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Tool wear compensation scheme for DTM

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Tool wear compensation scheme for DTM

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Abstract. This paper is aimed to monitor tool wear in diamond turn machining (DTM), assess effects of tool wear on accuracies of the machined component, and develop compensation methodology to enhance size and shape accuracies of a hemispherical cup. In order to find change in the centre and radius of tool with increasing wear of tool, a MATLAB program is used. In practice, x- offsets are readjusted by DTM operator for desired accuracy in the cup and the results of theoretical model show that change in radius and z-offset are insignificant however x-offset is proportional to the tool wear and this is what assumed while resetting tool offset. Since we could not measure the profile of tool; therefore we modeled our program for cup profile data. If we assume no error due to slide and spindle of DTM then any wear in the tool will be reflected in the cup profile. As the cup data contains surface roughness, therefore random noise similar to surface waviness is added. It is observed that surface roughness affects the centre and radius but pattern of shifting of centre with increase in wear of tool remains similar to the ideal condition, i.e. without surface roughness.

1. Introduction

Since the advent of CNC machines the quality of product rely heavily on programs and feedback of the system. With time the demand to improve accuracy and surface finish of component is ever growing. Tool wear, which mainly effects surface finish and form accuracy, etc., can be controlled by providing feedback from machining. Evaluating cutting tool wear at a regular time intervals and providing some compensation methodology is very important to control the process. The purpose of automated tool condition monitoring (TCM) in machining is to relate condition of the tool and the signals obtained during machining with least human supervision to predict tool wear. Optical measurement systems have been used to monitor tool wear during machining. The limitations of optical measurement technique are reviewed by various researchers [1, 2]. Using a pair of stereo images, Karthik et al.[3] have proposed a non-contact method that provides visualization of the tool wear geometry. In a hybrid approach, Dornfeld [4] used spindle current along with acoustic emission and force signals to monitor tool wear. Silva et al. [5] developed a robust tool wear monitoring system using spindle current signals, force, vibration and sound signal.

This paper presents on TCM focused to develop self-adjusting system with minimum operator supervision. The main motivation towards carrying out results is related to a manufacturing problem of nano-metrically-smooth optics by the diamond turning process. Diamond turning machines are used for manufacturing of components which require very high precision. The process is similar to a conventional lathe where cylindrical workpiece is rotated by the spindle and a single point diamond cutting tool removes the material. The process of tool wear in diamond turning is similar to conventional turning. Since we expect highest possible precision therefore researchers are not ignoring source of any small error. They have investigated various causes of errors. Gao et al. [6] focused on motions of the spindle and the slide which generate some surface form errors on the turned cylinder workpiece. They have proposed two measurement methods, which are referred to as the one- probe method and the two-probe method, for measurement of the Z-slide error of an ultra-precision diamond turning machine. The Z-slide error of the machine over a movement range of 126 mm has been measured to be 620 and 630 nm by the one-probe method and the two-probe method, respectively. In another investigation, Gao et al. [7] have studied the error motion of the X-slide and the spindle, which introduce *Z*-directional profile errors (out-of-flatness) on the grid surface.

Straightness errors (Z-direction) in X-slide create low frequency error over the surface. Straightness errors present in the slides show irregularities along the whole traversing length. These irregularities also may get reflected either in the form of convex or concave shape on the surface. Although spindle possesses axial and rotational accuracy in the order of few nanometers yet some tilt in the spindle will generate a DTM surface with 2 undulations per revolutions. The spindle rotation error in angular motion which generates two peaks and two valleys while traversing full circumference which also get reproduced on work piece surface. Kohno et al. [8] have studied diamond turned metal mirrors and proposed “Half-line Hartmann test” method to measure the concave mirror surface and applied as in-process measurement. Their results on controlled turning and non-controlled were presented.

This paper is focused on the enhancement of accuracies of the hemispherical cups which are machined on diamond turning machine. Surface roughness and form errors of cups of radius 5.05 mm are the major issues of the project. Tool wear play a significant role in the error of the product, therefore a theoretical model is proposed.

2. Mathematical model of diamond tool wear

In order to investigate the effect of tool wear on the profile of hemispherical cup, an idealized theoretical model is developed. Effects of tool wear are estimated by using MATLAB program.

