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Advance in Tool Wear Prediction in CNC Turning by Utilizing Average Variances of Dynamic Cutting Forces

Somkiat Tangjitsitcharoen [1*], Chawalit Wongtangthinthan [2]

[1, 2] *Department of Industrial Engineering, Faculty of Engineering, Chulalongkorn University Bangkok, Thailand*

Abstract

This paper proposes the in-process prediction of tool wear by monitoring the average variances of dynamic cutting forces in CNC turning. The prediction model of tool wear is developed based on the actual experiments with the coated carbide tool and the carbon steel AISI1045. The exponential function is employed to represent the relations of the tool wear and the cutting parameters which consist of the cutting speed, the feed rate, the depth of cut, and the ratio of dynamic cutting force. The dimensionless dynamic cutting force ratio is proposed to eliminate the irrelevant influences such as the hardness of work piece and the combination of cutting conditions. The dynamic cutting force ratio is determined by the ratio of the average variance of dynamic feed force dFy in the feed direction to the average variance of dynamic main force dFz in the cutting speed direction. The experimentally obtained results showed that the dynamic cutting force ratio trends to decrease when the tool wear progresses regardless of the cutting conditions. The in-process tool wear prediction model is verified by utilizing the new cutting tests and the obtained results are satisfied with the high accuracy of 93.5%.

Keywords— CNC Turning, Tool Wear, Prediction, Dynamic Cutting Force

Introduction

The carbon steel is the most favorable material used in CNC turning to obtain the designed shape. However, the tool wear mainly affects the productivity and currently there is no effective CNC machine is able to measure the tool wear level while cutting. Hence, it is important to develop the in-process monitoring to predict the tool wear in order to realize the intelligent machine which is expected to play a key role in the competitive situation. The highest advantage of the in-process tool wear prediction is that the tool wear level can be monitored continuously during the cutting and the intelligent CNC machine will be able to change a new cutting tool by itself. It means that the intelligent CNC machine does not have to be stopped to check the cutting tool which helps to reduce the production time and the cost. Therefore, it is necessary to model and develop the in-process prediction of tool wear prediction under the wide range of cutting conditions.

From the past, many research efforts have been dedicated so far to develop the tool wear prediction models (Moriwaki, Shibasaka, and Tangjitsitcharoen, 2004; Moriwaki, Shibasaka, and Tangjitsitcharoen, 2006; Tangjitsitcharoen, 2011; Badru and Singh, 2012; Tangjitsitcharoen, Rungruang, and Pongsathornwiwat, 2011; Krzysztof, Tomasz, Joanna, and Sebastian, 2012). It has been already known that the cutting force is affected by amount of tool wear (Tangjitsitcharoen, Rungruang, and Pongsathornwiwat, 2011). The cutting force signals generated by dynamometer or force sensor while cutting are commonly recognized as the most informative signal for tool wear condition monitoring by comparing with the other vibration sensor and acoustic sensor (Krzysztof, Tomasz, Joanna, and Sebastian, 2012). There was a further study to integrate these outputted signals via neural network and pattern recognition to monitor the tool wear level. However, the obtained model could not been used for the specific cutting conditions due to a requirement of the training data set (Tangjitsitcharoen, Rungruang, and Pongsathornwiwat, 2011). From some recent researches, the cutting force signals correspond with the tool wear progress (Moriwaki, Shibasaka, and Tangjitsitcharoen, 2004; Moriwaki, Shibasaka, and Tangjitsitcharoen, 2006; Tangjitsitcharoen, 2011; Badru and Singh, 2012; Tangjitsitcharoen, Rungruang, and Pongsathornwiwat, 2011; Krzysztof, Tomasz, Joanna, and Sebastian, 2012). The cutting forces signals relating with tool wear levels are recorded by utilizing the dynamometer under various cutting conditions. There are two types of the cutting force signal processing as shown in Fig.1. A static cutting force had been proposed to develop the tool wear prediction model (Youn,and Yang, 2001; Stein and Huh, 2002; Scheffer, Kratz, Heyns, and Klocke, 2003). A static cutting force is determined from the average cutting force signals from the dynamic cutting forces comparing to the average zero cutting force signals generated before cutting. However, it is proved that the dynamic cutting force corresponds to the tool wear progress (Tangjitsitcharoen,

