DYNAMICS OF COMPOSITE MATERIALS CUTTING

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Summary

The paper presents stability analysis of milling process of epoxide polymer composite material with carbon fibres. In order to determine zones of stable milling , times series of cutting forces are applied. Next, recurrence quantification analysis is conducted which can define three stability indexes: recurrence rate, ratio of recurrence rate to determinism, and recurrence time. Finally, stability lobs diagram for the composite material is proposed.

Keywords: milling stability, recurrence quantification analysis

Dynamika skrawania materiałów kompozytowych

Streszczenie

W pracy zaprezentowano wyniki badania stabilności procesu frezowania kompozytu epoksydowo--polimerowego wzmacnianego włóknem węglowym. Określono obszary skrawania stabilnego. Prowadzono analizę przebiegów czasowych sił skrawania opartą na kwantyfikatorach wykresów rekurencyjnych. Stosowano trzy z nich: recurrence rate, proporcję recurrence rate i determinizmu oraz czas rekurencji. Opracowano wykres stabilności frezowania materiału kompozytowego.

Słowa kluczowe: stabilność frezowania, wykresy rekurencyjne

1. Introduction

Composite materials are recently more and more popular especially in aerospace industry where high strength and stiffness of constructional elements connected with low mass is a serious advantage. On the other hand, the high strength causes a problem of composite materials machining. Often, composite materials are glass or carbon fibres reinforced, that additionally makes difficult their cutting process by reason of tool wear but on the other hand, improves strength properties.

The literature which deals with composite material machining, the most often focuses on question of wearing tools [1, 2] or methods of avoiding

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delamination [3]. An investigation of composite material machinability refers both to carbon-fiber or glass-fiber reinforced materials [4, 5] and metal matrix composites [6], but there is a lack of efficient method of process stability classification. For classical metal alloys, there are known methods which let us to determine safe cutting parameters which guarantee process stability and can eliminate large vibrations, called chatter. However, the method based on analytical models of milling need to have dynamic parameters of a tool – holder system and material being cut properties that is difficult to estimate in case of modern composites. Besides, the model-based results are often far from reality. Therefore, in the present study cutting forces signals collected during milling of epoxide-polymer matrix composite reinforced carbon fibres (EPMC-CF) are investigated using recurrence quantification analysis (RQA), and also Lyapunov and Hurst exponents. Finally, the new stability indexes are proposed that should tell a cutting machine operator when the process goes to dangerous vibrations. In the future, the stability index is planned to be implemented to control system of cutting machines.

2. Experimental setup and procedure

In the experiment of composite material milling, three components of the total cutting force (F_x, F_y, F_z) are measured with the help of the experimental set-up whose schematic diagram is presented in Fig. 1. The set up is composed of a CNC milling machine, a piezoelectric dynamometer for cutting forces measurement, a charge amplifier, a module for simultaneous sampling and a typical analog-digital converter. Cutting force signals measured by dynamometer are transmitted to the analog-digital converter which in turn is connected to the computer system.

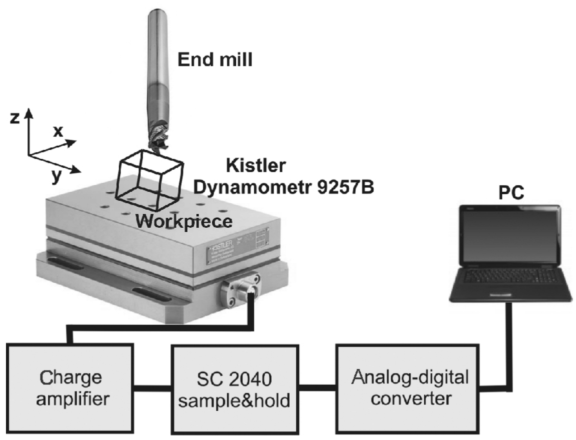

Fig. 1. Experimental setup scheme

Machining of epoxide-polymer matrix composite reinforced carbon fibres (EPMC-CF) is performed for various rotational speeds ranging from 2000 rpm to 8000 rpm. The mill is made of a diamond coated cutting steel having a diameter of 12 mm. The three components of total cutting force are measured with a sampling frequency of 4 kHz and recorded simultaneously, exactly at the same instant.

First, the rotational speed is changed from 2000 rpm to 8000 rpm while depth of cut a_p = 0.5, feed rate f = 520 mm/min. For the last measurements rotational speed n = 6000 rpm, depth of cut is changeable from 0.5 to 2 mm. In total 17 data points are recorded as presented in Table 1. Only stationary time series is taken for the analysis. Transient motion is rejected in order to guarantee repeatability of the process.

