Analysis of Surface Roughness Using Laser Optical Imaging Techniques

Hatem El-Ghandoor¹, Mohamed Saudy¹ and Ahmed Ashour²

¹. Physics Department, Faculty of Science, Ain Shams University, Abbasion, Cairo, Egypt
². Faculty of Engineering and technology, Future University, Al Tagamaa Al Khames, Cairo, Egypt

Received: August 26, 2010 / Accepted: September 25, 2011 / Published: January 25, 2012.

Abstract: Speckle phenomena were produced by using interference of scattered laser beams from certain rough object. Digital speckle images were recorded for different rougher and smoother surfaces, using an optical imaging system in two and three dimensions with a high resolution CCD camera. The obtained speckle images were transformed to equivalent binary images. The values of surface roughness depend on the degree of agglomeration of the speckle images. The optical density was calculated and it was found that it depends on the different conditions for the optical imaging system. The back projection technique was used to reconstruct 3-dimensional surface roughness profiles from multi-directional projection data. Also, interference microscope was used for the reconstruction of surface topography for different rough surfaces.

Key words: Surface roughness, laser optical imaging techniques, laser speckle, back projection technique, interference microscope, 3-dimensional surface roughness profiles, surface topography.

1. Introduction

The measurement of roughness on machined surfaces is of great importance for manufacturing industries as the roughness of a surface has a considerable influence on its quality and function of products [1]. Surface roughness measurement and the determination of the statistical properties of rough surfaces are very important in several fields of engineering and science. Many different parameters can be used in the characterization of surface roughness. Surface roughness parameters can be used for the differentiation between different rough surfaces. Statistical parameters such as the arithmetic mean of the surface roughness, \( R_a \) and the root mean square surface roughness, \( R_q \) are most frequently used. In mechanical engineering, \( R_a \) is preferred, while in optics \( R_q \) is used because of its high precision [2]. The stylus-type profile-meter as a mechanical profile-meter provides useful data to measure surface roughness. It measures the average height deviations from a reference line independent of correlation length of the surface. The resolution of this instrument depends mainly on the diameter of the measuring needle tip [2]. Other methods are thus developed for measuring surface roughness. Interferometric and light scattering techniques require that the height or depth of the rough surface to be in the order of the wavelength. The speckle contrast method (SCM) and the light scattering method (LSM) are two of the most promising optical techniques for on-line surface roughness measurement of slightly-rough surface [3].

Asakura and his colleagues [4-12] have extensively studied the statistical properties of speckle intensity variations produced in the imaging plane considering a rough object. The coherence conditions of the illumination and the point-spread function of the imaging system were considered for the investigation of the obtained speckles.

The light-scattering technique has received wide attention in the past few decades, which was measured
Analysis of Surface Roughness Using Laser Optical Imaging Techniques

and analyzed the reflected scattered light. The theoretical background of this technique is based on Beckmann’s rough-surface scattering model [13, 14]. The roughness height information is obtained from the intensity reflected in the specular direction, and the autocorrelation function of the surface height variations is determined from the scattered intensity. Basically, this technique is applied only to moderately rough surfaces, usually with heights less than 4 \( \mu m \).

The Fourier spectrum analysis technique [15] assesses surface roughness by analyzing the distribution of the spatial frequency of the scattered light. The upper limit for the measurement of roughness with the Fourier technique is less than 2 \( \mu m \), although a roughness of up to 5 \( \mu m \) has been successfully measured [16].

The laser light-scattering technique for surface roughness measurement has received wide attention in the past few decades, where the roughness information is obtained from the intensity scattered through certain directions. Also, the autocorrelation function of the surface height variations is determined from the scattered intensity [17]. The speckle contrast technique which relates the object surface roughness to the contrast of the speckle image is a scale of the speckle intensity variations [18]. A whole field speckle correlation has been used to determine the object surface roughness [19]. In speckle correlation technique, the average surface roughness calculated from the profile shapes of the autocorrelation function of the diffuser.

The reconstruction of three-dimensional information of rough object from multi directional projection data using the back projection technique was investigated [2]. In this technique image obtained when light passes through the object-at certain direction-represents a projection, the Fourier transform of such projection gives coefficients in a certain section of Fourier space then the reconstruction of the whole image by Fourier synthesis using all sections takes place. In this paper, known rough object is used to compare between reconstruction of surface roughness of the laser speckle pattern in 3-dimension, using the back projection technique and the reconstruction of surface topography of different surfaces using interference microscope.

The goal of the back projection technique is the reconstruction of 3-dimensional distribution of the object field, which is reduced to the reconstruction of a set of two dimensional density fields from one dimension line integrated experimental data. This data is obtained from the deflection angle of laser rays passing through the object field. However, different line integrals can display a group of different data points at different longitudinal angles representing different cross sections in the object region. The two-dimension density distribution for the different cross sections of the object region are then collected to reconstruct a whole field image of the target density distribution.

