Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 31
ISSUE 2
December
2008

Intelligent identification of cutting states by utilising Power Spectrum Density

S. Tangjitsitcharoen *
Department of Industrial Engineering, Faculty of Engineering,
Chulalongkorn University, Bangkok, 10330 Thailand
* Corresponding author: E-mail address: somkiat.t@eng.chula.ac.th

Received 28.10.2008; published in revised form 01.12.2008

Analysis and modelling

ABSTRACT

Purpose: This paper presents an in-process monitoring and identification of cutting states in turning process in order to realize the intelligent machine tools.

Design/methodology/approach: The developed method utilizes the power spectrum density, or PSD of dynamic cutting force measured during the cutting. The experimentally obtained results suggested that there are basically three types of patterns of PSD when the cutting states are the continuous chip formation, the broken chip formation, and the chatter. The broken chip formation is desired to realize safe and reliable machining. The method proposed introduces three ratios, which are calculated and obtained by taking the ratios of cumulative PSD for a certain frequency range of three dynamic cutting force components corresponding to those three states of cutting, to classify the cutting states. The algorithm was developed to calculate the values of three ratios during the process in order to obtain the proper threshold values for classification of the cutting states.

Findings: The method developed has been proved by series of cutting experiments that the states of cutting are well identified regardless of the cutting conditions. The broken chips are easily obtained by changing the cutting conditions during the processes referring to the algorithm developed.

Practical implications: There are still not many systems being used in practice mainly due to the lack of general applicability such as a requirement of automated machining systems regardless of the cutting conditions. The aim of this research is to develop an in-process monitoring system for identification of continuous chip, broken chip, and chatter regardless of the cutting conditions by spectrum analysis based on the power spectrum density, or PSD of dynamic cutting force measured during the cutting.

Originality/value: The largest potential advantage of the method proposed in this paper is that the states of cutting can be readily identified during the in-process cutting under any cutting conditions by simply mapping the experimentally obtained values of parameters referring to the proper threshold values in the reference feature spaces.

Keywords: CNC turning; Cutting force; Power Spectrum Density; Continuous chip; Broken chip; Chatter

1. Introduction

The cutting process is recognized as one of the most important processes, which requires reliable sensing or monitoring, since it plays the key role in quality of product and production rate as well as production cost. As the intelligent machine tool is expected to be realized in the near future, it is necessary to develop a methodology to identify the cutting states automatically, which is essential to guarantee the reliability of automated and unmanned cutting operations. In order to realize the intelligent machine tools, an in-process monitoring and identification of cutting states is developed for CNC turning machine to check and improve the stability of the processes.

In case of turning process, the continuous chips are often produced while turning steel family and aluminum alloys.

They apt to entangle the work piece or cutting tool, which causes deterioration of the finished surface and sometimes breakage of cutting tools as well as injuring the machine operator. Hence, it is desired to make chips broken into small pieces to realize safe and reliable machining [1-5].

The chatter is also one of the major limitations on productivity in turning process. It always affects surface finish, dimensional accuracy, and tool life. It is therefore necessary to avoid the chatter occurred during the cutting process.

Extensive research efforts have been devoted so far to develop sensors and methodologies for detection of chatter [6-8], and identification of chip forms [9,10]. It is already known that sensing cutting force signals from the cutting process is one of the most promising methods, and researches have been carried out from various points of views [11]. The generation of chatter affects mostly the main force component [12,13] while the feed force component is most sensitive to chip breaking [14]. Kim and Kweun (1997) [15] developed a chip breaker for mild steels. Andreasen and Chiffre (1993) [3] developed an automatic system for chip breaking detection in turning but the chip breaking cannot be detected when the chips are broken into quite different lengths. Fang, Fei and Jawahir (1996) [16] presented methodology to predict chip breakability and the chip shapes/sizes in the machining process planning systems. The artificial neural networks and clustering techniques have been employed by many researches [8,10], however the preliminary experiments for specific cases or different cutting conditions are always required to set up the database and train the system. The analysis of various cutting force signals, monitoring techniques and processing methods have been presented in recent paper [17] to identify the chip forms, especially the favorable and unfavorable chip types referring to ISO standard 3685 in 1977 and 1993 [18].

However, there are still not many systems being used in practice mainly due to the lack of general applicability such as a requirement of automated machining systems regardless of the cutting conditions. Hence, the aim of this research is to develop an in-process monitoring system for identification of continuous chip, broken chip, and chatter regardless of the cutting conditions by spectrum analysis based on the power spectrum density, or PSD of dynamic cutting force measured during the cutting. The dynamic components of cutting forces are adopted to monitor and identify the chip forms and chatter in this research in order to increase the reliability of automated and intelligent machine tools.

