High precision ball-end milling based on a geometric analysis of the cutting mechanism

Hisanobu TERAI[**], Teruyuki ASAO[**], Koichi KIKKAWA[***] and Yoshio MIZUGAKI[***]

Abstract

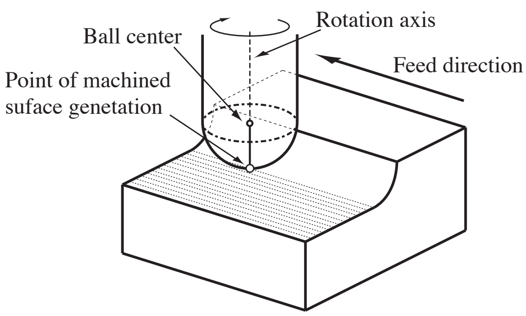
The ball-end milling has the problem of machining error by the elastic deformation of tool because of the low rigidity. So this report is set up the new method of the high precision machining used by the tool orientation control. The machining area at the point of the surface generation is changed depend on the tool orientation of the ball-end mill. The geometric mechanism is analyzed and the relationship between the machining area and the tool orientation is clarified. And the cutting force and the machining error are measured by the machining test that the tool orientation has been varied. As the result, it is verified that the machining error becomes large at the point, which the machining area is large. And the machining error estimation index has been proposed and calculated about three dimensional surface.

Key words: machining error estimation, machining area analysis, CMM, tool orientation

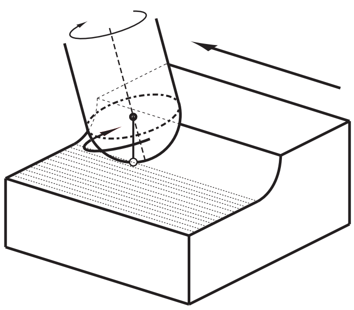
1. Introduction

The machining error of the ball-end milling due to the elastic deformation of the tool systems has become a problem, considers to the 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 the experiment is difficult for efficiency or repeatability, the study about the effect on the machining accuracy of the tool orientation is very few.

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.[1)-4)] 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.



(a) Case of right angle



(b) Case of inclination

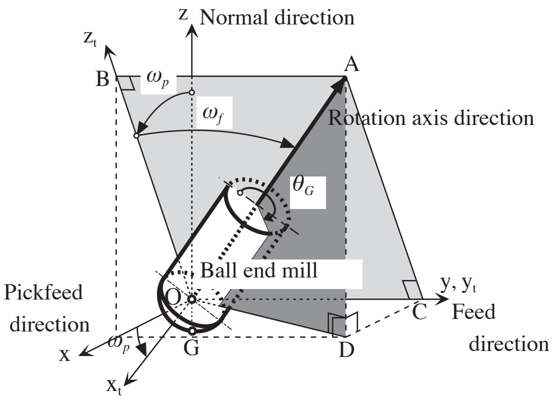
Fig. 1 Relationship between tool orientation and tool path

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 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 $x_t y_t z_t$ is defined. This coordination is inclined as angle ω_p around the y axis. So $y_t z_t$ plane include the tool rotation angle. In this plane the angle of the tool rotation angle and the z_t axis is called "the feed direction angle ω_f".

[**] Department of Creative Engineering, National Institute of Technology, Kitakyushu (5-20-1, Shii, Kokuraminami-ku, Kitakyushu, Fukuoka, 802-0985, JAPAN)

[***] Department of Mechanical and Control Engineering, Faculty of Engineering, Kyushu Institute of Technology (1-1, Sensui-cho, Tobata-ku, Kitakyushu, Fukuoka, 804-0015, JAPAN)



O: Ball center.

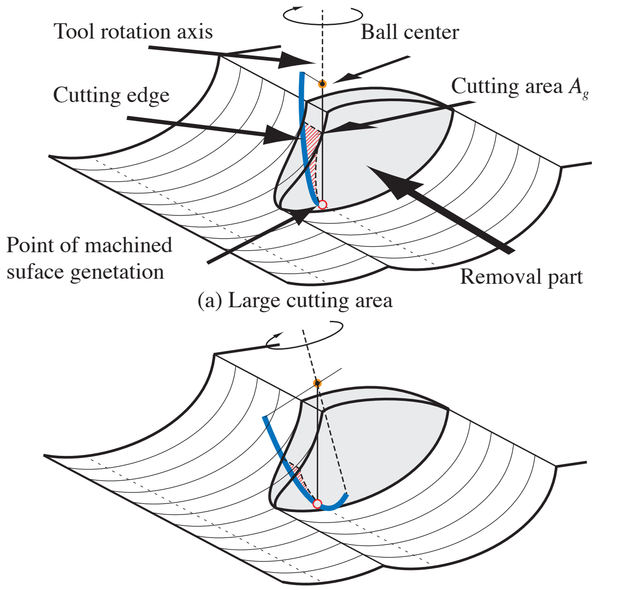
G: Point of machined surface generation.

