Evaluation of 3D Surface Roughness of Milled Surfaces using Laser Speckle Pattern

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Abstract. 3D surface roughness of milled aluminium surface was evaluated using the laser speckle pattern. The milled surface was produced from aluminium alloy Al 6061 material at ten different feed rates using CNC milling machine. Laser beam was directed onto the aluminium surface and the scattered beam from the surface of the sample underwent interference to produce laser speckle pattern. Coefficient of Determination between various characteristic features and 3D surface roughness were determined and it was found that 3D surface roughness parameter $Sv$ have coefficient determination above 0.5 with mean, $G_a$, roughness, entropy and normalized ACF.

1. Introduction

Surface roughness refers to the finely spaced surface irregularities which are result of machining operation in case of machined surface. The quality of the surface plays a very important role in the performance of milling operation as a good quality milled surface significantly improves fatigue strength, corrosion resistance, or creep life [1]. Surface roughness also affects several functional attributes of parts such as contact causing surface friction, wearing, light reflection, heat transmission, ability of distributing and holding a lubricant, coating, or resisting fatigue. Since surface roughness plays an important role in the quality of the milled surface, therefore surface roughness of milled surface must be verified that it is within the specified roughness.

Measurement of surface roughness can be done either by contact method or non-contact method. The widely used contact method is diamond stylus probe. This conventional approach has some drawbacks, although it is still widely used surface topography measurement technique. There are some critical factors such as stylus tip dimensions and scan parameters (sample length, evaluation length, speed, rate of scanning and force applied on the measured sample).

Optical methods are non-destructive, non-contact and accurate and therefore have advantages over stylus technique. There are various types of optical method and one among them is laser speckle method. When a coherent laser light falls onto a rough surface, the rough surface will act as a secondary source and scatters the laser light. This scattered light will undergo interference and will form randomly arranged granular structures called speckle pattern. There are two basic schemes of speckle pattern formation, one is known as objective speckle and another one is known as subjective speckle as shown

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in figure 1 [2]. In case of objective speckle, the patterns formed at free space geometry as shown in figure 1(a). In case of subjective speckle, the patterns formed are focused using a lens onto the screen as shown in figure 1(b).

For speckle interferometry, the properties of the laser beam has to be monochromatic and coherent and therefore the laser normally used are He-Ne lasers [3]. Laser mode of TEM00 is used as it produces a Gaussian beam.

Several surface roughness measurement method using laser speckle image had been proposed. In speckle contrast method, the relation between speckle contrast and surface roughness was used for determining the surface roughness. Speckle contrast method usually can evaluate surface roughness Rₐ < 0.3 µm. In case of angular speckle correlation method and polychromatic speckle correlation method, the relation between coefficient of correlation obtained from two speckle image and surface roughness was used for evaluation of surface roughness. Speckle correlation method can work on surface roughness between 1 and 30 µm. Speckle correlation method requires two slightly different speckle image which can be obtained by varying angle of illumination (Angular Speckle Correlation – ASC) or by varying the illumination frequency ( Spectral Speckle Correlation – SSC). However other characteristics features had been extracted from the speckle image for correlating with surface roughness. Various techniques which had been used for correlating the characteristics features with the surface roughness are grouped into speckle contrast, speckle correlation, binarisation, phase unwrapping, Hurst exponent, Tsallis Threshold, Neural Network, Gray Level Co-occurrence Matrix (GLCM).

Goh and Ratnam [4] had assessed the 3D roughness parameters of milled surfaces using charged coupled device (CCD) flatbed scanner. From the scanned image, various characteristic features such as average pixel intensity, root mean square pixel intensity, variance, black to white ratio, bright region average area were extracted and correlated with Average height Sₐ and Root-Mean-Square height S_q. They had obtained good correlation.

Currently available methods for determining 3D roughness parameters are mostly optical methods. Some of them are white light interferometers[5, 6], focus variation method [7], confocal microscopy [8]. As a milled surface is 3D, it is naturally more appropriate to quantify the characteristics of the surface using 3D surface parameters[4]. The objective of the study is to propose the evaluation of 3D surface roughness parameters of milled surface from the laser speckle pattern.