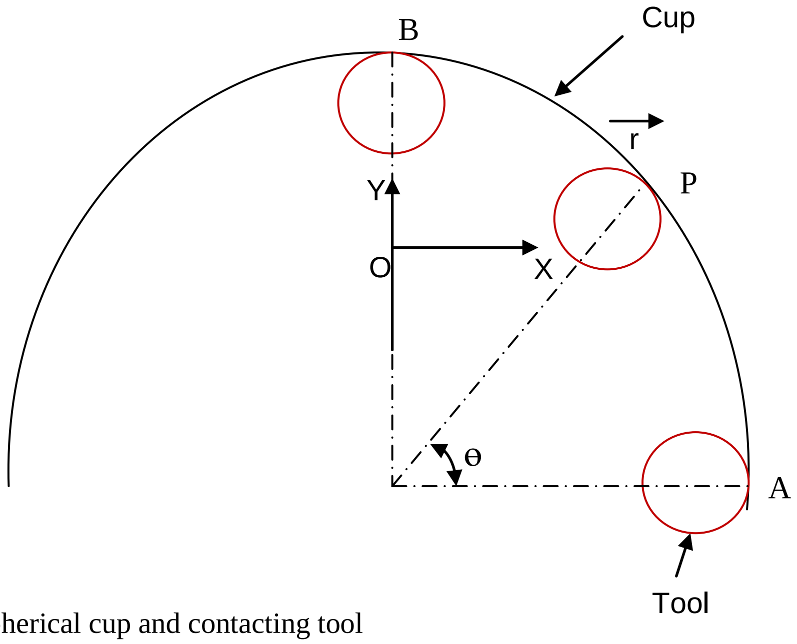

Fig 1. Hemispherical cup and contacting tool

Assumptions:

(i) There is only point contact between tool and hemisphere.
(ii) Tool has circular shape

Fig. 1 shows a hemispherical cup and a contacting tool. Initially, there is no wear. Let the contact point $P$of the tool with radius r has coordinates$(rcos(\theta), rsin(\theta))$. Since both the tool and cup are spherical/hemispherical, therefore a tangent to tool at the contact point will also be the tangent to hemispherical cup and the contact point P on the cup will have coordinates $(Rcos(\theta), Rsin(\theta))$. Wear at a point $P \propto$ total distance traversed by tool point P

$$\propto 2\pi R\, cos(\theta)$$

$$= k_1 2\pi R\, cos(\theta) \tag{1}$$

Where R is the radius of hemispherical cup and k_1 is the constant and it will depend on the velocity at the contact point. The wear will be maximum at angle $\theta = 0$. It is due to high velocity (largest k_1) and maximum distance traversed. Wear is a nonlinear function due to $cos(\theta)$ and k_1 terms. Wear will occur in ¼ part of the circular profile of tool.

In this part we developed a theoretical model for progressive estimation of tool radius and centre for tool offset adjustment with the progress of tool wear.

