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Out-of-plane light-scattering polarimetric imaging of a thread surface

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ABSTRACT

A novel polarimetric measurement based on hemispherical light-scattering for the assessment of superficial screw is presented. The optical system is capable of capturing polarized light images. The effect of the thread surface backscattering is estimated with the use of in-plane and out-of-plane illumination. The angular distributions of polarized light scattered by the ISO metric screws are measured for light incident from a green laser. A partial Stokes vector imaging detector is mounted on a motorized rotating arm at an oblique angle to the sample normal and consists of a 10-bit scientific camera, an object lens, and a polarizer. The partial Stokes vector images of light scattered towards the camera are generated for each direction and a useful decomposition of the partial Stokes vector is presented. The thread surface effects can be minimized using out-of-plane polarized illumination in conjunction with polarized images. The experimental result may provide a new polarized imaging technique for using visible light to inspect the key features of a screw in automated optical inspection system.

1. Introduction

The thread is a ridge wrapped around a cylinder in the form of a helix. Screws are used to fasten the various parts of an assembly together. The designer should be familiar with the different kinds of threads and with the method of specifying the desired tolerances for the fit between screw and nut. There are both mechanical and optical methods for measuring threads. The most practical mechanical method is the use of an outside micrometer. The traditional optical method is the use of the optical Fourier transform for the diffraction pattern of a screw [1]. A number of modified diffraction methods were developed for increasing the accuracy of measurement [2,3], but the diffraction methods are more suitable for measuring diameter of cylinder. Laser beam interferometers have been applied to measure surface profiles of shapes such as cylinder diameters, gear tooth flanks, and thread gauge [4–7]. They presented a ray-tracing-based method to measure vibrating interference fringe patterns of complicated shapes with a two-path interferometer. Sinusoidal phase modulating interferometry is applied for detection of the phase distribution of the interference pattern by vibration of the grating. The accurate simulation of interference fringe patterns is necessary in the measurement of complicated shapes. Therefore, it is difficult to apply interferometer for measuring complicated surfaces, such as gears and threads.

Laser light-scattering has been shown to be a powerful diagnostic technique for characterizing surface qualities [8]. However, scattered light may appear from a number of sources, such as surface topography, surface residue, particulate contamination, and subsurface bubbles. Analyzing the scattered intensity is required to accurately distinguish the surface features. The theoretical and experimental results have proved that a wealth of information is included in the polarimetric properties of many specimens [9–12]. The polarimetric properties of out-of-plane light-scattering can contain distinctions among different types of surface features. They have demonstrated experimentally and theoretically that polarization of light-scattering can be used to detect among various types of surface characterizations. The polarized light-scattering of a periodic structure on a surface can be very sensitive to the profile of that structure [13]. The different single-scattering mechanisms did not depolarize the light, but yielded different polarization states [14–16]. The roughness effects of shape could be minimized using out-of-plane Stokes spectropolarimetry [17]. The polarized light imaging techniques can be used to assess the complicated surfaces of thread.

In this paper, we demonstrate a novel polarimetric measurement based on hemispherical light-scattering for the assessment of superficial screw. Polarized light sources provide illumination in

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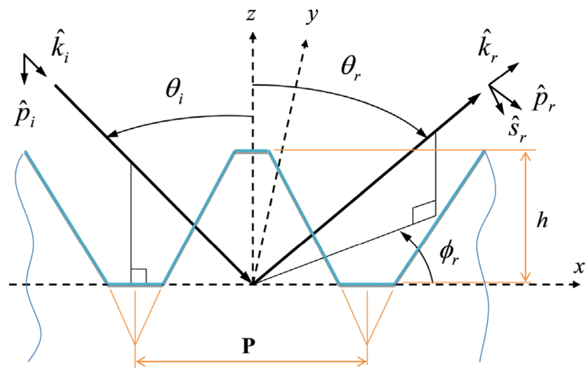

Fig. 1. Geometry of the scattering system for a thread.

and out of the plane of imaging at different detecting directions. A useful decomposition of the partial Stokes vector images is presented. The thread surface effects can be minimized using out-of-plane polarized illumination in conjunction with polarized images. The theoretical and experimental methods used in this paper are introduced in Section 2. The experimental data of the ISO metric screws are discussed in Section 3. Finally, the measurement results and future works are summarized in Section 4.

