenerative mechanism. The roughness of the surface machined at high speed revolutions is studied for both forced vibrations occurring during stable cutting and self-excited vibrations occurring during unstable cutting. It is shown that forced vibrations have only a very slight impact on product roughness, while self-excited vibrations lead to a significant increase in roughness.

This paper contains the extended research on Inconel milling stability for various cutting speeds that correspond both to a stable and an unstable regions in SLD. A bit similar experiment performed for increasing the depth of cut at constant cutting speed is published in [16]. The main aim of the present paper is to investigate the effect of cutting speeds on cutting stability via multiscale entropy and the recurrence quantification technique. Moreover, the analysis of cutting forces is made with new recurrence plot quantifiers together with statistical indicators. The determination of proper stability indicators, irrespective of the rotational speed of the spindle (cutting velocity), is the main objective of the paper. The indicators could be applied in the future to build a chatter control system for detecting stability loss symptoms on the basis of statistical parameters, entropy or recurrence plot analysis.

The paper is organized as follows: section 2 presents the methodology of experimental research. Next, in section 3, a statistical analysis of cutting forces is performed, and then a recurrence analysis is presented in section 4. In section 5, the multiscale entropy method is applied to analyse milling process stability. Finally, section 6 contains conclusions.

2. Experiment and methodology

The experimental investigations were conducted on Inconel 718 cut on the Blue Bird MG6037PKK milling machine. The experimental setup, shown schematically in Fig.1, is composed of two subsystems: a modal analysis system and a dynamometer system.

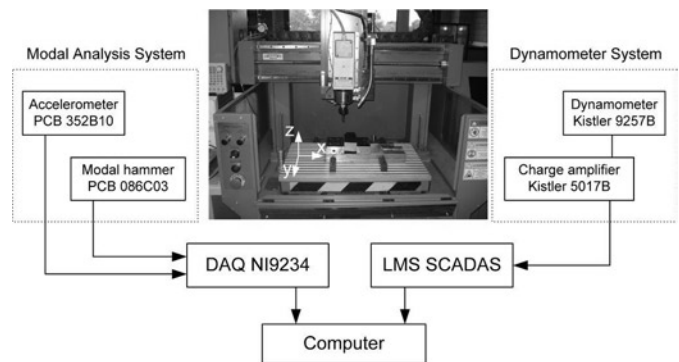


Fig. 1. Experimental setup of CNC milling machine with acquisition system scheme

The former is used to measure tool-holder stiffness and damping coefficient (modal parameters). It consists of the PCB 086C03 modal hammer, PCB 352B10 accelerometer and NI9234 data acquisition card (DAQ). The latter is used to measure the cutting force components (F_x , F_y and F_z) with the Kistler 9257B piezoelectric dynamometer connected to the Kistler 5017B signal conditioner and the SCADAS Mobile LMS analyser. Both experimental rigs are integrated with the computer system. Measurements are conducted in two steps. First, an impact test is performed to obtain data for a stability lobes diagram (SLD). The modal hammer is used to excite the tool, and then the resulting vibrations are measured by the low mass accelerometer mounted on the tool tip. Next, modal parameters in the form of frequency response function (FRF) are implemented to the CutPro9 software to calculate and plot an SLD (Fig. 2a). In the second step of the experiment, the unstable lobes are verified for a series of the spindle speed and the depth of cut marked as the points in Fig. 2b. The test is performed on Inconel 718 by a 12 mm diameter end milling cutter with flutes, made of PCD (FENES DIN 6527-A 12 KNZ4 13). The radial depth of cut equals 12mm (slot milling), the feed per flute is 0.01mm. The applied milling parameters are listed in Tables 1 and 2.

Table 1. Milling parameters applied in the experiment

Parameter	Value
Radial depth of cut (a_e)	12mm
Feed per flute (f)	0.01 mm
Axial depth of cut (a_p)	0.05 – 0.2 mm
Rotational speed of spindle (n)	3000 – 4150 rpm

Table 2. Milling parameters of measured points

Point name	n [rpm]	a_p [mm]	Point name	n [rpm]	a_p [mm]	Point name	n [rpm]	a_p [mm]
n1a1	3000	0.05	n2a1	3500	0.05	n3a1	4150	0.05
n1a2	3000	0.10	n2a2	3500	0.10	n3a2	4150	0.10
n1a3	3000	0.15	n2a3	3500	0.15	n3a3	4150	0.15
n1a4	3000	0.20	n2a4	3500	0.20	n3a4	4150	0.20

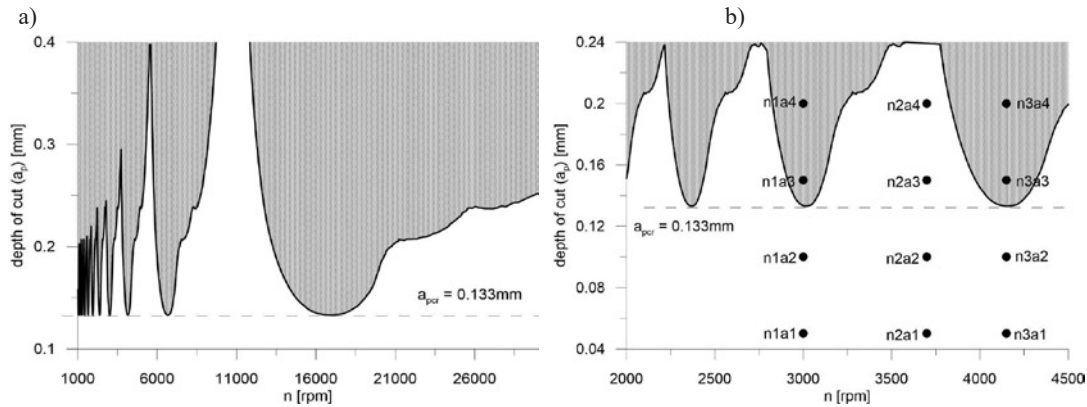


Fig. 2. Stability lobes diagram for Inconel 718, $a_e=12mm$, $f=0.01mm$.

The tool was changed after each test to provide identical cutting conditions and prevent tool wear which could affect process dynamics.