*All correspondence related to this article should be directed to Somkiat Tangjitsitcharoen, Chulalongkorn University, Bangkok,Thailand
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Jatinandana, and Senjunichai, 2015). The amplitude of the dynamic cutting force is relatively small when a tool wear is in the initial stage. However, the amplitudes of dynamic cutting forces are relatively large when the amount of tool wear increases (Tangjitsitcharoen, Rungruang, and Pongsathornwiwat, 2011; Lee, Lee, and Gan, 1989; Endres, Sutherland, Devor, and Kapoor, 1990; Hwang, Jeong, Chung, and Liang, 2014). Hence, the dynamic cutting force is adopted in this research because it is more accurate than the use of static cutting force to predict the tool wear (Tangjitsitcharoen, Thesniyom, and Ratanakuakangwan, 2014).

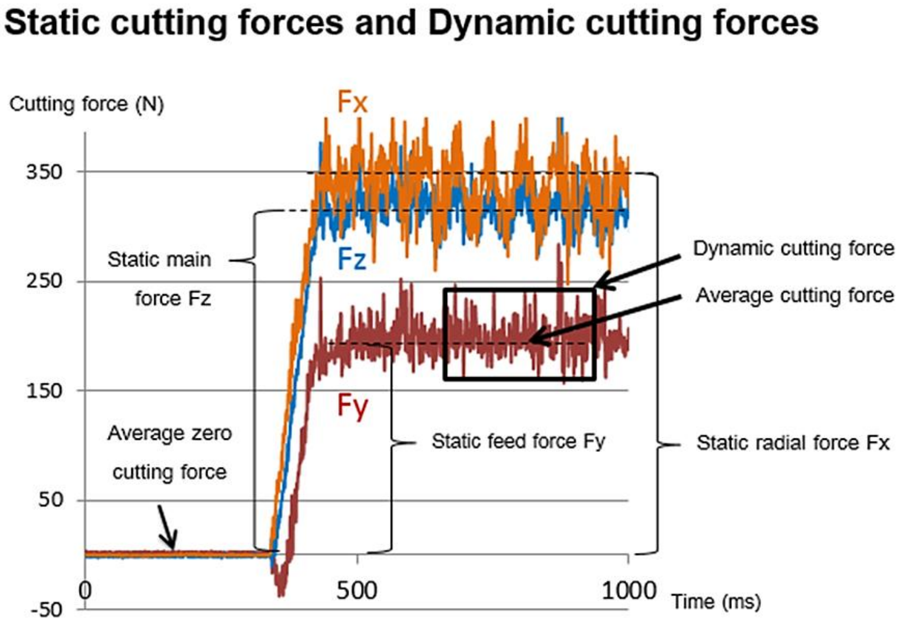

Figure1: Illustration of the static cutting forces and the dynamic cutting forces at cutting speed of 200 m/min, feed rate of 0.25 mm/rev, depth of cut of 0.8 mm, tool nose radius of 0.4 mm, rake angle of -6 degree, and tool wear level of 0.176 mm.

The aim of this paper is to propose the in-process prediction of tool wear in CNC turning by monitoring the dynamic cutting forces. The in-process prediction of tool wear is modeled and developed under the various cutting conditions which consist of the cutting speed, the feed rate, the depth of cut, and the ratio of the average variances of the dynamic cutting forces by simply employing the exponential function for the sake of tool wear model.

