Intensity and contrast based surface roughness measurement approaches for rough and shiny surfaces

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ABSTRACT

In manufacturing engineering the surface finish of a machined component is of fundamental importance in order to ensure its performance. A non-contact and non-destructive device based on optical technique, is a promising alternative to stylus based device for carrying out measurement of surface quality. In addition to this, in situ monitoring of surface roughness on a workpiece is an important requirement in modern machining process, since it would increase on-line machining rate and consequently productivity. Here, measurement approaches and system configuration for surface roughness measurement using laser speckle intensity and contrast are discussed. The technique would allow full-field measurement over sample of interest having both rough and shiny surface properties. Measurement data on standard calibration plates is presented with details on the measurement accuracy and reliability.

Keywords: Spectral speckle correlation, surface roughness, non-destructive testing, laser speckle.

INTRODUCTION

The surface roughness on engineering parts is generally measured using a stylus-based profilometer[1]. The stylus which is drawn at a constant speed over the surface creates a surface profile which will help to subsequently deduce the surface roughness parameters. The stylus probe has many limitations when it comes to measurement on different substrates[2]. The sharp probe of the stylus is not suitable for measurement on very delicate surfaces. The surface profile features collected is dependent on the diameter of the probe tip, which will limit the range of measurement. The measurement will lead to error when the stylus is used on a surface having a waviness or curvature. These drawbacks can be overcome if a non-contact method of surface roughness measurement is used[3]. Leveraging on optical methods offers fast and non-destructive way of measurement [4-15]. The interaction of coherent light with an optically rough surface creates diffraction, scattering and interference effects [16-24]. Optical surface measurement devices can be achieved through interferometric[25], scattering [17, 26] or microscopic methods[27]. The laser speckles are generated when a coherent beam of light interacts with an optically rough surface[28]. These speckles are characterized by its inherent properties which can be used for surface parameter extraction [29]. The speckle method can be applied with Fraunhofer diffraction model to record the power spectral density of the test surface at the imaging system, for roughness measurement[30]. The speckle correlation is another method for extracting surface roughness parameters from two speckles recorded from the same spot on a surface. Here the two speckle patterns are recorded with a change in angle of illumination or change in wavelength of illumination. It is also reported that Young's fringes can be used for surface roughness measurement through contrast measurement of the fringes[10]. This method has shown measurement capability on wide range of roughness values. However, the method is limited by the complicated operational procedures. In comparison to all these methods, speckle techniques which use the intensity or contrast measurement would offer a potential alternative for in-process measurement of surface roughness, provided the surface variations are always within the limit of wavelength of illumination.

In this paper, speckle statistics are analyzed on a calibration plate sample which has mean roughness varying between 0.1μm to 0.8μm. This range of roughness corresponds to a surface equality in highly specular (shiny) to

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diffusive (rough) region. The parametric study on surface roughness is conducted in order to evaluate the variation in intensity and contrast of speckle pattern recorded at these roughness values.

THEORY

The speckles are generated when a monochromatic, highly coherent wave is scattered by an optically rough surface. The speckle patterns are very irregular with statistical properties bearing direct relationship to the surface roughness. The speckle patters are generated from surfaces which are diffusive in nature, which means that the surface profile discrepancies are in the order of wavelength of illumination. When a laser light is shined on this surface the surface acts like a source of secondary wavelets due to scattering effect. A speckle pattern is formed from these wavelets due to their random interference in space. The microscopic details of the surface features can be extracted from the statistical interpretation of these speckle patterns. The resultant amplitude of the wavelets at a point varies from zero to a maximum value, depending on the relative phase and amplitude of the wavelets. The resulting amplitude of the waves, $A(x, y, z)$ can be written as shown below[28]

$$A(x,y,z)=\sum_{k=1}^{N}\left|a_k\right|\exp(i\phi_k) \tag{1}$$

Where N is a number which represents scattered wavelets and ak and φk are the amplitude and phase information from the k^{th} elements of scattering from the surface. The wave intensity I(x, y, z) is represented by

$$I(x,y,z)=\left|A(x,y,z)\right|^2 \tag{2}$$

The contrast of the speckle C, is factor which is determined by the ratio between standard deviation and the mean intensity $<I>$