During the milling process, the forces F_x , F_y and F_z are recorded with a sampling rate of 2 kHz; this value is a necessary minimum because the natural frequency of the spindle-tool system is about 740 Hz. On the one hand, this sampling rate meets the Nyquist-Shannon sampling theorem, and on the other hand, it is low enough to record the milling process for a sufficient period of time. In addition to this, the presence of very long time series poses difficulty in a recurrence analysis. In order to avoid the aliasing phenomenon, the Kistler measuring

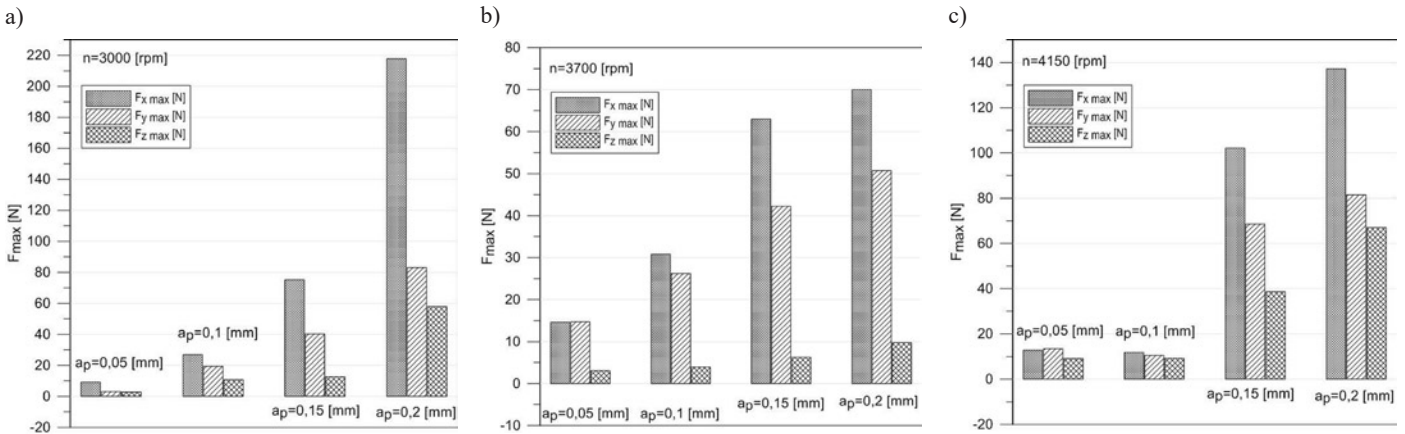


Fig. 3. Maximum values of cutting forces

system is provided with an anti-aliasing filter. Stable cutting occurs in the region below the stability boundary, while unstable machining should occur above the lobes (Fig. 2). According to the diagram, the critical cutting depth a_{per} is 0.133mm. For $a_p < a_{per}$ the process should be stable all the time regardless of the spindle speed. The subsequent section contains a force signal analysis aimed at analysing whether the cutting process with the assumed depth of cut and spindle speed is stable or not. This will help determine stability indicators taken directly from the experiment.

3. Statistical analysis

The statistical analysis is performed for three directions of the cutting force: F_x , F_y and F_z . Although F_x is the most important because its direction is compatible with the feed direction, all the three components are marked in Fig. 3 illustrating the distribution of the maximum cutting force.

A typical behaviour can be observed, namely, with increasing the depth of cut the force components increase too. In the case of unstable cutting (n1a3, n1a4, n2a3, n2a4, n3a3, n3a4 in Fig.2b), the maximum forces rapidly increase to high values (see $a_p=0.15$ and $a_p=0.2$ in Fig.3). Examining the distribution of the standard deviation (Fig.4) one can observe that the greatest dispersion of the results occurs in the case of unstable points $n=3000rpm$, $a_p=0.2mm$ (n1a4) and $n=4150rpm$, $a_p=0.2mm$ (n3a4). For the points located in the stable area, the dispersion of the results is reduced. A large dispersion of the results for the force component F_y from the stable area for the spindle speed $n=3700rpm$ can also be observed. Moreover, an analysis of the mean value is performed via kurtosis (Fig. 5). In the case of point n1a1, the kurtosis of all force components (F_x , F_y , F_z) proves that the force distribution is close to the normal one. The analysis of the distribution of the individual force components around the mean value demonstrates that the largest concentration of the results was obtained for point n1a3 ($n=3000rpm$, $a_p=0.15mm$).

