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A novel surface quality evaluation method in ultra-precision raster milling using cutting chips

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ABSTRACT

Although online surface quality evaluation is important in ultra-precision machining technologies, very little research has been reported on the topic. In this paper, cutting chips were employed to evaluate machined surface quality online under the occurrence of tool wear in ultra-precision raster milling. Cutting chips were collected and examined by a 3D scanning electron microscope. The inspected cross-sectional shape of 'ridges' imprinted by the tool fracture was approximated into two geometric elements so that it could be determined by a mathematical model. The geometric elements for every ridge were assembled into a virtual cutting edge so as to rebuild the machined surface. A mathematical model was established to realize the rebuilt machined surface and calculate the surface roughness under the consideration of tool fractures effects. The theoretical and experimental results show that the ridges imprinted on the machined surface can be predicted by examining a section of the collected cutting chips. It is interesting to note that the quality of the machined surface is reflected in the location and the height of ridges. This demonstrates that the online surface quality evaluation using cutting chips is a novel method as compared to conventional methods, since it can evaluate the machined surface and simulate the machined surface topography without the need to stop the cutting process.

1. Introduction

Online surface quality evaluation is an important research topic since it can detect deteriorated machined surfaces and potentially remedy them by optimizing cutting parameters and cutting strategies. According to the study by Azouzi and Guillot (1997), factors leading to the formation of poor surface quality include: (i) feed marks generated by the tool geometry and kinematics relative to the machined part, (ii) self-excited and machine tool vibrations, and (iii) plastic deformation of the machined surface caused by a worn tool, built-up edge or material softening due to high temperature. The combined effects of these factors deteriorate the surface quality of the workpiece. Accurate measurement of surface roughness is essential in the fields of the precision engineering and manufacturing. Although stylus devices have been widely used for measuring surface roughness with a high degree of reliability, it is hard to realize online measurement with them due to their inherent limitations. First, according to Al-Kindi and Shirinzadeh (2007), measuring with stylus devices to obtain 3D surface roughness data is very time-consuming since it needs multiple scans of the surface. Secondly, Samtaş (2014) pointed out that measurements using the stylus technique may damage the surface since there is contact with the machined surface. Thirdly, according to Dhanasekar and Ramamoorthy (2010), the measurements will not be accurate if the radius of the stylus is comparable to the surface structure, such that the stylus probe cannot contact all the way to the bottom of the structure.

The measurement of surface roughness by using optical systems can eliminate these problems. Surface roughness measurement by optical system is a contactless inspection method using an optical microscope, which can be realized by online measurement. In optical systems, capturing clear machined surface images and finding the correlation between image characteristics and surface roughness are important steps in predicting surface roughness and have been the focus of many precious studies. For example, Kamguem et al. (2013) utilized a new image characteristic named the gradient factor of the image to estimate the machined surface roughness and they found that several roughness parameters (R_a, R_q, R_v, R_t and R_z) can be estimated by using only image-extracted features

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Nomenclature

$o(xyz)$	global coordinate system
$o'(x'y'z')$	coordinate system for previous rotary cutting presentation
$o''(x''y''z'')$	coordinate system for previous step cutting presentation
$p(uw)$	coordinate system for tool edge profile presentation
$o_i(u_iw_i)$	coordinate system for the geometric elements presentation
s	step distance
l	swing distance
f	feed rate in mm/min
a_p	depth of cut
R	tool nose radius
e_i	width of geometric elements
h_i	height of geometric elements
δ_i	angle between two neighboring ridges
d_i	distance between two neighboring ridges
R_t	theoretical peak-to-valley roughness of machined surface
R_{t_tool}	peak-to-valley roughness of tool mark
R_{t_swing}	peak-to-valley roughness of swing mark
$R_{t\text{-}ridge}$	peak-to-valley roughness under the existence of ridges
θ	rotation angle
α	swing cutting angle
β	cutting edge angle

and models. Kumar et al. (2005) utilized a machine vision system to capture the images and then the machined surface roughness is quantified by using regression analysis; they estimated a parameter called G_a based on the surface image features and it is used to evaluate the machined surface roughness. By examining the machined surface images of GFRP using a CCD camera, Sarma et al. (2009) correlated and obtained a relation between the average gray scale values and surface roughness (R_a), by which the surface roughness can be evaluated. Other researchers used light scattering techniques to realize the online evaluation of machined surface roughness. For example, Younis (1998) presented a noncontact technique for online evaluation of machined surface characteristics based on the analysis of the scattered light pattern measured from the surface. Lu and Tian (2006) proposed an online surface roughness measurement method based on laser light scattering, by which the surface roughness is obtained from the spatial distribution of the scattered light intensity. Although optical systems can be successfully used to online evaluate machined surface quality, they have some limitations: first, the pile up of cutting chip and lubricant fluid on the machined surface will affect the measurement accuracy; and second, vibration from the machine tool will influence the measurement accuracy.