2. Monitoring of cutting states

2.1. Power Spectrum Densities and cutting states

The dynamic cutting force has its own characteristic pattern in each cutting situation of continuous chip formation, broken chip formation, and the generation of chatter. As the chips are broken during cutting, the dynamic cutting forces vary either due to chips hitting upon the cutting tool or workpiece. The dynamic component of the feed force, among the three force components, is relatively large in amplitude when the chips are broken into pieces, and the relatively large PSD appears in the frequency range, which corresponds to the chip breaking frequency when the chips are broken into pieces [9]. This applies to the case when the chips are regularly broken into pieces of nearly the same size and also to the case when regular broken chips and relatively long curled chips are mixed. The regular broken chips have nearly the same length that means the chip breaking frequency is nearly constant over a small time period. However, the mixed broken chips have the different length that means there are two frequencies of chip breaking due to the different length of mixed chips. On the other hand, the dynamic feed force is relatively small in amplitude when the chips are continuous, and the PSD is relatively large at low frequency range, typically less than 50 Hz.

However, the generation of chatter affects mostly the main cutting forces when the chatter appears [12]. It is then expected that the dynamic component of the main force is relatively large in amplitude, among the three force components, and the relatively large PSD will occur at the certain frequency, which corresponds to the natural frequency of each cutting system. Hence, the PSD of the dynamic main force of the chatter is also expected to be larger than the ones of continuous and broken chip formation.

The above mentions suggest that the continuous chip formation, the broken chip formation, and the chatter can be identified by monitoring the PSD of the dynamic cutting force components (which are main force Fm, feed force Ff, thrust force Ft). In general, the use of the dynamic cutting forces as a tool to identify the cutting states, it is necessary to eliminate the noise signals from other sources. Hence, the low-pass filter is utilized in the experiments too.

2.2. Power Spectrum Density analysis

When the continuous chip, the broken chip and the chatter occur, the maximum PSD appears at a certain frequency. The cumulative PSD around this frequency is relatively large and different in each cutting force component due to the states of cutting. Hence, a method is developed and proposed here to monitor and identify the cutting states by utilizing the cumulative PSD for a certain frequency range corresponding to the states of cutting of three dynamic cutting forces measured during the cutting process. The method proposed introduces three ratios, which are calculated and obtained by taking the ratio of cumulative PSD of dynamic main force S_m and dynamic feed force S_f, the ratio of cumulative PSD of dynamic main force S_m and dynamic thrust force S_t, and the ratio of cumulative PSD of dynamic feed force S_f and dynamic thrust force S_t.

Based on the above mentions, the following algorithm is developed to calculate the values of three ratios during the process in order to obtain the proper threshold values to identify the continuous chip formation, broken chip formation, and chatter. Figure 1 illustrates the method of an in-process monitoring and identification of cutting states.

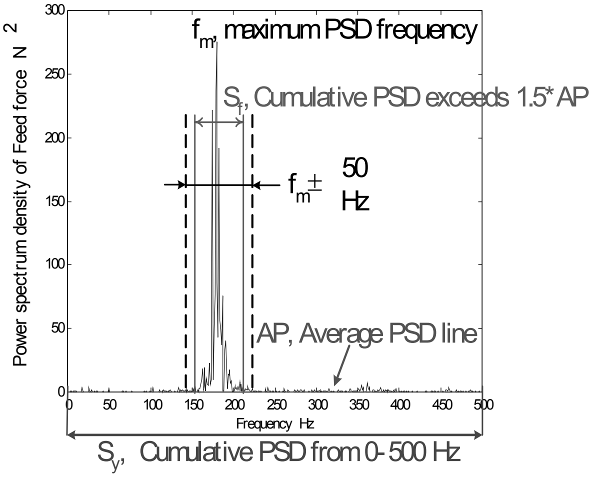

Fig. 1. The method of an in-process monitoring and identification of cutting states

