Cutting process of composite materials: An experimental study

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1. Introduction

Nowadays, composite material is more and more popular mainly because of its low mass and high strength. On the other hand, good mechanical properties can render machining of these materials difficult. Specifically chatter or vibration can occur resulting in low quality of surface finish and quite often accelerated tool wear. There are four different chatter mechanisms but two of them are the most important and widely encountered, viz. dry friction and regenerative effects. The former is typical for conventional cutting, the latter for high speed machining (HSM). Machining with high speed is one of key aspect of the modern technologies, which enables to increase efficiency, accuracy and quality of workpiece and at the same time decreases costs and machining time in comparison with conventional cutting.

In the literature frictional chatter and chaotic vibrations caused by dry friction phenomenon are described among other effects in [15,24–26]. Authors explore the problem of metal cutting stability using their own mathematical models of orthogonal cutting. Looking at the problem on the side of HSM process, a model of regenerative cutting seems to be more adequate. Such models are considered in [6,8,16–18,21–23]. Publications which are concerned with composite material machining, frequently focus on the question of tool wear [1,3] or methods of avoiding delamination [4]. In spite of the fact that the investigations of composite material machinability refers both to carbon-fiber or glass-fiber reinforced materials [5,11] and metal matrix composites [27], there is a lack of robust mathematical models which describes the cutting process of carbon-fiber reinforced composites.

The second important matter, which should to be discussed, is related to the methods of non-linear time series analysis. In this paper, method of delay coordinates is proposed, which is based on the Takens theorem [20]. All the calculations are performed with the help of Tisean package [10]. The same procedure has been used successfully in previous works as well (e.g., [2] and [14]). In [2], the primary investigation is on the cutting process dynamics by means of the false nearest neighbours method and chaotic behaviour is examined using Lyapunov exponents. Additionally, a wavelet analysis is employed in [14]. The latter also makes use of Tisean package for calculation of Lyapunov exponents [2]. Chatter and chatter free cutting processes are distinguishable in [9] where delay coordinates method is also used. Additionally, the cutting process is treated as a stochastic process rather than as a deterministic one.

This paper is an attempt at describing relations between the cutting forces and cutting process parameters, which gives the basis to build adequate models of cutting process of epoxide-polymer matrix composite reinforced carbon fibers (EPMC). In Section 1, a short review of literature is presented. Section 2 describes the experimental set-up and the details of the experiment and numerical tools used for the analysis. Section 3 contains the results of experimental measurement of cutting forces as functions of feed and rotational speed. Next, the analysis of time series with the help of Poincare maps and recurrence plots are performed. In the last section conclusions with practical directions are presented.

2. Experimental set-up and procedure of analysis

The measurements are conducted on the experimental set-up whose schematic diagram and a real image containing the face cutter and the workpiece are 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 are transmitted from the dynamometer to the analog-digital converter which in turn is connected to the computer system.

Machining of epoxy-polymer matrix composite reinforced carbon fibers (EPMC) is performed for various rotational speeds ranging from 2000 to 8000 rpm and feed from 200 to 720 mm/min. The mill is made of a diamond coated cutting steel having a diameter of 12 mm. All three components of the total cutting force \( F_x, F_y, F_z \) in \( x, y, z \) directions, respectively are measured with a sampling frequency of 4 kHz and recorded simultaneously, exactly at the same instant. Each experimental run is repeated eight times with the same workpiece, the same direction of tool movement and all other experimental parameters remaining the same to establish the repeatability of the experiment. Mean value of the selected parameters of force signal (RMS, mean, amplitude) are taken for further analysis. First, the feed rate \( f \) is taken as a variable and five different values viz. 200, 270, 370, 520 and 720 mm/min are considered with the other parameters fixed as follows: rotational speed \( f = 4000 \) rpm, depth of cut \( d_0 = 0.5 \) mm. In the second part of the experiment the feed rate \( f \) is 520 mm/min, depth of cut \( d_0 \) is 0.5 mm while the rotational speed is changed from 2000 to 8000 rpm with a step of 500 rpm. A total of 12 data points for the rotational speeds are obtained for this experiment. Only stationary time series is taken for the analysis where any transient motion is rejected in order to guarantee repeatability of the process.

