

Geometric Analysis of Machining Error with Tool Orientation in Ball End Milling

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Abstract:

This report is proposed a new concept for precise ball end milling used by the tool orientation control. The machining area at the point of the surface generation is changed depend on the tool orientation of the ball-end mill. So the machining error estimation index has been proposed and calculated about three dimensional surface. The machining error distribution of some three dimensional shape by machining test is supported the geometric analysis estimation.

Key words: CAM system, High precision machining, Geometric analysis, Evaluation of machining error, Tool orientation

1. Introduction

The machining error of the ball end milling due to the elastic deformation of the tool systems has become a problem, considers to the high accuracy of which is based on the cutting mechanism is not clarified yet. The cutting edge of the ball end mill has a three-dimensional curve, the cutting speed of the blade at each position during one rotation, trajectory, uncut chip thickness, the cutting length is all different. Therefore, as compared with other cutting methods the ball end milling have complicated the characteristic geometric cutting mechanism. For example, when the flat surface is machined shown in Fig. 1, there is no answer which direction is the best tool orientation. As

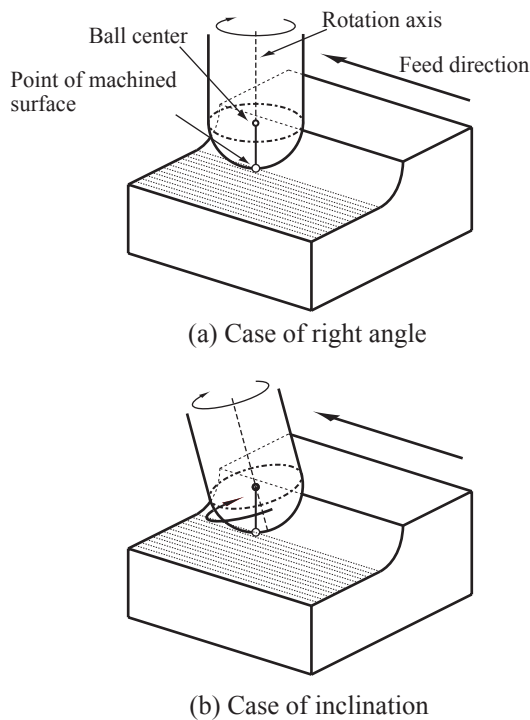


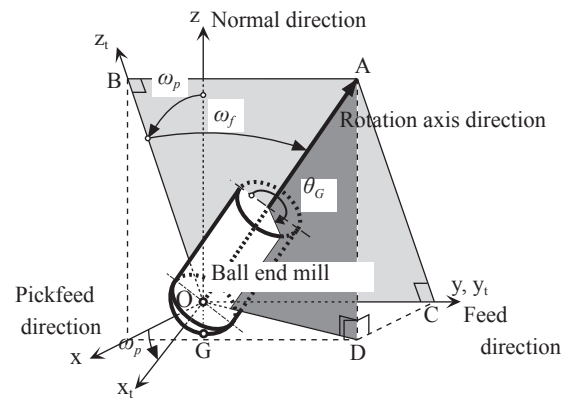
Figure 1: Relationship between tool orientation and tool path

the experiment is difficult for efficiency or repeatability, the study about the effect on the machining accuracy of the tool orientation is very few^{[1]-[5]}.

A geometrically seeks to develop a technique, that the different large cutting cross-sectional area(A_g) of the moment of creating the work surface with a difference of tool orientation was a uncut-chip thickness in any of the cutting edge position and tool rotation angle in the past revealed. Further, the relationship between the machining error and A_g revealed the effectiveness of the machining error index obtained geometrically that can evaluate the machining error by a cutting experiment.^{[6]-[12]} In this report, based on the geometric cut thickness analysis of more, to introduce a newly developed machining error index can program the calculation of in any of the three-dimensional shape.

2. Tool orientation and the cutting cross-section

In this study, we must discuss the influence of the tool orientation on the surface of the workpiece. So the



O: Ball center.

G: Point of machined surface generation.

AOD: Direction of cutting edge in passing the point G.

ABO: Initial direction of cutting edge.

ABOC: $y_t z_t$ plane includes the rotation axis.