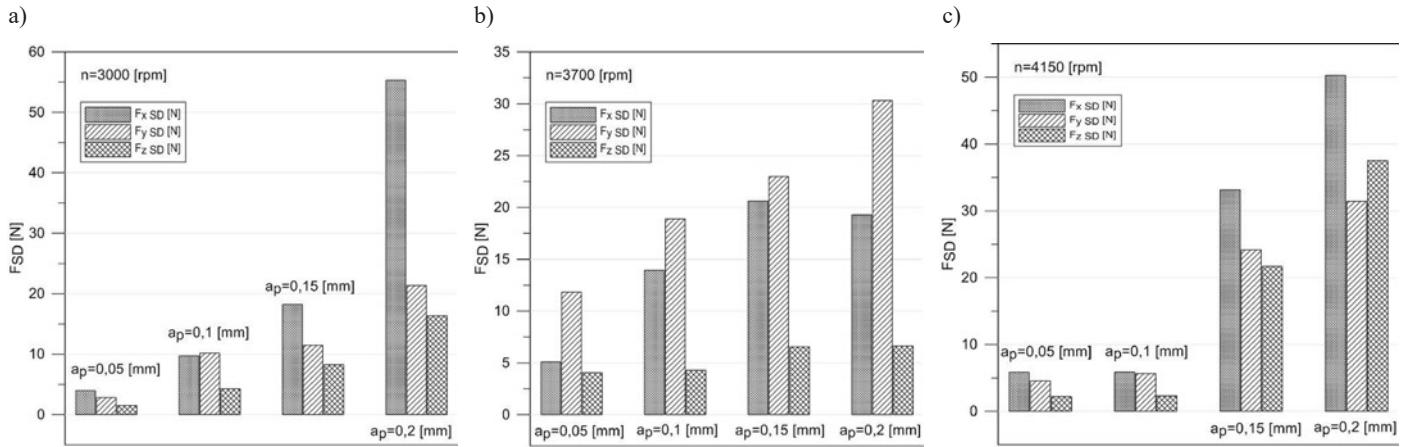


Fig. 4. Standard deviation of cutting forces

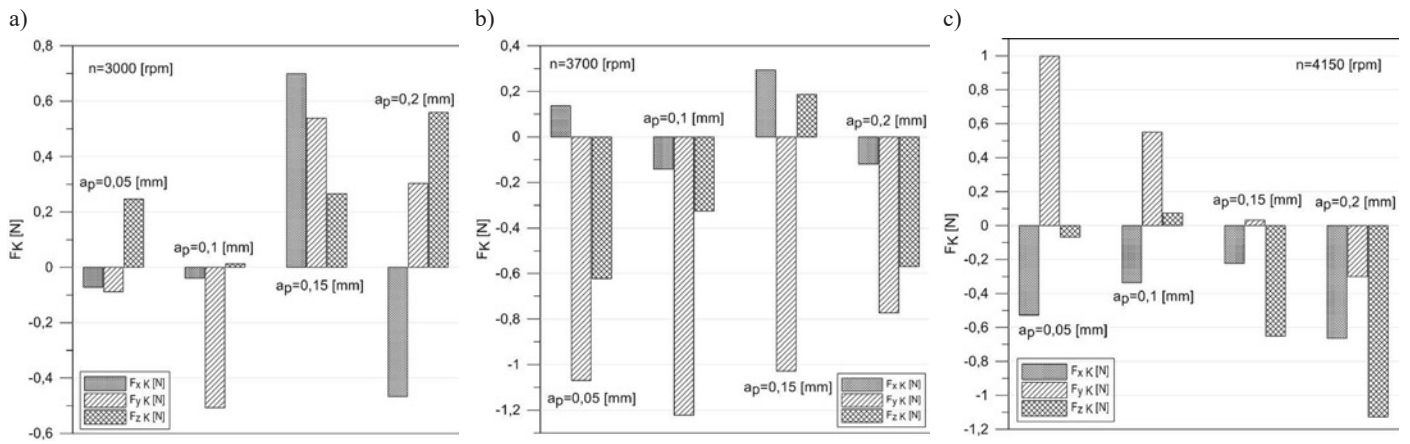


Fig. 5. Kurtosis of cutting forces

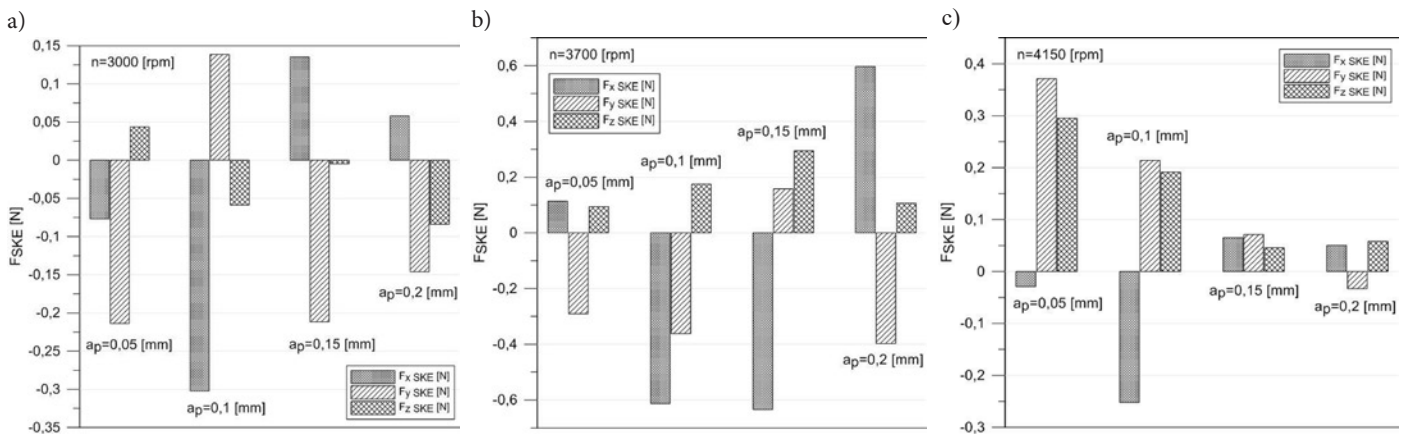


Fig. 6. Skewness of cutting forces

The results of all tests (particularly, the y component) at the spindle speed of $n=3700rpm$ show a great deviation from the average value. Considering all analysed force signals, the smallest asymmetry of results is obtained for the unstable points n3a3 and n3a4 which correspond to $n=4150rpm$, $a_p=0.15mm$ and $a_p=0.2mm$, respectively (Fig.6).

4. Recurrence plot

In order to ensure a more detailed force signals analysis and thorough verification of stability regions, the recurrence plot (RP) technique is employed. The RP approach provides a qualitative interpretation of hidden patterns of dynamical systems based on phase space

reconstruction. This technique was introduced by Eckmann et al. [9]. The general idea of phase space reconstruction rests on the assumption that any time series x_i can be presented as a delayed vector S_i in an m -dimensional space called reconstructed phase space:

$$S_i = (x_i, x_{i+d}, x_{i+2d}, \dots, x_{i+(m-1)d}) \quad (1)$$

where m is the embedding dimension and d stands for the time delay.

Usually the embedding parameters, i.e., the time delay (d) and the embedding dimension (m), can be estimated via the average mutual information function (AMI) and the false nearest neighbours method

(FNN). More information about the AMI and FNN functions can be found in [14, 29, 30]. In this study, the Tisean software [44] is used to obtain the embedding parameters. The recurrence plot technique is a graphical method designed to locate recurring patterns, non-stationarity and structural changes. It shows all time instants at which a state of the dynamical system recurs. The recurrence plot can be expressed as the matrix:

$$M_{ij} = \theta(\varepsilon - |s_i - s_j|) \quad (2)$$

where θ is the Heaviside step function, ε is a tolerance parameter (threshold), s_i and s_j are delay vectors.

If the trajectory in the reconstructed phase space returns at the time i into the neighbourhood of ε where it was before at the time j then $M_{ij}=1$, otherwise $M_{ij}=0$. These results are plotted as black ($M_{ij}=1$) and white ($M_{ij}=0$) dots, respectively. From a practical point of view, RPs can be presented in a more useful and certainly more convenient form via recurrence quantification analysis (RQA). RQA is a method which quantifies the number and duration of recurrences of a dynamical system presented by its state space trajectory. The measures of RQA were elaborated by Zbilut and Webber [44], and then developed and introduced to MATLAB by Marwan [25, 26]. The measures of RQA are based on the recurrence point density and the diagonal and vertical line structures of the recurrence plot. In this paper only the determinism (DET), average length of the diagonal line (L) and L entropy (L_{ent}) are applied to analyse milling stability. These measures are defined as follows: determinism (DET) is the fraction of recurrence points forming diagonal lines:

$$DET = \frac{\sum_{l=l_{min}}^N IP(l)}{\sum_{i,j=1}^N M_{i,j}} \quad (3)$$

The average length of the diagonal lines (L):

$$L = \frac{\sum_{l=l_{min}}^N lP(l)}{\sum_{l=l_{min}}^N P(l)} \quad (4)$$

L -entropy (L_{ent}) is the Shannons entropy of the diagonal line segment distribution:

$$L_{ent} = - \sum_{l=l_{min}}^N P(l) \ln P(l) \quad (5)$$

$P(l)$ is the histogram of the lengths l of the diagonal lines, $P(v)$ is the histogram of the lengths v of the vertical lines, N denotes the number of points on the phase space trajectory.

