International Journal of Mechanical Sciences 99 (2015) 196–207

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Chatter identification methods on the basis of time series measured during titanium superalloy milling

Rusinek Rafal [a,*], Lajmert Pawel [b], Kecik Krzysztof [a], Kruszynski Bogdan [b], Warminski Jerzy [a]

[a] *Lublin University of Technology, Nadbystrzycka 36, 20-618 Lublin, Poland*
[b] *Lodz University of Technology, Stefanowskiego 1/15, 90-924 Lodz, Poland*

ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form
11 April 2015
Accepted 17 May 2015
Available online 23 May 2015

Keywords:
Superalloy milling
Recurrence plots
Hilbert-Huang transform
Milling stability

ABSTRACT

The paper discusses the problem of stability in the milling process of titanium super-alloy Ti6242. Although this problem is often considered theoretically, theoretical findings do not always agree with experimental results. For this reason, the paper presents the methods for stability estimation in real milling processes. First, a stability lob diagram is created based on parameters determined in impact testing of an end mill. Next, the cutting forces are measured in an experiment where the axial cutting depth being gradually increased. Finally, the obtained experimental data is analysed with respect to stability using the recurrence plot technique and the Hilbert–Huang transform.

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1. Introduction

Physical mechanisms which cause chatter vibrations can be divided into four types [1]. One of the most common types of chatter is a regenerative chatter, also known as secondary chatter. However, Wiercigroch et al. [2,3], Lipski et al. [4] show that frictional effect is also important, as it can induce the so-called frictional or primary chatter. Chatter vibrations generated during cutting can lead to a lower quality of final product surface, shorter tool life and even tool or workpiece destruction. This can happen in the machining of difficult-to-machine materials such as titanium alloy which is investigated in this study.

Titanium alloys belong to the category of superalloys which have high strength combined with high heat and corrosion resistance. Due to their properties, titanium alloys are used for producing extremely loaded components e.g. in civil and military aviation. The demand for a steady growth in productivity and product quality requires that cutting parameters be increased; this, in combination with mechanical and physical properties of superalloys, can make the machining of these materials difficult. A higher productivity can be achieved using high speed machining (HSM) which is a very popular machining technique nowadays. However, this technique can induce self-excited vibrations caused by a regenerative mechanism. To avoid regenerative chatter, the cutting parameters responsible for instability must be defined. To this end stability lobe diagrams (SLDs) are usually created, where rotational speed and depth of cut determine the boundary between stable and unstable cutting, which is represented by characteristic lobes. This method makes it possible to predict an unstable region of cutting parameters prior to machining, thus ensuring that the cutting system is well identified. From a practical point of view, it would be better to control the process online and change the cutting parameters when some instabilities appear in the system. Therefore, this paper focuses on the methods which can predict chatter vibrations prior to their occurrence in machining. This involves performing a cutting force analysis using the recurrence plot technique (RP) [5], the recurrence quantification analysis (RQA) [6,7], the Hilbert–Huang transform [8,9] and entropy.

Most papers on the cutting of titanium alloys report experimental results of investigation of various cutting tools and their wear [4,10]. Moreover, the influence of cutting conditions on cutting forces [11,12] and surface roughness [13,14] is investigated. A comprehensive review of machinability of titanium alloys is presented in [15]. This work points out the main problems associated with the machining of titanium alloys as well as tool wear and the mechanism responsible for tool failure. It is found that straight tungsten carbide cutting tools are optimum for performing most machining processes, while CVD-coated carbides and ceramics turn out to be much worse tools for this purpose. A high cutting temperature is found to be the major cause of rapid tool wear, whereas a low modulus of elasticity of titanium alloys is the principal cause of chatter during machining. An interesting and novel solution to improve cutting productivity of titanium and nickel alloys is presented in [16], where the authors present a diamond tool equipped with a pressure cooling system which is efficient in high speed machining.

The cutting productivity of titanium alloys can be increased in a traditional way by the application of a higher cutting depth and/or

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[*] Corresponding author.
E-mail address: r.rusinek@pollub.pl (R. Rafal).

http://dx.doi.org/10.1016/j.ijmecsci.2015.05.013
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speed; this, however, often results in process instability which leads to self-excited chatter vibrations. Although there exist methods for eliminating self-excited vibrations, they are passive, i.e. a system which eliminates chatter should be adjusted before each cutting operation. These methods include a change of phase between the external and internal modulations in trace regeneration as well as the change of dynamical properties of the machine–tool system through the use of vibration eliminators [17]. The trace regeneration effect can be reduced by a change in the phase shift using a variable spindle rotational speed. The methods mentioned above are mainly applied for single point tools (e.g. in turning); when machining with multipoint tools, system vibrostability can be enhanced by introducing changes in tool geometry, e.g. by changing the rake angle or by applying unequal spacing of cutting plates in the milling head. Turner et al. [18] developed an analytical model of the cutting process to predict chatter stability of variable helix end mills. Their work provides a comparative study of the performance of variable helix and variable pitch end mills. Dombawari et al. [19] yield a similar effect by applying serrated milling tools. Their method for chatter suppression is based on the use of a vibration eliminator system which controls energy flow in the system. This system takes advantage of the force compensation principle which becomes significant in the resonance of the main system and decreases the amplitude of resonance vibration.

