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PRE-6297; No. of Pages 6

ARTICLE IN PRESS

Precision Engineering xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

On-machine measurement of microtool wear and cutting edge chipping by using a diamond edge artifact

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ARTICLE INFO

Article history:
Received 9 May 2015
Received in revised form 26 August 2015
Accepted 4 September 2015
Available online xxx

Keywords:
On-machine measurement
Cutting edge contour
Diamond tool
Wear
Fast tool servo
Force sensor
Cutting force

ABSTRACT

This paper presents precision on-machine measurement of microwear and microcutting edge chipping of the diamond tool used in a force sensor integrated fast tool servo (FS-FTS) mounted on a three-axis diamond turning machine. A diamond edge artifact with a nanometric sharpness is mounted on the machine spindle with its axis of rotation along the *Z*-axis to serve as a reference edge artifact. The diamond tool is placed in the tool holder of the FS-FTS to generate cutting motion along the *Z*-axis. By moving the *X*-slide on which the FS-FTS is mounted, the reference edge can be scanned by the diamond tool. During the scanning, the *Z*-directional position of the tool is closed-loop controlled by the FS-FTS in such a way that the contact force between the tool tip and the reference edge is kept constant based on the force sensor output of the FS-FTS. The tool edge contour can be obtained from the scan trace of the tool tip, whose *X*- and *Z*-directional coordinates are provided by the output of the linear encoder of the *X*-slide and that of the displacement sensor in the FS-FTS, respectively. Since the reference edge artifact has a good hardness and a nanometric sharpness to ensure the lateral resolution of measurement, a microwear on the cutting edge of the diamond tool can be indentified from the measured tool edge contour. Experiments of on-machine measurement of tool edge contour and microtool wear are carried out to demonstrate the feasibility of the proposed system.

1. Introduction

Single point diamond tools with geometrically defined cutting edges are widely utilized in a fast tool servo (FTS) for the fabrication of ultra-precision surfaces such as diffraction optics, microlens arrays and freeform optics [1–3]. The tool cutting edge is of crucial importance to ensure quality of fabricated surfaces [4,5]. During ultra-precision cutting process, tool wear and cutting edge chipping due to friction and thermal loads on the cutting edge significantly influences the form accuracy and surface finish of the fabricated workpiece [6]. Therefore, quantitative measurement of wear and edge chipping on a diamond tool is an important issue not only for understanding the wear or edge chipping mechanism as a function of the material and cutting parameters, but also for compensating the form error of the tool edge to maintain the accuracy of the fabricated surfaces. Moreover, on-machine measurement without removing the diamond cutting tool from the manufacturing instrument is also desired so that the measurement result can be easily fed back to the fabrication process.

The dimension of tool wear and cutting edge chipping in ultra-precision cutting is typically on a small scale of 1 μm or even sub-μm, while tip radii of cutting edges are up to the order of millimeters [4]. The measuring techniques for monitoring of tool wear and cutting edge chipping are traditionally categorized into direct and indirect methods [7]. Direct methods are realized by scanning the tool edge by using surface form measuring instruments with nanometric resolution, in which the tool wear or cutting edge chipping is directly inspected from the measured cutting edge profile. Scanning electron microscopes (SEMs) provide a wide field of view and a large depth of focus with a nanometric resolution [8,9]. However, SEM images are inherently two-dimensional (2D) projections of three-dimensional (3D) objects, and quantitative information cannot be directly extracted from the images [10]. A vacuum environment, which is required for SEMs, also makes it unsuitable for on-machine measurement. Atomic force microscopes (AFMs) are powerful tools for 3D profile measurement with sub-nanometric resolution [11]. However, it is very difficult and time-consuming to accurately align the AFM cantilever probe with respect to the diamond cutting edge [12,13]. Optical methods, such as CCD visions

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http://dx.doi.org/10.1016/j.precisioneng.2015.09.011
0141-6359/

Please cite this article in press as: Chen Y-L, et al. On-machine measurement of microtool wear and cutting edge chipping by using a diamond edge artifact. Precis Eng (2015), http://dx.doi.org/10.1016/j.precisioneng.2015.09.011

and white light interferometers, are also employed for tool wear measurement [14–16]. Although fast and non-destructive evaluation can be achieved by the optical methods, the lateral resolution is limited to be sub-μm order due to the diffraction and is not enough for quantitative measurement of tool wear. On the other hand, indirect monitoring of tool wear and cutting edge chipping is performed by in-process detection of the measurable process variables such as cutting force [17], acoustic emission (AE) [18], surface finish [19], cutting chips [20] and so on. Tool wear is estimated based on the analysis of the in-process measured signals. Although indirect methods are widely used in on-machine condition, they can only be used for monitoring of tool status and the occurrence of tool wear, it is difficult to use the indirect method for quantitative characterization of tool wear.