In-Process Monitoring of Tool Wear

Dynamic cutting forces and tool wear

According to the recent researches (Moriwaki, Shibasaka, and Tangjitsitcharoen, 2004; Moriwaki, Shibasaka, and Tangjitsitcharoen, 2006; Tangjitsitcharoen, 2011; Badru and Singh, 2012; Tangjitsitcharoen, Rungruang, and Pongsathornwiwat, 2011; Krzysztof, Tomasz, Joanna, and Sebastian, 2012)**,** there are three parameters mainly affecting the tool wear in CNC turning process which consist of the cutting speed, the feed rate, and the depth of cut. It is already known that the cutting force significantly increases with an increase in tool wear, consequently the cutting tool is vibrated (Tangjitsitcharoen, Rungruang, and Pongsathornwiwat, 2011). The small feed rate and depth of cut generates the low cutting force which causes the small vibration of cutting tool and the low rate of tool wear. Vice versa, an increase in cutting speed leads to the higher rate of tool wear and vibration of cutting tool afterwards. In conclusion, the cutting forces change depending on the cutting conditions and tool wear levels.

There are three components of dynamic cutting forces generates during the cutting which are the dynamic main force, the dynamic feed force, and the dynamic thrust force (Moriwaki, Shibasaka, and Tangjitsitcharoen, 2004; Moriwaki, Shibasaka, and Tangjitsitcharoen, 2006; Tangjitsitcharoen, 2011; Badru and Singh, 2012; Tangjitsitcharoen, Rungruang, and Pongsathornwiwat, 2011; Krzysztof, Tomasz, Joanna, and Sebastian, 2012). However, the dynamic feed force and the dynamic main force are considered to monitor the tool wear. Since the dynamic feed force is sensitive to the surface roughness caused by the tool wear and the dynamic main force is affected by the cutting conditions such as the hardness of material and the tool wear effect.

The dynamic main force is higher than the dynamic feed force. In addition, the dynamic cutting forces may be affected by the cutting conditions, the hardness of workpieces. Especially, an increase in feed rate or depth of cut leads to the tool wear progress directly (Satyanarayana, Venu Gopal, and Bangaru, 2012). The dynamic main force and the dynamic feed force are therefore important to be generalized to identify the amount of tool wear regardless of cutting conditions. The average variances of dynamic feed force dFy and the one of dynamic main force dFz are proposed and calculated for dimensionless dynamic cutting forces ratio (dFy/dFz) as shown in Fig.2. The dimensionless dynamic cutting force ratio is proposed to be able to eliminate the influence the combination of various cutting conditions in their components. Furthermore, the use of dynamic cutting force ratio to predict the tool wear has the highest advantage over the previous neural network methods because it is not necessary to train the system for the new specific cutting conditions.

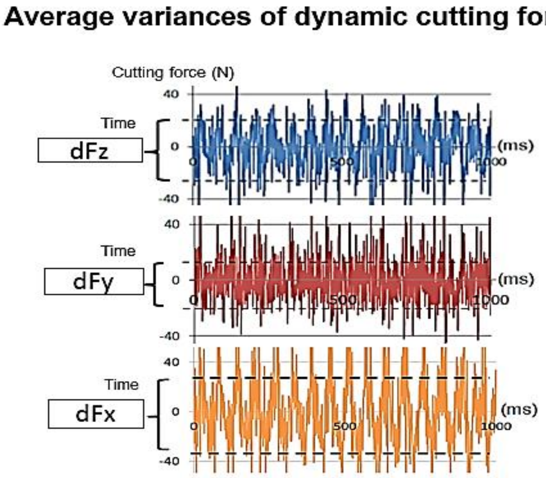

Figure 2: Illustration of the average variance of dynamic cutting forces at cutting speed of 200 m/min, feed rate of 0.25 mm/rev, depth of cut of 0.8 mm, tool nose radius of 0.4 mm, rake angle of -6 degree, and tool wear level of 0.176 mm.

Prediction of Tool Wear

In order to predict the in-process tool wear, the dimensionless dynamic cutting force ratio dFy/dFz and the focusing cutting parameters, which are the cutting speed, the feed rate, and the depth of cut, are proposed to develop the in-process prediction of tool wear by using the exponential function as shown in the equation (1):

$$V_b = C \cdot V^{a1} \cdot F^{a2} \cdot D^{a3} \cdot \left(\frac{dF_y}{dF_z}\right)^{a4} \qquad (1)$$

Where Vb is the amount of flank wear in mm, V is the cutting speed in m/minute, F is the feed rate in mm/rev, D is the depth of cut in mm, dFy/dFz is the dynamic cutting force ratio, a1, a2, a3, a4 , and C are the coefficients of model. The coefficients are obtained based on the actual results by utilizing the multiple regression analysis and the least square method.