The recurrence quantification analysis can provide useful information even for short and non-stationary data, where other methods fail. RQA can be applied for various kinds of data to recognize dynamical behaviour. The F_x component is chosen for the analysis because it is naturally dependent on cutting parameters. The idea of phase space reconstruction (necessary for RP) assumes that any time series from

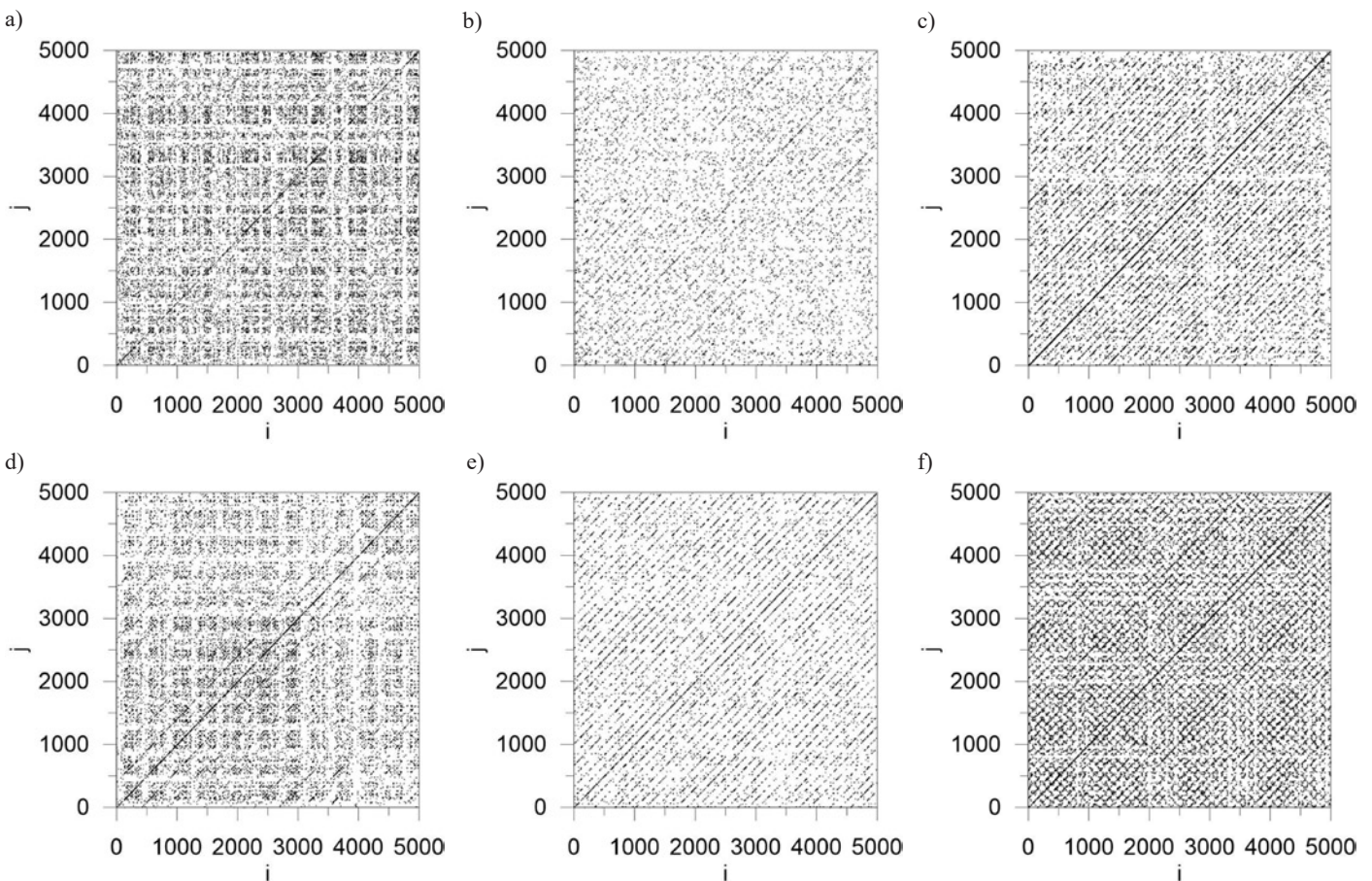


Fig. 7. Recurrence plots for cases of stable cutting (a)-n1a1, (b)-n2a1, (c)-n3a1, and unstable cutting (d)-n1a4, (e)-n2a4, (f)-n3a4.

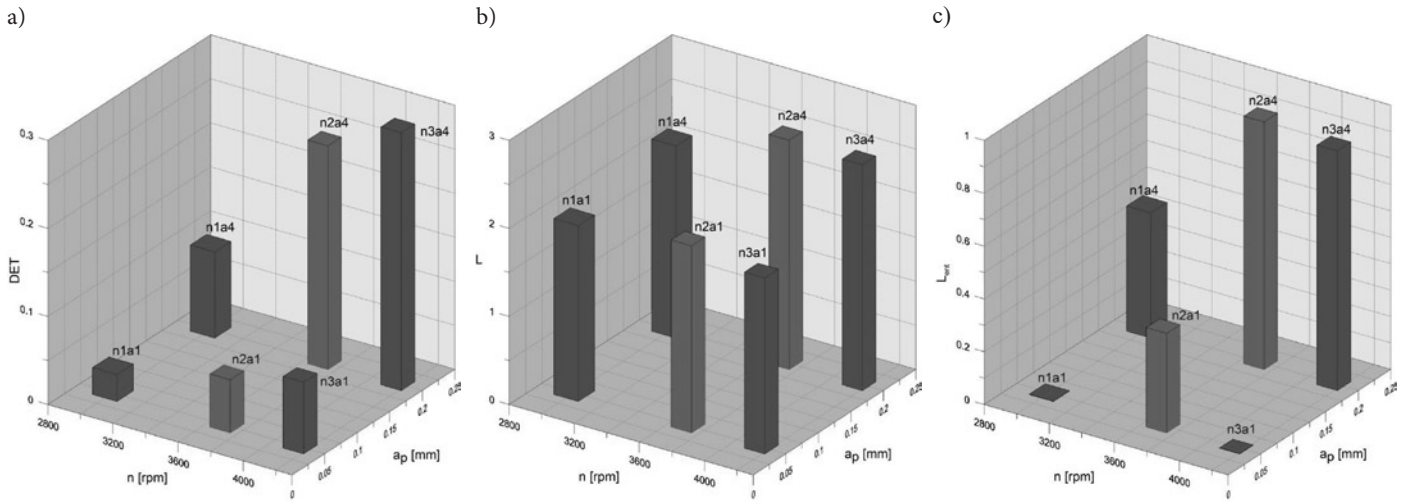


Fig. 8. Recurrence quantification analysis, determinism-DET (a), average length of the diagonal line-L (b) and L entropy-Lent (c).