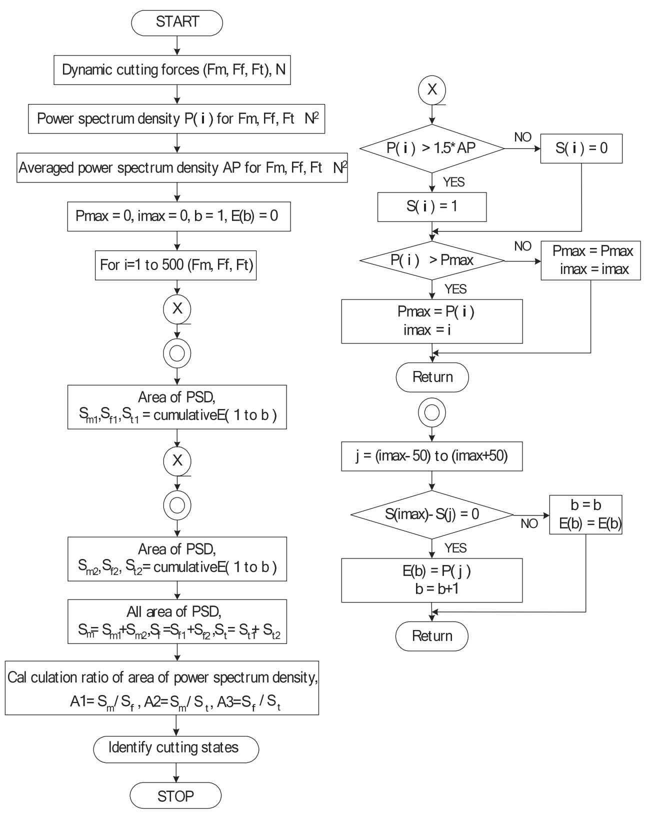

Fig. 2. Flow chart of the algorithm to calculate the parameters A1, A2, and A3

1. Calculate the average PSD (AP) of each dynamic cutting force (Fm, Ff, Ft) corresponding to the states of cutting by summing up the PSD of main force (S_x), feed force (S_y), and thrust force (S_z) from 0 to 500 Hz and divide the cumulative PSD (S_x , S_y , S_z) by the frequency range as shown in Fig. 1.
2. Search for the frequency f_m of each dynamic cutting force (Fm, Ff, Ft) at which the PSD is maximum.
3. Calculate the cumulative PSD (S_{m1} , S_{f1} , S_{t1}) of each dynamic cutting force for PSD which exceeds 1.5xAP for a frequency range from f_m-50Hz to f_m+50Hz.
4. Calculate the cumulative PSD (S_{m2} , S_{f2} , S_{t2}) of each dynamic cutting force for PSD which exceeds 1.5xAP for a frequency range from f_m-50Hz to f_m+50Hz for mixed broken chips.
5. Calculate the parameters of the ratios of cumulative PSD of three dynamic cutting forces ($S_m = S_{m1}+ S_{m2}$, $S_f = S_{f1} + S_{f2}$, $S_t = S_{t1}+ S_{t2}$).
6. Calculate the parameters of the ratios of cumulative PSD of three dynamic cutting forces ($A1=S_m / S_f$, $A2=S_m / S_t$, $A3=S_f / S_t$).
7. Determine the proper threshold values C1, C2, and C3 in the reference feature space for classification of the continuous chip, broken chip, and chatter.

The flow chart for the above algorithm is shown in Fig. 2. The trapezoidal rule is utilized to calculate the approximate value for the area of PSD.

3. Experimental setup and conditions

Series of cutting experiments were carried out in order to obtain the reference feature spaces and the proper threshold values (C1, C2, C3) for classification of the cutting states. The cutting tests are conducted on a commercially available small CNC turning machine as shown in Fig. 3.

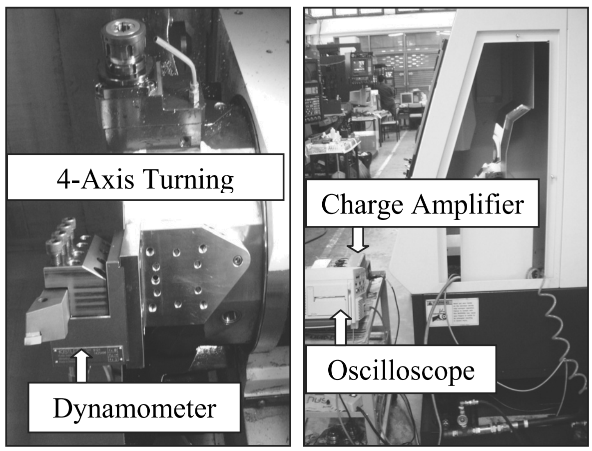

Fig. 3. Illustration of experimental setup

A tool dynamometer has been installed onto the tool turret of the machine. The major cutting conditions are summarized in Table 1. The tool life is set at the flank wear 0.4 mm.

The dynamic cutting force components detected by the tool dynamometer are amplified before digitization and FFT calculation within PC. The sampling rate is 1 kHz. It is proven that resonant frequency of the dynamometer is about 2.7 kHz, and hence the dynamic cutting force components are well detected with the dynamometer.

Table 1.
Major cutting conditions

Workpiece	Plain carbon steel (JIS:S45C)
Cutting tool	Coated carbide tool
Cutting speed, m/min	100, 150, 200, 250
Depth of cut, mm	0.5, 1, 1.5
Feed, mm/rev	0.05, 0.1, 0.15, 0.20, 0.25

4. Experimental results

4.1. Ratios of Power Spectrum Density

Series of cutting tests were carried out under the major cutting conditions mentioned above, and the dynamic cutting force signals were measured. Fig. 4 shows the typical examples of experimentally obtained power spectrum densities of three dynamic cutting forces at different cutting states.

