Development of Non-Contact Type On-Machine Shape Measuring Method for Rotating Tool

Kohei Itakura[1, a], Tatsuya Furuki[1,b *] and Hiroyuki Kousaka[1,c]

[1]Graduate School of Engineering, Gifu University, Yanagido 1-1, Gifu, Gifu 501-1193, Japan

[a]x4524013@edu.gifu-u.ac.jp, [b]furuki@gifu-u.ac.jp, [c]kousaka@gifu-u.ac.jp

Keywords: non-contact measurement, cutting tool, grinding wheel, machining center, dynamic run-out, abrasive grain projecting quantity

Abstract. The demand of high quality mold that having 3-dimensional fine shape has been increased in the various fields. Moreover, it has been required that the high hardness materials are applied as mold material to restrain increase of mold wear. In most other cases, the mold is fabricated with cutting tool or grinding wheel on a machining center. In the machining with this machine, the rotating tools are most used. The rotating tools having static run-out and dynamic run-out, these run-out effects on tool wear or shape accuracy of mold. Thus, it is necessary to evaluate the tool run-out with the tool is attached to spindle. In addition, the end-mill typed diamond electroplated wheel is expected to machine the cemented carbide. However, the abrasive grain projecting quantity of this wheel may be having large dispersion. Thus, the wheel having small dispersion should be used to obtain high machining accuracy. Therefore, in this study, the rotating tool shape measuring method without direct contact using CCD camera is developed. In this report, the cross-section profile of diamond electroplated tool was measured with developed system. Moreover, the successive cutting point spacing during tool rotating was calculated. It was clarified that the developed system can evaluate the outline shape of grinding tool with high accuracy.

Introduction

Miniaturization of electronic devices or development of medical technology are increasing, and the demands of the small sized precision components such as optical parts, micro-channel or micro-needle also increases [1-3]. Since these components requires a mass-production, a molding that uses mold and die is effective. This mold has fine structure is fabricated with a small diameter cutting tools. If use of small cutting tool, a depth of cut also becomes small about few microns. On the other hand, rotational cutting tools such as end-mill or milling cutter that are attached to machine spindle via a holder has a rotational run-out (Static tool run-out). Furthermore, the rotational run-out (Dynamic tool run-out) will become large in accordance with increase of spindle rotational speed. If the small cutting tool that has the large tool run-out cut the material, since the tool run-out is larger than the depth of cut, a tool wear or tool breakage are easy to occur. Therefore, management and reducing of rotational run-out are exceedingly important. In addition, a high wear resistant material that like a cemented carbide is paid the most attention to improve a mold wear. In order to machine this material, the novel tools such as PCD tool or diamond coated tool are developed, although these tools are expensive. Thus, a diamond electroplated tool that is cheapness compare than the novel tools is receiving a lot of attention. However, it is difficult to use of grinding tools than the cutting tools, because a disposition of grains on the grinding tool is irregularity. A maximum cutting thickness h_{max} that is shown in Fig. 1 is important, in order that the grinding tool can machine the cemented carbide with ductility mode. The maximum cutting depth is defined by Eq. 1 and

Eq. 2. Where, λ is a successive cutting point spacing, v_w is a feed speed of workpiece, v_s is a rotational speed of tool, a is a depth of cut, D is a tool diameter and θ is an exit angle. The maximum cutting depth of cemented carbide will become from several dozen nm to several hundred nm [4, 5]. Thus, the grinding condition should be decided so that the maximum cutting depth will become several dozen nanometers. However, since the successive cutting point spacing is not recorded on tool specifications, it is impossible to use Eq. 1 for the purpose of deciding the grinding condition. Therefore, in this study, a measuring system that evaluates dynamic tool run-out and successive cutting point spacing of grinding tool with CCD camera on the machine tool is developed.