$$C=\frac{\sigma}{\langle I\rangle} \tag{3}$$

Where, standard deviation of intensity is given by,

$$\sigma=\sqrt{\langle I^2\rangle-\langle I\rangle^2} \tag{4}$$

And mean intensity by,

$$\langle I\rangle=\frac{I_1+I_2+I_3+\ldots+I_N}{N} \tag{5}$$

The contrast is related to surface height variation σ_h through the following relationship

$$C=\sqrt{\frac{8(N-1)\left[N-1+\cosh\left(\left(4\pi\frac{\sigma_h}{\lambda}\right)^2\right)\right]\sinh^2\left(\left(4\pi\frac{\sigma_h}{\lambda}\right)^2\Big/2\right)}{N\left(N-1+e^{\left(4\pi\frac{\sigma_h}{\lambda}\right)^2}\right)^2}} \tag{6}$$

Where, N represents the number of surface height correlation areas within the corresponding zone of the point spread function

If the surface roughness is within the dimension of wavelength of illumination, the standard deviation would be lower than the mean intensity and the contrast C is always less than unity. Such speckles are termed as partially developed speckles. For surface features greater than wavelength of illumination, the speckle patterns are always within the negative exponential decay probability density and it is known as fully developed speckles. Since these speckles can be called as a direct fingerprint of the surface roughness, many researchers have studied different ways of using them to measure the surface roughness.

EXPERIMENTAL RESULTS AND DISCUSSION

The schematic of experimental set up is presented in Fig.4 (a). A Helium-Neon (He-Ne) laser with a wavelength of illumination λ = 0.633µm is used to illuminate the calibration plate, and the speckle pattern is captured with a CMOS camera placed in the far-field plane. NIST authorized calibration plate has a surface roughness variation between Ra=0.2µm to Ra=0.8µm. The angle of incidence is varied between $\theta=0^0$ and $\theta=45^0$ for parametric study on angle of illumination. Fig.1 (b) shows the experimental arrangement for angle of incidence at $\theta=0^0$ and $\theta=22^0$.

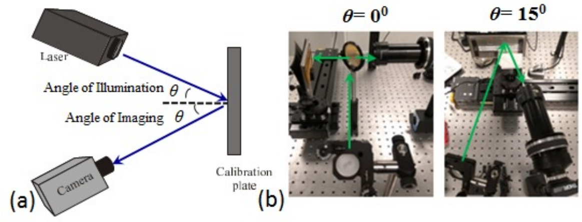

Fig.4 (a) Schematic of experimental arrangement for intensity and contrast measurement (b) photograph of experimental set up for angle of incidence variation

Intensity and contrast variation with respect to surface roughness

The intensity and contrast variation on the speckle generated from the standard Microinch Flexbar comparator BELT16044, with belt sanding machining method having a dimension of 25mm X 128mm is shown in Fig. 2. The angle of incidence is kept constant at $\theta=45^0$ throughout this experiment. It is observed that both the intensity and contrast value vary with surface roughness. The values are repeatable at single point with number of trial (N=10). The variation in speckle pattern intensity with respect to different surface roughness is shown in Fig.3

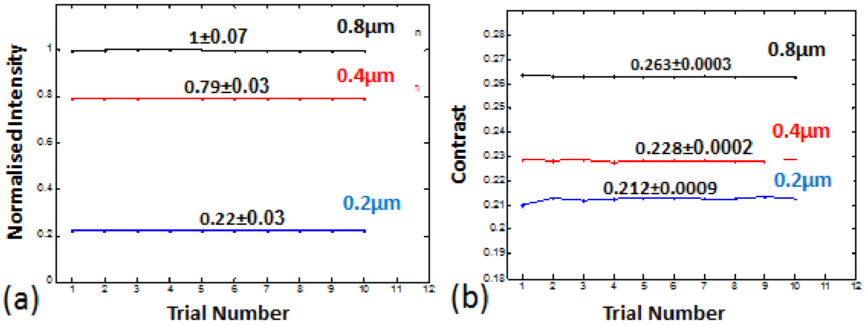

Figure. 2. (a) variation in normalised intensity and (b) contrast with respect to surface roughness

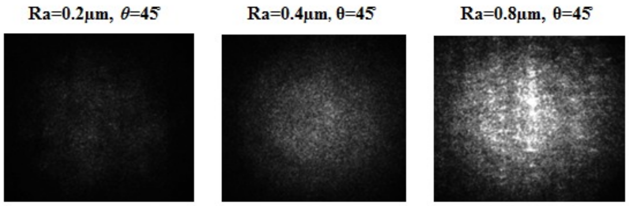
Ra=0.2µm, θ=45
Ra=0.4µm, θ=45
Ra=0.8µm, θ=45

Fig.3. Speckle pattern showing variation in intensity for different surface roughness values

Intensity and contrast variation with respect to angle of incidence.

