# Experimental investigations and parametric studies of surface roughness measurements using spectrally correlated speckle images

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## ABSTRACT

The surface roughness parameters encoded in a speckle pattern can be effectively extracted through correlation experiments. In the case of spectrally correlated speckle images, the degree of decorrelation arises from wavelength difference in the laser light irradiated on the surface. To obtain accurate results in such methodology, a proper design of experiments is important due to more than one parameter involved in the experiment. Here, experimental investigations and parametric studies of surface roughness measurements using spectral speckle correlation methodology are presented, considering the potential variables in the system. The sources of error and factors affecting the accuracy in measurement are identified and the experimental results obtained from standard calibration plate samples are presented.

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

## 1. INTRODUCTION

Surface roughness measurement of machined components measured with a high accuracy is important in engineering industries[1, 2]. Currently stylus based profilometers are generally used for surface roughness measurement on sample surfaces[3]. However, the stylus based profilometers, which have sharp diamond tips, might produce micro-scratches on the machined surface and consume lot of scanning time during measurement[4]. To subdue these problems, non-contact surface profilometers based on optical methods such as laser scanning, confocal scanning and white light interferometry can be employed. Although these non-contact optical methods can produce high-resolution 3D surface profile of rough or shiny machined surface, they are not suitable for in-process measurement due to their inherent working mechanisms. Thus, there is a growing need of non-contact and in-process measurement method which can evaluate surface roughness of machined surfaces at faster speed to match industry requirements [5]. Among the optical methods, laser speckle techniques offer fast and non-destructive way of measurement [6-17]. The interaction of coherent light with an optically rough surface creates diffraction, scattering and interference effects and generates speckles [18-29]. These speckles are characterized by its inherent properties which can be used for surface parameter extraction [30, 31]. When an optically diffusive surface is irradiated with a coherent wave, it gets scattered in all possible directions. The scattered waves undergo interference and develops interference pattern containing dark and bright spots, which are randomly spread in the area, known as speckle pattern. A fully developed speckle pattern is obtained when the phase difference in the illumination waves is large enough to cause a destructive interference. For a destructive interference, the path difference between waves should be $\geq \lambda/2$, where $\lambda$ is the wavelength of illumination. Thus, for a surface which doesn't form a fully developed speckle, the contrast of the speckle can be used for surface roughness evaluation[30]. Since the speckle statistics depends on the properties of coherent source and the scattering surface, the spatial parameters of the speckle pattern can be studied to identify the surface properties of sample under investigation[32]. The two speckle patterns form a single surface can be taken for correlation study if it is developed from an isotropic and homogeneous material, where shadowing and multiple reflections is negligible and the root mean square (RMS) surface roughness is greater than the wavelength of coherent illumination[33]. In particular, the intensity correlation of two different speckle patterns can be used for measuring surface profile parameters[8]. Both, the change in angle of

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illumination (Angular Speckle Correlation) and the change in illumination wavelength (Spectral Speckle Correlation) can be used to evaluate the degree of decorrelation of speckle patterns.

In this paper, SSC experiments are reported for surface roughness measurements of samples with mean roughness varying between 0.1µm to 1.6µm. This range of roughness corresponds to a surface quality of highly specular (shiny) to a diffuse (rough) region. The sources of error and the factors affecting the accuracy of measurement is identified, from the experimental results obtained using the standard calibration plates as test samples.

## 2. THEORETICAL ANALYSIS

The two speckle images from a rough surface can be correlated if (a) its root mean square (RMS) surface roughness is greater than the wavelength of coherent illumination; (b) it produces fully developed speckle patterns and surface profile probability distribution is Gaussian and (c) it is formed by isotropic and homogeneous material whereby shadowing, multiple reflections and volume scattering can be neglected. In a typical SSC experiment, two speckle patterns are recorded with two different wavelengths of illumination ($\lambda_1$ and $\lambda_2$) on a sample surface at a fixed angle of illumination ($\theta$) as shown in Fig.1. The two speckle patterns are then correlated to evaluate the surface roughness of the sample under investigation (Calibration plate). The correlation factor in such a case is given by [16] ,

$$C = \exp(-(2R_q \Delta k \cos\theta)^2) \tag{1}$$

Where, $Rq$ is R.M.S roughness of the sample and $\theta$ is the angle of illumination. The factor $\Delta k$ is the difference between the wavenumber of two illuminations and is given by

$$\Delta k = 2\pi\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right] \tag{2}$$