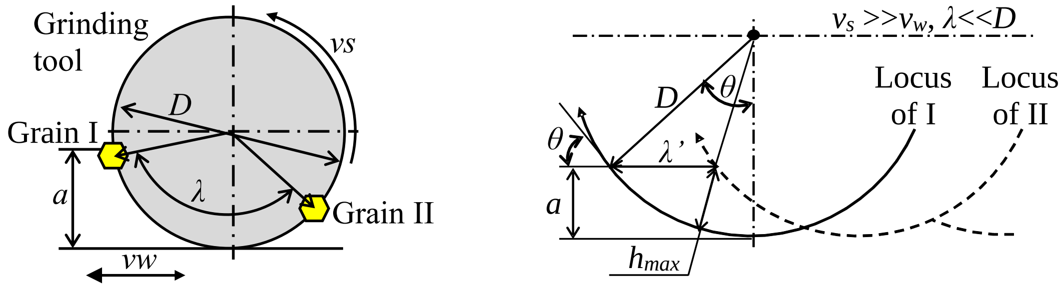


Fig. 1 Schematic illustration of simple grinding model.

$$\theta = \cos^{-1}\left(1 - \frac{2a}{D}\right) \tag{1}$$

$$h_{max} = \lambda' \sin\theta = 2\lambda \frac{v_s}{v_w}\sqrt{\frac{a}{D}} \tag{2}$$

Fabrication of non-contact type measuring device

In this study, the proposed method uses only CCD camera to measure tool run-out and shape profile of grinding tool. Overview of developed system is shown in Fig. 2. As the CCD camera, a high magnification CMOS camera STC-SPC312PCL (OMRON SENTECH Co., Ltd.) is used. The specifications of this camera are below: Image sensor is 1/1.8 type progressive CMOS (IMX256, SONY Corp.), Resolution is W2048 x H1536 pixel, Maximum frame rate is 1329 fps (Minimum frame rate is 57.1 fps), Exposure time is 1 μs ~47 second. A backlight (Red LED) is placed on the opposite side of the CCD camera to clearly observe the tool outline shape. In order to illumine the tool, two sub lights are placed at either side of backlight. A light quantity of these backlight can be adjusted with a DC stabilized power source equipment. This device is attached onto the XY table of machining center. The tool that is the target for measurement is located and rotated between CCD camera and backlight. The tool is recorded while the tool rotates. The measured video is transferred to the computer with USB3.0. The transferred video is analyzed, and the analysis results are outputted as tool run-out or successive cutting point spacing that according to the depth of cut.

Accuracy testing of developed device and analytical method of tool shape profile

In this report, the accuracy testing developed device under the static state is carried out at first. Next, the analysis method for measuring of successive cutting point spacing on diamond electroplated tool is proposed.

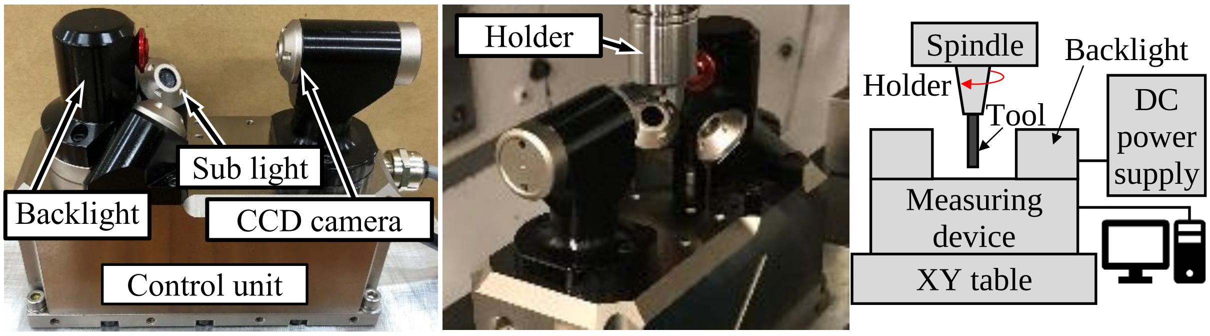
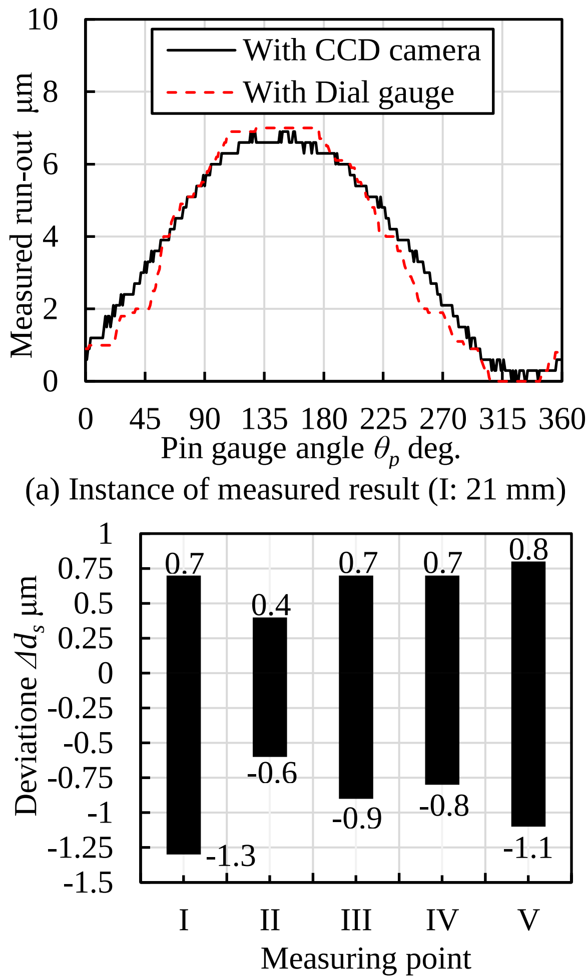


