Intelligent Monitoring of Surface Integrity and Cutter Degradation in High-speed Milling Processes

L-Y Zhai[1], M-J Er[1], X Li[2], O-P Gan[2], S-J Phua[2], S Huang[2], J-H Zhou[2], L San[1], and A.J. Torabi[1]

[1] *School of Electrical and Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798*
lyzhai@ntu.edu.sg

[2] *Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075*
xli@SIMTech.a-star.edu.sg

ABSTRACT

In high-speed milling process, dynamic monitoring and detection of work-piece surface defects and cutter degradation is a very important and also an extremely difficult task. Due to the inconsistency and variability of cutter geometry/dimensions, the uncertainties of machine tool conditions, as well as the complexity of the cutting process itself, the modelling of cutting performance in high-speed milling process has remained a challenging issue for both academia and industry. This paper attempts to exploit a force-based approach to model the cutting performance and detect the surface integrity of high-valued work-pieces in high-speed milling process. Experiments on high-speed dry-milling of Titanium (Ti6Al4V) using ball-nose end mills were conducted to verify the proposed approach. Preliminary findings from the study have shown that the force-based modelling techniques proposed is able to establish the association between cutting force signals and the degradation of cutting performance and so as to eliminate surface defects of work-pieces.*

1. INTRODUCTION

High-speed machining processes have become increasingly important in modern manufacturing industry. With the advent of recent advances in machine tools design, high-speed milling has become one of the most important manufacturing processes which is able to provide a cost-effective means to produce products with high surface quality, low variations in the machined surface characteristics, excellent dimensional accuracy and high productivity. However, high-speed milling process usually suffers from rapidly increasing tool-wear rate and the consequent degradation of work-piece surface finish as well as the drop in machined part dimensional accuracy. In high-speed milling process, detection of cutter performance degradation and work-piece surface defects is a very important and at the same time an extremely difficult task. On the other hand, due to the inconsistency and variability of cutter geometry/dimensions, the uncertainties of machine tool conditions, as well as the complexity of the cutting process itself, the modelling of cutting performance in high-speed milling process has remained a challenging issue for both academia and industry (Torabi *et al.*, 2009). As a result, the development of an effective means for performance modelling in high-speed milling is highly desirable.

2. RELATED WORK

Effective modelling and analysis of high-speed milling performance is a critical issue concerning manufacturing productivity, product quality and production cost. Many research works have been carried out to address this issue through various approaches, among which the chip formation theory/mechanism, thermal dynamics of cutting process, and vibration-force-acoustic properties of cutting process are the most widely used means to investigate the performance of high-speed milling process. For example, the work by Ning *et al.* (2001) investigated the mechanism of chip formation in high-speed ball-nose end milling process and their study discovered the relationships between chip formation and the chatter behaviour of cutters. A method to judge the performance of the milling process by chip

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formation analysis has been suggested in their work. Ekinovic *et al.* (2004) reported some observations of the chip formation process in high-speed milling of hardened steel. Their research provided a basis for the determination of optimal range of cutting speeds and feed rates in high-speed milling of hardened steels with the aim to minimize the work-piece defects and improve the machined surface integrity. Baker (2005) also reported some basic findings concerning several aspects of high-speed chip formation. Hortig and Svendsen (2007) carried out a systematic investigation of numerical solutions of chip formation during high-speed cutting process and their consequences for the cutting forces and other technological aspects were discussed.

On the other hand, thermal issues in high-speed milling process are a key factor that directly affects cutting tool-wear, work-piece surface integrity and machining precision. In general, thermal dynamics of cutting process provides another means to investigate the performance of high-speed milling process, and it usually complements the study of chip formation mechanism or other aspects of the machining process. For example, Özel and Altan (2000) employed process simulation using finite element method to predict cutting forces, tool stresses and temperatures in high-speed flat end milling. The method they proposed is able to predict cutting force, tool stress and cutting temperature with acceptable accuracy, which will provide useful information for improving cutting tool design and selecting optimum cutting conditions. The relationship between cutting temperature and tool-wear development is also investigated in their study. Kim et al. (2001) evaluated the thermal characteristics in high-speed ball-end milling process with the objective to find the optimal cutting environment which can increase the tool life at a given cutting speed. Chen *et al.* (2003) reported an experimental research on the dynamic characteristics of cutting temperature in high-speed milling process. The inverse heat-transfer model was used in their research to estimate the heat flux flowing into the work-piece and the temperature distribution at the interface between the tool and work-piece. Their research result can help to reveal the cutting mechanism of high-speed milling especially the machining of difficult-to-cut materials. Abukhshim *et al.* (2006) presented a thorough review of heat generation and temperature prediction issues in high-speed machining process. Various approaches including experimental, analytical and numerical analysis are critically reviewed. Some modelling requirements for computer simulations of high-speed machining processes are also suggested in their work.