Experimental Setup and Procedures

The series of cutting experiments are operated with the coated carbide tool and the carbon steel of AISI 1045 on CNC turning machine (Mazak NEXUS 200MY/MSY) to obtain the relation between the tool wear and the dynamic cutting force ratio. The dynamometer is employed and installed in order to measure the dynamic cutting forces as shown in Fig.3. The dynamic cutting forces are processed with the low-pass filter of 500 Hz by using the sampling rate of 1 kHz. The cutting conditions are listed in Table 1. The tool wear level is limited at the flank wear (Vb) of 0.2 mm. The tool wear is measured arbitrary by the digital microscope (Keyence VHX-600)

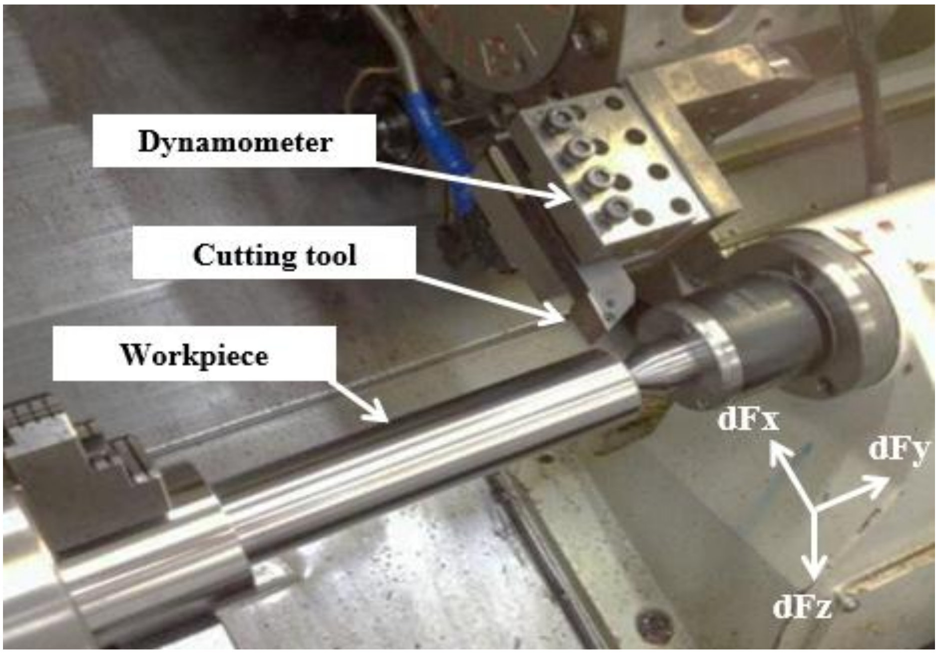

Figure 3: Illustration of experimental setup

Table 1:
Cutting Condition

Cutting Conditions	Dry cutting
Cutting tool	Coated carbide tool
Work piece	Carbon steel AISI 1045
Cutting speed (m/min)	100, 150, 200
Feed rate (mm/rev)	0.15, 0.20, 0.25
Depth of cut (mm)	0.4, 0.6, 0.8
Cutting tool nose radius (mm)	0.4
Cutting tool rake angle (degree)	-6°
Dynamic cutting force ratio	dFy/dFz
Limited tool wear (mm)	0.2 mm

Experimental Results and Discussions

While the tool wear increases, the dynamic cutting force ratio trends to decrease regardless of the cutting speed as shown in Fig.4. The more tool wear progresses, the more cutting force increases. The dynamic main force dFz also increases and significantly higher than the dynamic feed force dFy as a result of decrease in the dynamic cutting force ratio dFy/dFz at the same level of tool wear.