2. Experimental Procedure

Milled samples are produced by machining Aluminium alloy Al 6061 material at different feed rate but at constant spindle speed of 6000 rpm and depth of cut of 1 mm using CNC 5 axis milling machine (DMU 40) with 3 flute end mill cutter of carbide type with Ø12 mm, at feed rates of 220, 265, 310, 355, 400, 445, 490, 535, 580 and 625 mm/min. Using Alicona Infinite Focus Microscope measuring.
equipment following 3D surface roughness parameters is measured from the milled surfaces and tabulated in Table 1:-

- Arithmetic Mean Height \( S_a \)
- Root-Mean-Square Height \( S_q \)
- Maximum Peak Height \( S_p \)
- Maximum Valley Depth \( S_v \)
- Maximum Height \( S_z \)
- Ten Point Height \( S_{10h} \)
- Skewness \( S_{sk} \)
- Kurtosis \( S_{ku} \)
- Root Mean Square Gradient \( S_{dq} \)
- Developed Interfacial area ratio \( S_{dr} \)

Laser beam from Helium Neon Laser of wavelength 633 nm and max power of less than 35 mW are cleaned using a spatial filter which consist of microscope objective lens (Edmund EFL 8.00) fitted in reverse direction and mounted pinhole (Size 15 \( \mu \)m). The cleaned laser beam falls onto the machined surface at an angle of 26.9° and the scattered beam will undergo interference and forms laser speckle pattern. This laser speckle pattern are captured using CCD camera (JAI CV-M50) fitted with TV zoom lens (1:1.2 / 12.5 – 75) and extension tube of size 20 mm. The CCD camera is placed normal to the machined surfaces. The images are stored in Tag Image File Format (tiff). Figure 2 shows the experimental setup and Figure 3 shows the schematic diagram of the experimental setup.

![Figure 2. Experimental Setup](image1)

![Figure 3. Schematic Diagram of the Experimental Setup](image2)
Using MATLAB software, the image is converted from true color to gray scale image of size 768 pixels x 576 pixels. Figure 4 shows the laser speckle pattern image for surface no 1. Figure 5 shows image of rectangle shape captured using the CCD camera for determining the scaling factor in horizontal direction $SF_H$ and in vertical direction $SF_V$ as given by equation (1) & (2).

![Figure 4. Laser Speckle Pattern for Surface No.1](image1)

![Figure 5. Rectangle for scaling factor](image2)
Table 1. 3D Surface Roughness Parameter for each Milled Surfaces

| Surface No. | Spindle Speed (rpm) | Feed rate (mm/min) | Depth of cut (mm) | $S_a$ ($\mu$m) | $S_q$ ($\mu$m) | $S_p$ ($\mu$m) | $S_r$ ($\mu$m) | $S_{10z}$ ($\mu$m) | $S_{sk}$ | $S_{ku}$ | $S_{dq}$ (%) | $S_{dr}$ |
|-------------|---------------------|-------------------|------------------|----------------|--------------|--------------|--------------|----------------|--------|---------|--------------|---------|
| 1           | 6000                | 220               | 1                | 0.3926         | 0.5168       | 15.449       | 4.2402       | 19.689         | 7.8626 | 1.0879  | 25.125       | 0.1263  | 0.7841  |
| 2           | 6000                | 265               | 1                | 0.3884         | 0.5515       | 20.472       | 4.1385       | 24.61          | 21.99  | 5.1156  | 155.38       | 0.1475  | 0.9754  |
| 3           | 6000                | 310               | 1                | 0.4803         | 0.6591       | 24.538       | 5.6371       | 30.176         | 26.09  | 3.2782  | 80.089       | 0.1856  | 1.4313  |
| 4           | 6000                | 355               | 1                | 0.5665         | 0.7051       | 12.23        | 33.719       | 45.95          | 12.802 | 0.1977  | 7.8601       | 0.1558  | 1.2117  |
| 5           | 6000                | 400               | 1                | 0.5457         | 0.6863       | 16.406       | 4.2553       | 20.661         | 18.418 | 0.5930  | 10.744       | 0.1356  | 0.8701  |
| 6           | 6000                | 445               | 1                | 0.4387         | 0.5708       | 39.646       | 18.706       | 58.352         | 41.507 | 4.3443  | 253.81       | 0.1339  | 0.7801  |
| 7           | 6000                | 490               | 1                | 0.6156         | 0.8549       | 38.124       | 3.0996       | 41.224         | 39.76  | 6.9088  | 205.74       | 0.1992  | 1.3138  |
| 8           | 6000                | 535               | 1                | 0.8187         | 0.9762       | 5.6145       | 4.3118       | 9.9233         | 7.1029 | 0.1791  | 2.3002       | 0.1361  | 0.9215  |
| 9           | 6000                | 580               | 1                | 0.9114         | 1.0619       | 5.351        | 7.9208       | 13.272         | 6.7702 | 0.0988  | 2.0208       | 0.1269  | 0.8031  |
| 10          | 6000                | 625               | 1                | 0.9262         | 1.1137       | 5.4225       | 6.4135       | 11.836         | 8.1326 | -0.0964 | 2.3894       | 0.1567  | 1.2109  |
\[ SF_h = \frac{\text{actual length}}{\text{length in terms of number of pixels}} = \frac{10}{377} = 0.02 \text{ mm/pixel} \]  
(1)

