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

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.

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 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
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 MAG6037PKK 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](image)

The former is used to measure tool-holder stiffness and damping coefficient (modal parameters). It consists of the PCB 06C03 modal hammer, PCB 352B10 accelerometer and N9234 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.
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 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 $a_{pec}$ is 0.133 mm. For $a_p < a_{pec}$, 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 $n = 3000$ rpm, $a_p = 0.2$ mm (n1a4) and $n = 4150$ rpm, $a_p = 0.2$ mm (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 $n = 3700$ rpm 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 ($n = 3000$ rpm, $a_p = 0.15$ mm).

### Table 1. Milling parameters applied in the experiment

| Parameter                        | Value   |
|----------------------------------|---------|
| Radial depth of cut ($a_e$)      | 12 mm   |
| 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, $a_e = 12$ mm, $f = 0.01$ mm.](image)

![Fig. 3. Maximum values of cutting forces](image)
The results of all tests (particularly, the \( y \) component) at the spindle speed of \( n=3700 \text{rpm} \) 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 \( n=4150 \text{rpm}, a_p=0.15 \text{mm} \) and \( a_p=0.2 \text{mm} \), 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:

\[
S_i = (x_i, x_{i+d}, x_{i+2d}, \ldots, x_{i+(m-1)d})
\]  

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.
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:

\[ M_{ij} = \theta(\varepsilon - |y_i - s_j|) \]  

(2)

where \( \theta \) is the Heaviside step function, \( \varepsilon \) 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 \( \varepsilon \) 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 (Lent) are applied to analyse milling stability. These measures are defined as follows: determinism (DET) is the fraction of recurrence points forming diagonal lines:

\[ DET = \frac{\sum_{i,j}^N M_{ij}}{\sum_{i,j}^N M_{ij}} \]  

(3)

The average length of the diagonal lines (L):

\[ L = \frac{\sum_{i}^N |P(l)|}{\sum_{l}^N P(l)} \]  

(4)

L-entropy (Lent) is the Shannon's entropy of the diagonal line segment distribution:

\[ Lent = \sum_{l}^N P(l) \ln P(l) \]  

(5)

For 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.](image-url)
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 $n=3000\text{rpm}$ and $n=4150\text{rpm}$. For $n=3700\text{rpm}$, 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 $n=3700\text{rpm}$ (green bar), when both points n2a1 and n2a4 are stable, the Lent shows an increase that is smaller than for $n=3000\text{rpm}$ and $n=4100\text{rpm}$. 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 $n=3000\text{rpm}$ LentR=471, for $n=4150\text{rpm}$ LentR=908, while in the case of stable cutting at $n=3700\text{rpm}$ 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 $\tau$. 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 $\tau$ according to Eq. (6):

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

where $\tau=1, 2, 3$, when $\tau=1$, the vector $y=x$. 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 $\tau$ is calculated on the coarse-grained time series $y_{k,j}^{(r)}$:

$$\text{CSME}(x, \tau, m, r) = \frac{1}{\tau} \sum_{k=1}^{\tau} \text{SampEn}(y_{k,j}^{(r)}, m, r). \quad (7)$$
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.

\[
\begin{align*}
N_d &= N_n = 1 \\
&\quad \text{if} \quad \left| y^{(i)}(i) - y^{(j)}(j) \right| < r \quad \& \quad \left| y^{(i+1)}(i+1) - y^{(j+1)}(j+1) \right| < r \\
&\quad \text{if} \quad \left| y^{(i+2)}(i+2) - y^{(j+2)}(j+2) \right| < r \\
N_d &= N_d + 1;
\end{align*}
\]

(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:

\[
\text{SampEn}(\tau) = \ln \left( \frac{N_n}{N_d} \right).
\]

(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 \( r=0.1\sigma \) is applied where \( \sigma \) 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 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 \( \tau \), 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 even \( n=3000\text{rpm} \) (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

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

**Fig. 11.** Composite multiscale entropy analysis calculated for \( F_x \) force signals for two cutting depths \( a_1: a_p=0.05\text{mm} \) (a) and \( a_4: a_p=0.20\text{mm} \) (b) compared to spindle rotational speeds \( n_1: n=3000\text{rpm} \), \( n_2: n=3700\text{rpm} \) and \( n_3: n=4150\text{rpm} \).

**Fig. 12.** Composite multiscale entropy analysis calculated for \( F_x \) force signals for different ranges of the cutting depth \( a_1: a_p=0.05\text{mm} \) and \( a_4: a_p=0.20\text{mm} \) and rotational speeds of spindle \( n_1: n=3000\text{rpm} \) (a), \( n_2: n=3700\text{rpm} \) (b) and \( n_3: n=4150\text{rpm} \) (c)

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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 (f). 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 Shannon 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.

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