an analysed process has the same part of information. Moreover, the amplitude of F_x is the biggest therefore a ratio of noise to signal is the smallest. The recurrence plots of the force (F_x) for the selected stable cutting cases (n1a1, n2a1, n2a4, n3a1) and unstable cutting cases (n1a4, n3a4) are presented in Fig. 7. Although relatively small differences can be noticed between the stable and unstable cases, it is rather difficult to spot differences between the recurrence patterns obtained for stable cutting (Fig. 7a,b,c,e) and unstable cutting (Fig. 7d,f); therefore, the recurrence quantification analysis is applied here (Fig. 8). *RQA* gives more distinct information in the form of index about recurrence and system dynamics. The determinism (*DET*) presented in Fig. 8a illustrates well the differences between the depth of cut (a_p) and the rotational speed (n); however, the stable (n1a1, n3a1) and unstable (n1a4, n3a4) points can only be distinguished when $n=3000rpm$ and $n=4150rpm$. For $n=3700rpm$, both points (n2a1, n2a4) are stable, therefore they should have a similar *DET* factor. Unfortunately, the *DET* is not able to find any differences in stability. Nonetheless, the *DET* factor points to an increase in the rotational speed (n).

The average length of the diagonal lines (L) presented in Fig. 8b is the least significant stability factor. Moreover, the impact of the cutting depth (a_p) and the rotational speed (n) on L is insufficient. However, the Shannon's entropy (*Lent*) is also an efficient method for identifying cutting instability (Fig. 8c). Small values of *Lent* in the cases of stable cutting (n1a1, n3a1) considerably increase in the case of unstable cutting (n1a4, n3a4) when chatter occurs. Even in the case of $n=3700rpm$ (green bar), when both points n2a1 and n2a4 are stable, the *Lent* shows an increase that is smaller than for $n=3000rpm$ and $n=4100rpm$. This is because the increase is only caused by the change of the depth of cut and not by the change of stability.

Summing up, the *DET* shows the change of the cutting depth (a_p) and the rotational speed (n), while the *Lent* is additionally able to distinguish stable and unstable cutting for various rotational speeds. A new cutting stability indicator can be proposed which is defined as a ratio of the *Lent* for unstable to stable points (*LentR*). This ratio is vital because for $n=3000rpm$ *LentR*=471, for $n=4150rpm$ *LentR*=908, while in the case of stable cutting at $n=3700rpm$ *LentR*=2.5.

5. Entropy

When analysing complex systems with unpredictable behaviour, it is useful to apply the multiscale entropy method. The application of this method improves the understanding of complex phenomena and such analysis is becoming more and more popular [5, 6]. Multiscale entropy is used for determining the complexity of measured finite-length time-series signals.

MSE may be encumbered with some error, depending on the scale factor length τ . Therefore, in this paper composite multi-scale entropy (*CMSE*) is employed, which helps prevent the above-mentioned errors. The concept of composite multiscale entropy is based on the coarse-graining procedure that uses a coarse-grained time series as an average of the original data points within non-overlapping windows by increasing the scale factor τ according to Eq. (6):

$$y_{k,j}^{(\tau)} = \frac{1}{\tau} \sum_{i=(j-1)\tau+k}^{j\tau+k-1} x_i, \quad 1 \leq j \leq N/\tau, \quad 1 \leq k \leq \tau. \quad (6)$$

where $\tau=1, 2, 3$, when $\tau=1$, the vector $y_j=x_i$. The vector x is a row of one-dimensional time series. Figure 9 illustrates the averaged values. In this approach, the *CMSE* for each scale factor τ is calculated on the coarse-grained time series $y_{k,j}^{(\tau)}$:

$$CMSE(x, \tau, m, r) = \frac{1}{\tau} \sum_{k=1}^{\tau} SampEn(y_k^{(\tau)}, m, r). \quad (7)$$

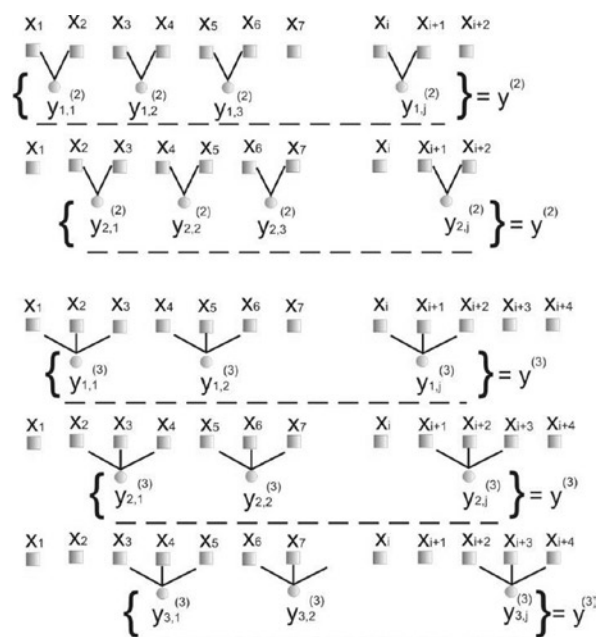


Fig. 9. Diagram of averaged values at the scale index $\tau=2$ and $\tau=3$ in *CMSE*

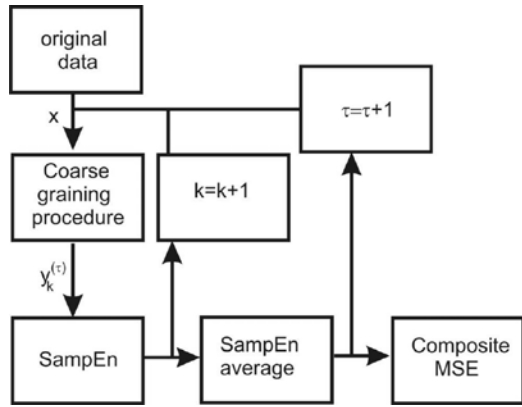


Fig. 10. Algorithm of composite multi-scale entropy (CMSE) calculation

When estimating SampEn in Eq. 7, the values of N_d and N_n should be calculated from prepared grained data $y(\tau)$ by the procedure defined in Eq. 8.

$$\begin{aligned}
 N_d &= N_n = 1 \\
 \text{if } &|y^{(\tau)}(i) - y^{(\tau)}(j)| < r \ \& \ |y^{(\tau)}(i+1) - y^{(\tau)}(j+1)| < r \\
 N_n &= N_n + 1; \\
 \text{if } &|y^{(\tau)}(i+2) - y^{(\tau)}(j+2)| < r \\
 N_d &= N_d + 1;
 \end{aligned} \tag{8}$$

Finally, *SampEn* is the logarithm of conditional probability that two sequences with a tolerance r from the points that remain within r to each other at the next point:

$$\text{SampEn}(y_k^{(\tau)}, m, r) = \ln \left(\frac{N_n}{N_d} \right). \tag{9}$$

In Eq. 9, the parameter m denotes the length of two likelihood occurrence chains that are similar toward each other in the tolerance r . For the analysis of the time courses $m=2$ is applied, whereas the tolerance of probability $r=0.1\sigma_x$ is applied where σ_x is a standard deviation of the original time course vector. Finally, the *CMSE* is calculated according to the algorithm shown in Fig.10.