The time series of the cutting forces are recorded on the computer hard disc using the LabView platform. Next, the recorded data are analysed by means of the method of delay coordinates [10]. The rationale behind using the method is to recognize a type of vibrations depending on cutting parameters by investigating the cutting forces. The method allows to reconstruct Poincaré map on the basis of time history of the signal. A numerical procedure developed by Hegger, Kantz and Schreiber is known as Tisean package. According to Takens theorem [20] measured time series can be presented as a vector in a new \( w \)-dimensional space [13]

\[
x(t) = [S(t), S(t+\tau_1), ..., S(t+(w-1)\tau_1)]
\]

The new space is called the embedding space, where \( w \) denotes the embedding dimension, \( \tau_1 \) is named as the delay or time lag. The time delay is taken as an integer multiple of the sampling time and is computed using the average mutual information [7] given by equation

\[
j(\tau_1) = -\sum p_k(\tau_1) \ln \frac{p_k(\tau_1)}{p_k p_l}
\]

where \( p_k \) is the probability to find a time series value in the \( k \)th interval, and \( p_k \) is the joint probability for which an observation falls later into the \( l \)th element. The average mutual information \( J \) is plotted versus the time lag, and the adequate value of \( \tau_1 \) corresponds to the first local minimum. This procedure is an equivalent of an autocorrelation function for a linear case. The embedding dimension \( w \) is obtained by means of false nearest neighbours function (FNN) that is based on searching for a \( w \)-dimensional state space in which there are no false crossings of the trajectories. Adequate figures with the time delay and embedding dimension are presented in the next section.

Next technique applied in the paper is called as a recurrence plot that is used for identification of non-linear systems with distinct possible behaviour. Such plots are constructed by spatial proximity analysis of the time series \( x \). For arbitrary \( i \) and \( j \) from the interval \([0, N]\), where \( N \) is the total number of points in a given time series, we plot a black dot on the graph if the following condition is fulfilled \( |x_i-x_j| < \varepsilon \), where \( \varepsilon \) is a small threshold number.

3. Results of investigations

First, the influence of the feed on the cutting force \( F_x \) during milling of EPMC is investigated. The \( x \)-component of the total cutting force \( F_x \) is chosen because this component of the total force is directly connected with the feed direction. As shown in Fig. 2a variation of the feed \( f \) causes a rise of the cutting force in a slightly non-linear fashion. The amplitude, the mean value and the root mean square (RMS) of the cutting force change when feed increases. The solid lines are obtained by measurements while, the line with circles represent fitted curves. Several different kinds of curves are tested (linear, logarithmic, exponential and power) in order to choose the best fitted curve both for the force amplitude and the mean value. As far as the amplitude is concerned, the highest coefficient of determination \( (R^2) \) is obtained as 0.86 for the exponential line. Thus, amplitude of the cutting force \( F_x \) can be described by the following empirical relationship:

\[
F_x(f) = F_0 \cdot e^{bf},
\]

where \( F_0 \) is a constant chosen for this particular process, \( b \) is a coefficient constant for a given feed, and \( f \) represents feed rate in mm/min. For the case presented here the parameters take the following values: \( F_0 = 39.5 \) N, \( b = 0.0007 \) min/mm. In the literature very often cutting force is defined by means of the empirical three-quarter rule [19] \( F_x = K w h^{3/4} \) where \( w \) denotes the constant chip width and \( K \) is an experimentally determined parameter and \( h = f t \) means the feed over a cutting period \( t \) (then a regenerative effect is neglected). However, this study shows that the
dependence, fitted for milling EPMC, expressed by Eq. (3) is not a power low but rather an exponential one.

On the other hand, when the mean value is considered, a stronger non-linear behaviour is observed. At the beginning the force increases very rapidly and above \( f = 400 \text{ mm/min} \) it saturates and reaches a steady value with no effect of the feed. For the first part also exponential function is suitable, but for the entire range the linear dependence is the simplest and more adequate. Thus, in the case of milling EPMC, the cutting force \( F_x \) versus feed \( f \) is slightly non-linear with sectors of stronger non-linearity for smaller feed rates.

Fig. 2b shows the variation in the cutting force \( F_x \) with a change of the rotational speed \( n \). This dependence is more complex than the effect of feed but at the same time allows to draw more interesting conclusions. Amplitude of the cutting force \( F_x \) and also the RMS oscillates decreasing and increasing its values. Such behaviour may mean that the stable and unstable lobes are possible for this particular case [16].

Fig. 3. Average mutual information versus time lag (a); and false nearest neighbours versus embedding dimension (b).

Experimentally, it is difficult to define the limit of stability clearly. The transition between stable and unstable cutting is sometimes blurred by the transient natural vibrations and most often by random and dynamic noise. Some authors propose that the ratio of dynamic force to static force can be used as a simple charter stability criterion for simulated time series [12]. In this study, for the need of verification of real force signal, the ratio of force amplitude to mean value of force is used as a simple stability criterion

\[
\eta = \frac{F_{mx}}{F_{xm}}
\]  