According to the projection theory of Fourier transform [2, 4], the Fourier transform does not appear explicitly in the final results. The convolution back projection technique consume less computing time and less sensitive to the experimental data error resulting from the noise. For these reasons the convolution back projection technique is chosen for the reconstruction of the object density field.

In this work, standard smoother and rougher surfaces are studied. Digital speckle images recorded. The optical density obtained at different conditions. The back projection technique was used to reconstruct 3-dimensional surface roughness profiles from multi-directional projection data. Also, interference microscope was used for the reconstruction of surface topography for different rough surfaces.

2. Experiment

The optical imaging system that has been used in this experiment is shown in Fig. 1, where the target density distribution is represented by \( f(x, y) \) in the XY plane. Light rays from a laser source are allowed to propagate along \( \rho \) direction. Let us consider the ray specified by
Analysis of Surface Roughness Using Laser Optical Imaging Techniques

Fig. 1  Fourier transform of a projection at different angels.

its perpendicular distance $S$ and the angle $\theta$.

The experimental observation of laser rays scattered at different angles are recorded using an optical imaging system for different viewing angles (projections). The laser rays propagation direction in the object region is along a straight line represented by $S = \text{constant}$. The accumulative effect on the deflection of light rays due to the density variation within the object region can be represented in the $(S, \theta)$ coordinate system.

According to the projection slice theory, the Fourier transform of a projection along $S = \text{constant}$ in the spatial domain ($x$-$y$ plane), produces a point at $R$, in the Fourier transform domain ($u$-$v$ plane) (Fig. 1). The Fourier transform of an infinite number of projections taking continuously in radial and angular directions ($S$ and $\theta$) fill the whole Fourier transform domain. In this case the inverse Fourier transform theoretically recover the original function in the spatial domain. This means that precise reconstruction can be obtained by using an infinite number of projections, but only a limited number of such projections can be recorded experimentally.

In order to introduce our experimental data into this transformation, a window function is introduced in the Fourier space with the aim of reconstructing a band limited function $f_B(x, y)$, which is a band limited approximation of $f(x, y)$. The sampling interval is defined as in the space domain as $\Delta s$, which corresponds to a cut-off frequency in the Fourier transform domain.

The simplest way to evaluate the back projection integral is to use the trapezoidal rule, for the numerical integration of we get:

$$f_s(k\Delta x, k\Delta y) = \Delta \theta \Delta s \sum_{n=1}^{N} \sum_{m=0}^{M} P(m\Delta s, \theta_{n}) \gamma(m\Delta s - m\Delta x)$$  \hspace{1cm} (1)

where $P(m\Delta s, \theta)$ is projections of the field $f$, on the line $s$ at angle $\theta$, $N$ is different viewing directions with equal angular intervals $\Delta \theta$, and a filter function $q(s' - s)$.

The far-field speckle contrast technique has been used for recording speckle images. Different rough surfaces of standard metal are used as rough object. Two different standard rough surfaces of low and high roughness are used. The standard smoother surfaces of roughnesses are 0.4, 0.6, 0.8, 1.1, 1.6, 2.3, 3.2, 4.6, 4.6,
and 6.4 μm. The other standard rougher object having roughness are 20, 80 and 600 μm. Fig. 2 shows the experimental set up used for recording of speckle images corresponding to different roughness of object surfaces. A collimated laser beam emitted from a He-Ne laser beam of power 10 mW at λ = 632 nm is used for illumination of optical system. The light is incident upon the rough object covering a certain cross-section area of diameter D = 0.5 cm. The scattered light is recording using a CCD camera placed at a large distance Z = 15 cm from the rough surface as compared with distance D. Hence, a numerical aperture NA = D/2Z = 0.016 is maintained constant during the recording of all studied surface.

3. Data Reduction

The obtained speckle images recorded at different conditions are shown in Figs. 3 and 4 for smoother and rougher surfaces. The measurements are recorded at fixed room temperature 25 °C. Figs. 3a and 4a showed the recorded speckle images at constant ζ = 40° and θ = 0°. In case of smoother surface roughness, the speckle images show a homogenous distribution of speckle pattern over the speckle image. While at rougher surface roughness the distribution of speckles over the image area is non-homogenous and the speckle patterns are not completed. Figs. 3b and 4b showed the recorded speckle images at constant ζ = 40°. Figs. 3c and 4c show the recorded speckle images at constant θ = 0°.

The roughness R is defined as:

\[
R = \frac{1}{N} \sum_{i=1}^{N} |\Delta r_i| \quad (2)
\]

This is the average of the surface height deviations \(\Delta r_i\) of N data points.