When the chips are continuous, the experimentally obtained power spectrum densities of three dynamic cutting forces are small at low frequency range as shown in Fig. 4.

The values of S_m, S_f, and S_t are nearly the same value. However, the experimentally obtained power spectrum densities of three dynamic cutting forces become larger when the chips are broken, especially at the dynamic feed force. Hence, the value of S_f of broken chip formation is larger than the values of S_m and S_t.

When the chatter occurs, the experimentally obtained power spectrum density of dynamic main force is the largest, among the three force components. The value of S_m is larger than the values of S_f and S_t. The chatter usually occurs in the radial and feed directions too, which lead to irregular distribution of chip thickness along the cutting edge in turning operation. The experimentally obtained power spectrum densities of dynamic thrust force and dynamic feed force of the chatter are then larger than those of the continuous chip formation. Fig. 5 shows the example of the experimentally obtained calculation of the cumulative PSD of three dynamic cutting forces of the chatter.

Figures 6-8 show the experimentally obtained reference feature spaces of A1 and A2, A1 and A3, and A2 and A3, respectively. The values of parameters A1 and A2 are relatively large when the chatters appear as shown in Fig. 6. It is understood that the cumulative PSD of the dynamic main force, Sm is larger than those of dynamic feed force, Sf and dynamic thrust force, St.

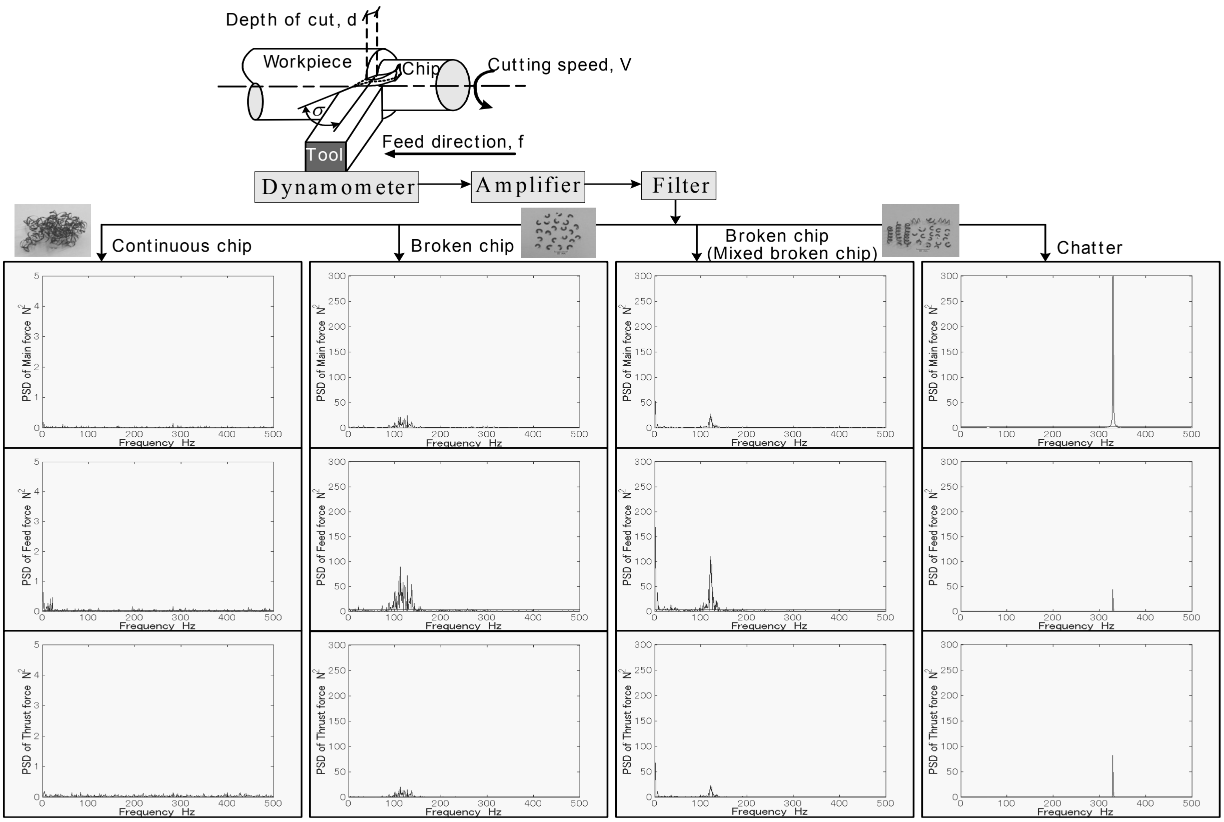

Fig. 4. Illustration of typical examples of experimentally obtained power spectrum densities of three dynamic cutting forces at different cutting state

