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Development of on-machine measurement for ultra-precision machining

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Abstract
Surface measurement is playing an increasingly important role in ultra-precision manufacturing. Nowadays, there is a technological shift from offline measurement to on-machine measurement, forming a closed-loop control for manufacturing processes. Conventionally, the transportation operations between the measurement and machine coordinates are time-consuming and inevitably induce more errors, which cannot be neglected, especially at the ultra-precision level. Development of on-machine measurement for ultra-precision machining processes will enable the reduction of measurement cycle time as well as potential improvement of machining accuracy. In the present study, an in-house designed interferometer probe, called Dispersed Reference Interferometer (DRI) is integrated on an ultra-precision diamond turning machine (Precitech Nanoform 250). The alignment method of DRI is firstly described, in order to establish the measurement coordinate. Different on-machine measurement strategies are also discussed, including multiple radial, multiple circular, and spiral trajectories. Experimental study has shown that the on-machine measurement results of a cosine form sample agree well with the offline measurement. The measurement error difference is less than 10% and correlation coefficient is 0.991.

Key words: ultra-precision diamond machining, on-machine measurement, non-contact, interferometry

1. Introduction

Ultra-precision machining is now capable of generating surfaces with sub-micrometre form accuracy and nanometre surface roughness, which are of high demand in the optical, electronic and aerospace industries [1]. However, many factors still induce surface deviations compared to the design, involving environmental factors, machine structural errors, vibration and tool wear etc. The process of metrology and compensation is indispensable and a fundamental technique for further development of surface accuracy. In order to increase the availability of metrology for applications in advanced manufacturing, a shift in the approach of metrology from offline, lab based solutions; towards the use of metrology integrated into manufacturing platforms is urgently needed [2]. On-machine metrology can avoid the errors caused by re-positioning workpieces and use the machine axes to extend the measuring range and improve the measuring efficiency [3]. Particularly in ultra-precision machining processes, the transportation of the workpiece between the machine tool and metrology platform is problematic. For the critical requirement of surface quality, the errors induced by removal and remounting process would deteriorate the quality if re-machining processes is necessary. Therefore, development of on-machine or in-process metrology in ultra-precision machining will enable the reduction of measurement cycle time, in addition to a potential improvement of surface quality.

In this paper, the system configuration and measurement strategy are firstly described. Then, on-machine measurement of a diamond turned sample is conducted and the form result is compared with offline profilometer results using correlation analysis.

2. Methodology

An in-house designed interferometer probe is integrated onto an ultra-precision machine Precitech Nanoform 250 with two linear hydrostatic axes and an air bearing spindle axis.

2.1. On-machine measurement system

The interferometer probe, is designed as a robust point tool for the measurement of distance and surface form-, which is potentially embedded in ultra-precision manufacturing environments. The nanometre resolution (down to 0.6nm) and millimetre vertical range (up to 800 µm) makes it a viable dynamic system for measuring precise complex geometries.

Dispersed reference interferometry (DRI) works on the principle of an interferometer having chromatic dispersion purposefully added in the reference arm. The low coherence source lends the method to an optical fibre based implementation and the potential for remote configuration and miniaturisation. More detailed information of the DRI can be found [4]. The configuration of on-machine measurement system is illustrated in Figure 1.

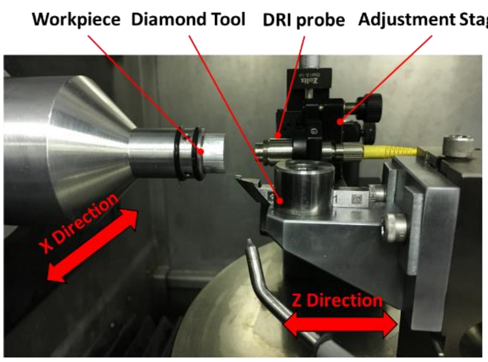

Figure 1. On-machine measurement system configuration

2.2. Measurement coordinate alignment

The key issue to integrate an on-machine measurement device is the alignment of the measurement coordinates. A self-turned convex spherical surface was employed to position DRI with the aid of a manual adjustment stage. Multiple parallel scanning along X axis was conducted and the highest measurement point was set to the zero position of DRI.

2.3. Measurement strategy

The DRI is scanned across the sample by the machine 3 axes' motion when C axis is enabled as a position controlled axis. In this work, multiple radial, multiple circular, and spiral paths are employed according to different surface patterns. The measurement paths are illustrated in Figure 2.