Figure 2: Definition of the tool orientation.

definition of the tool orientation is the most essential factor for this discussion. Fig. 2 illustrates the definition of the tool orientation in this study. The z axis is the normal direction of the surface of the workpiece in machining. The y axis is the direction of feeding. So the x axis is the direction of the pickfeed. On this coordination the 2 angles are defined for the tool orientation. One is the angle of the z axis and a plane including the tool rotation axis and the y axis as the rectangular ABOC. It is called "the angle of pickfeed direction ω_p ". In this case another coordination $x_p y_p z_p$ is defined. This coordination is inclined as angle ω_p around the y axis. So $y_p z_p$ plane include the tool rotation angle. In this plane the angle of the tool rotation angle and the z_p axis is called "the feed direction angle ω_f ".

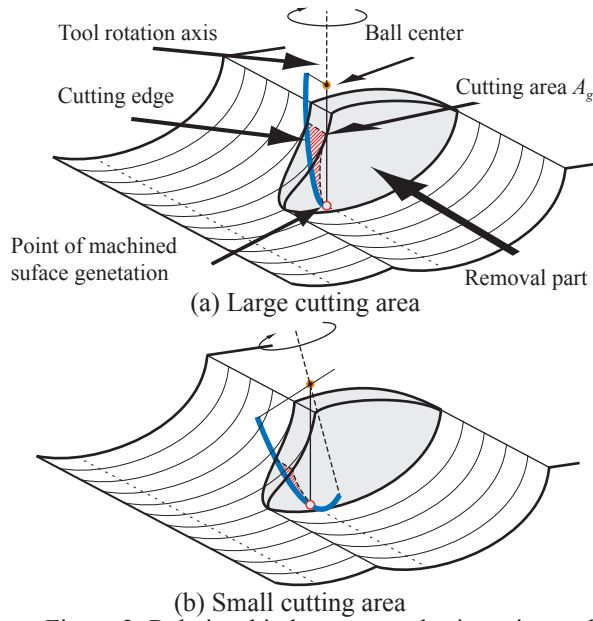


Figure 3: Relationship between tool orientation and cutting area

The situation of machining the flat plane of the ball-end mill is shown in Fig. 3. As cutting conditions and tool shape is the same, the removal volume at the cutting edge in one rotation is the same. However, in the ball-end milling, thereby greatly changes the state of interference between the cutting edge and the workpiece depend on "tool orientation". Interference of the cutting edge and the workpiece is different as shown in Fig. 3 by the tool orientation. As shown in Fig. 3 (a) and (b), the position of the ball center is the same, although the tool orientation of the tool axis of rotation is different. So the direction of the cutting edge to sweep the removal volume is different from the orientation of the tool rotation axis. From remaining as a surface of the final product at the ball-end milling is only in the vicinity of the perpendicular line drawn from the center of the ball of the workpiece. In this paper, the foot of this perpendicular line is referred to as a "surface generation point". Therefore, when considering the machining accuracy, there is a need to clarify the relationship between on the cutting edge and the workpiece at the moment that the cutting edge passes

just through the machined surface generation point. The cross-sectional area of the cutting edge at the moment of passing the working surface generation point (A_g) becomes small or large depend on the tool orientation as shown in Fig. 3 (a) and (b). Generally cutting resistance is considered to be proportional to the cutting sectional area, the greater the further the cutting resistance is large and the elastic deformation of the ball-end mill is also increased machining errors. Therefore, we can predict the machining error if a clear relationship between A_g and the machining accuracy.

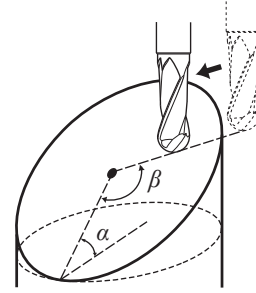


Figure 4: Inclination angle α and feed direction angle β



Figure 5: Machine tool for cutting experiments (MAKINO V33)

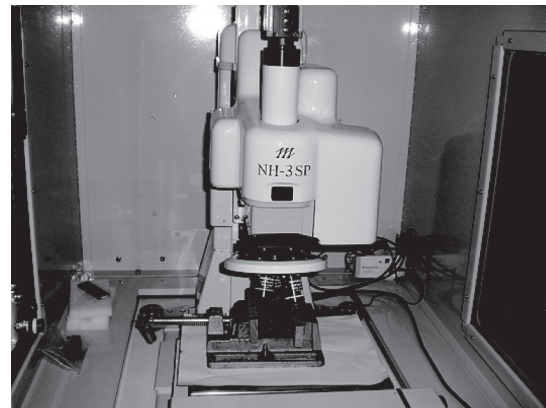


Figure 6: Non-contact three dimensional measurement device NH-3N (Mitaka Kohki.Co., Ltd.)