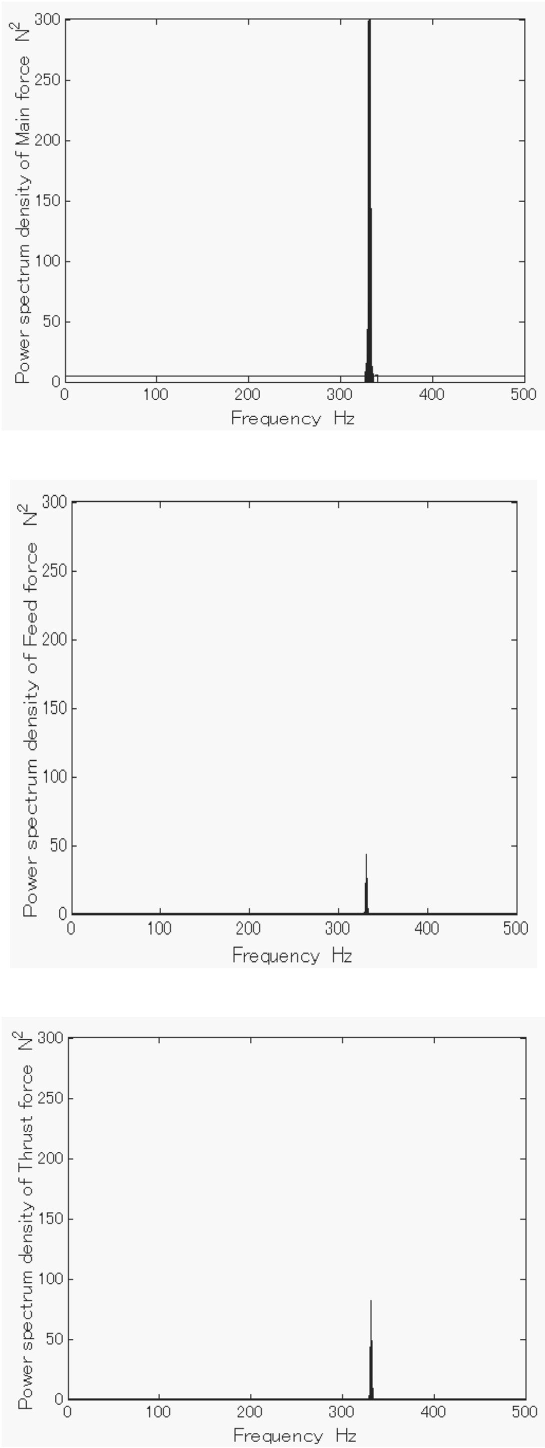

Fig. 5. Example of the experimentally obtained calculation of three dynamic cutting forces of the cumulative PSD of chatter: a) Experimentally obtained cumulative PSD of Fm, S_m, b) Experimentally obtained cumulative PSD of Ff, S_f, c) Experimentally obtained cumulative PSD of Ft, S_t

While the chips are broken, the values of parameter A3 are relatively large and the values of parameter A1 are relatively small as shown in Figs. 7-8. Since the feed force component is most sensitive to the chip breaking among the three force components. However, the values of parameter A1, A2 and A3 are relatively small when the chips are continuous as compared to others as shown in Figs. 6-8. It is understood that the cumulative PSD of the three dynamic cutting forces are less difference.

4.2. Identification of cutting states

According to the Figs. 6-8, the threshold values of each cutting state can be determined in the reference feature spaces. The proper threshold values of C1, C2, and C3 are defined as 20, 10, and 3 respectively. The cutting states can be simply identified during the in-process cutting regardless of the cutting conditions by mapping the experimentally obtained values of parameters A1, A2, and A3 into the reference feature spaces of Figs. 6-8, regarding to the threshold values C1, C2, and C3.

It is then concluded that:

1. the chips are identified to be broken when the parameter values of A1 and A2 are less than the threshold values C1 and C2 respectively, while the parameter value of A3 exceeds the threshold value C3;
2. the chatter is identified when the parameter values of A1 and A2 exceed the threshold values C1 and C2, respectively;
3. finally, the chips are identified to be continuous when the parameter values of A1, A2, and A3 are less than the threshold values C1, C2, and C3, respectively.