Combining Eqn (1) and Eqn (2) gives,

$$C = \exp\left[-\left[\frac{4\pi\Delta\lambda}{\lambda_1\lambda_2} R_q \cos\theta\right]^2\right] \tag{3}$$

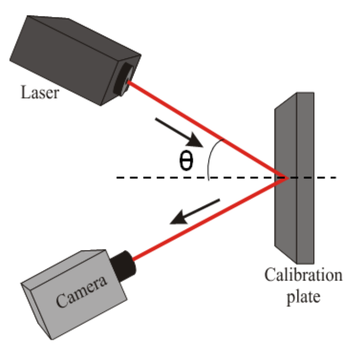


Figure 1. Schematic of experimental arrangement for SSC

The mathematical expression relating the arithmetic average height $Ra$ and RMS roughness $Rq$ is given by,

$$Ra = \frac{1}{l}\int_0^l |\, y(x)\,|\, dx \tag{4}$$

$$Rq = \sqrt{\frac{1}{l}\int_0^l \{y(x)\}^2\, dx} \tag{5}$$

Here, $y(x)$ is the shape deviance from the mean line and $l$ is the sample length. Also, assuming a Gaussian height distribution for the specimen surface under consideration, $Ra$ and $Rq$ can be related by[2],

$$Ra = \sqrt{\frac{2}{\pi}} Rq \tag{6}$$

This relation is valid for speckle patterns that are recorded on the optical axis, on the assumption that shadowing effects and multiple scatterings are negligible. The roughness parameter can be directly extracted from the $C$ value, knowing the other parameters in the experiment. The range of surface roughness measurement can be varied through proper selection of wavelengths of illumination.

Let $I_1\,(i,j)$ and $I_2\,(i,j)$ be the intensities at one point of two different speckle patterns obtained through two different wavelength of illumination $\lambda_1$ and $\lambda_2$, respectively. The spectral speckle correlation $C$ can be deduced from these images by using the following expression,

$$C = \frac{\langle I_1 I_2\rangle - \langle I_1\rangle\langle I_2\rangle}{\left[\left(\langle I_1^2\rangle - \langle I_1\rangle^2\right)\left(\langle I_2^2\rangle - \langle I_2\rangle^2\right)\right]^{1/2}} \tag{7}$$

Where, $\langle I\rangle$ and $\langle I_1 I_2\rangle$ is given by,

$$\langle I\rangle = \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n} I(i,j) \tag{8}$$

$$\text{And } \langle I_1 I_2\rangle = \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}\left[I_1(i,j) I_2(i,j)\right] \tag{9}$$

Where, n is the size of the sampling elements in the speckle image, i and j denote the individual picture element.

The relation ship between C and $Ra$ can be carefully analysed using Eqn(3) and Eqn(6). The range of surface roughness that can be sensitively measured through SSC is dependent on the chosen wavelengths, ($\lambda_1$ and $\lambda_2$) and difference in wavelength ($\Delta\lambda$) of illumination. Fig.2 shows variation of $C$ with respect to different $Ra$ values for a chosen value of $\Delta\lambda$. It shows that the illumination wavelengths need to be carefully chosen to make the variation of $C$ linearly cover the roughness range. For example, a $\Delta\lambda$ value of 26nm can be used to sensitively measure the surface roughness varying between 0.1μm to 1.6μm.

