

SURFACE GENERATION MECHANISM IN FLAT END MILLING

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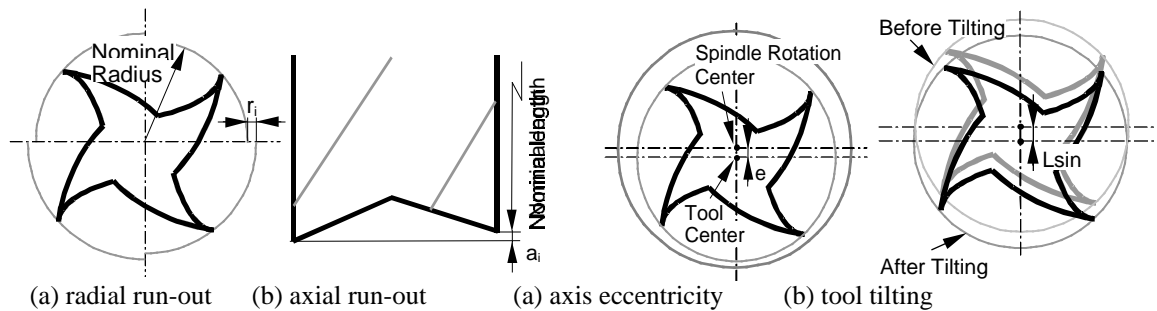
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1. Introduction

Recently, the demands for precision die and mold manufacturing technology are increasing. The quality of die and mold is determined by their surface roughness and form accuracy. In this regard, high speed machining is widely used for high productivity and high precision. In high speed machining, feed per tooth and pickfeed are very small compared to those in general machining. As a result, it is necessary to study surface texture characteristics precisely in microscopic view. End milling is an important machining process used extensively in the manufacturing industry to make flat surfaces of precision dies and molds. To date, considerable effort has been made to explain the surface generation mechanism of end milled surfaces. Recently, Sutherland⁽¹⁾ presented a two dimensional worst case analysis of the plane surface generated by the end cutting edges. Melkote⁽²⁾ improved the surface texture model including the effects of radial rake and primary relief angles. In this study, an effective surface prediction model in plane end milling is developed. Considered in this study are back cutting by the trailing cutting edge, tool run-out, tool setting error, and tool deflection caused by cutting forces. For understanding the surface texture more efficiently, three dimensional surface topography parameters such as RMS deviation, skewness and kurtosis are used in expressing the surface texture characteristics. From a series of cutting tests, it is verified that the presented model predicts the surface texture accurately.

2. Surface Generation

Plane surface is generated by the end cutting edges of an end mill. The end cutting edge angle is necessary for avoidance of rubbing between the tool and the machined surface. The rotation of the bottom edge makes the machined surface shape as a part of a conical surface. Plane surface texture is constructed by the superposition of a series of surface generation process in feed direction. The machined surface is cut once again by the trailing cutting edge. The shape of back cutting is determined by the phase difference and tool deflection. The magnitude of phase difference is decided by the combinations of tool diameter and feed per tooth. Tool deflection reduces back cutting. Surface texture and roughness are affected by tool run-out and tool setting error. Tool run-out consists of radial run-out and axial run-out (Fig. 1). Radial run-out has a serious effect on chip load variation of each flute. Axial run-out has an important role in surface texture generation. Tool setting error also influences surface texture characteristics. Tool setting error can be decomposed as eccentricity and tilting between tool axis and spindle axis (Fig. 2).



The factors determining surface texture are shown in Fig. 3. Two coordinates are established to describe the surface generation vectors more efficiently. X axis is in the feed direction and X axis is set in accordance with tool tilting direction. The position vectors, P , F_i , and V_i represent the peak point of bottom edge, cutting edge end point, and side cutting edge, respectively. The subscription i means the flute number. The vector origin, O , is the point of contact between the axis of spindle rotation center and the bottom surface of tool arbor. Surface texture is constructed through the superposition of surface generation process with cutting edge vectors expressed by a series

of vector transformations considering tool run-out and tool setting-error.