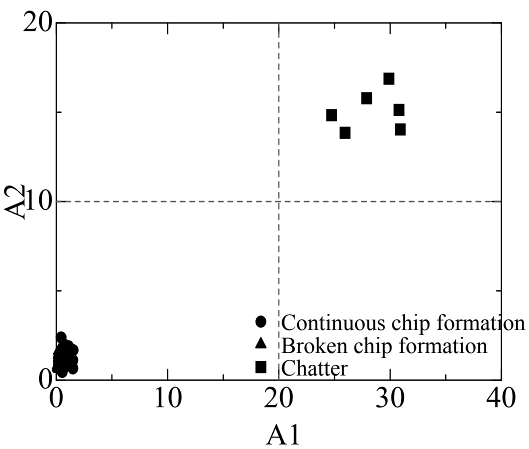

Fig. 6. Illustration of the experimentally obtained reference feature space between A1 and A2

Hence, the algorithm to identify the cutting states are developed referring to the threshold values C1, C2, and C3 inthe reference feature spaces as shown in Fig. 9. Figure 9 also illustrates the algorithm to avoid the chatter and make the continuous chips broken into small pieces by changing the cutting conditions during the in-process cutting The new cutting tests were employed under wide range of cutting conditions to identify the cutting states in order to check and verify the proper threshold values of C1, C2, and C3 in the reference feature spaces again by utilizing the new cutting conditions as shown in Table 2. The experimentally obtained values of parameters A1, A2, and A3 corresponded to the proper threshold values of C1, C2, and C3 in the reference feature spaces of Figs. 6-8. It is understood that the cutting states can be easily identified by referring to the proper threshold values of C1, C2, and C3 in the reference feature spaces of Figs. 6-8.

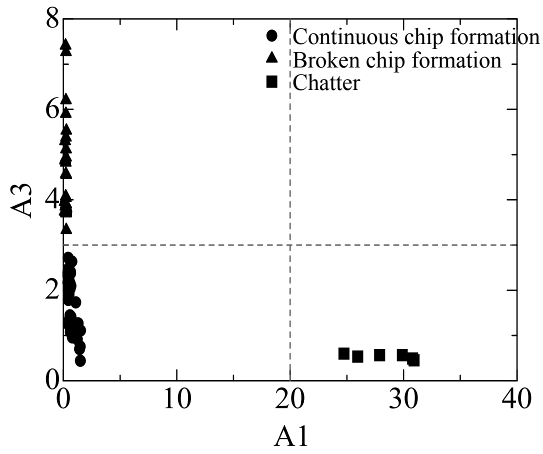

Fig. 7. Illustration of the experimentally obtained reference feature space between A1 and A3

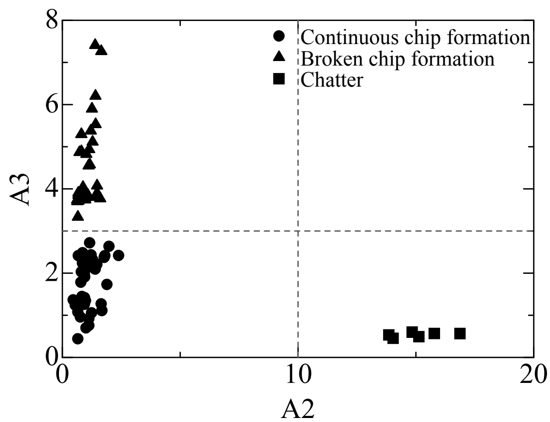

Fig. 8. Illustration of the experimentally obtained reference feature space between A2 and A3

Figure 10 summarizes the results for combinations of the cutting speed and the federate at a constant depth of cut 1 mm obtained when the cutting tool is new and worn with average flank wear of 0.1 mm. The photographs in thick black line frame are those of the mixed and broken chips which are obtained by using the proposed algorithm in Fig. 9.

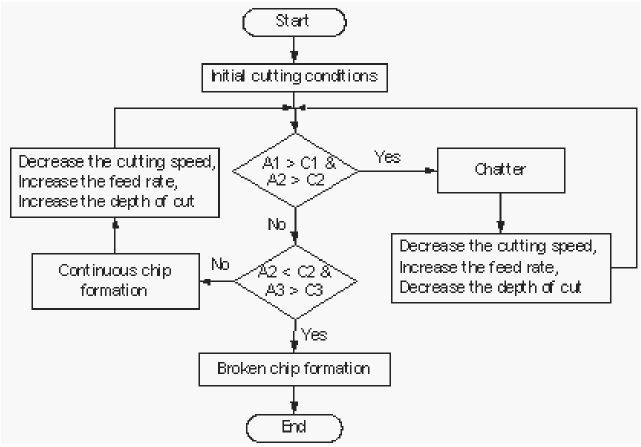

Fig. 9. Flow chart of the algorithm to identify the cutting states

Table 2.
New cutting conditions.