The *CMSE* signal analysis was applied to the measured signals of the cutting force in x -direction for different sets of two cutting process parameters: the cutting depth a_p and the angular velocity of the spindle n . Figs. 11 and 12 show the *CMSE* results. The composite multiscale entropy analysis revealed that the force signals demonstrate different levels of regularity. The case of machining with the angular velocity of spindle set to $n=4150\text{rpm}$ and the cutting depth $a_p=0.2\text{mm}$ produced the

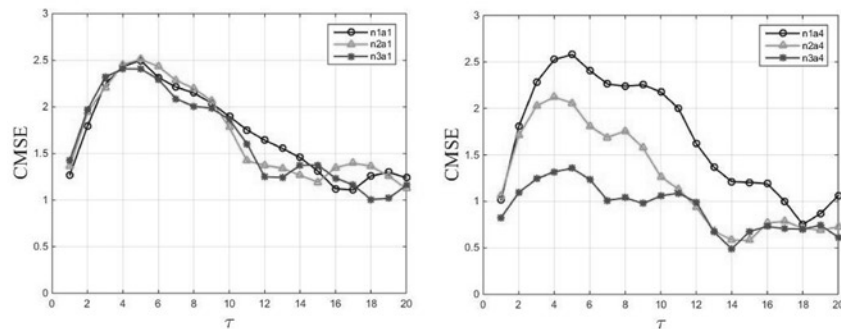


Fig. 11. Composite multiscale entropy analysis calculated for F_x force signals for two cutting depths a1: $a_p=0.05\text{mm}$ (a) and a4: $a_p=0.20\text{mm}$ (b) compared to spindle rotational speeds n1: $n=3000\text{rpm}$, n2: $n=3700\text{rpm}$ and n3: $n=4150\text{rpm}$.

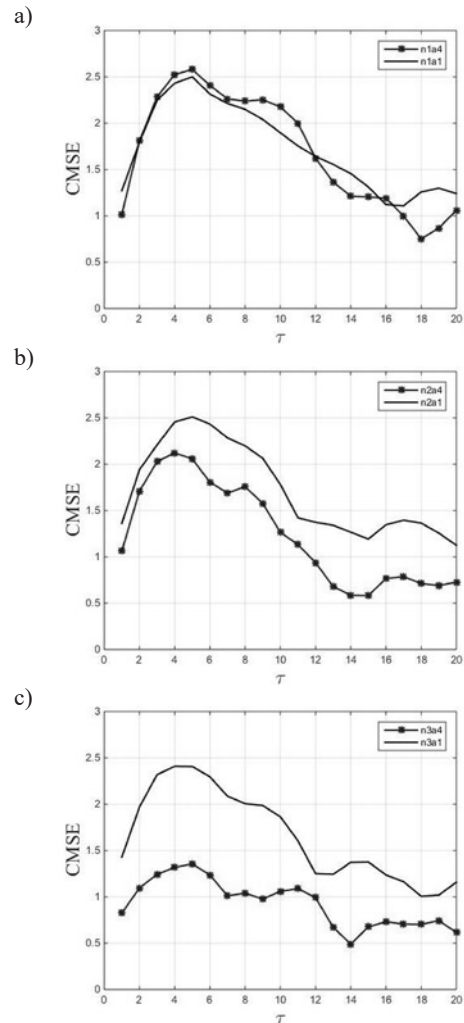


Fig. 12. Composite multiscale entropy analysis calculated for F_x force signals for different ranges of the cutting depth (a1: $a_p=0.05\text{mm}$ and a4: $a_p=0.20\text{mm}$) and rotational speeds of spindle n1: $n=3000\text{rpm}$ (a), n2: $n=3700\text{rpm}$ (b) and n3: $n=4150\text{rpm}$ (c)

most regular signals. In other cases, the *CMSE* reaches higher values, which points to irregularity of the measured signals. With the cutting depth set to $a_p=0.05\text{mm}$, vibration occurs in the process, irrespective of the spindle velocity n . In Figure 11a one can observe a similar *CMSE* for each scale factor τ , while Fig. 11b reveals significant differences for milling at $n=3000\text{rpm}$, $n=3700\text{rpm}$ or $n=4150\text{rpm}$.

The above is clearly shown in Figs. 12a, b and Fig. 12c, where it is plotted with respect to an increased angular velocity. Consequently, the signals are compared between the cases of inside and outside lobes shown in Fig. 2b. This corresponds to the stable and unstable conditions of the milling process. One can notice that the unstable case shown in Fig. 2 (point n3a4) turns out to be a more regular condition for machining (stars line in Fig. 11b or circles line in Fig. 12c) than the second set point n3a1 (stars line in Fig. 11a or black line in Fig. 12c). Moreover, when the angular velocity of the spindle is decreased to $n=3700\text{rpm}$ (Fig. 12b) or $n=3000\text{rpm}$ (Fig. 12a), the irregularity of the signals is similar to the case n3a1 ($n=4150\text{rpm}$, $a_p=0.05\text{mm}$ in Fig. 12c). The most significant difference can be observed for the highest analysed angular velocity (n3). The system is sensitive to process parameters and the *CMSE* shows a clear discrepancy whether the process is stable or not. For the angular velocity $n=3700\text{rpm}$ (Fig. 12b) or even $n=3000\text{rpm}$ (Fig. 12a), the *CMSE*

is similar, which indicates that the depth of cutting has no significant effect on machining stability. Finally, one can observe that the *CMSE* method provides an alternative approach to estimating conditions of the machining process.

6. Conclusion

The paper investigated the problem of the milling process stability for nickel alloy. First, a modal analysis was performed to obtain a stability lobes diagram; the diagram was then verified for selected points by the statistical method, recurrence technique and multiscale entropy method.