Fig. 2 Overview and schematic illustration of developed tool measuring device.

Evaluation experiment of developed measuring device

In order to investigate the measuring accuracy of developed device, the static run-out of pin gauge made of cemented carbide was measured with developed device and lever type dial test indicator on the machining center. The angle of pin gauge was positioned with a spindle indexing function. The static run-out was measured every 1 degree. The pin gauge was attached to the spindle via collet chuck type holder, and is having diameter of 6 mm. A protruded length from holder was 30 mm. The measured points were 5 points. The distance from pin gauge tip to measuring point is below: I: 21 mm, II: 16 mm, III: 11 mm, IV: 6 mm and V: 1 mm. As the dial gauge, TI-111HRX (Mitutoyo Corp.) was used. The specification of dial gauge is below: minimum scale value is 1 μm, measuring force is less than 0.3 N, repeatability is 1 μm and backlash error is 3 μm. Before that time, the length per pixel l_p of developed device is checked. First, the pin gauge was captured. Furthermore, the number of pixel from left edge of image to pin gauge edge was put P_i, and the machine coordinate value at this time was put X_i. Next, the pin gauge was moved on the machining center until the opposite edge of pin gauge is reflected on the monitor. At this time, the number of pixel from left edge of image to pin gauge edge was put P_e, and the machine coordinate value at this time was put X_e. The length per pixel were calculated by substituting these value for Eq. 3. As the result, the length per pixel l_p was 0.3 μm, and it was found that the developed device is having high measuring accuracy. Next, in order to confirmed that the measured result by the developed device is correct, the measured run-out between developed device and dial gauge was compared. Fig. 3 (a) shows the comparative example of measured result on the measuring point I (Distance from pin gauge tip to measuring point is 21



(a) Instance of measured result (I: 21 mm)

(b) Comparison result of static run-out

Fig. 3 Comparison of static run-out between developed device and dial gauge.

mm). This result indicates the static run-out on each angle of pin gauge. It is found that the run-out transition of both measuring results is correspond reasonably. The maximum and minimum deviation in this result was extracted as the evaluation value. The comparison result of all measuring points is shown in Fig. 3 (b). These deviations are within approximately ±1 μm. Since the backlash error of used dial gauge is 3 μm, it is seemed that the measured results of developed device are appropriate.

$$l_p = \frac{X_e - X_i}{P_e - P_i} \tag{3}$$

Evaluation result of shape profile of diamond electroplated tool

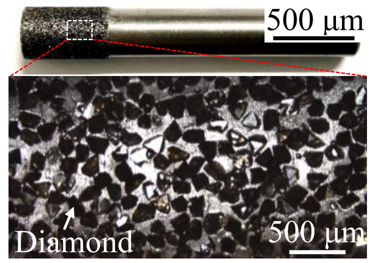


Fig. 4 Diamond electroplated tool (measuring object).

Since it was found that developed device is having enough measuring resolution, the analysis method for measuring of successive cutting point spacing on diamond electroplated tool is considered. This report attempts to evaluate the successive cutting point spacing that includes the dynamic run-out during rotation. In this report, the diamond electroplated tool (Kamogawa Co., Ltd.) as shown in Fig. 4 was used as the measuring object. The specification of this tool is below: diameter of base metal (shank) is 6 mm, abrasive type is diamond and grain size is #60 (Mean diameter: 260 μm). The data analyses described below are generated and carried out on "python 3.6.5".

