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IN-PROCESS MONITORING AND PREDICTION OF SURFACE ROUGHNESS IN BALL-END MILLING PROCESS

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Abstract: *The objective of this research is to propose a practical model to predict the in-process surface roughness during the ball-end milling process by utilizing the cutting force ratio. The proposed in-process surface roughness model is developed based on the experimentally obtained results by employing the exponential function with five factors of the spindle speed, the feed rate, the tool diameter, the depth of cut, and the cutting force ratio. The multiple regression analysis is utilized to calculate the regression coefficients with the use of the least square method. The prediction interval (PI) of the in-process surface roughness model has been also presented to monitor and control the in-process predicted surface roughness at 95% confident level. All those parameters have their own characteristics to the arithmetic surface roughness and the surface roughness. It is proved by the cutting tests that the proposed and developed in-process surface roughness model can be used to predict the in-process surface roughness by utilizing the cutting force ratio with the highly acceptable prediction accuracy.*
Key words: *ball-end milling process, monitoring, prediction, surface roughness, cutting force ratio*

1. INTRODUCTION

The ball-end milling process is one of the most important processes which are widely used to produce the mechanical parts. It is therefore required to know the surface roughness during the in-process cutting. Hence, the in-process monitoring and prediction of the surface roughness is proposed and developed in this research.

Extensive research efforts have been devoted so far to develop the surface roughness models (Cakir et al., 2009) and the surface roughness prediction by the factorial design of experiments combined with the techniques of regression (Benardos & Vosniakos, 2003). The cutting forces vary with the cutting conditions and the tool wear, which affect the surface roughness. In turning process, the cutting force ratio gives the good estimation of the tool wear regardless of the cutting conditions (Choudhury & Kishore, 2000). Hence, the cutting force ratio can be used to predict the surface roughness.

The aim of this research is to develop the model for predict the in-process surface roughness in ball-end milling process which can be used in practice. The in-process surface roughness models are developed under various cutting conditions by employing the exponential function with the aid of the multiple regression analysis and the use of the least square method.

2. IN-PROCESS PREDICTION OF SURFACE ROUGHNESS

2.1 Monitoring of cutting force ratio

It is known that the axial force affects the surface roughness directly due to the ball-end cutting edges while the tangential force depends on the work material, the cutting condition as well as the tool wear. The cutting forces are normalized and dimensionless by taking the the ratio of the corresponding time records of the tangential force Fx to the axial force Fz. The cutting force ratio $\left(\frac{Fx}{Fz}\right)$ is the important factor to estimate the in-process surface roughness during the cutting (Ignatov et al., 2008).

2.2 In-process prediction of surface roughness model

The exponential function is adopted here to develop the in-process surface roughness model are proposed here as:

$$R_a = C_1 \cdot V^{a_1} \cdot f^{a_2} \cdot \phi^{a_3} \cdot D^{a_4} \cdot \left(\frac{Fx}{Fz}\right)^{a_5} \quad (1)$$

$$R_z = C_2 \cdot V^{a_6} \cdot f^{a_7} \cdot \phi^{a_8} \cdot D^{a_9} \cdot \left(\frac{Fx}{Fz}\right)^{a_{10}} \quad (2)$$

where R_a is the arithmetic average surface roughness in μm, R_Z is the surface roughness in μm, V is the spindle speed in rpm, f is the feed rate in mm/rev, ϕ is the tool diameter in mm, D is the depth of cut in mm, $\left(\frac{Fx}{Fz}\right)$ is the cutting force ratio, a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_{10}, C_1, and C_2 are the regression coefficients of the model.

3. EXPERIMENTAL SETUP

Series of the cutting experiments are conducted on a commercially available 5-axis CNC machining center with the dynamometer is employed and installed on the table of 5-axis CNC machining center as shown in Fig.1. The carbon steel (AISI 1045) is adopted in the cutting experiments and The major cutting conditions are summarized in Tab 1. The relation of the surface roughness and the cutting parameters can be obtained by cutting the workpiece under various cutting conditions and calculating the in-process cutting force ratio with the measured surface roughness. Finally, the prediction accuracy of the obtained models are verified with the new cutting tests.

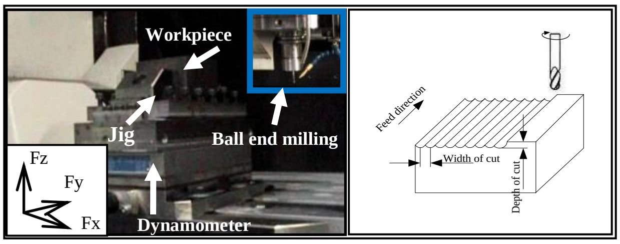

Fig. 1. Illustration of the experimental setup and the feed direction of the ball end mill

Cutting tool	Coated carbide ball end mill
Cutting condition	Dry cutting
Workpiece	AISI 1050 carbon steel
Spindle speed (rpm)	8,000; 10,000; 12,000
Feed rate, f (mm/rev)	0.01, 0.03
Depth of cut, D (mm)	0.3, 0.5
Tool diameter, ϕ (mm)	4, 6, 8
Force ratio	Tangential force (Fx) / Axial force (Fz)

Tab. 1. Major cutting conditions

4. RESULTS AND DISSCUSSIONS

4.1 Effect of cutting force ratios on surface roughness

The experimentally obtained relation of the surface roughness and the cutting force ratio is shown in Fig. 2. It can be stated that the greater the cutting force ratios are, the less the R_a will be obtained. It is interpreted that the surface roughness increases while the cutting force ratio decrease (El-Tamimi & El-Hossainy, 2008).