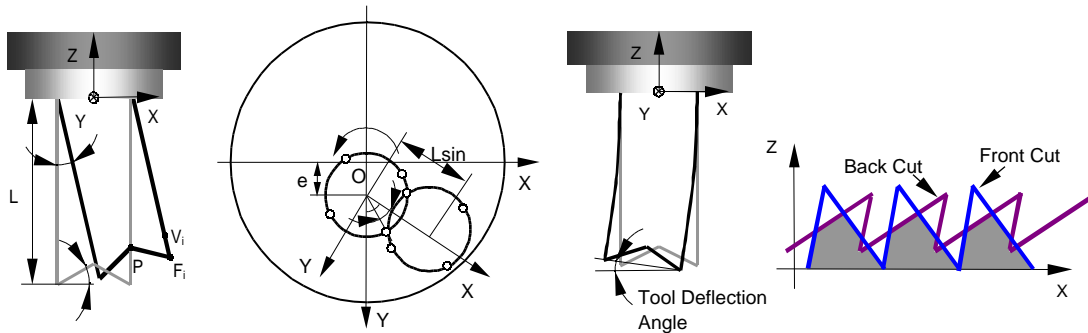


Fig. 3 Coordinate system

Fig. 4 Effect of tool deflection on surface generation

Tool deflection caused by cutting forces affects the surface texture and surface flatness. As shown in Fig. 4, the magnitude of back cutting is influenced by tool deflection. In this work, tool deflection angle is calculated using a cantilever beam theory under the assumption of quasi-static tool motion.⁽³⁾ The area moment of inertia of flute part is assumed to be equivalent to that of a cylinder with 0.8 times tool diameter.⁽⁴⁾

In end milled surfaces, the R_a and R_{max} values are quite different according to measurement position and direction.⁽³⁾ Hence three dimensional surface topography parameters are used for assessing the surface texture characteristics more precisely. In this paper, RMS deviation, skewness and kurtosis are used.⁽⁵⁾ The RMS surface roughness is a widely used parameter. Skewness indicates the asymmetry of surface deviations about mean plane and kurtosis represents the peakness or sharpness of the surface height distribution. These three parameters are used to analyze surface characteristics.

3. Results and Discussion

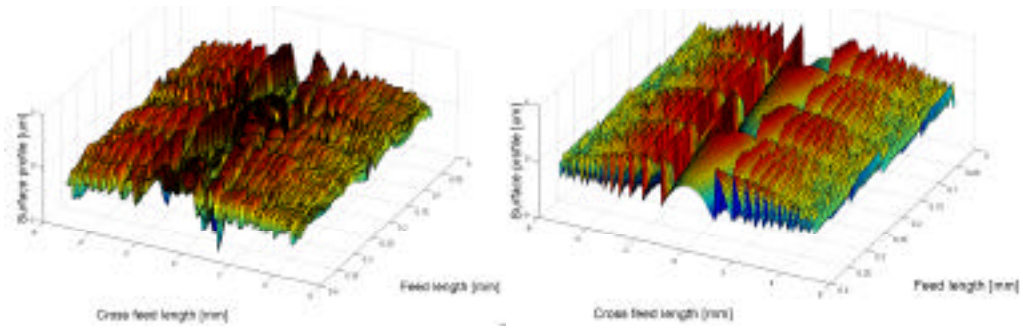
A set of cutting experiments were carried out to verify the surface generation model. The work material, SUS 420J2 stainless mold steel, was milled by two-fluted WC end mill with 30° helix angle. Tool run-out was measured using a vision system by mounting the tool on a V-block. Tool setting error was measured by capacitance type proximity sensors in air cutting condition. Table 1 lists the measured cutter geometry parameters and setting errors. The end cutting edge angle was measured indirectly by a coordinate measuring machine from a cast NYLON MC901 workpiece machined by the tool without feed motion. Surface texture was measured using Rank Taylor Hobson Form Talysurf.

