Precision Engineering 38 (2014) 1–8

Contents lists available at ScienceDirect

Precision Engineering

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

Surface texture assessment of ultra-precision machined parts based on laser speckle pattern analysis

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ARTICLE INFO

Article history:
Received 2 December 2012
Received in revised form 1 May 2013
Accepted 24 May 2013
Available online 4 July 2013

Keywords:
Surface texture assessment
Micro-structure
Laser speckle
Characteristic parameter
Machined surface

ABSTRACT

Surface texture plays an important role in overall product specification, because the surface quality of the product is dominated by the nano-scale surface texture. This paper presents a surface texture assessment method for evaluating roughness and periodicity of surface structure with a laser speckle pattern analysis. By investigating the relation between surface texture and laser speckle pattern, characteristic parameters for describing a laser speckle pattern are proposed. The proposed characteristic parameters can evaluate the surface texture in entire observed area and in limited area in any given direction. Furthermore, the surface texture can be qualitatively assessed with a radar chart of the proposed laser speckle characteristic parameters.

1. Introduction

Surface texture of ultra-precision machined parts may have a great significance on the performances of a product, such as friction, wear resistance, corrosion, fatigue, and wetting. For example, Bico et al. pointed out that the contact angle of a water drop is affected by surface roughness [1]. Moronuki et al. reported the relation between surface structure and friction coefficient [2]. Therefore, to assess nano-meter scale height or micro-meter scale periodicity of surface structure accurately plays an important role in product development process. For practical evaluation of ultra-precision surfaces, non-contact assessment method is required in order to estimate properties without damaging surfaces. Furthermore, it is also required to evaluate a large area efficiently. A laser speckle method is one of the most effective surface assessment methods to meet such demands. For this reason, various surface texture assessment methods have been investigated so far, such as a speckle contrast method [3,4], an angular speckle correlation method [5], and a polychromatic speckle correlation method [6]. The co-occurrence matrix of laser speckle pattern [7] and the speckle interferometry [8] can be also utilized for surface roughness evaluation. However, the conventional measurement methods using laser speckle can evaluate only one parameter of surface texture, mainly surface roughness.

This paper presents a surface texture assessment method which can evaluate both surface roughness and periodicity of micro-structure using several characteristic parameters obtained from a laser speckle pattern. A target of this study is to evaluate the height of surface structure below 600 nm, which is less than the visible light wavelength range. In addition, another target is to evaluate the surface structure period shorter than 100 μm on the tool mark direction and the surface structure period longer than 300 μm on the perpendicular direction with same method. Furthermore, the actual assessment results confirm that the laser speckle characteristic parameters can describe the surface texture qualitatively.

2. Theoretical description

2.1. Statistical property of laser speckle

When a coherent laser beam is irradiated onto a machined surface, the micro-structure on the surface reflects and scatters the light, as shown in Fig. 1. The scattered light distributions form the resulting pattern on a screen, i.e. laser speckle pattern. Laser speckle patterns obtained from the machined surfaces can be considered from two aspects; statistical and diffraction phenomena.

Considered as a statistical phenomenon, the probability density distribution of light intensity on a laser speckle pattern is affected by the surface roughness. According to Uozumi and Asakura, when

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http://dx.doi.org/10.1016/j.precisioneng.2013.06.005

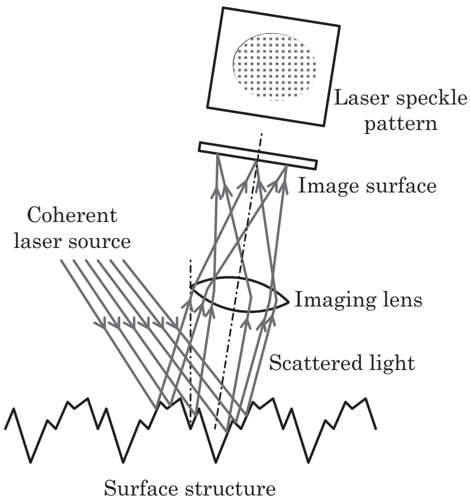

Fig. 1. Laser speckle formed by surface structure.

the surface roughness is smaller than the laser wavelength, the real and imaginary parts of the complex amplitude on the laser speckle intensity match the Gaussian distributions, respectively [9]. These Gaussian distributions have the different mean values and the standard deviations. Thus, the distribution of coupling probability can be given by Eq. (1),

$$P_{r,i}(A_r, A_i) = \frac{1}{2\pi\sigma_\tau\sigma_i(1-\rho^2)^{1/2}} \exp\left[-\frac{1}{1-\rho^2}\left\{\frac{(A_r - \langle A_r\rangle)^2}{\sigma_r^2} - \frac{2\rho(A_r - \langle A_r\rangle)(A_i - \langle A_i\rangle)}{\sigma_r\sigma_i} + \frac{(A_r - \langle A_i\rangle)^2}{\sigma_i^2}\right\}\right] \quad (1)$$

