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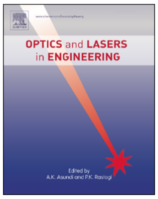

Study on the optical reflection characteristics of surface micro-morphology generated by ultra-precision diamond turning

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ABSTRACT

Ultra-precision single point diamond turning technology has been widely adopted to machine high precision reflectors. Diamond turned surfaces have special micro-morphology, which affect reflecting performance greatly. To reduce optical defects, the relationship between optical defects, surface micro-morphology and turning conditions will be analyzed theoretically, using the interference method and integral method, for turning reflectors. And turning experiments will be conducted to validate the analysis. The study can provide a new methodology for evaluating surface finish and it is with guiding significance for production and processing.

1. Introduction

The ultra-precision single point diamond turning (SPDT) has been used to generate optical surfaces directly for a long time [1–3]. Compared with grinding and polishing, the high efficiency and precision repeatability is achievable. To get a better surface quality and machine surface with a higher efficiency, there are considerable researches [4–6] engaging in analyzing diamond turned surface micro-morphology and improving surface quality, and selecting more suitable turning parameters to get a better surface.

Optical surfaces have specific optical parameters. For reflectors, one kind of optical device, it is important to assess the reflecting performance. Machining factors, such as tool wear, vibrations, materials effect, etc., affect the performance. Li et al. [7,8] systemically analyze how different machining factors, such as spindle speed, feedrate, tool condition selection affect surface micro-morphology turned by fly cutting, fast tool servo, slow tool servo, tool broaching, and affect reflectivity and diffraction. This research provides a thought for optics industry on how to decrease optical defects by optimizing machining parameters.

Conical reflector is one kind of reflector. It has the functions of generating omnidirectional imaging, that is, it can produce full circle 360° panoramic image [9], so it has been used in many fields such as mechanical, medical, astronomy [10–12]. With the requirement of high-quality imaging, the high surface precision and good roughness of conical surface is necessary. In conical reflectors machining, optical defects of conical reflectors are detected, which impede machining efficiency improving. How to decrease optical defects is critical.

To analyze what factors cause reflector optical defects in machining, interference theory and random rough surface scattering theory is used. Many typical studies have been focused on the rough surface scattering and they have displayed various methods to analyze the surface scattering [13–15]. And there are methods using in some commercial electromagnetic simulation software, like COMSOL.

The purpose of this study is to provide a methodology on how to analyze optical defects of reflectors both theoretically and practically, and how to select turning conditions to turn reflectors with high quality, and reduce rejection rate. Conical reflector is used as a major example to conduct analysis. In Section 2, several typical defects of conical reflector are described. Multiline phenomenon is analyzed both theoretically and experimentally in Section 3. Interference method based on interference theory and integral method based on rough surface scattering theory are used in analyzing multiline defect. And stray light and blurred line phenomena are analyzed preliminary in Section 4. In the last section, conclusion and future work are shown. The study provides a new thought to assess machined optical surface and help to machine surface with better surface finish.

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2. Problems description

As shown in Fig. 1, it is a device to detect optical defects of conical reflector. Fig. 1(a) is the schematic diagram to detect defects. Light source is laser diode that emits laser with 650 nm wavelength shown in Fig. 1(b). The performance of the reflecting image on the screen is supposed to be one clear and uniform line. Several typical optical defects will be discussed below.

The defective reflecting image on the screen can be observed when the conical surface of reflector is not good enough. Several typical defects are shown in Fig. 2.

Obviously, the reflecting image is closely related to surface accuracy and micro-morphology of conical surface. The conical surface with eligible quality is shown in Fig. 2(a), with reflecting image one clear and uniform line. The surface is observed under digital microscope (VHX-500). For defects like line non-uniform, the conical reflecting image and surface is shown in Fig. 2(b). Defect occurred above is caused by accidental factors like collision, scratch or dirt. The low magnification lens are used because scratch is seen clearly with 500 × lens. For stray light and multiline, the surfaces look relatively good under microscope as Fig. 2(c) and (d). The periodic surface texture can be seen in Fig. 2(c). In Fig. 2(d) and (e), the surface textures are irregular. It can be seen that stray light phenomenon appears so frequently that it is seen in all figures, while blurred line is caused by poorer surface roughness as Fig. 2(e).

In the next two sections, multiline phenomenon is analyzed both theoretically and experimentally in Section 3. And stray light and blurred line phenomena are analyzed in Section 4.

