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Technical note

A new representation with probability distribution for nanometric surface roughness in ultra-precision machining

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ABSTRACT

Ultra-precision machining (UPM) commonly produces nanometric surface roughness (NSR), which is governed by high-frequency components with tool marks sensitive to noise. Its spacing features (SF) majorly affect optical quality by diffraction and interference. However, the ISO SR standard cannot effectively represent SF. In this study, a new representation for SF was developed by evaluating surface derivative, as extra SR parameters. Probability distribution with the 95–99 rule was adopted to reduce noise effects. The results were found that the extra SR parameters well represents SF and are sensitive to spatial frequency. Probability distribution is an efficient means of reducing noise effects. Significantly, the proposed method is simple and efficient to represent SF of NSR in UPM.

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1. Introduction

Whitehouse stated that surface roughness (SR) is that part of the irregularities on a surface left inherently in the material removal process [1]. It is considered as a good predictor of the functional performance and lifetime of a component, because surface irregularities may form nucleation sites for cracks or corrosion [2]. Early in 1930, Harrison [3] made a first call for SR standards. In 1942, Schlesinger [4] wrote a book to introduce SR. Until now, a relatively comprehensive standards have been announced in ISO 4287 [5] and ISO 25178-2 [6]. SR is characterized by amplitude parameters, spatial parameters, hybrid parameters and functional parameters [7]. However, these SR parameters cannot effectively evaluate such NSR to reflect spacing features (SF) of a rough surface/profile.

SR parameters represent height information too much and do not much relate to spacing features of a rough surface/profile. The height information seems simpler to relate more readily to functional performances of components. Nevertheless, the SF is a very important surface characterization. To suggest SF, spectral analysis [8] and wavelet analysis [9] have been often used to characterize SR with much more spatial information. Yet, they are too complex and non-intuitive to use.

Especially in ultra-precision machining (UPM), nanometric SR (NSR) is governed by low-frequency components, middle-frequency components, and high-frequency components [10,11], which crucially affect optical quality by diffraction and interference. However, the SR parameters are not sensitive to spatial frequency. Further, in UPM high-frequency components and tool marks make a significant contribution to NSR generation [11], which is extremely sensitive to noise. Nevertheless, noise effects produce an important impact upon NSR.

Therefore, it is necessary to propose extra SR parameters, which can represent SF simply and efficiently. In additions, the noise effects can be reduced or eliminated effectively. In this study, a new representation for SF of NSR has been developed from surface derivatives, extra SR parameters. Probability distribution with the 95–99 rule was used to reduce noise effects. Finally, the theoretical results have been verified experimentally.

2. Theoretical modelling

In ISO 4287 [5], the basic SR parameters are arithmetical average roughness R_a, root mean square roughness R_q, ten-point peak-to-valley average roughness R_z, maximum peak-to-valley roughness R_t, respectively, which are sensitive to noise. In this study, to eliminate or reduce the noise effects, the statistical method is employed

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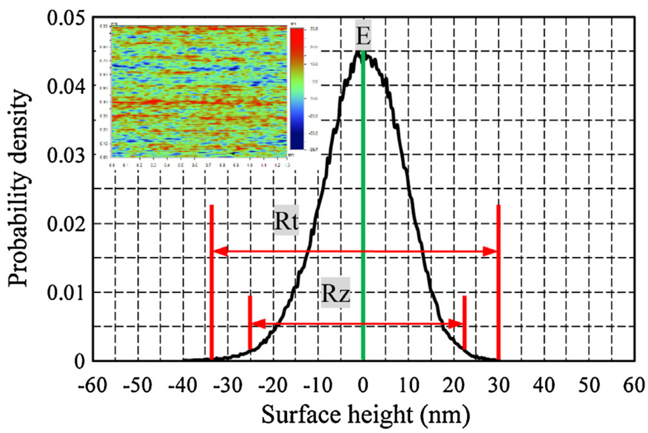

Fig. 1. Probability density of an ultra-precision raster milled surface.

for the measured surface. A probability distribution of surface height is provided with probability density. Then, the mean of surface height E is expressed as:

$$\mathrm{E}(x) = \int_{-\infty}^{+\infty} x p(x)\,\mathrm{d}x \tag{1}$$

where x is surface height, $p(x)$ is probability density. Therefore, following the analogue definitions of the basic SR parameters, the new SR parameters R'_a and R'_q, are expressed as below, respectively.