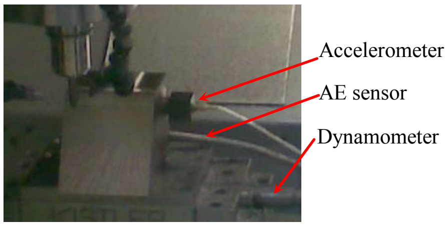
As a most widely used approach to investigate the complex high-speed machining process, the multi-sensor force-vibration-acoustic system has received tremendous applications in various studies concerning high-speed milling processes. Dimla and Lister (2000) described an experimental and analytical method using three mutually perpendicular components of cutting forces and vibration signature measurements to analyse the relationships between the measured signals and the accrued tool-wear. Dimla (2000) presented a comprehensive review of critical methods using sensor signals for tool-wear monitoring in metal cutting operations. Ertekina *et al.* (2003) tried to identify the most influential and common sensory features related to the process quality characteristics (dimensional accuracy, surface roughness and tool-wear rate) in CNC milling operations. The identified sensory features can be used for the reliable and accurate control of milling operations. Haber *et al.* (2004) carried out an investigation of tool-wear monitoring in a high-speed machining process based on the analysis of multi-channel signals' signatures in the time and frequency domains. Information from relevant sensors including dynamometer, accelerometer and acoustic-emission (AE) sensor was compared and analysed. The analysis results discovered the relevance of cutting-force and vibration signals' signatures for tool-wear development in high-speed machining processes. The spectrum analysis of AE signals in their research also revealed that AE sensors are most sensitive to the changes of tool conditions. Orhan *et al.* (2007) proposed a tool-wear evaluation method by vibration analysis in end milling process. The relationship between the increase of vibration amplitude and the tool-wear development was established through a series of experiment. Huang *et al.* (2007) presented a model-based monitoring and failure detection approach for ball-nose end milling process. A mechanistic force model has been established for high-speed milling on hardened stavax steel with 6 mm micro-grain tungsten carbide 2-flute ball-nose end mill. Marinescu and Axinte (2008) presented a critical analysis of using acoustic emission (AE) signals to detect tool and work-piece degradations in milling operations. Their research focused on the calibration of AE sensory measures against the gradual increase of tool-wear/force signals and the detection of work-piece surface defects.

Although there have been various techniques/methods proposed for the performance modelling of high-speed milling process, it should be envisaged that cutting force as one of the most informative signals in the process, carries substantive information about the immediate interactions between the cutter and work-piece, and should play an important role in analysing the performance of the cutting process. Based on a series of experiments on high-speed dry-milling process of Titanium (Ti6Al4V) work-piece using 6 mm diameter 2-flute ball-nose end mills, this paper attempts to exploit and develop a force-based approach to model the cutting performance and detect the surface integrity of high-valued work-pieces in high-speed milling. Preliminary findings from the study have shown that the force-based modelling techniques proposed is able to establish the association between cutting force signals and the degradation of cutting performance and so as to eliminate surface defects of work-pieces. The remainder of the paper is organized as follows. Section 3 presents a brief introduction to the experiment set-up of high-speed dry-milling process of Titanium (Ti6Al4V) work-piece on a 3-Axis Röders high-speed milling machine. A multi-sensor data acquisition system is also introduced in this section. Section 4 elaborates the force-based modelling and analysis of experiment data and conclusions are summarized in Section 5.