The application of the CutPro commercial software [20] is another method for chatter prediction which is widely used in industry. CutPro is based on modal analysis of a spindle–tool system. Its correctness strongly depends on the number of modes taken into consideration [21]. Given the above, the problem of verifying SLDs correctness remains open. Some researchers measure acoustic emission during the milling process to obtain experimental SLD, e.g. in the studies [22,23].

From our point of view, it is better to control chatter during the process and suppress vibrations in real time. Therefore, the chatter identification methods based on the recurrence plot (RP) technique, the Hilbert–Huang transform (HHT) and entropy are discussed here. Although the non-standard statistical methods are not new, they provide interesting results when applied to various processes. The RP technique is applied in order to identify various phenomena, e.g. in combustion engine [24] and the cutting process [25–29]. The use of HHT in [30,31] also seems to be a useful method for detecting instabilities at the beginning of their appearance in milling or grinding processes [32,33]. Entropy-based methods are the most popular tools of chatter analysis, e.g. in grinding [34], turning [35] and milling [36]. A quite new method for dynamical behaviour analysis is presented in [37,38], where chatter is investigated using rescaled range [38] and detrended fluctuation analysis [37].

The present paper investigates stability of the milling process of titanium alloy Ti6242 on the basis of experimental time series of cutting forces. In order to find the initial point of chatter vibrations, the recurrence quantification analysis and the HHT are employed. In the future, the results can be applied to identify self-excited vibrations in an active chatter control system.

2. Experimental procedure

The experimental investigations were conducted on Ti6242 titanium alloy using the Haas MiniMill CNC milling machine, available in a laboratory at the Lodz University of Technology. The experimental setup, presented schematically in Fig. 1, comprises two parts: a modal analysis system on the left and a force measurement system on the right. The former was used to measure viscoelastic properties of the machine–tool system. It consisted of a PCB 086C03 modal hammer, a PCB 352B10 accelerometer and an NI9234 data acquisition card (DAQ). The latter part was used to measure three components (F_x, F_y and F_z) of the resultant cutting force~~s~~ and torque (M_z) using a Kistler 9123C piezoelectric rotating dynamometer. The dynamometer was connected to a Kistler 5223 signal conditioner and a 2855A4 data acquisition card. Both experimental rigs were integrated in a computer system and controlled by the DynoWare software to record measured signals.

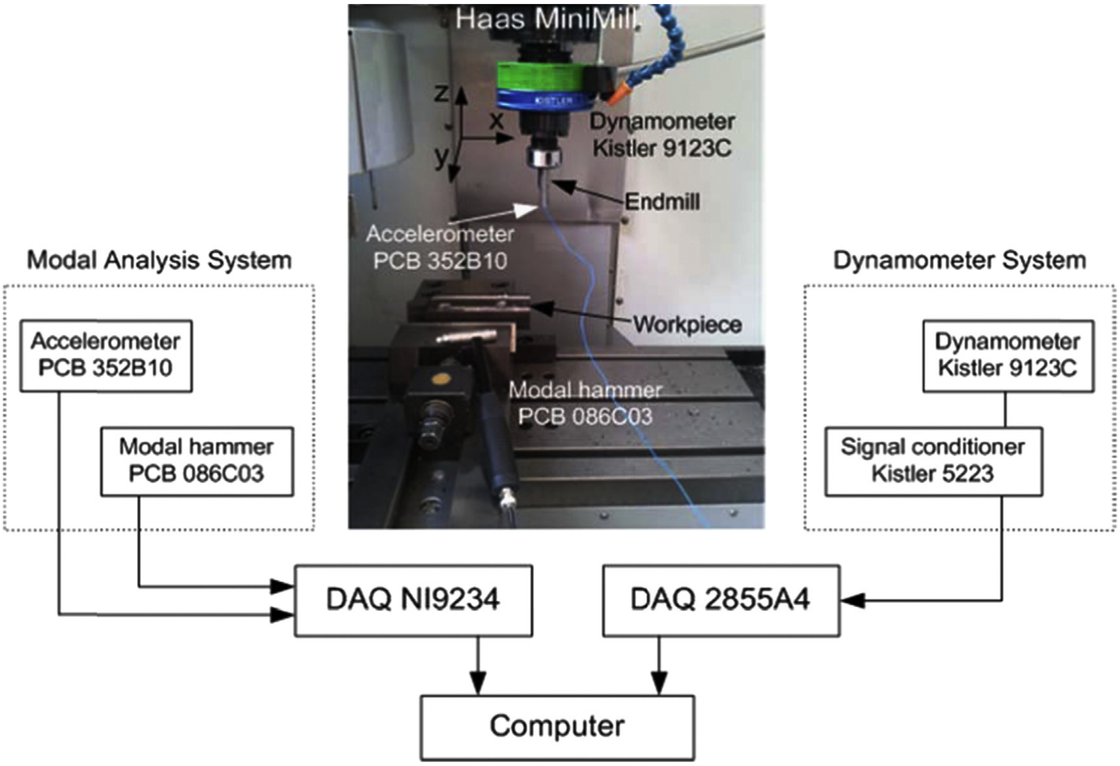

Fig. 1. Schematic diagram of the experimental set-up.

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