Table 1. Milling parameters used in experiment

Point	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Speed n, krpm	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	6.0	6.0	6.0	6.0
Depth of cut a_p, mm	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.5	2.0

3. Milling process analysis

An analysis of cutting stability plays a key role in the machining process design but also ability of cutting control is very important. Here, the recurrence plots technique is engaged to estimate when milling is stable and when not. Recurrence plots (RP) are originally introduced by Eckmann et al. in 1987 [7]. RP graphically presents the system state when recurrence between points exists. More detailed description of RP technique and the delay coordinates method which is used to obtain embedding parameters required for RP construction can be found in [8, 9]. Analysis of RPs sometimes may be labour consuming and equivocal therefore later the recurrence quantification analysis (RQA) is developed mainly by authors of the following papers [10-12]. RQA quantifies the number and duration of recurrences of a dynamical system presented by its state space trajectory. The main advantage of RQA is that it can provide useful information as a index number even for short and non-stationary data. There are fourteen measures of RQA. In this study the recurrence rate (RR), ratio DET/RR between determinism (DET) and RR, and also recurrence time 1st type (T1) are selected for cutting process analysis. These measure are selected experimentally after the cutting forces analyses. Recurrence Rate (RR) is the density of recurrence points in a recurrence plot. Determinism or Pre-dictability (DET) is the fraction of recurrence points forming diagonal lines. T1 is the time when recurrence occurs. The results of calculations RR and DET/RR and T1 for EPMC-CF are presented in Fig. 2, 3 and 4 respectively. If RR is higher than some critical value (RR_{cr}, dashed line in Fig. 2) the milling process at the point can be treated as stable whereas the ratio DET/RR is small for stable points (Fig. 3). In this case $(DET/RR)_{cr}$ can be estimated as well (dashed line in Fig. 3). The third measure T1 is smaller for stable process (points) than unstable ones. All stable points in Fig. 2-4 are circled.