\[ SF_v = \frac{\text{actual length}}{\text{length in terms of number of pixels}} = \frac{6}{242} = 0.02 \text{ mm/pixel} \]  
(2)

Scan region of Alicona Infinite Focus Microscope is 544.74 µm by 5.7283 mm and scanning were done at the center of the sample. These scanned region dimension were converted in terms of number of pixels using the scaling factor and found the scanning region to be 27 pixels by 285 pixels which is shown as rectangle box in figure 6. Region for analysis (Cropped region) on the laser speckle pattern was chosen such that its region is smaller and within the Alicona Infinite Focus Microscope scan region.

Using MATLAB software, the 10 surfaces were cropped to region of interest of size 23 pixels x 281 pixels at starting coordinate (354,68) as shown in Figure 7.

**Figure 6.** Rectangle box represents the Alicona Infinite Focus scanning area

**Figure 7.** Cropped Images for surface No.1

From the cropped image Histogram based (Statistical) features and Texture feature were extracted as follows:-

- Histogram based (Statistical) features
o Mean
Mean of gray value of the image $m$ obtained from original image $f(x,y)$ of size $M \times N$ as in equation (A.1).

o Arithmetic Average of Intensity $G_a$ as in equation (A.2).

o Root Mean Square (RMS)
Root mean square is square root of mean of each pixel gray value as in equation (A.3).

o Skew
Skew is a measure of histogram’s asymmetry about mean level as in equation (A.4).

o Energy
The energy descriptor provides another measure on how pixels values are distributed along the gray level range and can be calculated for gray scale image as in equation (A.5).

o Entropy
Entropy descriptor provides the information about the complexity of the image as in equation (A.6).

- Texture Features
  - Roughness
    Normalised descriptor of roughness $R$ is as in equation (A.7).

- Autocorrelation Coefficient Function (ACF)
  Autocorrelation coefficient is calculated by shifting two copies of the same laser speckle pattern against each other as in equation (A.8).

- Gray Level Co-occurrence matrix (GLCM)
  Histogram based texture descriptors are limited as it does not have any information about the spatial relationship among pixels. These information can be obtained using Gray-Level Co-occurrence Matrix (GLCM). These matrix holds the information of number of times pixels with intensities $z_i$ and $z_j$ occur in image $f(x,y)$ in position specified by displacement vector $d = (d_x,d_y)$. In this work displacement vector was choosen as $d=(0,1)$. The matrix is normalized as in equation (A.9).

  o Maximum Probability as in equation (A.10).
  o Correlation as in equation (A.11).
  o Contrast as in equation (A.12).
  o Energy as in equation (A.13).
  o Homogeneity as in equation (A.14).
  o Entropy as in equation (A.15).

- From the binary image following characteristic features are extracted:-
  o Total Black pixels to Total White pixels ratio (B/W)
  o Total White pixels to Total Black pixels ratio (W/B)

3. Result and Discussion
Table 2 is the tabulation of coefficient of determination between characteristic features and 3D roughness parameters.
From the table 2, it is found that $S_v$ has coefficient determination above 0.5 with mean, $G_a$, Roughness, Entropy and ACF characteristic features. Figure 8 shows the scatter plot between mean, $G_a$, Roughness, Entropy and ACF characteristic features and $S_v$.