3. The machining error model of ball-end milling

Already, experimental methods, cutting can be realized in any tool orientation with a three-axis controlled machine have been developed⁵⁾⁻⁷⁾. The idea of this method is shown in Fig. 4. Round bar having a workpiece inclination angle α degrees inclined surface is

Table 1: Cutting conditions

Tool geometries :	
Ball radius (mm)	R
Number of teeth	n
Cutting conditions :	
Feed per revolution (mm/rev.)	f
Depth of cut (mm)	a
Feed per track (mm/track)	p
Tool orientation :	
Angle of pickfeed direction (rad.)	ω_p
Angle of feed direction(rad.)	ω_f

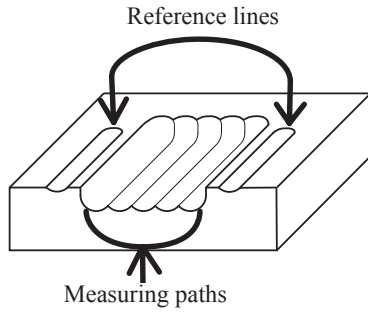


Figure 7: Cutter path for measuring of machining error

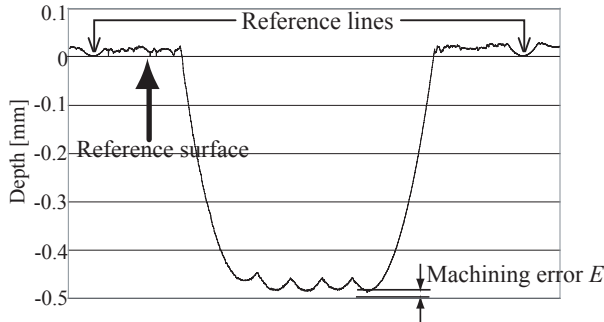
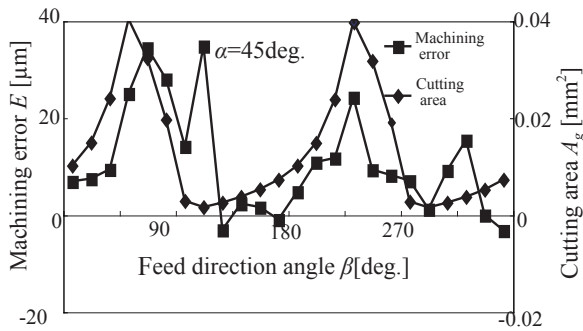


Figure 8: Definition of machining error

Figure 9: Relationship between machining error and cutting area ($\alpha=45\text{deg.}$)

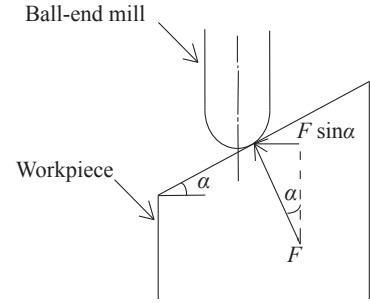
attached to the table. On the surface of the tool, it is sent to the direction of the direction angle β . In this experiment α is set $\pi/4$, $\pi/6$ and $\pi/12$ rad. And, β is set 24 types in the $\pi/12$ rad. increments from 0 rad. to $7\pi/4$ rad..

Machine tool is Makino Milling Co., Ltd. vertical machining center V33 shown in Fig. 5. And the machined

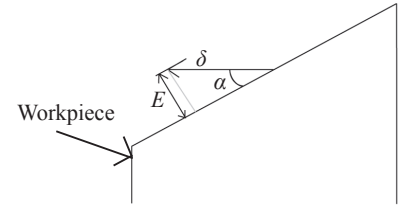
surface shape measurement were used as the Mitaka optical device manufactured by laser non-contact three-dimensional measuring device NH-3N (depth resolution 10 nm) shown in Fig. 6.

Cutting conditions are shown in Table 1, the ball radius $R=5$ mm, feed rate $f=0.1$ mm/rev., Depth of cut (normal direction) $a=0.5$ mm, are the main spindle rotation speed $N=5000$ rpm. Work material is SKD7 using a straight blade with carbide the tool material.