Analysis of tool outline shape. First, the transferred video to the computer is converted to the numerous images. Then, since these divided images are the grey scale, these are converted to the binary images. At this time, if the luminance of each pixel in the grey scale image larger than 180, that pixel was put 1 (white). When the threshold value is 180, the difference of static run-out between developed device and dial gauge became the minimum deviation. In addition, in order to increase the frame rate, the imaging region was reduced to W2048 x H32 pixel. The binarized data was stored as the two-dimensional array.

The extraction method of the pixel of tool edge on one row [6, 7] is mentioned below. First, the binarized image is vectorized in accordance with Eq. 4. Where, in this report, n is 2048 and m is 32. Then, one row data is converted as the vector representation based on Eq. 5. Next, the first column of this converted vector is deleted. Moreover, the last column of converted vector is also deleted. Finally, the difference between these vectors that were deleted first and last column are differentiated based on Eq. 8, and the variation point is calculated. These processes are repeated until last row. The outline of tool is analyzed by connecting the calculated variation points. This analysis method required 0.2 second to calculate the one image. On the other hand, if simply searching the tool edge from left edge of image, the analyzing time was 33 seconds. Therefore, the processing speed became 165 times.

Next, the angles of these calculated outline shape data are calculated. In this study, the rotational error of spindle is utilized to obtain the outline shape on the finely tool angle. The first data of outline shape is set as the base data, and the data that identical with the base data is searched (concordance rate is more than 95%). The number of frame between these is put F. The laps of tool until the searched data correspond to base data is put N, and is defined as N= (60 x f)/S. Where, f is the frame rate (in this report, f=1329 fps), S is the given spindle rotational speed. Thus, the moving angle Q until the searched data correspond to base data is calculated by Q= (360 x N)/F. Moreover, the outline shape data G in finely angle is obtained by using Eq. 7.

In addition, the calculated method of tool center is below. The arbitrary image of tool was chosen, and the distance from left edge of image to shank edge was put X_{si}. Then, the tool rotated by 180 degrees, and moved until the left edge of tool appears. The feed amount at this time was put X_{cm}. The distance from right edge of image to shank edge was put X_{se}. Where, width of image is 0.6144 mm. By applying these value to Eq. 8, the tool diameter was calculated. Since the calculated diameter of electroplated tool that was used in this report was 5.994 mm, it was found that this calculating method is effective.

$$L = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_m \end{pmatrix} \tag{4}$$

$$\overrightarrow{L_m} = (a_{m1} \quad a_{m2} \cdots a_{m2047} \quad a_{m2048}) \begin{pmatrix} x_1 \\ \vdots \\ x_{2048} \end{pmatrix} \tag{5}$$

$$(\overrightarrow{L_m'} - \overrightarrow{L_m''})' = (a_{m2} - a_{m1} \quad a_{m3} - a_{m2} \cdots a_{m2047} - a_{m2046} \quad a_{m2048} - a_{m2047}) \tag{6}$$

$$G = Q\left(\left[(N-1)\frac{360}{Q}\right] - \left[(N-1)\frac{360}{Q}\right]\right) \tag{7}$$

$$D = (0.6144 - X_{si}) + (X_{cm} - 0.6144) + (0.6144 - X_{se}) \tag{8}$$

From above analysis method, the analyzed outline profile of the diamond electroplated tool on XY plane is shown in Fig. 5. This figure indicates the relationship between tool angle and protruded height of grains. In the measuring experiment, the vertical three axis machining center MD-46VA (OKUMA Corp.) and the collet chuck type holder were used. In addition, the tool rotational speed was 4000 min^{-1}. The matching degree between dynamic state (during tool rotation) and static state (outline shapes were measured every 1 degree) is more than 92%. It is considered that this error occurred with the occurrence of slight phase difference that did not be able to revised. In addition, the successive cutting point spacing λ can be evaluated in accordance with the depth of cut. In this case, if the depth of cut is 5 μm, the effective abrasives are only two grains on this circumferential direction, and the minimum λ=3.86 mm.

Summary

In this report, in order to evaluate the successive cutting point spacing of diamond electroplated tool on the machining center, the tool outline shape measuring device that uses only CCD camera and analysis method were proposed. In the development process, following knowledges were obtained.