In responding to the background described above, the authors have proposed a self-evaluation method for measurement of the cutting edge contour of a microdiamond tool on a force-sensor integrated FTS, which is referred to as the FS-FTS, without using any additional surface form measuring instruments [21]. Based on the force feedback control of the FS-FTS, the diamond cutting tool mounted in the tool holder of the FS-FTS is utilized as a force-controlled stylus to scan across a sharp line structure on an aluminum workpiece, which is employed as a master artifact for measurement. During the scanning, the contact force between the tool edge and the line structure is maintained to be constant by controlling the cutting tool displacement. The cutting edge contour is obtained from the tracing path of the tool, which is a geometrical convolution of the cutting edge contour and the shape of the line structure apex. On-machine measurement of the cutting edge contour is possible with the proposed method. However, the lateral resolution is not enough for characterization of microtool wear because of the insufficient sharpness of the aluminum line structure as well as the damages on the line structure caused by the contact force during the scanning [21].

The aim of this study is to demonstrate the feasibility of on-machine characterization of tool wear and cutting edge chipping with a sub-micrometer resolution and a measuring range on the order of 100 μm, which would be sufficient for measuring the cutting edge wear [4]. A diamond reference edge artifact with a nanometric sharpness is employed as the measuring artifact instead of the aluminum line structure not only for improvement of the measurement resolution but also for avoiding damages on the artifact surface so that the self-evaluation method can be applied to measure the microwear and cutting edge chipping of diamond tools. After descriptions of the measurement principle and the system setup, experiments on quantitative characterization of the cutting edge contour and wear of diamond tools are presented. The measured tool edge contours are then compared with those acquired by a commercial stylus profiler to demonstrate the reliability of the proposed method.

2. Measurement principle and system setup

A schematic of the measuring system on a three-axis diamond turning machine for quantitative characterization of the cutting edge contour and wear of a round nose of a diamond tool is shown in Fig. 1(a). A reference edge with nanometric sharpness, serving as an artifact for measurement of a cutting edge contour and wear, is mounted on the spindle house of the diamond turning machine. The spindle house can be moved along the Z-direction by the Z-slide. The FS-FTS, which is mounted on the X-slide of the diamond turning machine, can be moved along the X-direction by the X-slide. A diamond tool with possible microwears is mounted in the tool holder of the FS-FTS.

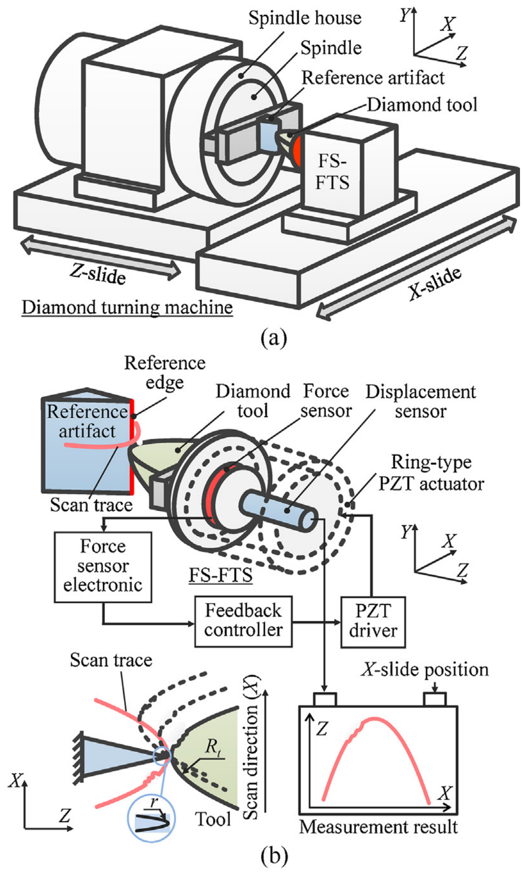

Fig. 1. (a) A schematic of the on-machine measurement system. (b) Principle for measuring the cutting edge contour and edge wear of a diamond tool with the FS-FTS on a three-axis diamond turning machine.

Fig. 1(b) shows a schematic of the measurement principle based on the system shown in Fig. 1(a). The FS-FTS consists of a piezoelectric (PZT) actuator to generate the Z-directional tool displacement, a highly sensitive force sensor to measure the contact force between the tool edge and the reference edge, a displacement sensor to measure the Z-directional tool motion. When tool wear measurement is required, the diamond tool on the FS-FTS is brought to scan across the reference edge along the X-direction based on a contact force feedback control loop applied to the FS-FTS. During the scanning, the contact force between the tool cutting edge and the reference edge is kept constant by controlling the Z-directional tool displacement so that the cutting tool edge contour can be traced by the reference edge. The X-directional displacement of the tracing profile, which is the geometrical convolution between the cutting edge contour and the reference edge, is measured by the X-linear encoder in the X-slide of the machine, while the Z-directional displacement of that is measured by the displacement sensor in the FS-FTS. In the case that the apex of the reference edge has an ignorable radius of r compared with the dimension of the cutting edge and tool wear, the measured scan trace directly represents the contour of the cutting edge, from which the shape of the tool wear can also be represented.

3. Experiments

An experimental set-up based on a three-axis diamond turning machine is shown in Fig. 2. Since the edge sharpness of a diamond tool is typically on the order of 40–100 nm [22,23], which is small enough compared to the cutting edge contour, a commercially-available diamond tool edge is employed as the reference edge artifact for tool wear measurement, in which the edge is finished