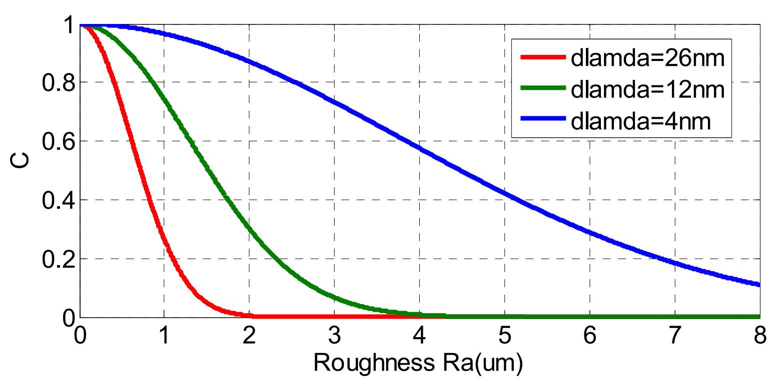


Figure 2. Spectral speckle correlation factor(C) as a function of arithmetic mean surface roughness (*Ra)* for different spectral difference $\Delta\lambda$ .

From the analysis, it is also found that the initial illumination angle plays a role to affect the correlation factor. Fig.3 shows the varitaion of *C* with respect to *Ra* values in the range 0.1µm to 1.6µm, for different angles of illumination. The correlation factor is observed to be approximately invariant only when the angle of illumination is small.

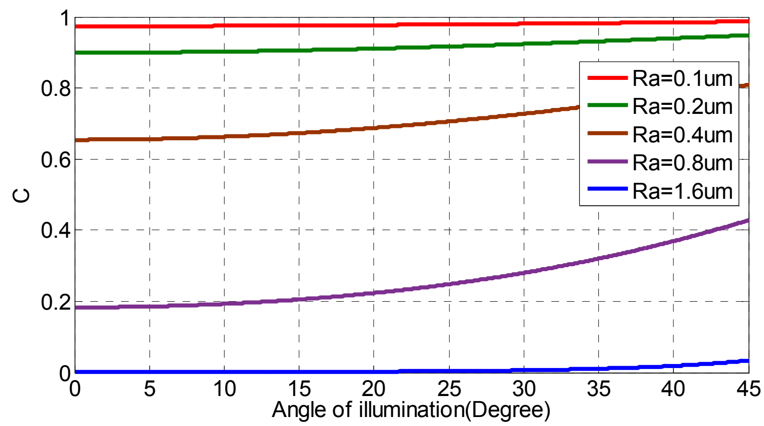


Figure.3. Spectral speckle correlation factor (*C*) as a function of arithmetic mean surface roughness (*Ra)* for different angles of illumination.

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

The schematic of the experimental arrangement is shown in Fig.4(a). An Argon laser with a multiline emissions at 488nm and 514nm is used in the experiment. NIST authorsied calibration plate with surface roughness varying bewteen *Ra*=0.1µm and *Ra*=1.6µm is used for experiment. The angle of illumination is varied from $\theta=0^0$ to $\theta=45^0$ for parametric study on angle of illumination. Fig.4 (b) shows the experimental arrangement for angle of illumination at $\theta=0^0$ and $\theta=15^0$. A CMOS camera with a lens having an aperture control is used for capturing the speckle images.

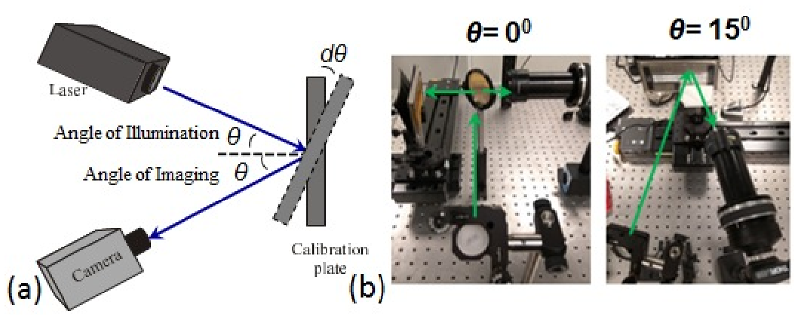


Fig.4 (a) Schematic of experimental arrangement for SSC study (b) experimental set up for angle of illumination variation