1) The analysis method that searches the variation point can increase the processing speed by 165 times compared with the simply searching method that searches the changing pixel from left edge of image.
2) The outline shape on finely tool angle can obtain by initiatively utilizing the rotational error of spindle.
3) By using proposed analysis method, the tool outline shape during rotating can obtain to an accuracy of 94%.

From the above, it was found that the developed device and analysis method can evaluate the successive cutting point spacing of diamond electroplated tool on the machining center.

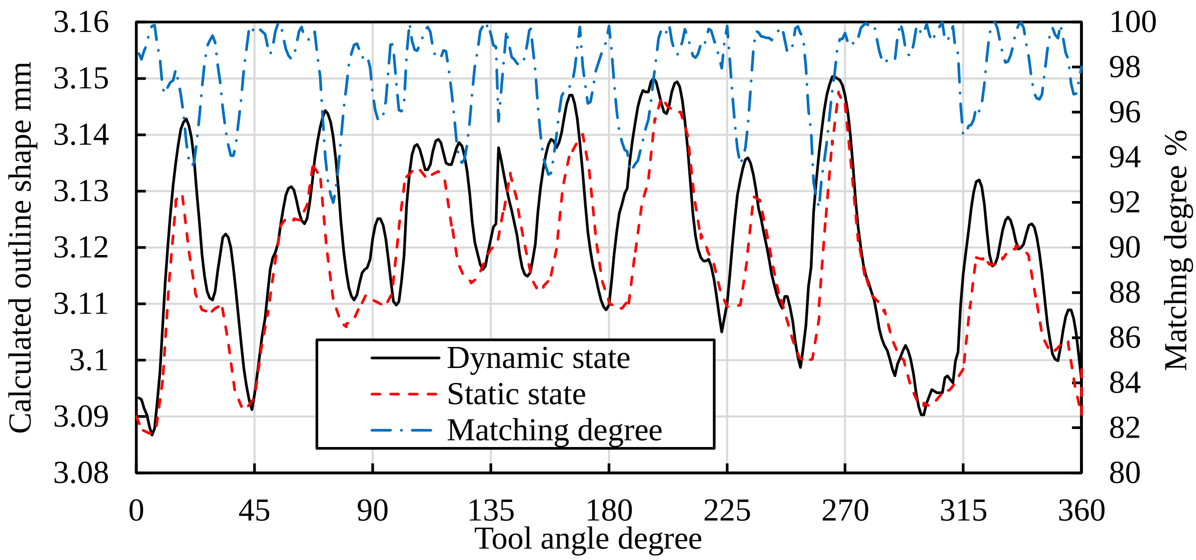


Fig. 5 Analyzed result of cross-section outline shape on XY plane.

Acknowledgement

This research was supported by a grant from the OGAWA Science and Technology Foundation. The developed measuring device was fabricated by the support from “BIG DAISHOWA SEIKI Co., Ltd.”.

References

[1] Zhiyu Zhang, Huanming Peng and Jiwang Yan, Micro-cutting characteristics of EDM fabricated high-precision polycrystalline diamond tools, International Journal of Machine Tools & Manufacture, Vol. 65 (2013) 99-106.

[2] Firas Sammoura, Jeong Jin Kang, Young-Moo Heo, TaeSung Jung and Liwei Lin, Polymeric microneedle fabrication using a microinjection molding technique, Microsystem Technologies, Vol. 13 (2007) 517-522.

[3] Hirofumi Suzuki, Mutsumi Okada, Katsuji Fujii, Shinsuke Matsui and Yutaka Yamagata, Development of micro milling tool made of single crystalline diamond for ceramic cutting, CIRP Annals-Manufacturing Technology, Vol. 62 (2013) 59-62.

[4] Jianguo Zhang, Norikazu Suzuki, Yilong Wang and Eiji Shamoto, Fundamental investigation of ultra-precision ductile machining of tungsten carbide by applying elliptical vibration cutting with single crystalline diamond, Vol. 214 (2014) 2644-2659.

[5] Kui Liu and Xiaoping Li, Ductile cutting of tungsten carbide, Journal of Materials Procesing Technology, Vol. 113 (2001) 348-354.

[6] Srefan van der Walt, S. Chris Colbert and Gael Varoquaux, The NumPy Array: A Structure for Efficient Numerical Computation, Computing in Science & Engineering, Vol. 13, Issue 2 (2011) 22-30.

[7] Wes McKinney, Data Structures for Statistical Computing in Python, Proceedings of the 9th Python in Science Conference, Texas, 2010, 51-56.