Advance in Monitoring and Process Control of Surface Roughness

Somkiat Tangjitsitcharoen and Siripong Damrongthaveesak

Abstract—This paper presents an advance in monitoring and process control of surface roughness in CNC machine for the turning and milling processes. An integration of the in-process monitoring and process control of the surface roughness is proposed and developed during the machining process by using the cutting force ratio. The previously developed surface roughness models for turning and milling processes of the author are adopted to predict the in-process surface roughness, which consist of the cutting speed, the feed rate, the tool nose radius, the depth of cut, the rake angle, and the cutting force ratio. The cutting force ratios obtained from the turning and the milling are utilized to estimate the in-process surface roughness. The dynamometers are installed on the tool turret of CNC turning machine and the table of 5-axis machining center to monitor the cutting forces. The in-process control of the surface roughness has been developed and proposed to control the predicted surface roughness. It has been proved by the cutting tests that the proposed integration system of the in-process monitoring and the process control can be used to check the surface roughness during the cutting by utilizing the cutting force ratio.

Keywords—Turning, milling, monitoring, surface roughness, cutting force ratio.

I. INTRODUCTION

AS the intelligent machine tool is expected to be realized, which can monitor and control the surface roughness of the machining parts autonomously. It is therefore necessary to estimate and control the in-process surface roughness during the cutting.

Machining process is one of the most important processes, which is widely used to produce the mechanical parts. One of the critical results in the machining process is the surface roughness of the machining parts. Since, the surface roughness cannot be measured during the cutting while there are many parameters affecting to the surface roughness. It is therefore desirable to know the surface roughness during the in-process cutting.

Hence, the in-process monitoring and estimation of surface roughness models in turning and milling processes of the author are adopted and utilized in this research [1], [2].

The process control is generally employed to control the process capability [3]. However, the changes in the cutting conditions affect the process capability of the cutting performance such as the surface roughness of the machining

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parts and the standard deviation of the machining processes, which cause a decrease in the process capability. Hence, the integrated system of the in-process monitoring and process control of surface roughness for the intelligent CNC machine is expected to be realized in the near future as shown in Fig. 1.
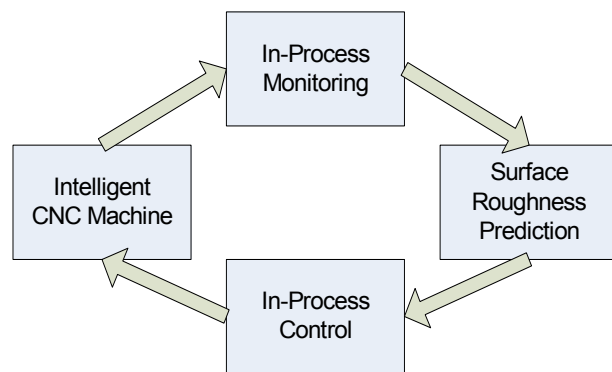

Fig. 1 Illustration of integrated system of in-process monitoring and process control of surface roughness for intelligent CNC machine

The surface roughness models are proposed and developed by many researchers [4]-[7]. It is already known that the force sensor is able to generate a signal corresponding to the in-process surface roughness [8]-[10]. The feed force is most sensitive to the surface roughness in turning while the main force is affected by the cutting conditions [11]-[13]. Since, the cutting forces may be affected by the cutting conditions. The cutting forces are therefore necessary to be generalized and non-scaled in order to estimate the in-process surface roughness regardless of the cutting conditions. The ratio of the cutting is proposed to predict the surface roughness because it is not sensitive to the variation of the cutting conditions in its components. The proposed dimensionless cutting force ratio consists of the main cutting force F_z as the denominator and the feed force F_y as the numerator.

However, the cutting forces F_x and F_z for milling process in X axis and Z axis respectively are normalized and dimensionless by taking the ratio of the cutting force F_x to the cutting force F_z [2].

The aim of this research is to develop an integrated system of the in-process surface roughness and the in-process process control of the predicted surface roughness in CNC turning and CNC machining center. The in-process prediction of surface roughness models are adopted from the previous researches of the author by monitoring the in-process cutting force ratio [1], [2]. The cutting force ratio is the important factor to estimate

the in-process surface roughness during the cutting.