Workpiece	Plain carbon steel (JIS:S45C)
Cutting tool	Carbide tool, P10
Tool geometry	-5°, -6°,5°,6°,15°,15°,0.4 mm (SNMN 120404)
Cutting speed, m/min	150, 230, 300
Depth of cut, mm	1, 1.5
Feed, mm/rev	0.1, 0.2

It is understood that the broken chips appear as the feed rate increases. When the feed rate increases the thickness of chip becomes thicker and the chip tends to curl, which results in broken chip formation. The chip breaking improves, when turning with the worn tool as compared to the new tool. It is understood that an increase in tool wear causes the larger cutting edge roundness, which means that the nominal effective rake angle is reduced. As a result of the larger chip thickness, and hence the chip breaking becomes good.

5. Conclusions

In order to realize an intelligent machine tool, a method has been developed for in-process monitoring and identification of cutting states, which are continuous chip formation, broken chip formation, and chatter for CNC turning. on the analysis of the PSD of three dynamic cutting forces measured during the in-process cutting. A method proposed introduces three parameters A1, A2, and A3, which are calculated and obtained by taking the ratio of the cumulative PSD for a certain frequency range of three dynamic cutting force components corresponding to those three states of cutting, to classify the cutting states. The reference feature spaces and the proper threshold values of C1, C2, and C3 are determined for classification of the cutting states.

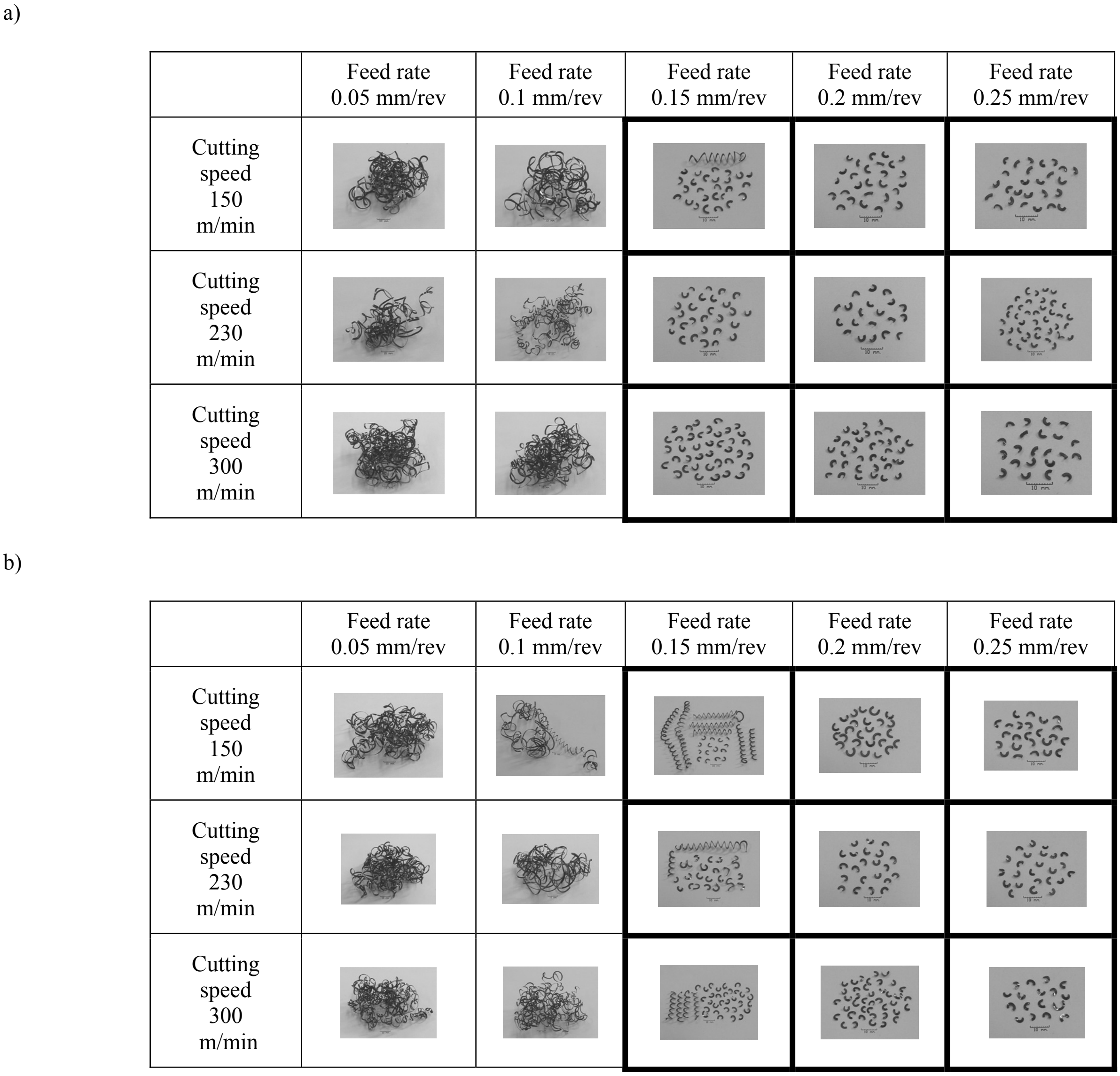

Fig. 10. Photographs of chips obtained for combinations of cutting speed and feed rate; a) New tool, depth of cut 1.0 mm, tool nose radius 0.4 mm, b) Worn tool, depth of cut 1.0 mm, tool nose radius 0.4 mm