Table 1 Tool specification and setting error

| Overhang (mm) | Axial run-out (μm) | Radial run-out (μm) | Tilting angle (degree) | Eccentricity (μm) |
|---------------|---------------------------------|----------------------------------|------------------------|--------------------------------|
| 86 | 1.8 | 23.9 | 0.0096 | 29.5 |

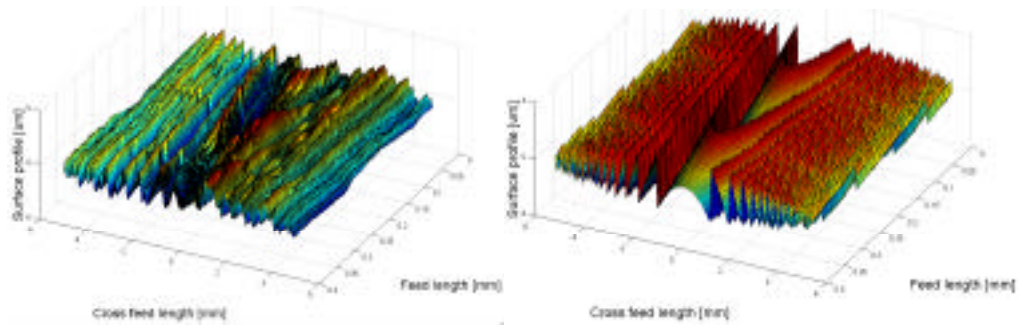
Figures 5 and 6 show the measured and the predicted surface textures in slot cutting with 0.05mm and 0.3mm axial depth of cut, respectively. In Fig. 5, back cutting occurred in all area because of small tool deflection. However, back cutting didn't occur in Fig. 6 because tool deflection is large. It can be shown that real surface textures agree well with those obtained from the simulations. Smearing of the cut surface in the middle area results from the interference between chip and sharp peaks.

Figure 7 shows the R_a and R_{max} variations according to measurement direction of end milled surface. Deflection, run-out and setting error are not considered in this simulation. Feed per tooth is 0.1mm and other tool geometry is equivalent to that used in cutting experiments. Surface roughness in the middle area is worse than that in the side area by about $2\mu\text{m}$ in R_{max} and $0.5\mu\text{m}$ in R_a . Figure 8 shows the difference of surface roughness according to the combinations of feedrate and pickfeed. In this simulation, cutting conditions are selected as having the same material removal rate and cutting time with the same tool. It can be seen that surface roughness is better at low feedrate with large pickfeed than that at the high feedrate with small pickfeed.



(a) measured (b) predicted

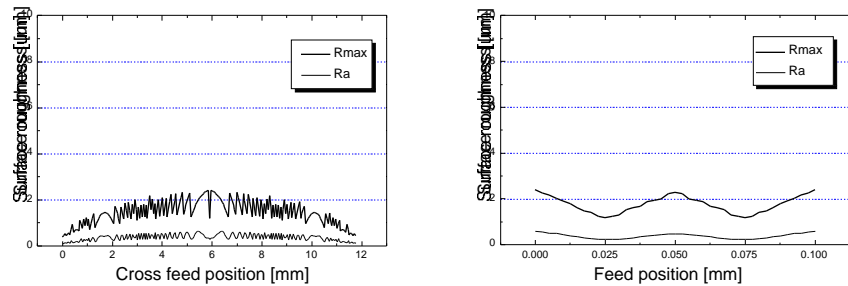
Fig. 5 Surface texture (depth of cut: 0.05mm, feed per tooth: 0.1mm)



(a) measured (b) predicted

Fig. 6 Surface texture (depth of cut: 0.3mm, feed per tooth: 0.1mm)

The relationships between surface topography parameters and tool run-out and setting error are simulated in Figs. 9 and 10. As run-out increases, the RMS deviation increases and skewness and kurtosis decrease. Tool tilting increases RMS deviation but decreases skewness and kurtosis. The result means that tool tilting and run-out reduce the peaks of surface texture. But these factors are insensitive to eccentricity.