### 3.1 The study of correlation factor variation with respect to surface roughness

Ten trails are performed for each of the roughness regions of the calibration plate. A standard Microinch Flexibar comparator BELT16044 with mean roughness (Ra) range between 0.1µm and 1.6µm is used for the tests. The comparator plate which has been manufactured by the belt sanding technique has a dimension of 15mmx24 mm in each area. The angle of illumination has been kept constant at θ=450 throughout the experiment. The results obtained are plotted in Fig.4. A negative exponential variation in C with respect to Ra values is observed. Table.1 summarizes the values of correlation and the calculated Ra in comparison to the Ra of a standard calibration plate. It can be observed that the SSC method offers a very consistent measurement of Ra between the 0.2µm and 0.8µm, with a standard deviation less than or equal to 0.1.

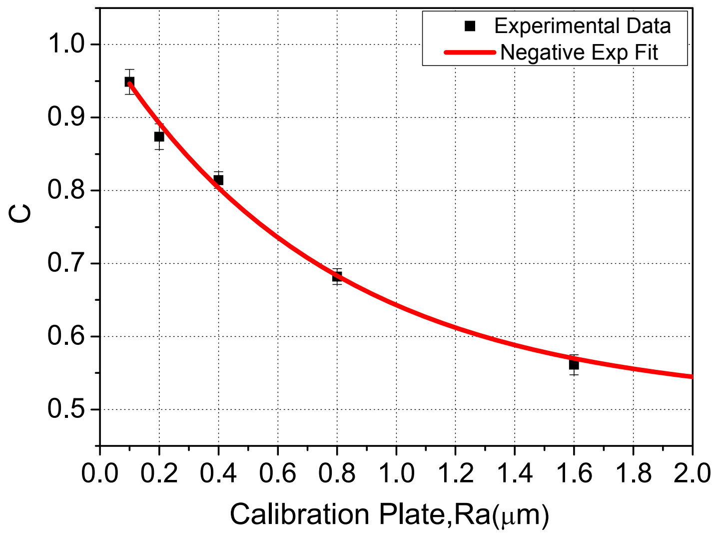


Figure. 4. Spectral speckle correlation factor variation with respect to Ra values on the calibration plate

Table 1. Comparison between surface roughness parameters of standard Microinch Flexbar calibration plate and the mean correlation(C) and roughness (Ra) with standard deviation obtained from spectral speckle correlation method ($\theta = 45^0$)

| Calibration plate *Ra* (μm) | SSC correlation Factor(C) | SSC measured Ra (μm) |
|---|---|---|
| 0.1 | 0.95±0.02 | 0.10 ± 0.03 |
| 0.2 | 0.87±0.02 | 0.24 ± 0.03 |
| 0.4 | 0.81±0.01 | 0.37 ± 0.03 |
| 0.8 | 0.68±0.01 | 0.81 ± 0.05 |
| 1.6 | 0.56±0.01 | 1.74 ± 0.19 |

### 3.2 The study of correlation factor variation with respect to angle of illumination

The angle of illumination has been varied between $\theta = 0^0$ and $\theta = 45^0$, in order to study the variation in *C*. Fig.5(a) shows variation in *C* with respect to different angles of illumination. The experimental curve matches with theoretical analysis obtained as shown in Fig. 3. The correlation values are observed to be uniform for an angle of illumination between $\theta = 0^0$ and $\theta = 22^0$

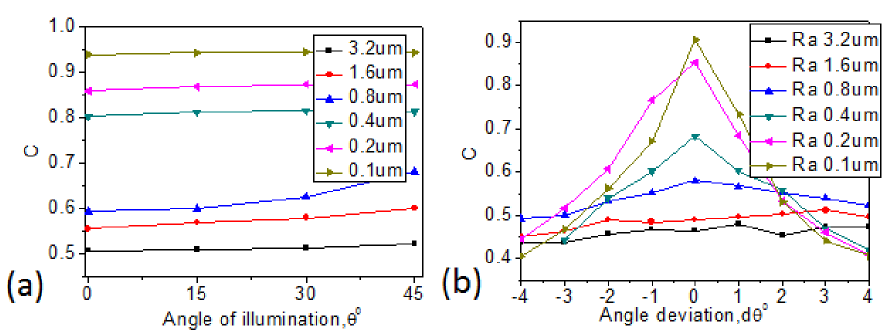


Fig.5 Variation in correlation value (*C*) with respect to (a) angle of illumination (θ) (b)angle of deviation d$\theta$