### Table 2. Coefficient of determination for linear regression between characteristic features and 3D roughness parameter

|          | $S_a$ (µm) | $S_q$ (µm) | $S_p$ (µm) | $S_r$ (µm) | $S_v$ (µm) | $S_{sk}$ (µm) | $S_{ku}$ (µm) | $S_{dq}$ (µm) | $S_{dr}$ (µm) |
|----------|------------|------------|------------|------------|------------|--------------|--------------|--------------|--------------|
| mean     | 0.0119     | 0.0103     | 0.0001     | 0.5207     | 0.1815     | 0.0005       | 0.0009       | 0.0036       | 0.0499       |
| $G_a$    | 0.0357     | 0.0400     | 0.0032     | 0.6743     | 0.2881     | 0.0069       | 0.0027       | 0.0000       | 0.0143       |
| Roughness| 0.0118     | 0.0122     | 0.0020     | 0.6106     | 0.1885     | 0.0004       | 0.0077       | 0.0115       | 0.0403       |
| Skewness | 0.1339     | 0.1669     | 0.2684     | 0.0371     | 0.2699     | 0.2132       | 0.0372       | 0.2500       | 0.0721       |
| Uniformity| 0.0208     | 0.0189     | 0.0021     | 0.4420     | 0.1890     | 0.0094       | 0.0005       | 0.0004       | 0.0281       |
| Entropy  | 0.0253     | 0.0254     | 0.0011     | 0.5428     | 0.2184     | 0.0048       | 0.0004       | 0.0001       | 0.0245       |
| RMS      | 0.0023     | 0.0092     | 0.0012     | 0.1133     | 0.0304     | 0.0002       | 0.0097       | 0.0018       | 0.1144       |
| B/W      | 0.1052     | 0.1052     | 0.3785     | 0.0459     | 0.3699     | 0.3477       | 0.1277       | 0.4110       | 0.0000       |
| W/B      | 0.0899     | 0.0825     | 0.3319     | 0.0231     | 0.2921     | 0.2881       | 0.1337       | 0.3580       | 0.0115       |
| ACF      | 0.0136     | 0.0143     | 0.0014     | 0.6168     | 0.1954     | 0.0002       | 0.0073       | 0.0098       | 0.0369       |
| Max Prob.| 0.0016     | 0.0021     | 0.0452     | 0.1245     | 0.0021     | 0.0246       | 0.0033       | 0.0286       | 0.0019       |
| Correlation| 0.1135     | 0.1716     | 0.1428     | 0.2625     | 0.3624     | 0.1407       | 0.0018       | 0.1746       | 0.2286       |
| Contrast | 0.1961     | 0.2030     | 0.1519     | 0.2582     | 0.0000     | 0.0887       | 0.0764       | 0.0830       | 0.0305       |
| Energy   | 0.0103     | 0.0063     | 0.0008     | 0.3140     | 0.1284     | 0.0078       | 0.0036       | 0.0000       | 0.0598       |
| Homogeneity| 0.1943     | 0.2167     | 0.1292     | 0.1205     | 0.0052     | 0.0645       | 0.0286       | 0.0632       | 0.0452       |
| Entropy  | 0.0193     | 0.0175     | 0.0000     | 0.4749     | 0.1705     | 0.0012       | 0.0007       | 0.0031       | 0.0414       |
From the Table 2 it is clear that there is no correlation between characteristic features and the 3D surface roughness for certain 3D surface roughness. These could be due to:

- The cropped region is too small
- The size of speckle pattern is too small for analysis. This problem can be resolved by increasing the magnification of the image captured.
- There are some pixels having intensity of value 255 grayscale value. This can be overcome by using Neutral Density filter to cut off the brightness at lower aperture setting.
- There is poor correlation for experimental work using illumination angle of 26.9°. The experiment shall be repeated at different illumination angle and check if there is any improvement in the correlation.

Previous works shows there are good correlation between laser speckle pattern and 2D surface roughness [9-10].

4. Conclusion

From the current experimental work, the result shows that there is only some correlation between Sv and certain characteristic features. Effect of the image crop size on the correlation shall be studied in detail as well the magnification on the correlation. The effect of angle of incident on the correlation shall be studied in detail.