Based on the statistical analysis results, it is found that in the case of unstable cutting (points above the stability lobes), there is a significant increase in the maximum cutting force, particularly in the feed direction (x). Similar conclusions can be reached by analysing the standard deviation that is quite obvious in this case. However, it is interesting to observe that a greater symmetry and concentration of the analysed signals occur in the unstable points. Recurrence plots and especially *RQA* are useful for identification chatter vibrations in cutting processes. Given a variety of *RQA* indexes, only a few of them were tested here to select the best one. Undoubtedly, the Shannons entropy (Lent) is the best because it can distinguish stable and unstable cutting for various rotational speeds (cutting speeds). The Lent ratio (between unstable and stable cutting) is the best indicator of cutting instability. *L*-entropy is

extremely high when chatter vibrations appear (unstable cutting), because chatter vibrations show a higher regularity than small-amplitude stochastic vibrations in stable cutting. The recurrence diagrams are not useful to a sufficient degree because it is difficult to estimate differences in the *RPs* and the differences are subjective.

Independently of the above, the composite multiscale entropy analysis revealed a certain degree of signal regularity, which may prove useful when estimating which can give a hint if the milling conditions are profitable for the process. As regards the analysed force signals, it was noticed that increasing the rotational speed of the spindle causes the system to behave in a more regular way, provided that the cutting depth has been selected properly. This observation can be useful when other methods such as *RP* and *RQA* fail or their results are questionable. Since some of the analysed indexes show quite significant differences between stable and unstable cutting, the proposed methods have potential to be employed in the future in a chatter control system.

Acknowledgement

The work of the first author was financially supported by the National Science Centre under the project no. DEC- 2013/09/N/ST8/01202. The second and third authors' research was supported by the Polish Ministry of Science and Higher Education (S3/M/2016). The contribution of the fourth author was financially supported by the National Science Centre under the project no. DEC-2011/01/B/ST8/07504.

References

- Adetoro O, Sim W, Wen P. An improved prediction of stability lobes using nonlinear thin wall dynamics. *Journal of Materials Processing Technology* 2010; 210: 969-979, <https://doi.org/10.1016/j.jmatprotec.2010.02.009>.
- Altintas Y, Budak E. Analytical prediction of stability lobes in milling. *CIRP Annals - Manufacturing Technology* 1995; 44: 357-362, [https://doi.org/10.1016/S0007-8506\(07\)62342-7](https://doi.org/10.1016/S0007-8506(07)62342-7).
- Altintas Y, Budak E. Analytical prediction of chatter stability in milling-part I: general formulation. *Journal of Dynamic Systems, Measurement, and Control* 1998; 120: 22-30, <https://doi.org/10.1115/1.2801317>.
- Bayly P V, Halley J E, Mann B P, Davies M A. Stability of interrupted cutting by temporal finite element analysis. *Journal of Manufacturing Science and Engineering* 2003; 125: 220-225, <https://doi.org/10.1115/1.1556860>.
- Borowiec M, Sen A K, Litak G, Hunicz J, Koszałka G, Niewczas A. Vibrations of a vehicle excited by real road profiles. *Forschung im Ingenieurwesen* 2010; 74(2): 99-109, <https://doi.org/10.1007/s10010-010-0119-y>.
- Borowiec M, Rysak A, Betts D, Bowen C, Kim H, Litak G. Complex response of a bistable laminated plate: Multiscale entropy analysis. *European Physical Journal Plus* 2014; 129(211): 1-7, <https://doi.org/10.1140/epjp/i2014-14211-3>.
- Davies M A, Balachandran B. Impact dynamics in milling of thin-walled structures. *Nonlinear Dynamics* 2000; 22: 375-392, <https://doi.org/10.1023/A:1008364405411>.
- Ding Y, Zhu L, Zhang X, Ding H. A full-discretization method for prediction of milling stability. *International Journal of Machine Tools and Manufacture* 2010; 50: 502-509, <https://doi.org/10.1016/j.ijmachtools.2010.01.003>.
- Eckmann J P, Kamphorst S O, Ruelle D. Recurrence plots of dynamical systems. *Europhysics Letters (EPL)* 1987; 4: 973-977, <https://doi.org/10.1209/0295-5075/4/9/004>.
- Gang L. Study on deformation of titanium thin-walled part in milling process. *Journal of Materials Processing Technology* 2009; 209: 2788-2793, <https://doi.org/10.1016/j.jmatprotec.2008.06.029>.
- Gradisek J, Govekar E, Grabec I. Chatter onset in non-regenerative cutting: a numerical study. *Journal of Sound and Vibration* 2001; 242: 829-838, <https://doi.org/10.1006/jsvi.2000.3388>.
- Inspurger T. Act-and-wait concept for time-continuous control systems with feedback delay. *IEEE Transactions on Control Systems Technology* 2006; 14: 974-977, <https://doi.org/10.1109/TCST.2006.876938>.
- Izamshah R, Mo J, Ding S. Hybrid deflection prediction on machining thin-wall monolithic aerospace component. *Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture* 2012; 226: 592-605, <https://doi.org/10.1177/0954405411425443>.
- Kęcik K, Rusinek R, Warmiński J. Stability lobes analysis of nickel superalloys milling. *International Journal of Bifurcation and Chaos* 2011; 21: 1-12, <https://doi.org/10.1142/S0218127411030258>.
- Kęcik K, Rusinek R, Warmiński J, Weremczuk A. Chatter control in the milling process of composite materials. *Journal of Physics: Conference Series* 2012; 382: 012012, <https://doi.org/10.1088/1742-6596/382/1/012012>.
- Kęcik K, Borowiec M, Rusinek R. Verification of the stability lobes of Inconel 718 milling by recurrence plot applications and composite multiscale entropy analysis. *The European Physical Journal Plus* 2016; 131: 27-36.
- Krauze K, Jankowski Z, Blaschke J. Cutting forces evaluation for tangential-rotational tool basing on laboratory experiments. *Eksploatacja i Niezawodność - Maintenance and Reliability* 2004; 24: 9-14.
- Litak G, Syta A, Rusinek R. Dynamical changes during composite milling: recurrence and multiscale entropy analysis. *International Journal of Advanced Manufacturing Technology* 2011; 56: 445-453, <https://doi.org/10.1007/s00170-011-3195-8>.
- Litak G, Rusinek R. Dynamics of a stainless steel turning process by statistical and recurrence analyses. *Meccanica* 2012; 47: 1517-1526,