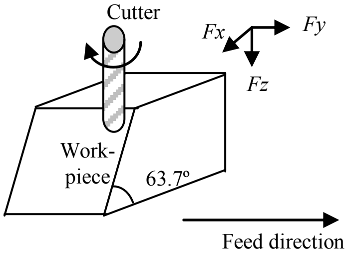
3. EXPERIMENT SET UP

In this research, a series of experiments were conducted on a 3-Axis Röders high-speed milling machine. Destructive tests using 6 mm diameter, 2-flute micro-grain tungsten carbide ball-nose end mills were carried out on Titanium (Ti6Al4V) work-piece. An 8-channel data acquisition system was set up with Kistler multi-sensor system composed of a 3-component dynamometer, a 3-component accelerometer, and an acoustic emission sensor. The machine tool employed is 3-Axis Röders Tech RFM760 high-speed milling machine with a variable spindle speed of up to 42,000 rpm, a maximum power of 14 kW, and a variable feed-rate of up to 30m/min. The work-piece is a block of solid Ti6Al4V material with both width and height of 78 mm. The surface to be machined is inclined at the angle of 63.4 degrees, which is set to obtain a ratio of 2 between the axial and radial depths of cut. The cutting conditions were fixed as follows: spindle speed of 10400rpm, feed per tooth of 0.04 mm/tooth, axial depths of cut of 0.2 mm and a radial depth of cut of 0.1 mm. Cutting force components (*Fx*, *Fy*, and *Fz*) were acquired using Kistler quartz 3-component platform dynamometer (type 9254) connected with Kistler amplifiers (type 5070A). As a complement and in order to judge the force signals collected, 3-component vibration and AE signals were also collected at the same time through the 8-channel data acquisition system. Fig. 1(a) shows the experiment set-up and Fig. 1(b) shows the work-piece orientation and force components.

Tool-wear was measured using a Leica microscope with a resolution of 0.001 mm. A Mitutoyo portable surface roughness tester (Surftest SJ-201) was used to measure the surface roughness of the work-piece. The average roughness (R_a) is used in this study. R_a values were read from four equally divided regions of the work-piece surface, called quadrants 1 to 4 in anti-clockwise direction. Each of the R_a values was repeated five times and the average of these readings was recorded as the final value. Surface roughness measurements were carried out in both vertical (perpendicular to the cutting direction) and horizontal directions.



(a) Experiment set-up

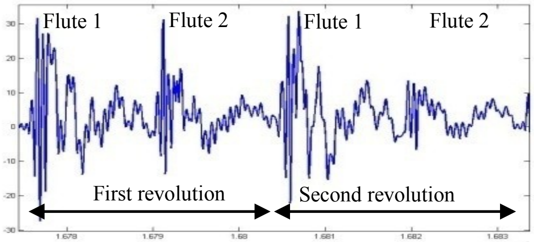


(b) Cutting force components

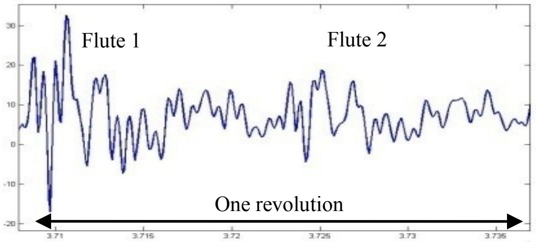
Figure 1: Experiment set-up and cutting force components

4. ANALYSIS OF TOOL DEGRADATION AND SURFACE INTEGRITY

As mentioned earlier, this paper aims to develop a force-based approach to detect the cuter degradation and the surface integrity of high-valued work-pieces in high-speed milling process. In this regard, many research works have shown that the dynamic *Fy* force component (i.e. cutting force in the feed direction) is the most sensitive force signature to the changes in cutting conditions due to its lowest damping ratio during the cutting process compared to the other two axes (Ning *et al.*, 2007; Toh, 2004). A thorough investigation into the characteristics of the *Fy* force component in this research has also verified this conclusion. The dynamic performance of the cutting process is reflected by the signature of *Fy* force component clearly. For example, Fig. 2 shows two typical signatures of the *Fy* force component with two different cutting performances, where Fig. 2(a) is the typical pattern of intermittent cutting or chattering, and Fig. 2(b) is the typical pattern of rubbing. Fig. 2(a) shows 2 revolutions of the *Fy* force signal. It is clear that in the first revolution both flutes of the cutter were engaged in cutting whereas in the next revolution, the second flute just swept over the work-piece surface. Further investigations into the signals find that this signature "pattern" continues and forms a regular intermittent cutting. Fig. 2(b) shows 1 revolution of the cutting force signal. It is clear that both flutes of the cutter rubbed on the work-piece surface and not really cut into the work-piece. As a direct result, the surface roughness of the work-piece corresponding to these two force patterns are found much higher than that of the normal cutting force patterns.