II. SURFACE ROUGHNESS MODELS

The in-process surface roughness models of the turning process, which are the arithmetic average surface roughness R_a and the surface roughness R_Z, consist of the cutting force ratio (Fy/Fz), the cutting speed (V), the feed rate (f), the tool nose radius (Rn), the depth of cut (D), and the rake angle (γ) as shown in (1) and (2) adopted from the previous research of the author [1].

$$R_a = 53.52 \cdot V^{-0.122} \cdot F^{1.6} \cdot R_n^{-0.519} \cdot D^{0.108} \cdot \left(\tfrac{F_y}{F_z}\right)^{-0.296} \cdot e^{-0.00187\gamma} \quad (1)$$

$$R_z = 757.48 \cdot V^{-0.263} \cdot F^{1.59} \cdot R_n^{-0.205} \cdot D^{0.163} \cdot \left(\tfrac{F_y}{F_z}\right)^{-0.18} \cdot e^{-0.00998\gamma} \quad (2)$$

For the milling process, the in-process surface roughness model is expressed in (3) which is obtained from previous work of the author [2]. The model includes the cutting force ratio (Fx/Fz), the spindle speed (s), the feed rate (f), the depth of cut (D), and the tool diameter (Di).

$$R_a = 7.5 \cdot 10^{-6} \cdot V^{0.964} \cdot F^{0.195} \cdot D_i^{2.69} \cdot D^{0.917} \cdot \left(\tfrac{F_x}{F_z}\right)^{-0.26} \quad (3)$$

The experimentally obtained in-process surface roughness models are valid at 95% confident level. Hence, the adopted models are reliable to estimate the in-process surface roughness of turning and milling process by utilizing the in-process monitoring system of the cutting force ratio.

III. IN-PROCESS CONTROL OF SURFACE ROUGHNESS

The control limits of the upper specification limit (USL) are decided based on the required surface roughness. The USL is set as the process control to monitor and check the predicted surface roughness from the models. If the predicted surface roughness is out of the USL, the red warning point will be appeared on the control chart as shown in Fig. 2. The proposed procedures to vary the cutting conditions are referred to the previous researches of the author [1], [2].

The user interface between the in-process monitoring and process control of surface roughness in turning and milling processes has been developed to monitor and control the surface roughness referring to the control limit of USL as shown in Fig. 3.
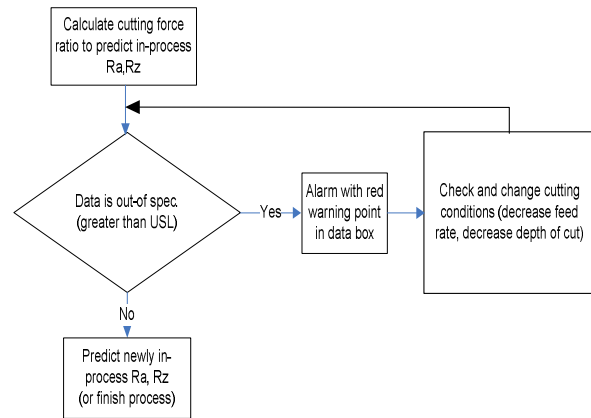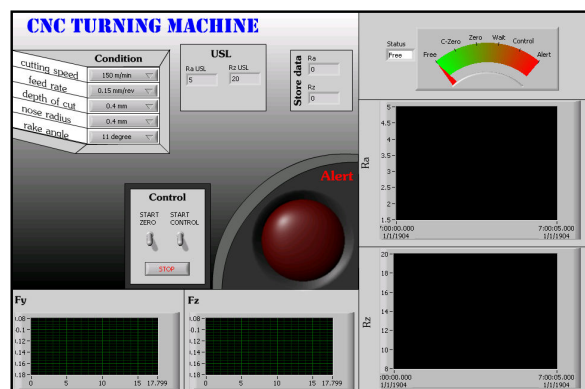

Fig. 2 Illustration of in-process control of predicted surface roughness

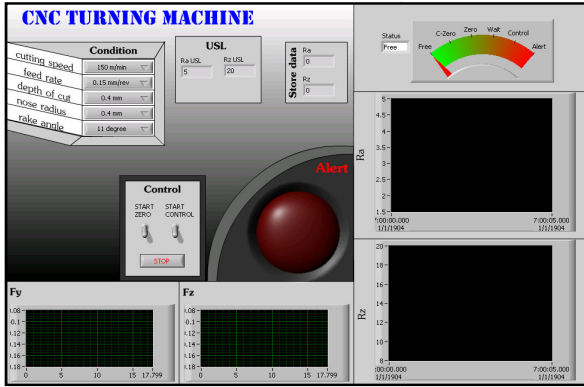## IV. EXPERIMENTAL SETUP AND PROCEDURE

Series of the cutting experiments had been carried out in the previous research of the author [1], [2] in order to obtain the surface roughness models. However, the cutting tests are conducted here to verify the system of the in-process monitoring and process control of the predicted surface roughness. The cutting tests are conducted on the CNC turning machine and 5-axis CNC machining center as shown in Figs. 4 and 5. The dynamometers are employed and installed on the turret of CNC turning machine and the table of the 5-axis CNC machining center in order to calculate the cutting force ratios during the in-process cutting as shown in Fig. 4.