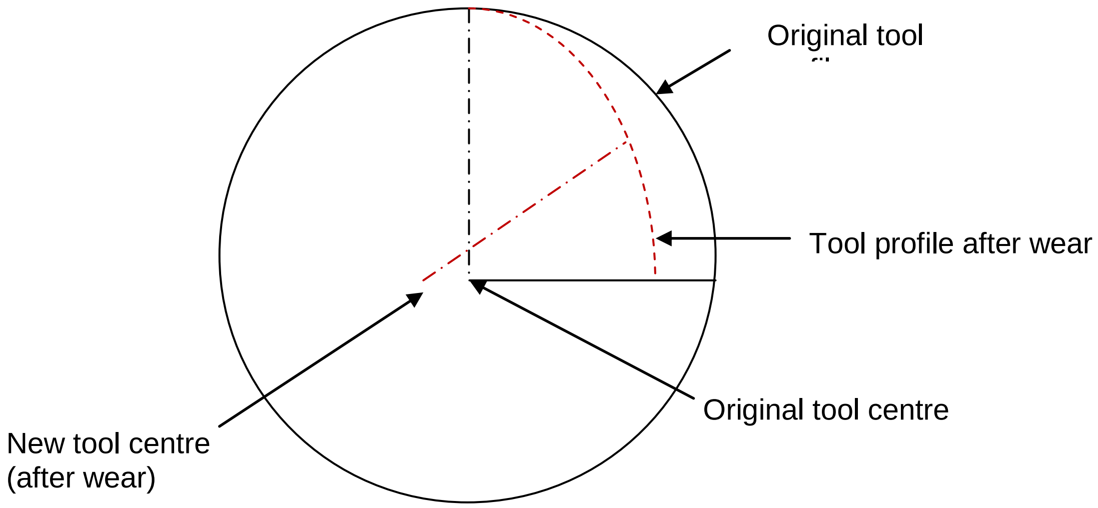

Fig. 2. Change in centre and radius of diamond tool due to wear

For progressive estimation of tool radius and centre, we assumed that tool profile remains circular after wear but with new centre and radius. To find the centre and radius of the tool, we need three points. However for the better curve fit, we assumed n points. Let (a, b) is new centre and r_{new} is new radius. For any point on the tool surface $(x_i\,,\ y_i)$, we can write the equation of spherical tool (which is a circle in 2D as shown in Fig. 2) in the matrix form for n points as:

$$\begin{bmatrix} 2(x_1 - x_2) & 2(y_1 - y_2) \\ 2(x_2 - x_3) & 2(y_2 - y_3) \\ 2(x_3 - x_4) & 2(y_3 - y_4) \\ . & . \\ . & . \\ . & . \\ 2(x_{n-1} - x_n) & 2(y_{n-1} - y_n) \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} {x_2}^2 - {x_1}^2 + {y_2}^2 - {y_1}^2 \\ {x_3}^2 - {x_2}^2 + {y_3}^2 - {y_2}^2 \\ {x_4}^2 - {x_3}^2 + {y_4}^2 - {y_3}^2 \\ . \\ . \\ . \\ {x_n}^2 - {x_{n-1}}^2 + {y_n}^2 - {y_{n-1}}^2 \end{bmatrix} \tag{2}$$

or

$$[M]_{nX2}\begin{bmatrix}a\\b\end{bmatrix}_{2X1} = [N]_{nX1} \tag{3}$$

or

$$\begin{bmatrix}a\\b\end{bmatrix}_{2X1} = ([M]_{2Xn}^{T}[M]_{nX2})^{-1}[M]_{2Xn}^{T}[N]_{nX1} \tag{4}$$

The above equation is used to estimate the best fit centre of the circle. The radius can be estimated from the equation of circle. In this case, RMS value of radius is considered. A MATLAB program is developed to calculate radius and centre. Though at present we assumed the point on the curve $(x_i\ ,\ y_i)$ from the previous theoretical model but the surface roughness data can be easily used to predict the worn tool profile.

3.Results and Discussion

In order to find change in the centre and radius of tool with increasing wear of tool, the MATLAB program is used. For maximum tool wear which will occur at the bottom of tool (part which will be in contact with base of the cup), profile is obtained by using Eq (1). Centre and radius of new profile are calculated. Table 1 shows the maximum tool wear and corresponding change in centre for increment of 0.01 micron of maximum tool wear. This data can be used for finding tool offset. In practice, x-offsets are readjusted for desired accuracy in the cup which is listed in Table 1 and the results of theoretical model show that change in radius and z-offset are insignificant however x-offset is proportional to the tool wear.

Table 1. Change in tool centre and radius with tool wear & experimental value of tool offset.

S.N.	Max. Tool Wear (micron)	New Centre of Tool		New Radius of Tool (micron)	Experimental value of Tool x- Offset (micron)
		x-coordinate	z-coordinate		
1	0.01	-0.0100001296	0.0000001293	200.0000001252	
2	0.02	-0.0200005185	0.0000005172	200.0000005009	
3	0.03	-0.0300011665	0.0000011637	200.0000011269	0.03 (number of component machined 28)
4	0.04	-0.0400020736	0.0000020691	200.0000020033	
5	0.05	-0.0500032399	0.0000032332	200.0000031300	
6	0.06	-0.0600046652	0.0000046563	200.0000045069	
7	0.07	-0.0700063495	0.0000063383	200.0000061341	
8	0.08	-0.0800082928	0.0000082794	200.0000080114	0.05 (number of component machined 51)
9	0.09	-0.0900104951	0.0000104796	200.0000101389	
10	0.10	-0.1000129562	0.0000129390	200.0000125165	
11	0.11	-0.1100156763	0.0000156578	200.0000151442	
12	0.12	-0.1200186551	0.0000186358	200.0000180218	
13	0.13	-0.1300218927	0.0000218733	200.0000211495	
14	0.14	-0.1400253890	0.0000253703	200.0000245271	
15	0.15	-0.1500291441	0.0000291269	200.0000281545	
16	0.16	-0.1600331578	0.0000331431	200.0000320319	
17	0.17	-0.1700374301	0.0000374191	200.0000361590	
18	0.18	-0.1800419610	0.0000419548	200.0000405359	0.1 (number of component machined 48)
19	0.19	-0.1900467505	0.0000467505	200.0000451626	
20	0.20	-0.2000517984	0.0000518061	200.0000500389	