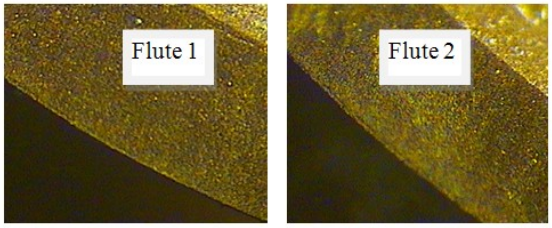
(a) Intermittent cutting (chattering)



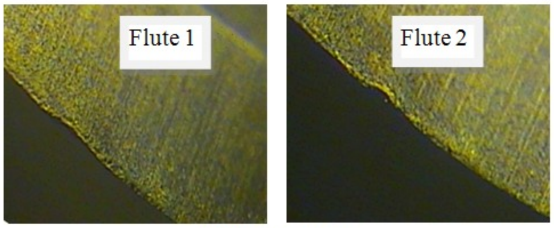
(b) Rubbing

Figure 2: Typical signatures of *Fy* force component

In the destructive tests carried out in this study, the work-piece surface roughness and tool-wear were measured every time when a face (layer) was cut. Fig. 3 shows the degradation process of the cutter. Fig. 3(a) is the new cutter before use whereas Fig. 3(b) is the worn cutter after cutting 35 faces of the work-piece. Analysis of the tool-wear of each face finds that the degradation of the cutter develops in a nonlinear manner. In the destructive test, it was found that the speed of tool-wear was relatively fast in the first few faces. This is due to the quick wear-off of the sharp and thin edges of the cutter. After this "grinding-in" stage, the tool-wear progressed at a steady speed and the surface roughness of the work-piece remained at a steady level. This is the "golden age" stage for the cutter as the resulting surface quality can be well predicted and guaranteed. However, after this stage, the tool-wear entered an "unstable" stage in which the surface roughness of the work-piece experienced some sudden jumps, most probably due to the periodical built-up edge phenomenon. A preliminary study on the tool-wear estimation using Fuzzy-Neural-Network-based modelling technology has also confirmed the above characteristics of tool degradation in high-speed milling operations (Li *et al.*, 2009).



(a) New cutter



(b) Worn cutter

Figure 3: Cutter degradation

The above nonlinear cutter degradation process is also well reflected in the work-piece surface roughness. Fig. 4 shows the average vertical and horizontal surface roughness values measured from the 1st face to the 35th face. It is clear that both vertical and horizontal surface roughness values increase in the first a few faces (i.e. the grinding-in stage) and converge at a stable level (i.e. the golden age stage) respectively until the 26th face where both vertical and horizontal roughness values shows a sudden jump. This is in fact the first occurrence of the important symptoms of cutter degradation, which implies that the tool-wear is going to enter the unstable stage. In the destructive test, the cutter finally failed after cutting another 8 faces after that. Further analysis of the relationship between the tool-wear and surface roughness reveals that they are closely associated with each other. Therefore, in practice, any one of the two can be predicted based on their relationship if the other one is known or detected.

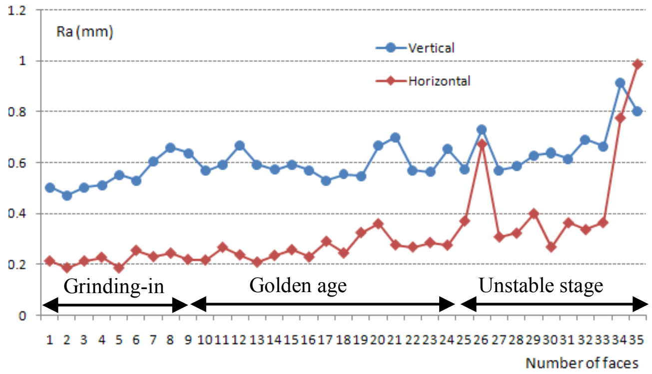


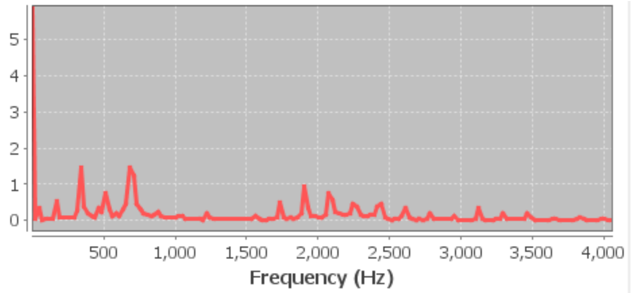
Figure 4: Surface roughness of work-piece