2. Experimental methods

Detailed descriptions of light-scattering by a surface feature have been developed in many scientific literatures [8–16]. Following the contribution of the references, the light-scattering theory is outlined below briefly. In order to examine the experimental data from bidirectional ellipsometry directly, a geometric coordinate system is displayed in Fig. 1 to represent the polarization and the angular dependence of the scattered fields from a thread. The pitch and the height of a thread are **P** and h, respectively. A polarized plane lightwave with wavelength λ is irradiated to the surface of a thread at an incident angle of θ_i in the x–z plane. The polarization of lightwave scattered in the direction defined by a polar (in x–z plane) angle θ_r and an azimuthal (out-of-plane) angle ϕ_r is measured. Unit vectors $\hat{k}_i$ and $\hat{k}_r$ describe the directions of propagation of the incident and scattered light. We assume that the incident light is p-polarized when it is polarized with its electric filed parallel to $\hat{p}_i$ direction in the x–z plane. The polarization of the scattered light is described by its components along the $\hat{s}_r$ and $\hat{p}_r$ directions, where $\hat{s}_r$ is a unit vectors perpendicular to both $\hat{k}_r$ and z and $\hat{p}_r = \hat{k}_r \times \hat{s}_r$. The Jones scattering matrix **S** is defined as the relationship between the incident and scattered electric fields for describing the polarization of light-scattering. The property of scattering matrix **S** is the main focus for determining the surface features from the light-scattering. The equivalent intensity relationship can be expressed using the Stokes–Mueller representation via the bidirectional reflectance distribution function [10]. The polarimetric properties of lightwave are described by a Stokes vector. A Stokes vector power Φ is represented by each of its elements Φ_j (j=0, 1, 2, 3). The first three elements of the Stokes vector correspond to linear states of polarization. We discover that it is convenient to indicate the polarization states by clarifying the degree of polarization and the principal angle of the polarization ellipse. The principal angle η of the polarization is presented by

$$\eta = \frac{1}{2}\arctan\left(\frac{\Phi_2}{\Phi_1}\right) \tag{1}$$

Viewing into the source, the principal angle η is measured counterclockwise with respect to the $\hat{s}$ direction when p-polarized light is incident on the sample [10]. The linear degree P_L of polarization is

$$P_L = \frac{\sqrt{\Phi_1^2 + \Phi_2^2}}{\Phi_0} \tag{2}$$

Since the thread sample is illuminated with linearly polarized light, these parameters entirely characterize the polarization states of light-scattering. Besides, these parameters are easily derived from the three first components of the Stokes vector. The P_L is equal to 1 for linearly polarized light and the P_L is equal to 0 for unpolarized light or circularly polarized light. The certain issues can be avoided by placing attention on the principal axis of the polarization ellipse. The foremost question is the scattering from other objects in the space that are illuminated by the specular beam. According to Mie approach, the exact Mie solution is used to express the optical diffraction of the scattered field by a homogeneous roughness. It is assumed that lightwave is scattered by specular reflection by facets on the surface. The polarization state of light-scattering is determined by reflection in the local reference frame for each facet and distribution of surface slopes. In this paper, we use these parameters to characterize the intensity and polarization of scattered light.

The goniometric imaging system is used to study in-plane and out-of-plane polarized light-scattering from the thread samples. The experimental apparatus of polarimetric imaging system is shown in Fig. 2. An incidence ray from continuous-wave diode-pumped solid-state laser (Cobolt® Fandango 515 nm) passes through an iris (I), a circular variable filter (F), a $\lambda/2$ waveplate (WP), a Glan–Thompson polarizer (POL1), and a spatial filter system (SFS) before being focused with a super-polished concave mirror (M) at the center of a goniometer. Spatial filter system using an objective lens and a precision pinhole provides a clear beam by removing wavefront noise and distortion. The incident light is collimated and the beam diameter is approximately 3 cm. The incident beam is polarized with a linear POL1 oriented parallel (p) to the x–z plane. The detector assembly is mounted on a motorized rotating arm that detecting polar angle θ_r could be varied. A 10-bit 1380 × 1030 pixel CCD camera (JAI® CV-M4+ CL) serves to capture the polarization states and transfers the image data through a framegrabber board to an industrial computer. Another Glan–Thompson polarizer (POL2) is mounted on a motorized rotational stage in front of the camera in order to filter three different linear polarized light states: parallel (p), perpendicular (s), and 45° to the x–z plane. The distance from the thread surface to the camera is

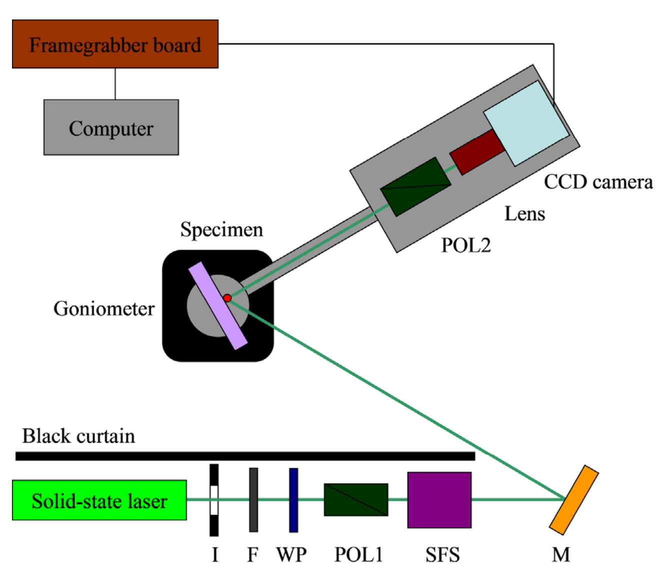

Fig. 2. Overall schematic diagram of polarimetric imaging system.