This method appeared to us very promising if we could measure tool profile with progress of wear but with the available tool offset data, we are guessing the tool wear. Nevertheless, the model shows that change in z-offset and tool centre is insignificant and this is what assumed by DTM operator while resetting tool offset.

Since we could not measure the profile of tool and on the other hand measurement of cup profile is used by DTM engineers so we modelled our program for cup profile data. Cup profile data can be considered as dual of tool profile data. If we assume no error due to slide and spindle of DTM then any wear in the tool will be reflected in the cup profile. Table 2 shows change in the centre and radius of cup with tool wear. Change in the centre is clearly visible with progress of wear either we take full curve (curve along half of the hemisphere) or part of the curve (here we tried 10% of the curve).

Table 2. Change in centre and radius with wear for ideal curve without random noise.

Wear Coefficient (Wr)	Complete Curve		10% of Curve	
	Centre (µm)	Radius (µm)	Centre (µm)	Radius (µm)
Wr=0	(-650, -1730)	2500	(-650, -1730)	2500
Wr=0.1	(-650.1, -1730)	2500	(-650.1, -1730)	2500
Wr=0.5	(-650.5, -1730)	2500	(-650.5, -1730)	2500
Wr=2	(-652, -1730)	2500	(-652, -1730)	2500
Wr=5	(-655, -1730)	2500	(-655, -1730)	2500
Wr=10	(-660, -1730)	2500	(-660, -1730)	2500
Wr=20	(-670, -1730.1)	2500	(-670, -1730.1)	2500

Since cup data contains surface roughness, therefore random noise similar to surface waviness is added and shift in centre and change in radius is noted. In Table 3, it can be observed that surface roughness affects the centre and radius but pattern of shifting of centre with increase in wear of tool remains same.

Table 3. Change in centre and radius with wear for ideal curve with random noise

Wear Coefficient (Wr)	Complete Curve			10% of Curve (interval 11)		
	Centre (µm)	Rad. (µm)	Max error	Centre (µm)	Rad (µm)	Max error
Wr=0	(-644.8, -1739.9)	2489	0.0040	(-646.7, -1733.9)	2494.9	0.0039
Wr=0.1	(-654.9, -1739.9)	2489	0.0042	(-648.3, -1732.2)	2497.1	0.0041
Wr=0.5	(-645.3, -1739.9)	2488.9	0.0040	(-646.6, -1734.6)	2494.0	0.0040
Wr=2	(-647.8, -1739.6)	2489.3	0.0039	(-647.3, -1735.5)	2492.8	0.0036
Wr=5	(-649.7, -1740.1)	2488.7	0.0042	(-653.6, -1731.7)	2497.8	0.0039
Wr=10	(-654.9, -1739.7)	2489.1	0.0036	(-653.6, -1737.6)	2490.1	0.0036
Wr=20	(-665, -1739.6.1)	2489.3	0.0043	(-667.2, -1733.5)	2495.6	0.0040

4. Conclusions

In this project, mathematical model for tool wear in DTM is developed. This model is used to estimate change in centre and radius of tool with the progress of wear which can be used in DTM programming. However, due to limitation in tool wear measurement, we used data of surface profile of hemispherical cups. Using our model, we are able to see that the manufactured cups are very accurate Moreover; industrial data regarding tool offsetting can also be used to estimate the tool wear pattern and therefore estimation of centre and radius of tool for DTM programming.

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