Autocorrelation analysis of spectral dependency of surface roughness speckle patterns

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Abstract: When a surface is illuminated with a highly coherent light such as a laser beam, the speckle pattern of bright and dark regions is observed. It depends on the surface parameters and carries important information about the roughness of the surface. Various methods and techniques are employed for the determination of surface roughness parameters from speckle pattern properties. In this paper, an experimental approach for surface roughness evaluation based on the autocorrelation analysis of the spectral properties of speckle patterns caused by milled metal surfaces is reported. The speckles at three 633, 604 and 543 nm wavelengths of He-Ne laser were analyzed. It was found that autocorrelation analysis is very sensitive to small variations in speckle sizes, caused by spectral properties of speckle patterns such as increasing the wavelength lead to increased speckle sizes. The results are in good agreement with the results obtained from the mechanical stylus profilometer for the milled metal surfaces with roughness values \( R_a ; 0.36 \mu m \) (low roughness) and 1.98 \( \mu m \) (high roughness). The technique reported here has a great potential for precise and non-contact optical measurements of rough surfaces.

Keywords: Laser speckle images, Surface roughness, speckle correlation analysis, spectral dependency

I. INTRODUCTION

Surface roughness plays a great role in determining the desired quality of a machined metal surface for today’s engineering industry. The roughness is defined as the irregularities on a material surface as a result of various machining operations. The symbol \( R_a \) is commonly used to describe it in literature as an average roughness. Theoretically, \( R_a \) is the arithmetic average value of departure of the profile from the mean line throughout the sampling length. \( R_a \) is also an important factor in controlling machining performance during end milling operations [1]. Nevertheless, the surface roughness measurements based on the stylus instrument have some drawbacks such as possible surface damages, long measuring times and difficulty of in-situ measurement process. These drawbacks have prompted the development of alternative techniques including optical methods such as optical interference and light scattering techniques for the surface roughness measurement as non-contact optical methods leading to non-destructive, fast and continuous measurements [2-6].

When a laser beam is shone onto a rough surface, a grainy pattern is observed in the reflected beam. This pattern is called “speckle pattern” as shown in Fig.3. It is caused by the interference of the laser light shone onto the rough surface due to random phases based on the surface roughness. Furthermore, this pattern carries important information about the roughness of the surface.

A number of studies have been reported in literature evaluating the surface roughness on the machined metal surfaces by using non-contact optical methods including speckle pattern method [7-8]. An experimental approach has been introduced in [9] based on the speckle pattern correlation technique for the measurement of the surface roughness on the machined surfaces such as grinding and milling. The speckle patterns of the machined surfaces are captured using a collimated laser beam (He-Ne laser, 10 mW, \( \lambda =633 \) nm) and a CCD camera. A theoretical approach depending on the speckle pattern has been presented for the measurement of the surface roughness in [10]. Toh et al. [11] reported a speckle correlation technique for the estimation of the surface roughness ranging from 1.6 to 50 \( \mu m \) at different incidence angles (5º, 15º, 30º, 45º) in the far-field plane. Persson [12] has presented an experimental work evaluating the surface roughness by utilizing angular speckle correlation (ASC) technique on the machined surfaces where a laser beam (He-Ne) is employed to illuminate the surface at an incidence angle of 45º. Wong and Li [13] focused on a new optical system which utilizes the combined effects of interference and light scattering for the surface roughness measurements in a grinding process. Tay et al. [14] have proposed a light scattering technique to measure the roughness of semi-conductor wafers. This technique utilizes a low power He-Ne laser beam and records surface roughness in the nanometer range with a high degree of accuracy. Tian et al. [15] showed that a new approach integrating speckle pattern correlation and light scattering methods to evaluate surface roughness for a measuring range.

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from 0.05 to 1.6 μm. This approach employs a laser and two cameras. The laser emits a certain light pattern on the surface to be measured and while camera 1 is used to measure the surface form and waviness using the light scattering method, camera 2 is used to control surface roughness with speckle pattern.

In this paper, the spectral properties of speckle patterns of face-milled metal surfaces were analyzed by means of statistical autocorrelation method. The variation of various autocorrelation parameters with different wavelengths and surface roughness were investigated. The results are in good agreement with the surface roughness values obtained by the mechanical system (the stylus method).