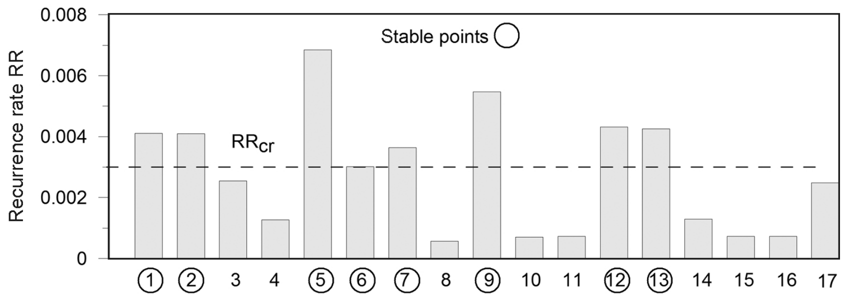

Fig. 2. Recurrence rate for milling parameters – Table 1

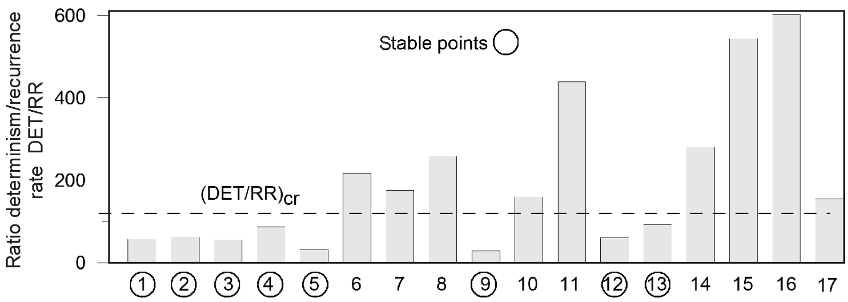

Fig. 3. Ratio determinism to recurrence rate for milling parameters – Table 1

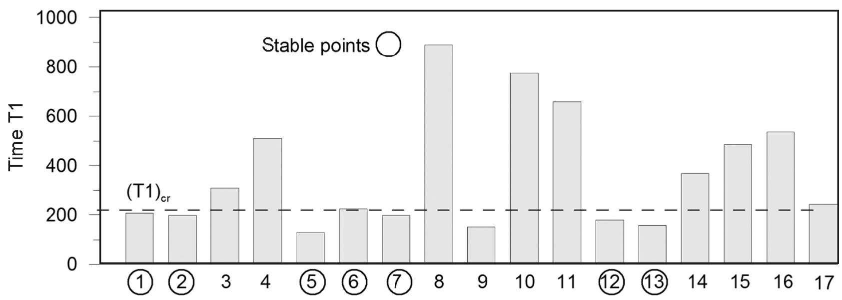

Fig. 4. Recurrence time 1st type for milling parameters – Table 1

These results of milling stability are compared with simple stability criterion proposed in [13]. Process is unstable when the ratio of maximum force to its mean value is greater than 4. Using this criterion, the stable points (circled points) are indicated in Fig 5. Taking all the outcomes into consideration, the stable points of milling EPMC-CF are chosen and shown in stability lobs diagram (Fig. 6) where the stable points are below the curve while unstable ones above the stability lobs.

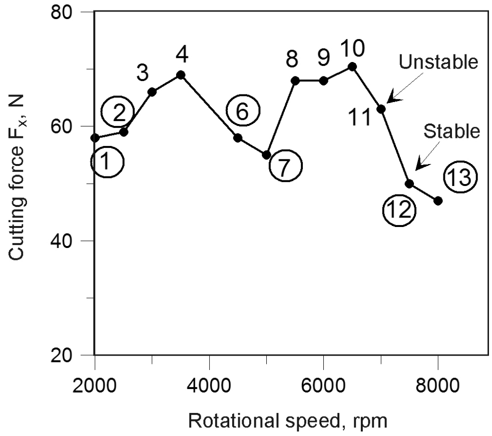

Fig. 5. Maximal cutting force F_x versus rotational speed (points from Table 1)

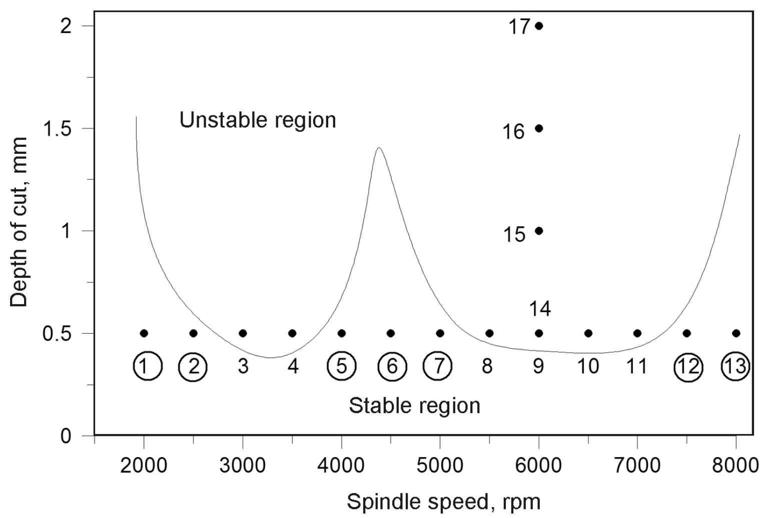

Fig. 6. Proposed stability lobs diagram for milling EPMC-CF (points from Table 1)

Also Hurst and Lyapunov exponents have been calculated for all 17 measurements but the results do not give satisfactory values. Differences between stable and unstable points are not clear therefore these exponents are not recommended for verification of stability process.

4. Conclusions

This study focuses on milling process stability problem in case of composite materials. Stability of cutting process of typical, common used materials can be calculated quite easy using modal analysis and commercial software to obtain SLD. The problem arises when workpiece is made of material which has heterogeneous properties e.g. composite (EPMC-CF). In this case recurrence quantifications analysis looks promisingly. Among all recurrence quantification measures the recurrence rate (RR), ratio DET to RR and recurrence time (T1) are chosen because their efficiency is satisfactory. In case of stable cutting, RR of cutting force signal is higher than some critical value RR_{cr} on the other hand DET/RR ratio is less than critical indicator $(DET/RR)_{cr}$. Recurrence time is also smaller when cutting process is stable. Taking all results together they lead to a conclusion that time series of cutting force is more regular and the force amplitude is higher when process is stable. The proper choice of critical value of RR_{cr}, (DET/RR) and T1 is the main problem which should be solved. The critical value of indexes ought to be about half of maximum value of the measures obtained both for stable and unstable cutting parameters and should be selected individually for the process. Unfortunately, neither Hurst or Lyapunov exponents can be used to identify the process stability mainly because of the short time series which are long enough for RQA and are too short to exponents calculations. The results demonstrate that RQA method can be used for short time series analysis that can be also taken in damage detection of cutting tool, dull of tool or instability control.

Acknowledgements

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