$$R'a = \int_{-\infty}^{+\infty} (|x| - E(x))\,p(x)\,\mathrm{d}x \tag{2}$$

$$R'q = \sqrt{\int_{-\infty}^{+\infty} (|x| - E(x))^2 p(x)\,\mathrm{d}x} \tag{3}$$

where R'_z is the 95% confidence interval of surface height, and R'_t is the 99% confidence interval of surface height under the assumption of 1% noise. The 95–99 rule is used in this study in order to reduce the effects of noise on the SR parameters. Fig. 1 shows the probability density of an ultra-precision raster milled surface for E, R'_a, R'_q, R'_z and R'_t.

The above-mentioned SR parameters only reflect height features, but not represent spacing features. Consequently, new extra SR parameters are developed to fill up the gap estimating spacing features. In this study, the first-order difference method was adopted, named surface derivative, which is sensitive to spatial frequency. The surface derivative was evaluated following the analogue definitions of the new SR parameters, R'_a, R'_q, R'_z and R'_t.

Table 1
Cutting conditions.

Tool nose radius (mm)	2.453
Tool rake angle (°)	0
Front clearance angle (°)	15
Swing distance (mm)	38.23
Depth of cut (μm)	3
Spindle speed (rpm)	2000
Feed rate (mm/min)	50
Step distance (μm)	30
Cutting strategy	Horizontal cutting
Cutting mode	Up-cutting

The new extra SR parameters are denoted as D_a, D_q, D_z and D_t, respectively.

3. Experimental setup

In this study, two flat cutting tests in UPM have been carried out on an ultra-precision raster milling machine (Precitech Freeform 705G) under the cutting conditions of Table 1 to generate two flat surfaces. The workpiece materials were copper and albronze, respectively. A natural single crystal diamond tool whose parameters are presented in Table 1 was used in UPRM. The milled surfaces were measured by the Optical Profiling System (WYKO NT8000) to discuss SR evaluation. The measured surface size is 309 μm long × 231 μm wide. In UPM, the tool mark dominantly affects SR, which size is 25 μm long × 30 μm wide obtained from the cutting conditions.

4. Results and discussion

Albronze and copper have been performed in UPRM with the same cutting conditions of Table 1 to produce two flat surfaces. The surface topographies were measured by the Optical Profiling System, as shown in Fig. 2. The surface topographies include low-frequency components, middle-frequency components, and high-frequency components. The low-frequency components are induced by low-frequency vibration and motion errors. The middle-frequency components are corresponding to tool marks. The high-frequency components are caused by material factor. Tool marks have a major impact upon SR generation. Fig. 2(a) shows tool marks with more effects of material factor and Fig. 2(b) demonstrates that tool marks are clearer. The ideal tool mark size is 25 μm long × 30 μm wide.

In SR estimation, the sampling interval is a very important factor influencing the values of SR parameters. For NSR, the spatial resolution can be smaller than the sampling interval limited by the measurement instrument. Consequently, in practice the sampling interval must be chosen as small as possible by the measurement instrument. Fig. 3 shows the effects of the sampling interval the measured results of Fig. 2. It indicates that the sampling frequency

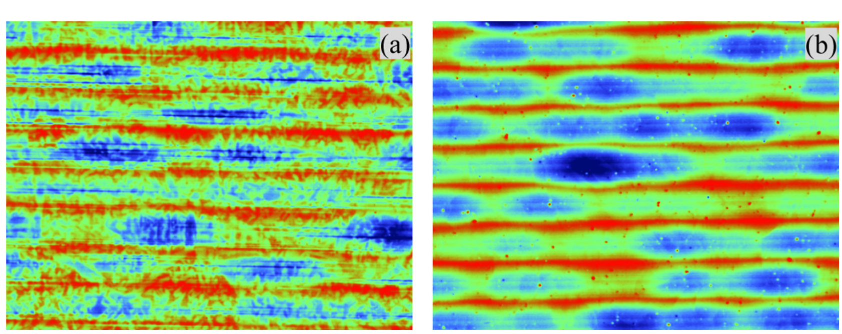

Fig. 2. Measured surface topographies of (a) albronze and (b) copper.

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