3. Analysis of multiline phenomenon

Multiline phenomenon is analyzed in this section. It is caused by regular and periodic surface micro-morphology. Firstly, the turned surface model is built. Secondly, scattering of ideal SPDT surface is analyzed using interference theory to calculate critical feedrate (μm/r) that can machine reflectors without multiline, and the integral of random rough surface scattering theory based on Kirchhoff approximation [13] is used to calculate the surface scattering characteristic precisely. Finally, experiments will be conducted to validate the analysis and explore more practical parameters.

3.1. Ideal SPDT turned surface and 2-D simplification

Fig. 2(c) shows that surface with turning tool mark, which can be seen ideal SPDT turned surface may cause multiline phenomenon.

The conical reflector turning schematic diagram is shown in Fig. 3(a). The ideal SPDT machined surface micro-morphology is like Fig. 3(b) in the assumption of the ideal arc tool nose and absence of material effect, rotational errors of the spindle, vibration during machining, etc. [16–18]. The assumption that surface micro-morphology is mapped by tool nose is satisfied. To simplify furthermore, we only analyze the 2D curve intersected by 3D space conical surface and rotary surface shown in Fig. 3(c), which is a period set of concave arc. It is reasonable for analyzing scattering characteristic of 2D curve instead of 3D surface. Firstly, the conical reflector is axial symmetry. Secondly, the scattering image space of 2D curve is a line space coplanar with the curve and rotary axis. The whole 3D surface can be seen the combination of 2D bus bar curves of the cone, the same as scattering images.

R is the tool nose radius; f is the feedrate (μm/r) for manufacturing, and the chord length of arc tool mark; and h is the residual peak height.

3.2. Analysis of the relationship between multiline defects and micro-morphology

In Section 3.2, it is analyzed how to select feedrate to avoid multiline phenomenon. For simplification, the material is assumed to be perfect conductor, so that all incident light is scattered without transmitted. The materials of reflector, like aluminum, accord with this assumption.

3.2.1. Scattering of single arc structure

Fig. 4 is the scattering model of single concave arc. Since f in actual manufacturing is always much larger (more than 10 times) than visible light wavelength, geometrical optics theory is used to analyze the scattering. When observing arc reflector in far-zone, the incident light can be observed along a range of direction besides reflecting direction. How can we calculate the range? The range of observing direction obeys the expression $[\theta_r \min, \theta_r \max]$. Moreover, reflecting light intensity is seen constant in the range of the whole direction.

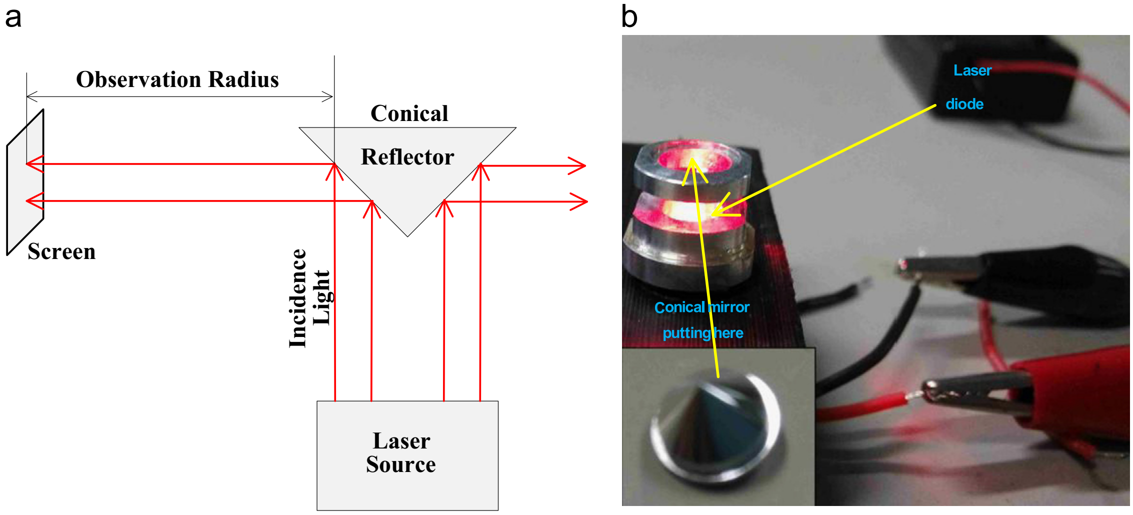

Fig. 1. Conical reflector optical defects detecting schematic diagram and device. (a) Detecting device schematic diagram and (b) detecting device.