- <https://doi.org/10.1007/s11012-011-9534-x>.
20. Litak G, Kęćik K, Rusinek R. Cutting force response in milling of Inconel: Analysis by wavelet and Hilbert-Huang transforms. *Latin American Journal of Solids and Structures* 2013; 10: 133-140, <https://doi.org/10.1590/S1679-78252013000100013>.
 21. Litak G, Polyakov Y S, Timashev S F, Rusinek R. Dynamics of stainless steel turning: Analysis by flicker-noise spectroscopy. *Physica A: Statistical Mechanics and its Applications* 2013; 392: 6052-6063, <https://doi.org/10.1016/j.physa.2013.07.079>.
 22. Lopez Lacalle L N. *Machine tools for high performance machining*. London: Springer, 2009, <https://doi.org/10.1007/978-1-84800-380-4>.
 23. Mane I, Gagnol V, Bouzgarrou B, Ray P. Stability-based spindle speed control during flexible workpiece high-speed milling. *International Journal of Machine Tools and Manufacture* 2008; 48: 184-194, <https://doi.org/10.1016/j.ijmactools.2007.08.018>.
 24. Mann B P, Insuperger T, Bayly P V, Stepan G. Stability of up-milling and down-milling, part 2: experimental verification. *International Journal of Machine Tools and Manufacture* 2003; 43: 35-40, [https://doi.org/10.1016/S0890-6955\(02\)00160-8](https://doi.org/10.1016/S0890-6955(02)00160-8).
 25. Marwan N, Kurths J. Nonlinear analysis of bivariate data with cross recurrence plots. *Physics Letters A* 2002; 302: 299-307, [https://doi.org/10.1016/S0375-9601\(02\)01170-2](https://doi.org/10.1016/S0375-9601(02)01170-2).
 26. Marwan N, Thiel M, Nowaczyk N R. Cross recurrence plot based synchronization of time series. *Nonlinear Processes in Geophysics* 2002; 9: 325-331, <https://doi.org/10.5194/npg-9-325-2002>.
 27. Merdol S D, Altintas Y. Multi frequency solution of chatter stability for low immersion milling. *Journal of Manufacturing Science and Engineering-Transactions of the Asme* 2004; 126: 459-466, <https://doi.org/10.1115/1.1765139>.
 28. Peigne G, Paris H, Brissaud D, Gousskov A. Impact of the cutting dynamics of small radial immersion milling operations on machined surface roughness. *International Journal of Machine Tools and Manufacture* 2004; 44: 1133-1142, <https://doi.org/10.1016/j.ijmactools.2004.04.012>.
 29. Rusinek R. Vibrations in cutting process of titanium alloy. *Eksploracja i Niezawodność - Maintenance and Reliability* 2010; 3: 48-55.
 30. Rusinek R. Cutting process of composite materials: An experimental study. *International Journal of Non-Linear Mechanics* 2010; 45: 458-462, <https://doi.org/10.1016/j.ijnonlinmec.2010.01.004>.
 31. Rusinek R, Borowiec M. Stability analysis of titanium alloy milling by multiscale entropy and Hurst exponent. *The European Physical Journal Plus* 2015; 130: 194, <https://doi.org/10.1140/epjp/i2015-15194-1>.
 32. Rusinek R, Lajmert P, Kęćik K, Kruszyński B, Warmański J. Chatter identification methods on the basis of time series measured during titanium superalloy milling. *International Journal of Mechanical Sciences* 2015; 99: 196-207, <https://doi.org/10.1016/j.ijmecsci.2015.05.013>.
 33. Rusinek R, Zaleski K. Dynamics of thin-walled element milling expressed by recurrence analysis. *Meccanica* 2016; 51: 1275-1286, <https://doi.org/10.1007/s11012-015-0293-y>.
 34. Seguy S, Dessein G, Arnaud L. Surface roughness variation of thin wall milling, related to modal interactions. *International Journal of Machine Tools and Manufacture* 2008; 48: 261-274, <https://doi.org/10.1016/j.ijmactools.2007.09.005>.
 35. Semotiuk L. An analysis of the operational characteristics of innovative tool structures used in high speed rough milling processes. *Eksploracja i Niezawodność - Maintenance and Reliability* 2009; 41: 46-53.
 36. Schmitz T L, Medicus K, Dutterer B. Exploring once-per-revolution audio signal variance as a chatter indicator. *Machining Science and Technology* 2002; 6: 215-233, <https://doi.org/10.1081/MST-120005957>.
 37. Thevenot V, Arnaud L, Dessein G, Cazenave-Larroche G. Integration of dynamic behaviour variations in the stability lobes method: 3D lobes construction and application to thin-walled structure milling. *The International Journal of Advanced Manufacturing Technology* 2006; 27: 638-644, <https://doi.org/10.1007/s00170-004-2241-1>.
 38. Voronov S, Kiselev I. Dynamics of flexible detail milling. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics* 2011; 225: 299-309, <https://doi.org/10.1177/1464419311418735>.
 39. Wiercigroch M, Budak E. Sources of nonlinearities, chatter generation and suppression in metal cutting. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 2001; 359: 663, <https://doi.org/10.1098/rsta.2000.0750>.
 40. Wiercigroch M, Krivtsov A M. Frictional chatter in orthogonal metal cutting. *Phil. Trans. The Royal Society Society of London A Mathematical Physical and Engineering Science* 2001; 359: 713-738.
 41. Wojciechowski S, Twardowski P, Pelic M, Maruda R W, Barrans S, Krolczyk G M. Precision surface characterization for finish cylindrical milling with dynamic tool displacements model. *Precision Engineering* 2016; 46: 158-165, <https://doi.org/10.1016/j.precisioneng.2016.04.010>.
 42. Wojciechowski S, Maruda R W, Barrans S, Nieslony P, Krolczyk G M. Optimisation of machining parameters during ball end milling of hardened steel with various surface inclinations. *Measurement* 2017; 111: 18-28, <https://doi.org/10.1016/j.measurement.2017.07.020>.
 43. Zębala W, Słodki B, Struzikiewicz G. Productivity and reliability improvement in turning Inconel 718 alloy - case study. *Eksploracja i Niezawodność - Maintenance and Reliability* 2013; 15: 421-426.
 44. Zbilut J P, Webber C L J. Embeddings and delays as derived from quantification of recurrence plots. *Physics Letters A* 1992; 171: 199-203, [https://doi.org/10.1016/0375-9601\(92\)90426-M](https://doi.org/10.1016/0375-9601(92)90426-M).
 45. Zhenyu S, Luning L, Zhanqiang L. Influence of dynamic effects on surface roughness for face milling process. *The International Journal of Advanced Manufacturing Technology* 2015; 80: 1823-1831, <https://doi.org/10.1007/s00170-015-7127-x>.

Andrzej WEREMCZUK

Marek BOROWIEC

Michał RUDZIK

Rafał RUSINEK

Department of Applied Mechanics

Lublin University of Technology

ul. Nadbystrzycka 36, 20-816 Lublin, Poland

E-mail: a.weremczuk@pollub.pl, m.borowiec@pollub.pl, m.rudzik@pollub.pl, r.rusinek@pollub.pl