It has been proved that the states of the cutting processes are sufficiently classified by method proposed even though the cutting conditions are changed. The algorithm is proposed to obtain the broken chips in order to increase the stability and reliability in turning process by changing the cutting conditions during the process.

The largest potential advantage of the method proposed here is that the states of cutting can be readily identified during the in-process cutting under any cutting conditions by simply mapping the experimentally obtained values of parameters A1, A2, and A3 referring to the proper threshold values of C1, C2, and C3 in the reference feature spaces.

Acknowledgements

This work was performed with partial funding from Thailand-Japan Technology Transfer Project (TJTTP) under Japan International Cooperation Bank (JBIC).

References

[1] T. Moriwaki, T. Somkiat, T. Shibasaka, Intelligent monitoring and optimization of cutting process for CNC

turning, Proceedings of the 14th International Conference "Flexible Automation and Intelligent Manufacturing", Toronto, 2004, 82-89.
[2] W. Grzesik, P. Bernat, An investigation of the cutting process for chip breaking monitoring in turning of steels, Journal of Manufacturing Science and Engineering 120 (1998) 555-562.
[3] J.L. Andreasen, L.D. Chiffre, Automatic chip-breaking detection in turning by frequency analysis of cutting force, Annals of the CIRP 42 (1993) 45-48.
[4] I.S. Jawahir, C.A. Luttervelt, Recent developments in chip control research and applications, Annals of the CIRP 42 (1993) 659-685.
[5] S. Sawai, I. Inasaki, Identification of chip form in turning process, International Journal of Japan Society of Mechanical Engineers 34 (1991) 553-560.
[6] Y. Altintas, P.K. Chan, In-process detection and suppression of chatter in milling, International Journal of Machine Tools and Manufacture 32 (1992) 329-347.
[7] M. Rahman, In-process detection of chatter threshold, Journal of Engineering for Industry 110 (1988) 44-50.
[8] J. Hino, C. Su, T. Yoshimura, A study on chatter prediction in high-speed end milling process by fuzzy neural network, International Journal of Japan Society of Mechanical Engineers C 47 (2001) 825-831.
[9] T. Moriwaki, T. Shibasaka, T. Somkiat, Development of in-process chip-breaking detection system in turning, Memoirs of graduate school of science and technology, Kobe University, 22-A, 2004, 1-19.
[10] T. Moriwaki, Y. Mori, Sensor fusion for in-process identification of cutting process based on neural network approach, Proceedings of the IMACS/SICE International Symposium "Robotics, Mechatronics and Manufacturing systems", Kobe, 1992, 245-250.
[11] K. Matsushima, T. Sata, On-line control of the cutting state by the pattern recognition technique, Annals of the CIRP 23 (1974) 151-152.
[12] T. Sata, K. Matsushima, T. Nagamura, E. Kono, Learning and recognition of the cutting states by the spectrum analysis, Annals of the CIRP 22 (1973) 41-42.
[13] K. Ueda, S. Miyamoto, T. Sugita, An approach to adaptive control based on pattern recognition of cutting states, Proceedings of the 6th International Conference "Production Engineering", Osaka, 1987, 212-217.
[14] L.C. Lee, K.S. Lee, C.S. Gan, On the correlation between dynamic cutting force and tool wear, International Journal of Machine Tools and Manufacture 29 (1989) 295-303.
[15] J.D. Kim, O.B. Kweun, A chip-breaking system for mild steel in turning, International Journal of Machine Tools and Manufacture 37 (1997) 607-617.
[16] X.D. Fang, J. Fei, I.S. Jawahir, A hybrid algorithm for predicting chip form/chip breakability in machining, International Journal of Machine Tools and Manufacture 36 (1996) 1093-1107.
[17] R. Teti, I.S. Jawahir, K. Jemielniak, S. Segreto, S. Chen, J. Kossakowska, Chip form monitoring through advanced processing of cutting force sensor signals, Annals of the CIRP 55/1 (2006) 75-80.
[18] M.C. Shaw, Metal cutting principles, Second Edition, Oxford University Press, 2005, 494-497.
[19] C. Chungchoo, D. Saini, The total energy and the total entropy of force signals-new parameters for monitoring oblique turning operations, International Journal of Machine Tools and Manufacture 40 (2000) 1879-1897.