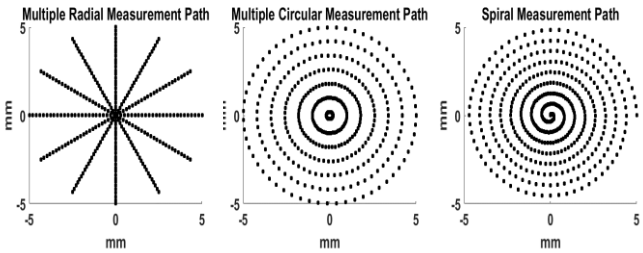

Figure 2. Multiple radial, multiple circular, spiral measurement paths

3. Experiment results

A cosine curve ($Z = A\cos(2\pi/\lambda\, X)$) with A=5um and λ=2.5mm was fabricated, measured by both DRI on-machine and offline measurement. The machining parameters are listed in Table 1.

Table 1 Machining Parameters

Parameters	Value
Tool nose radius (mm)	0.5mm
Spindle Speed (RPM)	1000rpm
Feedrate (mm/min)	0.5mm/min
Cutting depth (um)	5µm
Workpiece radius (mm)	4.5mm

Based on the surface pattern, multiple radial paths were adopted for DRI on-machine measurement. The pre-mapped machine geometric error was subtracted from on-machine measurement results. 6 profiles are equal-angle spaced across the surface as shown in Figure 3.

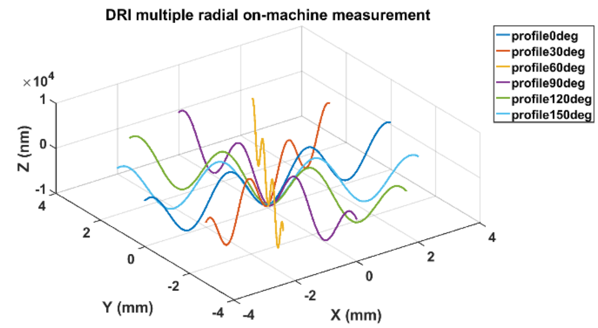

Figure 3. On machine measurement results (multiple radial path)

Offline measurement was carried out on a Talysurf PGI profilometer. Figure 1 (a) and (b) indicate that DRI on-machine measurement agrees well with PGI offline measurement in terms of form evaluation. The derived form error also has similar shape and characterization parameters, summarized in Table 2. It is also noticed that DRI on-machine measurement acquires more surface components of short wavelength for the reason that DRI probe has smaller spot size than the PGI stylus tip.

Table 2 Comparison of form error characterization

Parameters	DRI on-machine	PGI offline
Error PV (nm)	257.6	241.1
Error RMS (nm)	58.6	65.7

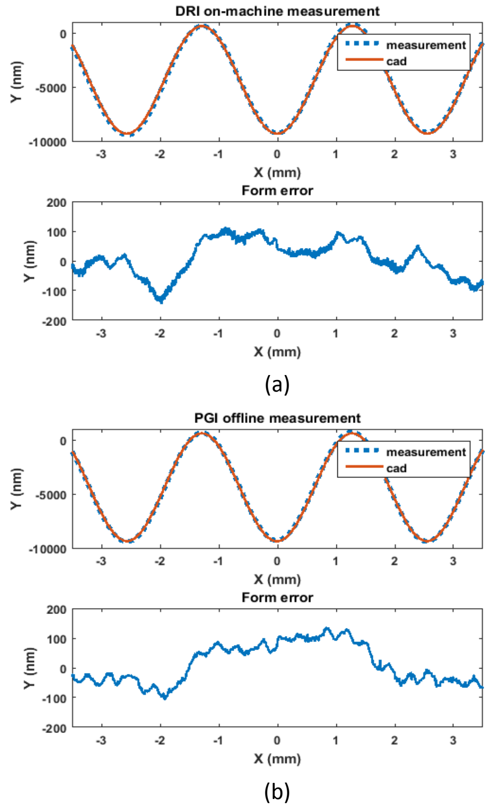

Figure 4. Measurement results and error analysis of DRI on-machine measurement (a) and PGI offline measurement (b)

For similarity quantification, Pearson's coefficient (P=0.991) was calculated as a measure of correlation between the two profiles measurements, which is described as follows [5]:

$$P(X,Y) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{X_i - \overline{X}}{S_x}\right)\left(\frac{Y_i - \overline{Y}}{S_y}\right) \quad (1)$$

where S_x and S_y are the sample standard deviation.

4. Conclusion

The paper presents integration of a DRI on-machine measurement system in an ultra-precision diamond turning machine. DRI alignment and measurement path are also discussed in detail. Experimental study has shown that the on-machine measurement results of a cosine curve form sample highly correlate with offline measurement. Future work will include on-machine measurement and correction machining of complex geometries. This work is supported by the Engineering and Physical Sciences Research Council (EPSRC) and China Scholarship Council (CSC).

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