The optical density of the speckle image is defined as the integrated area of the speckle grains \(A_S\) considered as a signal divided by the total area of the whole image \(A_T\), i.e.,

\[
\text{Optical density} = \frac{A_S}{A_T}
\]

where \(A_T = A_S + A_n\) and \(A_n\) is considered as a noise background. This optical density is considered as the

---

**Fig. 3** (a) Recorded speckle images of smoother surface at constant \(\zeta = 40^\circ\) and \(\theta = 0^\circ\). (b) Recorded speckle images at constant \(\zeta = 40^\circ\) and \(R_a = 3.2\ \mu\text{m}\). (c) Recorded speckle images at constant \(R_a = 3.2\ \mu\text{m}\) and \(\theta = 0^\circ\).
Fig. 4 (a) Recorded speckle images of rougher surface at constant $\zeta = 40^\circ$ and $\theta = 0^\circ$. (b) Recorded speckle images at constant $\zeta = 40^\circ$ and $R_a = 80 \, \mu m$. (c) Recorded speckle images at constant $R_a = 80 \, \mu m$ and $\theta = 0^\circ$. Degree of agglomeration of the speckle image. The optical densities of speckle pattern obtained from different samples at different conditions are evaluated using a computer program. The determined values of the optical density are plotted versus an angle $\theta$ at constant arithmetic mean surface roughness $R_a = 3.175 \, \mu m$ and angle $\zeta = 40^\circ$ as shown in Fig. 5. The figure showed that the optical density is changed with an angle $\theta$ as a Gaussian shape. Also, it shows that the rougher the surface the slower the backscattering optical density falls from its maximum value. Fig. 6 plots the optical density, versus the arithmetic mean surface roughness $R_a$ at constant angles $\theta = 0^\circ$ and $\zeta = 40^\circ$. The figure shows that the optical density increased means that the speckle pattern tends to be agglomerated as the surface roughness increases, and then nearly saturated with more increase in surface roughness. The optical density change is very sensitive to the roughness variations, but for rougher surface the optical density is high than the smoother surface due to the speckle agglomeration [18]. For the smoother surface, more light is reflected and thus its intensity recorded by CCD camera will be lower. For the rougher surface, it will produce a less dense reflected, so it gives higher optical density. This explains the increase of optical density with surface roughness.

The measured values of the optical density, versus the angle $\zeta$, at constant arithmetic mean surface roughness $R_a = 3.175 \, \mu m$, 80 $\mu m$ and angle $\theta = 0^\circ$. The figure showed that the optical density decreases with the increase of an angel $\zeta$ due to the decrease of correlation between speckles.

The numerical (binary) image of speckle grains can be obtained using a computer program [1]. The contours of binary speckle images are a two-dimensional mapping of the image, which can be used to describe the external contours of the speckle image. Hence, the shape distributions for these contours can be determined. The three-dimensional representation is a pattern of $(x, y, z)$ coordinates where
Analysis of Surface Roughness Using Laser Optical Imaging Techniques

Fig. 5  Relation between measured values of the optical density, versus the angle \( \theta \) at constant angle \( \zeta = 40^\circ \). (a) at constant \( R_a = 3.175 \mu m \). (b) at constant \( R_a = 80 \mu m \) and angle \( \zeta = 40^\circ \).

Fig. 6  Relation between measured values of the optical density, versus arithmetic mean surface roughness \( R_a \), at constant the angle \( \theta = 0^\circ \) and angle \( \zeta = 40^\circ \).

Fig. 7  Relation between the measured values of the optical density, versus the angle \( \zeta \), at constant angle \( \theta = 0^\circ \). (a) at constant \( R_a = 3.175 \mu m \). (b) at constant \( R_a = 80 \mu m \).
contours for different sections are represented by coordinates x, y and the height of the speckle patches are represented by the z coordinate.

Fig. 8 shows the 3-dimensional representation of speckle image at different surface roughness. It was shown that the separation between the speckles and their definite positions are dependent upon the mean surface roughness. As the mean surface roughness increase, the degree of agglomeration of speckle patches increases limited by the measured surface roughness. These results confirm that, the optical density can be used as an experimental parameter to study the changes in surface roughness of different samples at the same experimental conditions.

Fig. 8  Three-dimensional representation of speckle image from numerical image at different surface roughness, at constant $\zeta = 40^\circ$ and $\theta = 0^\circ$. 
Fig. 9 shows the topography of 3-dimensional surface roughness using the interference microscope. This result is nearly similar to that obtained from the 3-dimensional numerical image.

Fig. 10 shows the 3-dimensional reconstruction of the back projection technique at constant angles $\theta = 0^0$ and $\zeta = 40^0$. The figures demonstrated that the back projection technique is more sensitive to rougher surface roughness than smoother surface.

### 4. Discussion and Conclusions

This work proposes the investigation of the optical density variation for various rough surface of different rough objects at different conditions of an angle $\theta$ and $\zeta$.

The patches of the speckle images are more agglomerated for high surface roughness as compared...
Fig. 10 Three-dimensional representation of surface roughness using back projection technique, at constant $\zeta = 40^\circ$ and $\theta = 0^\circ$.

with low surface roughness. The optical density changed at different condition. Its change as a Gaussian shape with angle $\theta$, its increase with surface roughness and decrease with angle $\zeta$. The 3-dimensional representation of speckle image at different surface roughness is performed using two different techniques namely, speckle contrast technique and interference microscope. The experimental results verify the coincidence of the measured surface roughness.

References