It is assumed that if \( \eta > 4 \) process is considered unstable. Then, the black points in the diagram (Fig. 2b) represent unstable points, while the circled points are stable. An existence of such kind of relationship where the force amplitude decreases and increases commutatively with the rotational speed allows us to postulate that the regenerative effect is dominant in the milling and has stronger influence on the process than the frictional one. First, this may be explained by low friction of the epoxide-polymer matrix composite with carbon fibers, and second, by lack of a typical chip which rubs the rake surface of the cutting tool. In this case a dust is generated instead of a chip. Besides, absence of typical chip has other consequences, namely the tool cannot give back heat to the chip and also is not able to transfer heat to the workpiece because its thermal conductivity is low. Taking all these aspects into account, one can explain the rapid tool wear during cutting of such kind of materials. If the process could proceed the way for which the cutting force is below the dashed line then the cutting process should be stable. This observation can have practical gain in terms of a longer tool life. The equation of dashed line can be presented as follows:

\[
F_{\text{min}} = 62.5 - 0.0018 \cdot n
\]
A detailed analysis of the experimentally obtained cutting force requires special technique because the signal from cutting process is partially stochastic. In this paper the method of delayed coordinates is applied in order to reconstruct Poincare sections for points from 1 to 5 (see Fig. 2b). The embedding parameters $\tau_1$ and $w$ are obtained on the basis of plots presented in Fig. 3. The first local minimum of $J(\tau_1)$ and $FNN(w)$ points at the optimal time delay and the embedding dimension, respectively. Their values are inserted in Table 1. High embedding dimension suggests that the signal contains a stochastic component. Therefore, time series were filtered from noise before further analyses using Tisean. For points 2 and 4 laying at the top of lobes (Fig. 2b) signal of cutting force characterizes higher embedding dimension then for point 1,3,5 which are at the bottom.

Before doing any sophisticated non-linear time series analysis, one should try to establish that non-linearity is indeed present in the analysed signal. The most suitable method for this is the approach of surrogate data. Tisean package provides this procedure that generates surrogate data with the same distribution as a stochastic Gaussian process. By comparing the original time series with the surrogated one, it is possible to determine whether original signal is stochastic or deterministic. This procedure will be implemented for the cutting process data obtained from our experiments.

Now the reconstructed Poincare sections from the cutting force signal are made for points 4 and 5 (see Fig. 2b) and presented in Fig. 4. Unstable cutting (point 4) can be characterized as vibrations with period 2 or rather period 1 with small stochastic component. Whereas stable point 5 seems to be less regular. For comparison, the Poincare section for surrogate data is shown in Fig. 5. The map for point 4 is completely different and suggests that the analysed signal is not a linear Gaussian process. Point 5 contains higher stochastic component then point 4, because the surrogate signal has similar Poincare map to the original cutting force signal.

Recognizing a type of motion is essential to understand the process and phenomena which occurs. However, therefore the analysis is completed with recurrence plots (Fig. 6). Generally, 3 diagonal lines (one strong in the middle and one below and above) speak well for regularity (Fig. 6a) whereas, in the case of stable point 5, the motion is disrupted (Fig. 6b).

Table 1
The time lag $\tau_1$, embedding dimension $w$ for experimental signals.

<table>
<thead>
<tr>
<th>Point no.</th>
<th>Rotational speed, rpm</th>
<th>Time lag, $\tau_1$</th>
<th>Embedding dimension, $w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>3500</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>5000</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>6500</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>8000</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

Fig. 4. Reconstructed Poincare maps (a) Point 4—6500 rpm; and (b) Point 5—8000 rpm.

Fig. 5. Reconstructed Poincare maps from surrogates time series (a) Point 4; and (b) Point 5.
4. Conclusions

In this paper the experimental study of carbon composite (EPMC) milling process is presented with the aim to develop a new model of composite material cutting process. Two main observations are made in the present analysis. The first observation shows how the feed influences the cutting force, when the feed raises the cutting resistance grows as well. From the practical point of view, smaller values of feed are better as far as tool life is concerned. On the other hand, this causes the process to be more time consuming and expensive.

The second observation unveils how the change of rotational speed can lead to stable and unstable cutting regions, called lobes. An existence of such kind of relationship that reveals stable points with no chatter and unstable ones with chatter proves that the regenerative effect is dominant in the milling of EPMC and more strongly influences the process than frictional one. In order to avoid chatter vibrations (with large amplitudes) rotational speed must be set up in the region where cutting force has a local minimum. That is a typical phenomenon for the regenerative chatter therefore, for milling process of composite material with carbon fiber (EPMC), a new model with regenerative effect and non-linear force should be proposed.

The analysis of experimentally obtained time series of the cutting force by means of delay coordinates method demonstrates that oscillations of cutting force are more regular, with larger amplitude, in case of unstable cutting, while cutting is stable (with less amplitude) the signal has stochastic component that is visible in Poincare maps and recurrence plots.

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References


Fig. 6. Recurrence plots (a) Point 4—6500 rpm; and (b) Point 5—8000 rpm.