The cutting force components detected by the dynamometer are amplified and low-pass filtered with the cut-off frequency of 5 kHz prior to digitization and calculation within PC. The sampling rate of 10 kHz is set to monitor the in-process cutting forces. It is proven that the resonant frequency of the dynamometer is about 2.7 kHz.

The carbon steels of AISI 1045 and AISI 1050 are adopted in the cutting experiments. The acceptable specifications of the surface of R_a and R_Z are 5 and 20 µm, respectively. The major cutting conditions are summarized in Table I.

(a) In-process control of surface roughness in turning process

(b) In-process control of surface roughness in milling process

Fig. 3 Illustration of user interface between in-process monitoring and process control of surface roughness
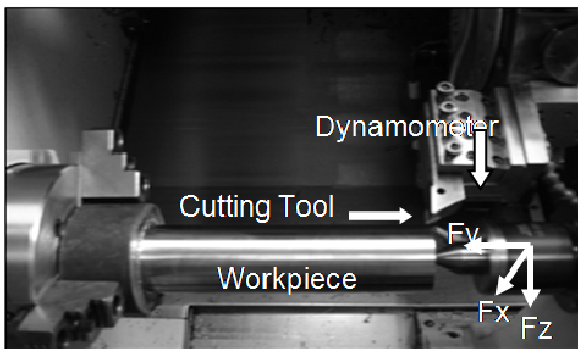

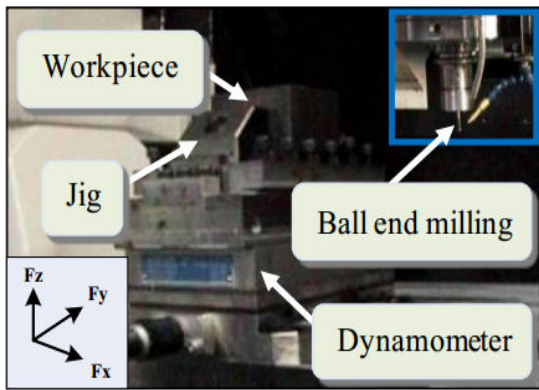Fig. 4 Illustration of experimental setup in CNC turning machine

Fig. 5 Illustration of experimental setup in 5-axis CNC machining center

TABLE I
MAJOR CUTTING CONDITIONS

Cutting condition	CNC turning machine	5-axis CNC machining center
Cutting tool	Coated carbide tool	Coated carbide tool
Tool geometry	TNMG 160404HQ TNMG 160408HQ DNMG 150604FN DNMG 150608FN	2 fluted ball end mill (diameter 6)
Workpiece	AISI 1045 Carbon steel	AISI 1050 Carbon steel
Cutting speed (m/min)	150, 200	
Spindle speed (rpm)		8,000, 10,000, 12,000
Feed rate (mm/rev)	0.15, 0.20	0.01, 0.03
Depth of cut (mm)	0.4, 0.8	0.3, 0.5
[Width of cut (mm)]		[1.5]

The following procedures are proposed and used to predict the in-process surface roughness and monitor the predicted surface roughness by using in-process control during the actual cutting;

1. Develop the USL chart for the in-process control in turning and milling processes to monitor the in-process predicted surface roughness.
2. Measure the cutting force ratios when the surface roughness is to be monitored, and calculate the predicted surface roughness from the in-process surface roughness models adopted.
3. Calculate and feed the predicted surface roughness obtained from the models into the in-process control which is developed to monitor the in-process predicted surface roughness on the USL chart.
4. Change the cutting conditions if the values of R_a and R_Z are out of the control limits of USL until the values of R_a and R_Z are in the control limits of USL.