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.

Fig. 2 Definition of the tool orientation.



(a) Large cutting area

(b) Small cutting area

Fig. 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.

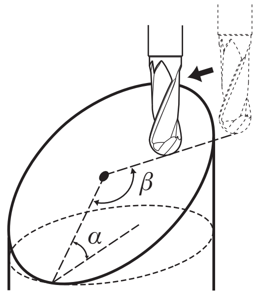


Fig. 4 Inclination angle α and feed direction angle β

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

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 developed[5)-7)]. The idea of this method is shown in Fig. 4. Round bar having a workpiece inclination angle α degrees inclined surface is 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.

Fig. 5 Machine tool for cutting experiments(MAKINO V33)

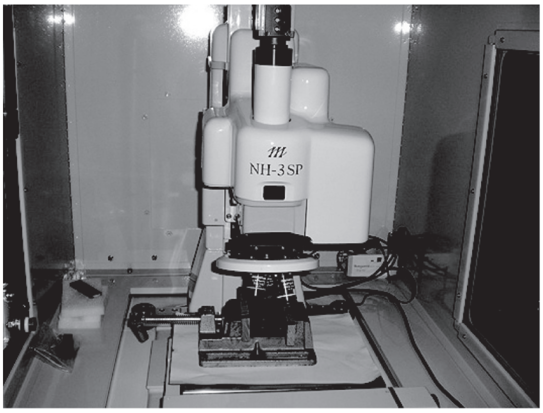
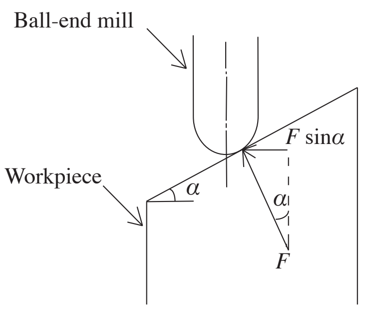
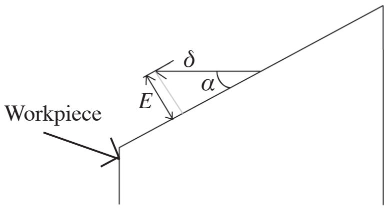


Fig. 6 Non-contact theree dimensional measurement device NH-3N (Mitaka Kohki.Co., Ltd.)



(a) The model of cutting force



(b) The model of elastic deformation

Fig. 7 Elastic deformation model at the top of the ball-end mill

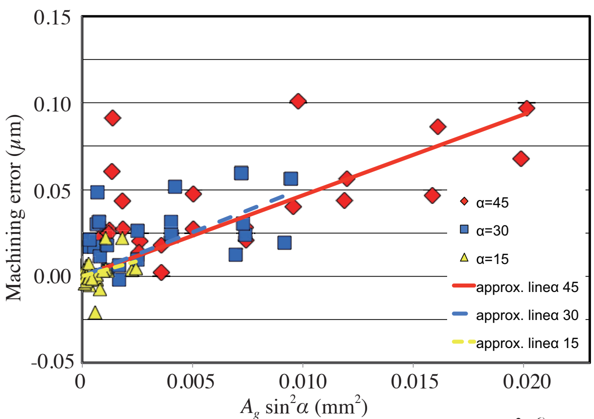
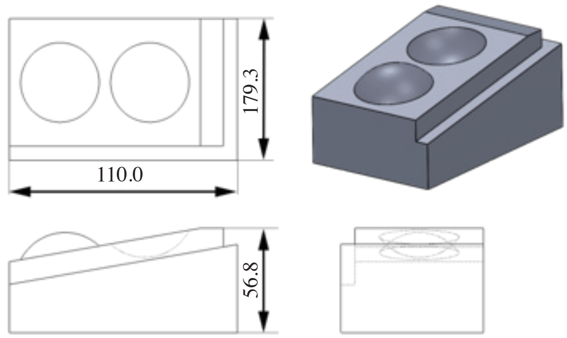


Fig. 8 Comparing machining error with A_g $\sin^2\alpha$[6]