Fig. 5 shows a comparison between the acceptable and unacceptable work-piece surfaces. Fig. 5(a) is the acceptable surface quality with $R_a < 0.6$ mm whereas Fig. 5(b) is the unacceptable surface quality with $R_a > 1$ mm. A thorough comparison among the 35 faces finds that similar patterns of Fig. 5(a) dominate the surface quality before the 26th face and similar patterns of Fig. (b) gradually appear more and more often.

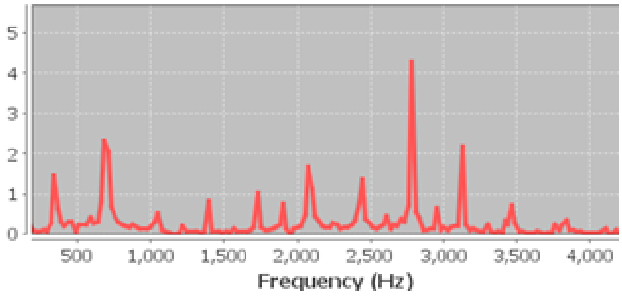
(a) Acceptable surface (b) Unacceptable surface

Figure 5: Degradation of work-piece surface

It should be noted again that the objective of this study is to use the measurable force signals to model and detect the cutter degradation and surface roughness. Therefore, it is necessary to investigate the characteristics of the force signatures while the cutter wears and the surface roughness degrades. In this study, a Fast Fourier Transform (FFT) analysis of the *Fy* force component was carried out. The frequency domain characteristics of the *Fy* force component reveal its direct association with the cutter degradation and surface roughness. Fig. 6(a) shows the frequency content of the *Fy* force component when the cutter is degrading but the surface roughness is still acceptable. In Fig. 6(a), there are two major frequency components at 2X (approximately 350 Hz) and 4X (approximately 700 Hz) of the spindle frequency (approximately 175 Hz) respectively. This can be easily understood as the cutter has two flutes. However, in Fig. 6(b), where the cutter has worn and the work-piece surface has degraded to the unacceptable level, the frequency contents at the 2X and 4X of the spindle frequency are no longer the dominant components of the spectrum. Instead, the high frequency contents of the *Fy* force component have become dominant with the spectrum amplitude increased up to two times of the amplitude of the 2X and 4X contents. In addition, the overall amplitudes of all major frequency contents in Fig. 6(b) have increased significantly compared to those in Fig. 6(a), which is due to the increase of cutting force when the tool is worn.



(a) Normal tool



(b) Worn tool

Figure 6: FFT spectrum of force signals

The findings from Fig. 6 can be used to implement a force-based modelling and detection system to predict the status of tool-wear and surface degradation in high-speed milling process. In this study, the relationships between the cutting force signatures and the cutting performance enable the establishment of a force-based online modelling and detection system to monitor and predict the status of tool-wear and surface degradation in high-speed milling process. In such a system, force components acquired though a high-speed data acquisition system will be processed online by FFT analysis, from which the frequency characteristics will be collected and used to evaluate the cutting performance.

5. CONCLUSION

This paper proposed a force-based approach for the modelling and detection of cutter degradation and surface integrity in high-speed milling process. The experimental study carried out has shown that cutting force components are closely associated with the cutting performance and can be used to predict the premature failures in high-speed milling so as to prevent damages to high-valued work-pieces. The result of this study will promote and enable the establishment of a force-based online intelligent predictive monitoring system to estimate the useful tool-life of cutters and detect the surface degradation prior to costly failure and damage to high-valued work-pieces.

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L-Y Zhai received his PhD and M.Eng (both in Mechanical Engineering) from Nanyang Technological University of Singapore in 2010 and 2000, respectively. His B.Eng degree in Mechanical Engineering was awarded by Xi'an Jiaotong University (China) in 1994. He has been actively engaged in several funded research projects concerning product design and manufacturing system design/optimisation in the past ten years. His publication includes more than 20 refereed international journal papers, book chapters and international conference papers. His main research interests include product design methodologies, fault diagnosis, optimisation techniques, fuzzy logic and rough sets, knowledge discovery and intelligent systems.