The angle of incidence is varied between $\theta = 0^0$ and $\theta = 45^0$, in order to study the variation in mean intensity $<I>$ and contrast (C) of the speckle pattern. Fig.4 shows $<I>$ variation with respect to different angles of incidence. The intensity is observed to be increasing with increasing roughness. However, the linearity of intensity variation is not good with respect to roughness variation. A better linearity is observed only at an angle of incidence $\theta = 22^0$.

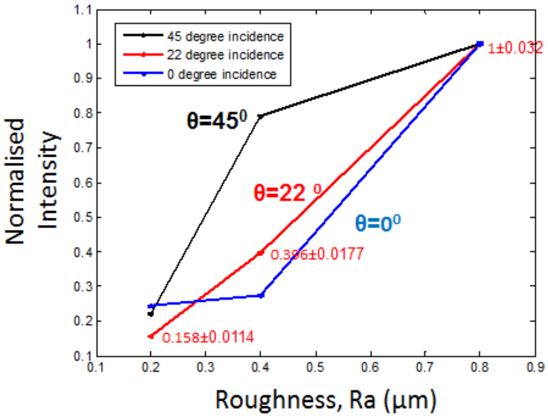

Fig.4. Variation in normalised intensity with respect to surface roughness (Ra) for different angles of incidence.

Variation in contrast with respect to surface roughness variation is shown in Fig. 5. A linear variation in contrast with respect to different *Ra* values. The sensitivity of contrast variation is more prominent for normal angle of incidence. The sensitivity goes on decreases and reaches a lowest value at $\theta = 45^0$.

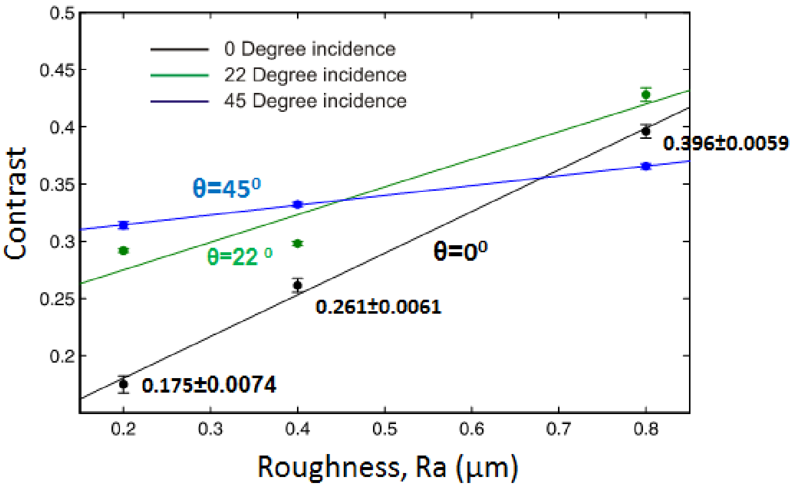

Fig.5. Variation in contrast value (C) with respect to surface roughness (Ra) variation for different angles of incidence

These results shows that first order parameters such as normalised intensity and contrast measurement can be adopted for surface parameter extraction. Contrast variation is more linear with respect to Ra variation. An angle of incidence between 0^0 to 22^0 is optimal for the measurement so that more sensitivity is obtained for the measurement system.

CONCLUSIONS

In this paper, the speckle intensity and contrast is used for measurement of surface roughness of standard calibration plate sample with *Ra* varying from 0.2µm to 0.8µm. The measurement technique is very simple and requires one laser and an imaging system. The effects of variation in Ra and angle of incidence on the speckle statistics are studied. It is found that for an angle of incidence on between 0^0 to 22^0, the speckle contrast is more sensitive to the surface roughness variation. The speckle contrast measurement technique has many advantages as it can be implemented as a non-destructive and non-contact surface roughness measurement method. Hence it is foreseen that this acclaimed methodology can be applied to in-process industry measurements.

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