V. IN-PROCESS MONITORING AND PROCESS CONTROL OF SURFACE ROUGHNESS

The cutting tests are conducted in order to verify the system of the in-process monitoring and process control of the predicted surface roughness in turning and ball end milling processes. Figs. 6 and 7 show the comparison between the ±10% measured surface roughness and the predicted surface roughness obtained from (1) to (3). It is understood that the proposed in-process surface roughness models can be effectively used to monitor and predict the in-process surface roughness.
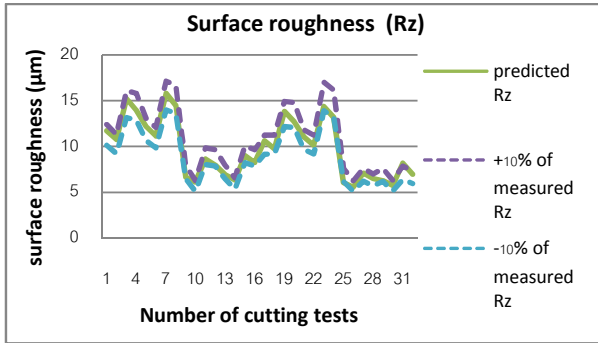
(a) R$_z$
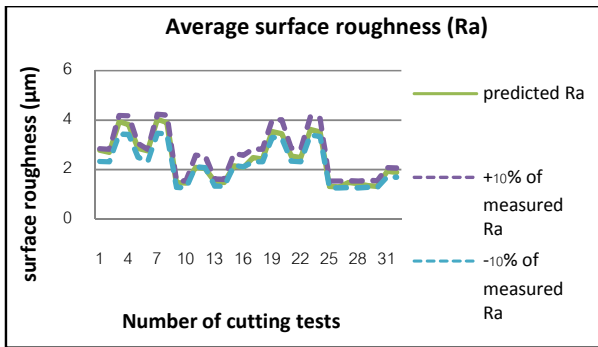
(b) R$_a$

Fig. 6 Illustration of the in-process predicted surface roughness in turning process, and the $\pm10\%$ measured surface roughness lines
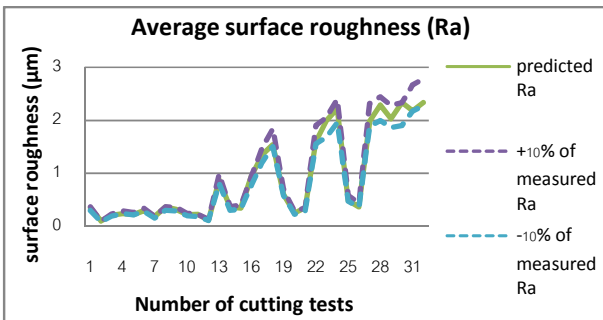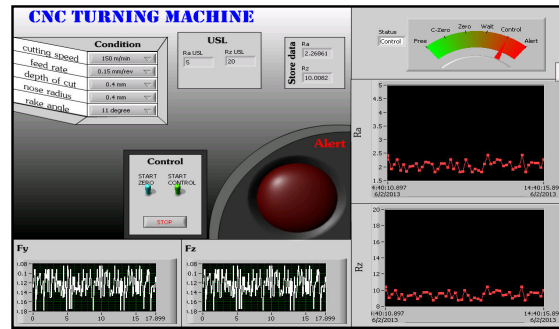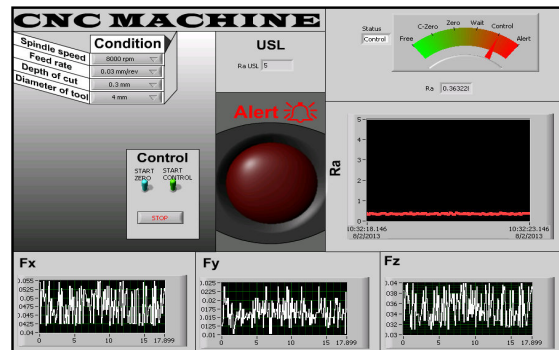

Fig. 7 Illustration of the in-process predicted surface roughness in ball end milling process, and the $\pm10\%$ measured surface roughness lines

Fig. 8 shows the in-process control of the R_a and R_Z by utilizing the USL chart under the acceptable specification of the R_a and R_Z which are 5 and 20µm, respectively. If the values of the R_a and R_Z are out of the control limits of USL, the alarm with the red point will appear and the cutting conditions, such as the feed rate and the depth of cut, will be checked and changed until the in-process predicted surface roughness is in the control limit of USL.

(a) In-process control of predicted surface roughness in turning process

(b) In-process control of predicted surface roughness in ball end milling process

Fig. 8 Illustration of in-process control of predicted surface roughness

Since the proposed models are developed from the actual cutting data, it can be effectively used to predict the in-process surface roughness for any cutting condition while the others cannot. It is implied that the higher cutting performance and the better surface finish can be obtained, which leads to the higher productivity.

VI. CONCLUSIONS

The system has been proposed and developed to integrate the in-process monitoring and process control in order to realize the intelligent machine tool. The in-process surface roughness models are adopted to predict the in-process surface roughness in turning and ball end milling processes.

The in-process monitoring is employed to measure the cutting forces in order to predict the in-process surface roughness under various cutting conditions during the cutting. The cutting force ratio is utilized to predict the in-process surface roughness even though the cutting conditions are changed.

The largest potential advantage of the proposed integration system is that the in-process control can be utilized to monitor and control the in-process predicted surface roughness during the actual cutting referring to the control limit of the upper specification limit (USL) in turning and ball milling processes.

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