where σ_r and σ_i are the standard deviations of the distributions of the real and imaginary parts, $\langle A_r\rangle$ and $\langle A_i\rangle$ are the mean value of the distributions of the real and imaginary parts, and ρ is the correlation coefficient between A_r and A_i. Both the mean value and the standard deviation of laser speckle intensity are affected by the value of surface roughness: the mean values decrease to close to zero and the standard deviations get closer as the surface roughness becomes larger. In consequence, when the surface roughness is larger than the laser wavelength, the distribution of coupling probability is asymptotic to Eq. (2),

$$P_{r,i}(A_r, A_i) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{A_r^2 + A_i^2}{2\sigma^2}\right) \quad (2)$$

where σ is the standard deviation of the distributions of the real and imaginary parts, which is unaffected by surface roughness. However, under the condition that the surface roughness is smaller than the laser wavelength, the surface roughness can be evaluated by the mean value of the laser speckle intensity.

2.2. Diffraction phenomena by machined surfaces

In most cases, the machined surfaces such as ground or milled surfaces contain periodic micro-structures. Thus, the laser speckle patterns formed of machined surfaces can be considered as diffraction images from multiple apertures. When the optical system shown in Fig. 1 satisfies the Fraunhofer condition, i.e. the machined surface and the image screen are located on the focal distance of the imaging lens, the laser speckle pattern is the Fourier transform image of the surface texture. In the case of the periodic micro-structure on a milled surface shown in Fig. 2 as a type of diffraction grating, the Fraunhofer diffraction intensity at the angle θ by the periodic micro-structure can be expressed by Eq. (3),

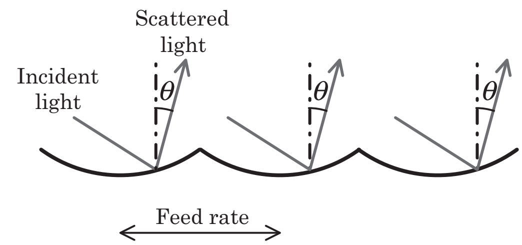

Fig. 2. Light scattering at periodic structure on a machined surface.

$$I(\theta) = \frac{1}{N^2} I_0 \left\{\frac{\sin(\pi dNL\theta/\lambda)}{\sin(\pi dL\theta/\lambda)}\right\}^2 \left\{\frac{\sin(\pi aL\theta/\lambda}{\pi aL\theta/\lambda}\right\}^2 \quad (3)$$

where I_0 is the light intensity at $\theta = 0$, λ is the laser wavelength, d is the grid interval, a is the slit width, N is the lattice constant, and L is the distance between of the diffraction grating and the imaging lens. Thus, a possible diffraction intensity distribution obtained by a milled surface is Fig. 3, and the interval of bright lines is equal to $L\lambda/d$. In consequence, the periodicity of micro-structure can be evaluated from the bright line interval of a laser speckle pattern.

In this paper, the relation between surface texture and laser speckle patterns is experimentally investigated, and then the characteristic parameters are obtained from a laser speckle pattern. The proposed characteristic parameters correlate with the surface texture parameters.

3. Experimental method

A laser speckle observation instrument was developed, as shown in Figs. 4 and 5. The laser source of this instrument was a laser diode, and the wavelength of a laser beam was 635 nm. The beam diameter was 2 mm at the aperture of the laser source. The lens A, the lens B and the pinhole collimated the laser beam, and expanded its diameter. The lens C irradiated the sample fixed on an indexing stage. The spot diameter on the sample was 8 mm. The scattered light from the light spot on the sample surface at a given moment could be observed with the CCD camera through the lens D, and then the evaluated area size is same as the spot size of ϕ 8 mm. The observing direction was beside the specular reflection angle. In addition, the sample and a CCD camera were located on the focal distance of the lens D. The CCD camera has 640 × 480 pixels, and the size of each cell is 7.4 μm × 7.4 μm.

Roughness standard specimens made of magnesium and aluminum alloy shown in Fig. 6 were used as the samples. The specimens were for three types of machined surfaces, i.e. lapped, ground, and milled surfaces. Each specimen contained several surfaces which had different roughness. The surface textures of

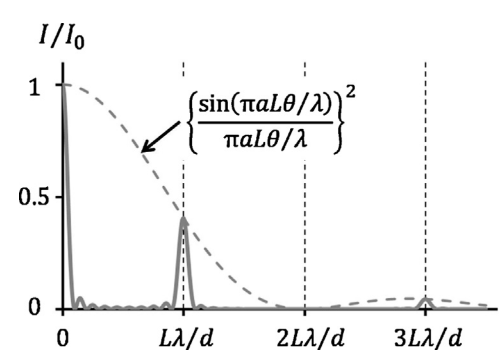

Fig. 3. Diffraction intensity distribution on a milled surface.