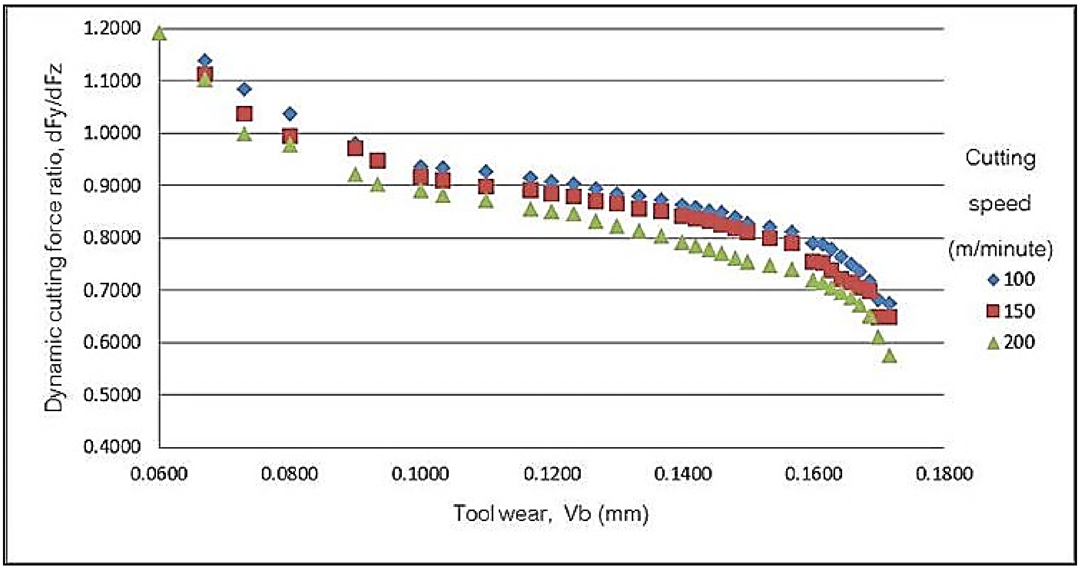

Figure 4: Example of experimentally obtained relation of dynamic cutting force ratio dFy/dFz and tool wear under various cutting speeds at feed rate of 0.25 mm/rev and the depth of cut of 0.8 mm.

The effect of feed rate is shown in Fig.5. It has been understood that the larger feed rate causes the higher cutting force due to the larger cutting area. Hence, the more vibration of cutting tool increase as well as the more tool wear progresses. Due to the higher vibration of cutting tool, the dynamic main force dFz becomes larger than the dynamic feed force dFy. Thus, the dynamic cutting force ratio dFy/dFz at the large feed rate is less than that at the small feed rate when the amount of tool wear is the same.