II. EXPERIMENTAL SET-UP

Experimental set-up is in two stages: first one is the milling and measuring of CK 45 steel specimens and the second is the optical system making use of the speckle pattern method. Several experiments were performed to collect the surface roughness values on MANFORD CNC milling machine controlled with Fanuc i-MC series under wet conditions. The CK45 steel material samples had the dimensions of 40x40x40 mm³. The surfaces were measured by MAHR Perhometer S4P roughness tester. The cut-off length was set to be 2.5 mm. The milling process is shown in Fig.1.a and the surface roughness measurements are illustrated in Fig.1.b.

Figure 1. The milling process on CK45 steel specimens (a) and surface roughness measurements by profilometer the surfaces (b).

The optical system shown schematically in Fig.2 was designed for the measurement of the surface roughness on CK45 steel specimens by using spectral speckle pattern properties. Three wavelengths of CW He-Ne laser (λ=633, 604 and 543 nm) were used to illuminate the sample surfaces where the angle of illumination is 45°. A spatial filter (f/4) was utilized to create smooth laser transverse intensity profile. A lens (f=50 mm) was employed to produce a small intense light spot on the specimen surface. The scattered light was recorded by a long distance microscope (LDM) (8x) and by CCD camera Prosilica-GC11350 with a full resolution of 1024x1360 pixels, placed perpendicularly to the surface.

The output power of He-Ne laser at various wavelengths is different. On other hand, the spectral sensitivity of CCD pixels also varies with wavelength. We have therefore performed a radiometric calibration of optical system using a smooth white surface. The output power of laser at 543 nm (lowest for this laser) was attenuated by a set of neutral density filters to a desired value at which the gray level of the reflected from the reference surface image pattern at a given exposure time was below saturation. The gray level histogram of this image was selected as a reference for the intensity calibration of other (λ=633 and 604 nm) wavelengths, whose histograms were adjusted by means of additional neutral density filters and small changes in exposure times. The beam was plane polarized at every wavelength.

Distance between surface (L) and LDM was kept constant for all the surface measurements. The illuminated area of the rough surface was 1 mm². Speckle pattern images were recorded for two different metal surfaces of roughness values Rₐ; 0.36μm (low roughness) and 1.98μm (high roughness). Fig.3 shows a CCD image of the speckle pattern obtained by using this optical measurement system.

Figure 2. Schematic diagram for speckle pattern formation where LDM, L, ND, P and SF are long distance microscope, lens, neutral density filter, pinhole and spatial filter, respectively.

III. RESULTS AND DISCUSSIONS

If the speckle is recorded directly by means of any 2D detector without any imaging optics in the free space, the
obtained pattern is called “objective” speckle. In this case, the average speckle size is:

\[ d = 1.2\lambda \frac{L}{D} \]  

(1)

where, \( L \) is the distance from surface to the observation plane, \( D \) is diameter of the illuminated spot and the \( \lambda \) is the wavelength of the laser beam. It is clear that for a given geometry \( (L/D) = \text{const.} \), the average speckle size is proportional to the incident laser wavelength.

Another type of speckles is called “subjective” speckles. Every imaging system (human eye, microscope objective, etc.) between reflecting surface and recording detector alters the coherent superposition of waves and thus produces its own speckle size. Detailed information on “subjective” speckles can be found elsewhere [16]. We will however give the final formula for the average speckle size:

\[ d = 1.2\lambda(1 + M) \frac{f}{D} \]  

(2)

where, \( M \) is the imaging system magnification, \( f \) is focal distance and \( \lambda \) is the wavelength of the laser beam.

It is obvious that for a given surface and constant imaging system parameters, the average speckle size will increase with increasing wavelength.

The speckle patterns obtained in our experiments are the “subjective” speckles. Fig. 3 depicts a typical pattern obtained from the experimental set-up where a CCD image (1024x1360 pixels) of a speckle pattern obtained from the surface of a milled specimen with a roughness of \( R_a = 1.98 \mu m \)

Fig. 4. shows gray level distribution along the central line of the digital speckle patterns for 543 nm and 633 nm illumination wavelengths. A correlation analysis together with computation of several parameters which established a quantitative relationship between speckle pattern and surface roughness have been introduced in [17]. As a figure of merit, various parameters of the normalized autocorrelation (AC) function was employed as given below

\[ AC = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} (g(i,j) - g_o)(g(i + \delta_i, j + \delta_j) - g_o)}{\sum_{i=1}^{M} \sum_{j=1}^{N} g^2(i,j)} \]  

(3)

Here, \( g(i, j) \) is the actual grey level obtained from subtraction of noise signal obtained from the dark image of the CCD camera from the recorded original grey level and \( g_o \) is the mean intensity value. The integers, \( \delta_i = 1, ..., M \) and \( \delta_j = 1, ..., N \), are pixel shift values. In this study, we examined the observed patterns with the following parameters:

- (1) Integrated autocorrelation coefficient, \( ACI(X) \), (shift in x-direction of lag length \( \delta_j \) which varies between 1 and \( N) \)

\[ ACI(X) = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} g(i,j) x g(i, j + \delta j)}{\sum_{i=1}^{M} \sum_{j=1}^{N} g^2(x,y)} \]  

(4)
(2) Integrated autocorrelation coefficient \( ACI(Y) \) is calculated shifting the image in the y-direction with steps of \( \delta i \) which varies between 1 and M.

\[
ACI(Y) = \frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} g(i, j) x g(i + \delta i, j) - \sum_{i=1}^{M} \sum_{j=1}^{N} g^2(x, y) \tag{5}
\]

(3) Integrated autocorrelation coefficient \( ACI(XY) \) is calculated shifting the image in the diagonal direction with steps of \( \delta i \) and \( \delta j \) where \( i \) and \( j \) vary between 1 and M, 1 and N, respectively.

\[
ACI(XY) = \frac{1}{MN} \sum_{i=1}^{M} \sum_{j=1}^{N} g(i, j) x g(i + \delta i, j + \delta j) - \sum_{i=1}^{M} \sum_{j=1}^{N} g^2(x, y) \tag{6}
\]

Figures 5 and 6 show the variation of \( ACI(X) \), \( ACI(Y) \), and \( ACI(XY) \) with laser wavelength for the metal surface with \( R_a \); 0.36\( \mu \)m and 1.98\( \mu \)m, respectively. Since we have used normalized autocorrelation functions, their values are equal to unity at the origin. By increasing the shift in both directions the function decreases to a certain constant value. This behaviour was observed for all patterns. The fall speed autocorrelation functions characterize the speckle size. The decrease of the fall speed with increasing wavelength was observed for all patterns.

Tables 1, 2 and 3 show integrated \( ACI(X) \), \( ACI(Y) \), \( ACI(XY) \) autocorrelation function parameters versus with illumination wave length. It has also been observed that the parameters decrease with decreasing illumination wave lengths.

### Table 1. Variation of integrated autocorrelation function parameters with 633 nm illumination wave length and Stylus roughness values of the surfaces.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Stylus values (( \mu )m)</th>
<th>Integrated Autocorrelation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ra</td>
<td>AC(X)</td>
</tr>
<tr>
<td>1</td>
<td>0.36</td>
<td>156.21</td>
</tr>
<tr>
<td>2</td>
<td>1.98</td>
<td>166.21</td>
</tr>
</tbody>
</table>

### Table 2. Variation of integrated autocorrelation function parameters with 604 nm illumination wave length and Stylus roughness values of the surfaces.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Stylus values (( \mu )m)</th>
<th>Integrated Autocorrelation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ra</td>
<td>AC(X)</td>
</tr>
<tr>
<td>1</td>
<td>0.36</td>
<td>138.38</td>
</tr>
<tr>
<td>2</td>
<td>1.98</td>
<td>160.34</td>
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</table>

### Table 3. Variation of integrated autocorrelation function parameters with 543 nm illumination wave length and Stylus roughness values of the surfaces.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Stylus values (( \mu )m)</th>
<th>Integrated Autocorrelation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ra</td>
<td>AC(X)</td>
</tr>
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<td>0.36</td>
<td>133.56</td>
</tr>
<tr>
<td>2</td>
<td>1.98</td>
<td>157.96</td>
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</tbody>
</table>
Figure 5. Changes of AC function of speckle patterns with laser wavelength for the low rough surface. Shifting was carried out in X, Y and diagonal (XY) directions.

Figure 6. Changes of AC function of speckle patterns with laser wavelength for the high rough surface. Shifting was carried out in X, Y and diagonal (XY) directions.
CONCLUSIONS

An experimental investigation of the spectral properties of speckle patterns from the rough metal surfaces was studied. The variation of the autocorrelation parameters with various illumination wavelengths was examined. It was found that, with increasing wavelengths, the average speckle size increases. It is known that light source selection using rough surface illumination is crucial when especially high accuracy roughness measurements are required [18]. It is therefore important to establish an extensive relationship between the wavelength, speckle size and roughness. Once this relationship is established, it would then be possible to utilize laser based systems with better flexibility for white light interferometers. In addition, the results show that the autocorrelation analysis has a great potential for the noncontact optical surface roughness measurements.

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REFERENCES