(a) surface roughness in feed direction (b) surface roughness in cross feed direction

Fig. 7 Surface roughness deviations with respect to measurement direction

(a) feed per tooth: 0.1mm, pickfeed: 12mm (b) feed per tooth: 0.3mm, pickfeed: 4mm

Fig. 8 Effects of feed per tooth and pickfeed on surface roughness

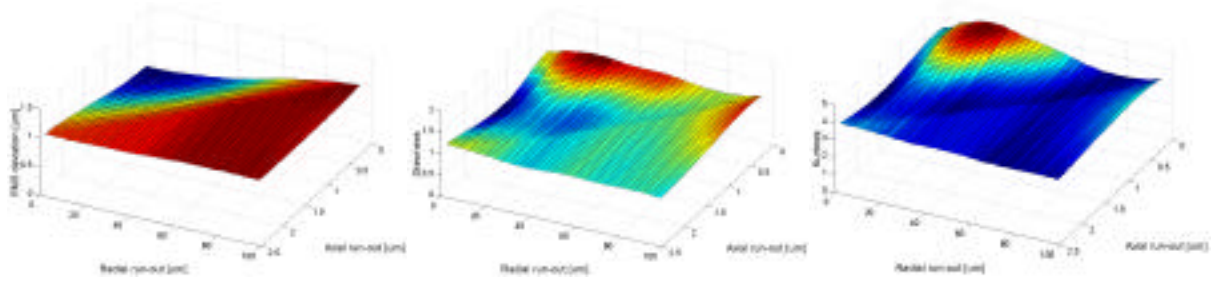


Fig. 9 Variations of surface topography parameters with respect to tool run-out

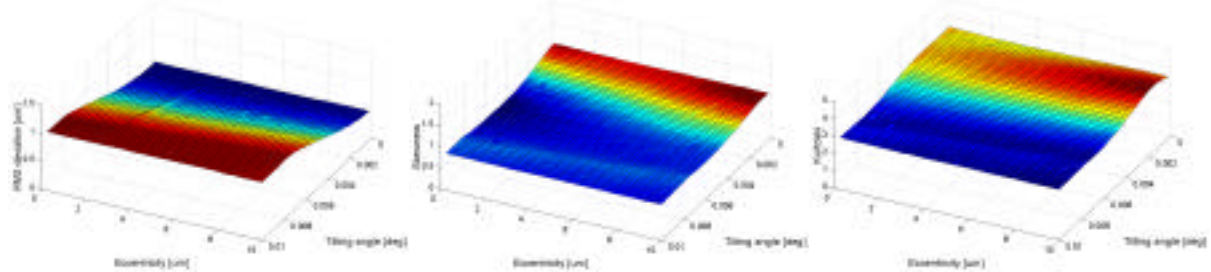


Fig. 10 Variations of surface topography parameters with respect to tool setting error

4. Conclusions

In this research, surface generation mechanism in plane machining with a flat end mill is studied. The cutting edges are expressed by the position vectors. Surface is generated through a series of vector transformations considering tool run-out and tool setting error. Developed model considers back cutting frequently observed in finishing process. Tool deflection is also included under the assumption of quasi-static tool motion using a cantilever beam theory. Surface topography parameters are introduced and used in expressing the surface texture characteristics. For a range of cutting conditions, it is confirmed that the presented model predicts the surface profile precisely. The following conclusions can be made based on the simulated and experimental work.

Surface roughness in the middle area is worse than that in the side area by about $2\mu\text{m}$ in R_{max} and $0.5\mu\text{m}$ in R_a under the test condition. Surface roughness is better at low feedrate with large pickfeed than that at the high feedrate with small pickfeed. The R_a and R_{max} values are not sufficient for representing the whole surface characteristics because these values are quite different according to measurement position and direction. So it is necessary to use three dimensional surface topography parameters. As tool run-out increases, the RMS deviation increases and skewness and kurtosis decrease. Tool tilting increases RMS deviation but decreases skewness and kurtosis. The results show that tool run-out and tool tilting reduce the peaks of surface texture. But surface topography parameters considered here are insensitive to eccentricity. This study contributes to effective cutter design, optimal cutting condition selection and tool path generation for the reduction of machining and manual finishing time especially in precision die and mold industry.

Acknowledgments

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