Before the machining of the measured path, 2 paths are carved slightly on both side for making reference line shown in Fig. 7. An example of measured surface profile is shown in Fig. 8. The bottom of 4 paths, except the first path, are measured each, and the actual depth of cut is obtained by averaging these values. The difference between the preset depth of cut and real one is the machining error E . The positive value means the over cutting and the negative value means the less cutting. Both value of the machining error by cutting experiments and the cutting area A_g by the geometric analysis are also

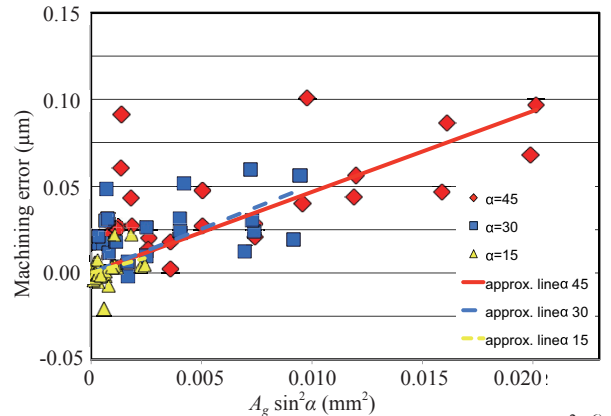


(a) The model of cutting force



(b) The model of elastic deformation

Figure 10: Elastic deformation model at the top of the ball-end mill

Figure 11: Comparing machining error with $A_g \sin^2 \alpha^6$

plotted in same graph shown in Fig.9. The tendency of both value along with the feed direction angle β is similar to each other in case of $\alpha=45\text{deg.}$. Same tendency can be observed in other inclination angles.

Figure 10 is a model of a machining error caused by the elastic deformation of the ball-end mill proposed in this study. While machining the slope of the inclination angle α as shown in Fig. 10 (a), the deformation of the tip of the ball-end mill according to thrust force F at the machining point, believed to be proportional to $F\sin\alpha$. The main component force is the extremely small effect on the working errors for a direction parallel to the working surface. If the amount of elastic deformation of the tooltip, as shown in Fig. 10 (b) δ machining errors E generated becomes $\delta\sin\alpha$. δ is proportional to $F\sin\alpha$, further F is proportional to the A_g . Therefore, machining errors E can be regarded as proportional to $A_g\sin^2\alpha$. In this study it will be referred to the $A_g\sin^2\alpha$ as "machining error estimation index". The relationship of the machining error and machining error estimation index in each tool orientation that has been measured by the above experiment is shown in Fig. 11. Straight line in the figure

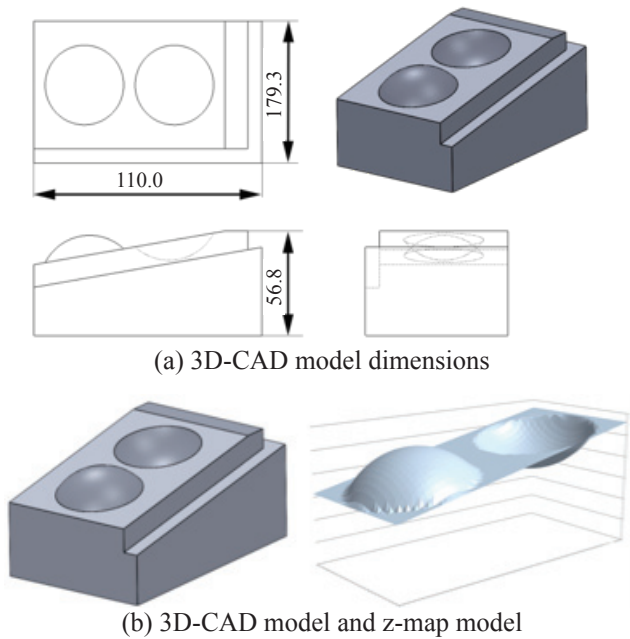


Figure 12: The analysis model for the machining error estimation index

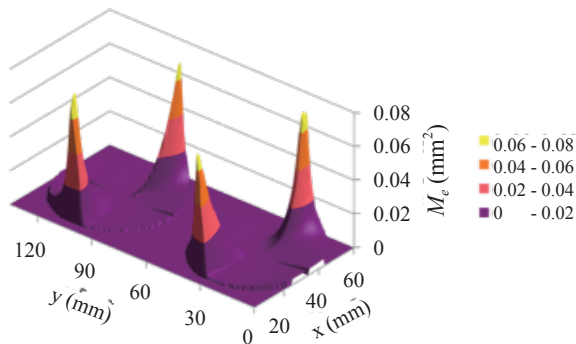


Figure 13: The result of the machining error estimation index M_e calculation

is an approximate line in the inclination angle α . All of the approximate line is aligned in one straight line, the machining error estimation index, regardless of the angle of inclination is considered to be consistent with the trend of the machining error.