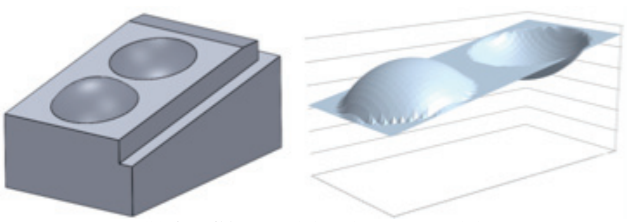
Cutting conditions are shown in Table 1, the ball radius R=5 mm, feed rate f=0.1 mm/rev., Depth of cut (normal direction) a=0.5 mm, are the main spindle rotation speed N=5000 rpm. Work material is SKD7 using a straight blade with carbide the tool material.

Figure 7 is a model of a machining error caused by the elastic deformation of the ball-end mill proposed in the this study.While machining the slope of the inclination angle α as shown in Fig. 7 (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. 7 (b) δ machining errors E generated becomes $\delta\sin\alpha$. δ is proportional to F sinα, 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. 8. Straight line in the figure is an approximate line in the inclination angle alpha. 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



(a) 3D-CAD model dimensions



(b) 3D-CAD model and z-map model

Fig. 9 The analysis model for the machining error estimation index

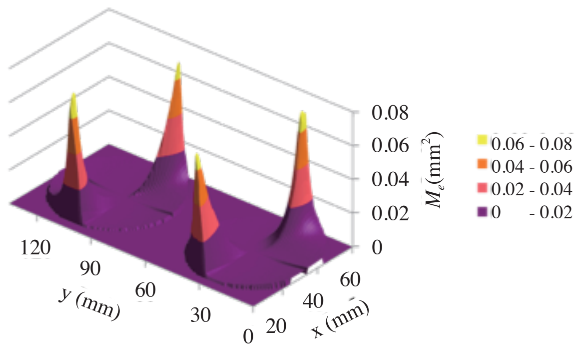


Fig. 10 The analysis of the machining error estimation index M_e

error estimation index. It can be considered to have been included in the cause of the non-elastic deformation of the tool. 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 analysis

Three-dimensional shape shown in Fig. 9 (a) is created by 3D-CAD (SolidWorks), the z-map shown in Fig. 9 (b) are created by processing this 3D-CAD data. A program for analyzing a machining error estimation index along the tool path has been developed. Analytical results of the machining error estimation index(*Me*) are shown in Fig. 10. In this result, there is a large part of the value of Me. High accuracy can be realized by applying the tool orientation that machining error estimation index(*Me*) decreases in the actual machining.

5. 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, 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 posture as "machining error estimation index" becomes smaller to reduce the machining error by the elastic deformation of the tool, high-precision machining can be realized.

References

1) H. Terai, M. Hao, K. Kikkawa and Y. Mizugaki: Theoretical Analysis of Undeformed Chip Thickness for Multi-Axis Ball-Bosed End Milling(in Japanese), Journal of JSME C, 67, 654, 553-558 (2001) .
2) H. Terai, M. Hao, K. Kikkawa and Y. Mizugaki: Study on Generation of Machined Surface Based on Geometric Analysis of Machining Mechanism for Ball-Nosed End Milling (in Japanese), Journal of JSME C, 68, 672, 2457-2463 (2002).
3) H. Terai, M. Hao, K. Kikkawa and Y. Mizugaki: Geometric Analysis of Undeformed Chip Thickness in Ball-nosed End Milling, JSME International Journal, Series C, Vol.47, No.1, 2-7, (2004).
4) H. Terai, T. Asao and Y. Mizugaki: Geometric simulation of ball end milling and application for the precise machining International Journal of Machining and Machinability of Materials, 6, 1, 83-94 (2009).
5) H. Terai, T. Asao, K. Kikkawa and Y. Mizugaki: Research about elastic mechanism of error generation in ball end milling based in geometric analysis, Proceedings of the 14th International ESAFORM Conference on Material Forming Esaform, 573-578 (2011).
6) H. Terai, T. Asao, K. Kikkawa and Y. Mizugaki: Proposition of Evaluation Index based on Geometric Analysis for Precise Machining of Ball End Milling, Proceedings of The 6th International Conference on Leading Edge Manufacturing in 21st Century (LEM21 2011) , 1, 1 83-94 (2011) .
7) H. Terai, T. Asao, K. Kikkawa and Y. Mizugaki: Experimental Research into Elastic Deformation of Tool on Machining Accuracy in Ball End Milling, Proceedings of the 6th International Conference on MicroManufacturing ICOMM/2011, 405-409 (2011).