Figure 8. Correlation between Characteristic Features and Sv.
Appendix A

\[ m = \frac{1}{MN} \sum_{x=1}^{M} \sum_{y=1}^{N} f(x, y) \]  
(A.1)

\[ G_a = \frac{1}{MN} \sum_{x=1}^{M} \sum_{y=1}^{N} |f(x, y) - m| \]  
(A.2)

\[ RMS = \sqrt{\frac{f(x,y)^2}{MN}} \]  
(A.3)

\[ \text{skew} = \frac{\text{mean} - \text{mode}}{\text{standard deviation}} \]  
(A.4)

\[ \text{energy} = \sum_{j=0}^{255} p(r_j)^2 \]  
(A.5)

Where \( p(r_j)^2 \) is probability of occurrence of \( j^{\text{th}} \) gray level \( r_j \)

\[ \text{entropy} = -\sum_{j=0}^{255} p(r_j) \log_2[p(r_j)] \]  
(A.6)

\[ R = 1 - \frac{1}{1 + \frac{\sigma^2}{255^2}} \]  
(A.7)

\[ ACF = \sum_{x=1}^{M} \sum_{y=1}^{N} \sum_{x'=1}^{M} \sum_{y'=1}^{N} A(s, t) A \left( ((x-1) + s), ((y-1) + t) \right) \]  
\[ \sum_{x'=1}^{M} \sum_{y'=1}^{N} (A(s, t))^2 \]  
(A.8)

\[ N_{g}(i,j) = \frac{g(i,j)}{\sum_{i} \sum_{j} g(i,j)} \]  
(A.9)

The following texture based features are computed using a normalized GLCM, \( N_{g}(i,j) \).

\[ \text{Maximum probability} = \max N_{g}(i,j) \]  
(A.10)
\[ \text{Correlation} = \frac{\sum_i \sum_j (i - \mu_i)(j - \mu_j)N_g(i,j)}{\sigma_i \sigma_j} \]  
\[(A.11)\]

\[ \text{Contrast} = \sum_i \sum_j (i - j)^2 N_g(i,j) \]  
\[(A.12)\]

\[ \text{Energy} = \sum_i \sum_j N_g^2(i,j) \]  
\[(A.13)\]

\[ \text{Homogeneity} = \frac{\sum_i \sum_j N_g(i,j)}{\sum_i \sum_j 1 + |i - j|} \]  
\[(A.14)\]

\[ \text{Entropy} = -\sum_i \sum_j N_g(i,j) \log_2 N_g(i,j) \]  
\[(A.15)\]

References

[1] Lou M S, Chen J C and Li C M Nov 1998- Jan 1999 Surface roughness prediction technique for CNC End-Milling Journal of Industrial Technology 15(1) 1 - 6

[2] Tian G Y, Lu R S and Gledhill D 2007 Surface measurement using active vision and light scattering Optics and Lasers in Engineering 45(1) 131-9

[3] Popov I A, Sidorovsky N V, Veselov I L and Hanson S G 1998 Statistical properties of focal plane speckle Optics Communications 156(1-3) 16-21

[4] Goh C S and Ramam M M 2015 Assessment of Areal (Three-Dimensional) Roughness Parameters of Milled Surface Using Charge-Coupled Device Flattened Scanner and Image Processing Experimental Techniques 1-9

[5] Manojlovic L M, Zivanov M B and Marincic A S 2010 White-Light Interferometric Sensor for Rough Surface Height Distribution Measurement IEEE Sensors Journal 10(6) 1125-32

[6] Gao F, Leach R K, Petzing J and Coupland J M 2008 Surface measurement errors using commercial scanning white light interferometers Measurement Science and Technology 19(1) 015303

[7] Danzl R, Helmli F and Scherer S 2011 Focus Variation—A Robust Technology for High Resolution Optical 3D Surface Metrology 245-56 p

[8] Al-Shammery H A O, Bubb N L, Youngson C C, Fashinder D J and Wood D J 2007 The use of confocal microscopy to assess surface roughness of two milled CAD–CAM ceramics following two polishing techniques Dental Materials 23(6) 736-41

[9] Jayapoovan T, Murugan M and Bovas B C 2012 Statistical analysis of surface roughness measurements using laser speckle images World Congress on Information and Communication Technologies (Trivandrum, India) (IEEE Computer Society) 378-82

[10] Dhanasekar B, Mohan N K, Bhatari B and Ramamoorthy B 2008 Evaluation of surface roughness based on monochromatic speckle correlation using image processing Precision Engineering 32(3) 196-206