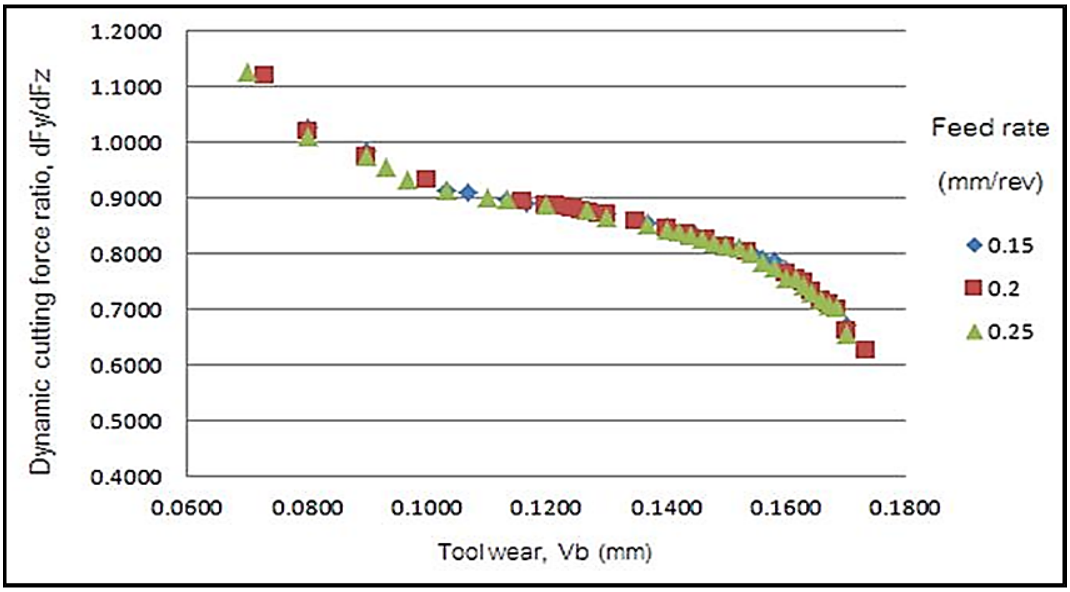

Figure5: Example of experimentally obtained relation of dynamic cutting force ratio dFy/dFz and tool wear under various feed rates at cutting speed of 150 m/ minute and depth of cut of 0.6mm.

Figure 6 shows the effect of depth of cut. Since the larger depth of cut results in the more cutting forces and the more vibration of cutting tool due to the larger cutting contacting area between cutting tool and workpiece. The dynamic main force dFz, which directly responds to the tool wear and the cutting condition, is higher than the dynamic feed force dFy. Hence, the dynamic cutting force ratio dFy/dFz trends to decrease. At the same amount of tool wear, the dynamic cutting force ratio dFy/dFz becomes lower than the one from the small depth of cut. It means that the dynamic main force is higher when the depth of cut is larger.

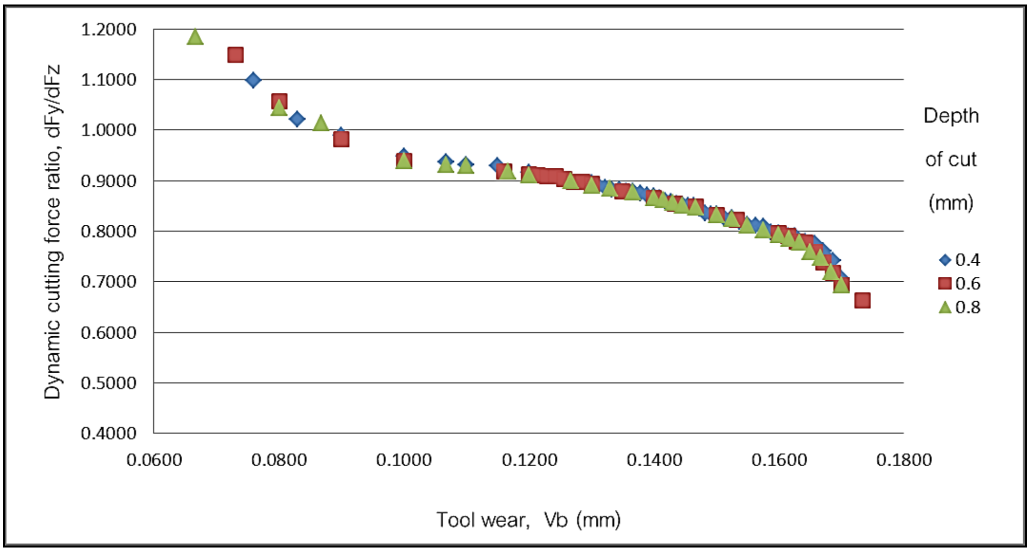

Figure 6: Example of experimentally obtained relation of dynamic cutting force ratio dFy/dFz and tool wear under various depths of cut at cutting speed of 100 m/minute and feed rate of 0.2 mm/rev.

The relation between the tool wear and the dynamic cutting force ratio dFy/dFz under various cutting conditions shows the same trend while tool wear increases. It is noticed that the dynamic cutting force ratio dFy/dFz is able to predict the in-process tool wear.