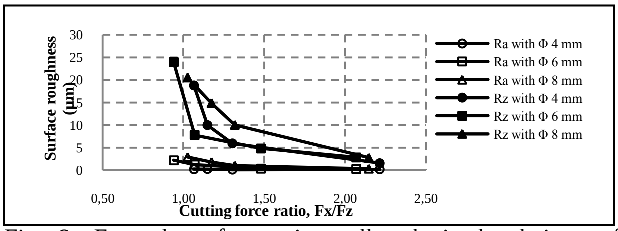

Fig. 2. Examples of experimentally obtained relations of surface roughness, and cutting force ratio at V 10,000 rev/min, f 0.03 mm/rev, D 0.3 mm

4.2 Surface roughness prediction

The experimentally obtained in-process surface roughness models are shown as below:

$$Ra = 7.5 \cdot 10^{-6} \cdot \upsilon^{0.964} \cdot f^{0.195} \cdot \phi^{2.69} \cdot D^{0.917} \cdot \left(\frac{Fx}{Fz}\right)^{-2.6} \quad (3)$$

$$Rz = 2.91 \cdot \upsilon^{0.16} \cdot f^{0.438} \cdot \phi^{1.25} \cdot D^{0.474} \cdot \left(\frac{Fx}{Fz}\right)^{-2.84} \quad (4)$$

The experimentally obtained in-process prediction of surface roughness models are valid at a high significance (P-value = 0.000) at 95% confident level. Therefore, the proposed method is reliable and usable to predict the in-process surface roughness in ball-end milling process by utilizing the in-process monitoring system of the cutting force ratio with the cutting conditions of the spindle speed, the feed rate, the tool diameter, and the depth of cut as the important predictors.

Finally, the prediction interval (PI) of the in-process surface roughness model at 95% confident level is calculated PI-lines give the highest advantage of monitoring and controlling the in-process surface roughness.

4.3 Surface roughness prediction accuracy

Fig. 3 shows the examples of experimentally measured surface roughness of Ra and Rz, and the in-process predicted surface roughness obtained from the equations (4). The in-process predicted Ra and Rz are very close to the experimentally measured surface roughness line.

The PI of the in-process surface roughness models are computed to predict the distribution of the individually predicted values of the in-process predicted surface roughness. The example of the upper line and the lower line of the PI of the in-process predicted surface roughness, Ra are shown in Fig. 4.

Since the proposed models are developed from the actual cutting data with no any dummy level sets, it can be effectively used to predict the in-process surface roughness for any cutting conditions while the others cannot.

5. CONCLUSIONS

The in-process monitoring is proposed to measure the cutting forces in order to predict the in-process surface roughness in ball-end milling process under various cutting conditions during the cutting.

A cutting force ratio is proposed to predict the in-process surface roughness even though the cutting conditions are changed, which is the ratio of the corresponding time records of the tangential force to the axial force.

The relations of the surface roughness, the spindle speed, the feed rate, the tool diameter, the depth of cut, and the cutting force ratio are investigated to develop the in-process surface roughness model. The exponential function is employed to represent the relation of the surface roughness, the cutting force ratio, and the cutting parameters.

It is proved by the cutting experiments that the in-process surface roughness can be predicted and obtained with the high accuracy by using the in-process surface roughness model proposed. However, another tool geometry should be studied and included in the models to obtain the higher prediction accuracy.

The largest potential advantage of the method proposed here is that the 95% PI of the in-process surface roughness model can be utilized to check and control the in-process surface roughness during the cutting referring to the upper and lower lines of the in-process predicted surface roughness. The obtained models will be used with the in-process statistical control in the future work to increase the process capability.

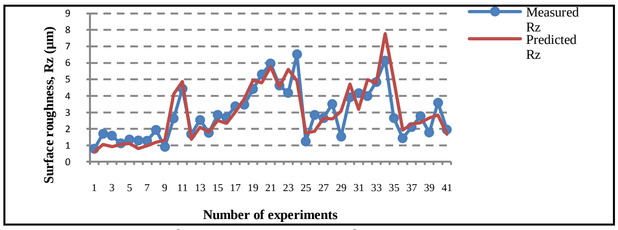

Fig. 3. Example of the measured surface roughness and the predicted surface roughness, Rz

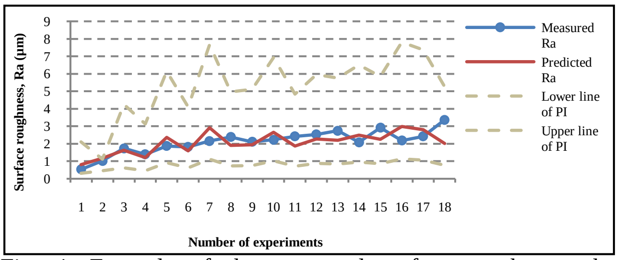

Fig. 4. Example of the measured surface roughness, the predicted surface roughness, and the 95% prediction interval of the predicted surface roughness, Ra

6. ACKNOWLEDGEMENT

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