The sensitivity of C to the tilt of the sample is studied through small angle deviation d$\theta$ given to the calibration plate surface. The correlation is observed to be sensitive to the angle deviation for more specular surface type as shown in Fig.5 (b). Therefore in a real measurement system the optical axis misalignment should be minimized for obtaining more accurate results. This can be achieved through proper positioning of the camera and maximizing the speckle intensity in the field of view of the camera.

### 3.3 Effect of aperture, exposure time and ambient light variation

The average speckle size is inversely proportional to the aperture size of the imaging system. In order to resolve the speckles completely, the speckle size must be comparable to the pixel size of the camera. Thus in order to increase the average speckle size, a smaller aperture would be required. It is observed that the correlation values remains constant until an *f*-stop of f/11, when the aperture size is increased from *f*/22 to *f*/4. Beyond the aperture setting *f*/11, the correlation property of the two speckle images are lost due to multiple speckles that flood a single pixel on the sensor. Fig.6 shows the *C* variation obtained for an aperture variation in an imaging lens. The spectral speckle correlation value is observed to be insensitive to the exposure time and ambient light in the lab. To verify the dependency of SSC on the ambient light, experiments were conducted in darkroom and lab light environment. It is observed that SSC is independent on the ambient light. For example SSC in dark room condition is observed to be $SSC_{dark}$= 0.5904 and lab light condition is observed to be $SSC_{light}$=0.5975., for *Ra*=0.8um. The ambient light dependency can be completely eliminated through proper filter usage in the camera.

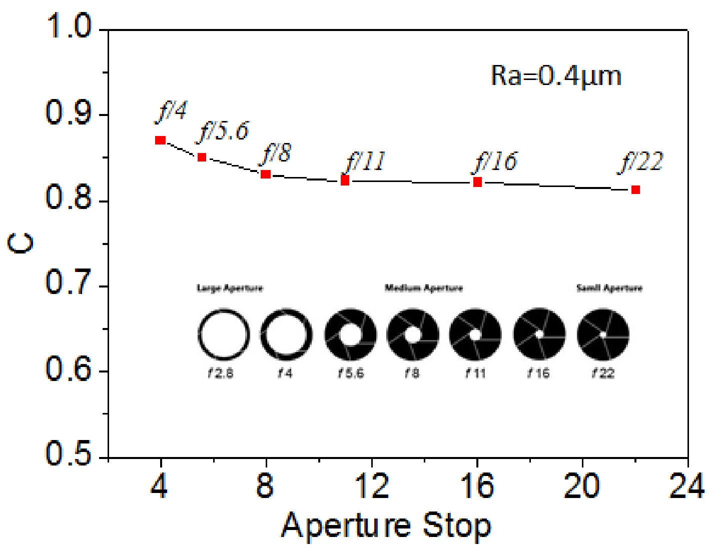


Figure 6. Variation in C with respect to aperture size of the imaging lens

## 4. CONCLUSIONS

In this paper, the spectral speckle correlation technique is used for measurement of surface roughness of standard calibration plate sample with *Ra* varying from 0.1µm to 1.6µm. The measurement technique requires minimum optical components but is sensitive to alignment according to our study. The affect of angles of illumination and its deviation on the correlation value is studied and it is found that if the angle of illumination on the specimen surface is between $0^0$ to $22^0$, the correlation is nearly uniform. The surface roughness parameter is directly related to the correlation factor between two speckle images obtained in the far-field plane of the sample rough surface illuminated at two different wavelengths. The roughness parameters measured with this method are consistent with standard optically diffusive specimens. The spectral speckle correlation technique has many advantages in terms of repeatability, accuracy and time efficient measurement and it can be implemented as a non-destructive and non-contact surface roughness measurement method. Hence, it is envisaged that this proposed methodology can be applied to in-process industry measurements in the future.

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