There is a case machining error is large when small machining error estimation index. It can be considered to have been included in the cause of the non-elastic deformation of the tool for example some plastic deformation at the tool tip, some roughness by slow cutting speed and so on. In addition, in the range machining error estimation index is large it can be seen that the approximate line value less than less. In other words, if it is possible the tool orientation such that at least a machining error estimation index increase to avoid, machining error is reduced. In other words, at least machining error estimation index in order to machine with a high degree of accuracy must be small.

4. Machining error estimation index calculation

Machining error estimation index (M_e) has to be calculated along the tool path for some three dimensional surface. When the three dimensional surface like a metal mold is machined, 3D-CAD software is used. And the tool path is calculated by CAM software. So M_e value must be calculated based on the 3D-CAD data and the tool path data. The software for M_e value calculation for the three dimensional surface is developed.

The sample shape for M_e value calculation shown in Fig. 12(a) that is created by 3D-CAD software (SolidWorks). This shape is composed the convex semisphere and concave semisphere with same radius. The feed direction is a longitudinal direction and downward.

For the M_e value calculation the normal direction vector is necessary, but the 3D-CAD data format is not adapted. So z-map data is processed using by API program of 3D-CAD software. The z-map data is shown in Fig. 12(b). Along the tool path a small triangle patch is selected from the z-map data. From this small triangle patch the normal direction is calculated. Adjacent to this area the flat surface is machined approximately. At the same time the feed value and depth of cut value is converted depends on the inclined angle and feed direction angle.

A program for analyzing the M_e value distribution along the tool path has been developed based on the above process. Analytical results are shown in Fig. 13. In this result, there is a large part of the value of M_e . The analysis conditions are same as the cutting conditions described in chapter 3. There is some large value part, it forecasts the machining error is different depends on the tool orientation even if same cutting conditions.

5. Machining test and machining error measurement

For verification of M_e value, same shape as Fig.13 is machined and measured the machining error. The cutting condition is same as chapter 3 and the material is aluminum alloy. The shape data of the machined

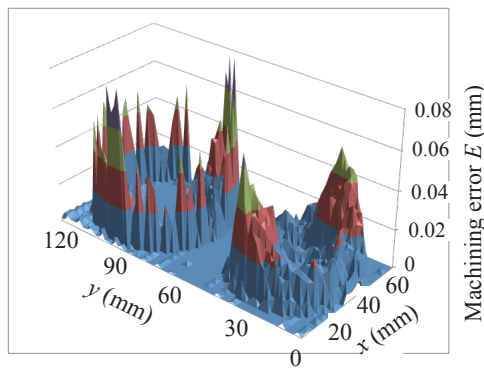


Figure 14: The result of machining error measurement

surface is measured using by CNC-CMM (MITUTOYO CRYSTA-Apex707). The machining error is calculated comparing with 3D-CAD data. Actually this operation is so sensitive that many times of try-and-error is needed.

Fig.14 shows the machining error distribution measuring by CMM. There is a large part on the edge of convex semisphere, because 3D-CAD model is not considered the ball radius. The tendency of Me value distribution is similar to the machining error distribution. It can be considered that the Me value indicates the large point of the machining error. So the precise machining can be realized by applying the tool orientation control that the machining error estimation index(Me) decreases.

6. Conclusions

Aim to the realization of high-precision ball-end milling, as a result of carrying out the cutting experiment with geometric analysis of the uncut chip thickness, the following findings were obtained.

- 1) From the elastic deformation model of the tool "machining error estimation index", it is revealed to be useful.
- 2) The 3D-CAD model of any three-dimensional shape, analysis method along a tool path can be calculated "machining error estimation index" has been developed.
- 3) To control the tool orientation as "machining error estimation index" becomes smaller to reduce the machining error by the elastic deformation of the tool, high-precision machining might be realized.

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