In view of the limitations of optical systems, some researchers explored many other surface quality evaluation methods. For example, Chen et al. (1999) proposed a novel method for evaluating surface roughness based upon wavelets theory, whereby the surface roughness can be separated from the actual surface profile $f(t)$. Coker and Shin (1996) utilized a newly developed system to measure surface roughness using the intensity of ultrasonic beams reflected from the machined surface, and evaluated the in-process measurement capability of this system under machine vibration and tool wear. Grzesik and Brol (2009) characterized the surface profiles generated in longitudinal turning operations using continuous wavelet transform (CWT) and normalized fractal dimension D_n. Karayel (2009) presented a neural network approach for the prediction and control of surface roughness in a computer numerically controlled (CNC) lathe. Singh et al. (2004) revealed a new methodology for predicting surface roughness of engineering surfaces based on acoustic characterization. However, these indirect surface evaluation methods cannot predict the machined surface topography and their measurement accuracy is relatively low.

Ultra-precision raster milling (UPRM) is a machining method for producing non-rotational symmetric surface structures. The intermittent cutting property of UPRM makes the cutting chip fully generated in rotary cutting. The most comprehensive research related to surface roughness in UPRM was conducted by Kong et al. (2009) who explored the factors affecting surface generation in UPRM, and Zhang et al. (2014a,b) studied on tool fracture monitoring methods by using cutting chips and the relationship between tool wear and cutting chip morphology. However, the research into online surface quality evaluation in UPRM has received little attention.

Based on the fact that tool fractures can be imprinted both on cutting chips and machined surface as a group of ridges, this study proposes an online surface quality evaluation method using cutting chips. The research involved the measurement of the parameters of the ridges, such as distance between two neighboring ridges and the height and width of the ridges' cross-sectional profile, to simulate the surface topography of the machined surface. A mathematical model taking in account of tool fractures was established to determine the surface roughness of machined surfaces. The surface quality evaluation method based on cutting chips is a progressive method as compared to conventional methods. It not only realizes the online evaluation of surface roughness, but also be able to predict the machined surface topography. The result is very accurate since the measurement is not influenced by the background vibration and noise existed in the cutting process.

2. Experiment

The cutting experiment was conducted on the Precitech Freeform 705G (Precitech Inc., USA) multi-axes CNC ultra-precision raster milling machine, which comprises five-axes including three linear axes (x-direction, y-direction and z-direction) and two rotary axes (B-axis and C-axis). The machine can realize the cutting of freeform surface and non-rotational symmetric surface with nanometric surface roughness. The experimental setup is shown in Fig. 1(a), while the graphical illustration of the cutting mechanism and surface generation in UPRM is shown in Fig. 1(b). To obtain the designed flat surface and cutting chips, an Apex insert diamond tool (Apex Inc., UK) is used as the cutting tool with tool radius of 0.631 mm, rake angle of −2.5°, and clearance angle of 15°. The cutting parameters include: feed rate 200 mm/min, depth of cut 0.03 mm, spindle speed 4500 rpm, swing distance 28.35 mm, and step distance 0.025 mm. The cutting environment is lubricated and horizontal cutting strategy is used. The workpiece material is CuZn30 and the cutting distance is about 1000 m.

Two CuZn30 bulks were prepared for the experiment. One (no. 1 workpiece) of them was cut by a fresh tool while the other (no. 2 workpiece) was finished by the same tool after it had cut for 1000 meters. After one layer of surface cutting, the no. 1 workpiece was dismounted and examined by a Wyko NT8000 White Light Interferometer (WLI) profiler. The no. 2 workpiece was then installed on the fixture and the cutting continued with the same tool. At the end of the flat cutting, the cutting chips were collected and inspected by a Hitachi TM3000 scanning electron microscope (SEM). Results of the inspection were processed and used to simulate the machined surface topography. After the cutting process, an Olympus BX60 optical microscope and a Wyko NT8000 WLI profiler were used to examine the no. 2 workpiece. The diamond tool was