Tool Wear Prediction and Model Accuracy

The experimentally obtained in-process prediction can be expressed in the equation (2);

$$V_b = e^{-1.43} \cdot V^{-0.209} \cdot F^{-0.0574} \cdot D^{-0.034} \cdot \left(\frac{dF_y}{dF_z}\right)^{-1.81} \qquad (2)$$

Regarding to the above model, the magnitude of the power responses to those parameters in the model while the sign of the power presents how it affects to the tool wear which are consistent with the experimentally obtained results as shown in Fig.4 to 6.

According to equation (2), the tool wear progresses with an increase in cutting speed, feed rate, and depth of cut. No matter what cutting parameters have been changed, the dynamic main force dFz increases outstandingly more than the dynamic feed force dFy which causes the dynamic cutting force ratio dFy/dFz decrease simultaneously corresponding to the progress of tool wear during the cutting.

In order to verify the obtained model, the new cutting tests are performed. Figure 7 illustrates the measured tool wear, the ±10% of the measured tool wear and the in-process prediction of tool wear, respectively. The accuracy of in-process prediction tool wear Vb is approximately 93.5%. The predicted tool wear falls in the ±10% of the measured tool wear. Therefore, it is proven that the developed model is reliable and able to monitor and predict the in-process tool wear during the CNC turning.

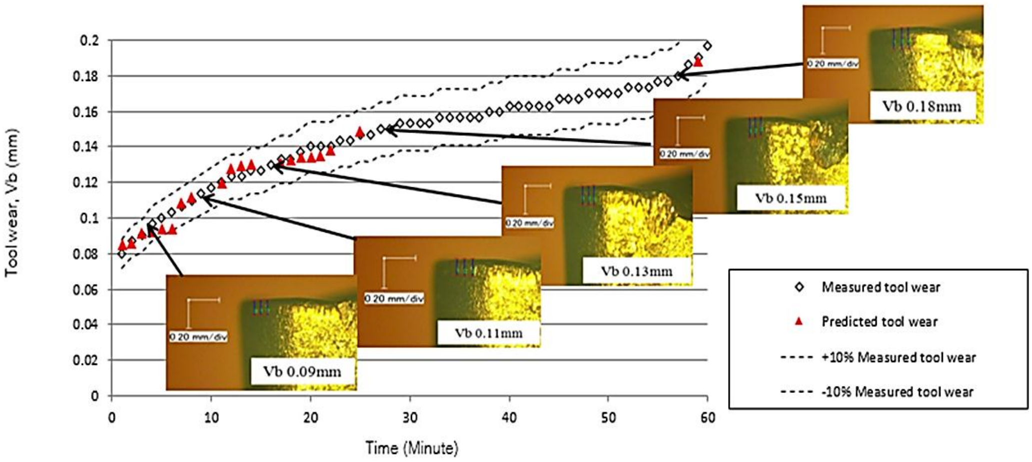

Figure 7: Illustration of the experimentally measured tool wear, the ±10% of measured tool wear, and the predicted tool wear at cutting speed of 220 m/min, feed rate of 0.1 mm/rev, and depth of cut of 1.0 mm.

Conclusion

Since the tool wear in CNC turning affects the productivity, hence this research proposes the in-process tool wear prediction by utilizing the dynamic cutting force ratio based on the average variances of dynamic cutting forces to monitor the in-process tool wear under various cutting conditions in order to realize the intelligent CNC machine in the future.

The experimentally obtained results showed that the dynamic cutting force ratio dFy/dFz becomes lower corresponding to the tool wear progresses even though the cutting conditions are changed. It is understood that the dynamic cutting force ratio dFy/dFz is able to predict the in-process tool wear during the cutting. The exponential function is employed to demonstrate the relation of tool wear, the dynamic cutting force ratio, and the cutting parameters such as the cutting speed, the feed rate, and the depth of cut. The multiple regression analysis is adopted to calculate the coefficients of the in-process prediction of tool wear model by using the least square method.

It is verified by the new cutting tests that the obtained model can predict the in-process tool wear at the high accuracy of 93.5% referring to the ±10% lines of the measured tool wear.

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