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Procedia CIRP 33 (2015) 251 – 256
www.elsevier.com/locate/procedia

9th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '14

Multi-dimensional assessment of precision machined surface texture based on laser speckle pattern analysis

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Abstract

Surface texture of precision machined surfaces plays an important role in providing various functions to product surfaces. This paper presents a surface texture assessment method based on a laser speckle pattern analysis. Considered as simple light scattering phenomenon, laser speckle intensity can represent surface roughness. On the other hand, considered as diffraction phenomenon, the period of anisotropic pattern on a laser speckle is estimated to be inversely proportional to the period of micro structure. The proposed method evaluates multiple properties of surface texture from a laser speckle pattern, such as roughness, period, and degree of similarity in periodic micro surface structures. By investigating experimentally the relation between surface texture and laser speckle pattern of machined surfaces, several characteristic parameters of laser speckle, such as the mean intensity, the autocorrelation length of intensity distribution, and the degree of similarity between adjacent speckle patterns are proposed for evaluating surface texture properties. In addition, the anisotropy of micro surface structure is assessed by using the proposed parameters of laser speckle pattern.

Selection and peer-review under responsibility of the International Scientific Committee of "9th CIRP ICME Conference"
Keywords: Surface analysis; Metrology; Micro structure; Laser speckle; Characteristic parameter

1. Introduction

Surface texture of precision machined surfaces dominates the performances of them, such as friction, wear resistance, corrosion, fatigue, and wetting. Therefore, assessing surface texture which has nano-meter scale height and micro-meter scale periodic structure has been important in product development. To evaluate the surface texture in a large area at high speed without damaging surface, a laser speckle method is effective due to non-contact method with high efficiency. However, most of the conventional laser speckle methods describe complex speckle patterns with one parameter, mainly for evaluating surface roughness. For instance, a speckle contrast method [1] [2] uses relation between contrast of laser speckle pattern and surface roughness. In an angular speckle correlation method [3] and a polychromatic speckle correlation method [4], the correlation coefficient between two speckle patterns obtained under different conditions is calculated for roughness measurement.

A target of this study is to present a new surface texture assessment method which evaluates multiple properties of surface texture from a laser speckle pattern. This study proposes several characteristic parameters obtained from laser speckle pattern to evaluate roughness, period, and degree of similarity in periodic micro surface structure. In addition, the anisotropy of micro surface structure is assessed by using the proposed parameter.

2. Theoretical description

As shown in Fig.1, laser beam scattered with a micro surface structure forms a resultant light distribution on an image surface, i.e. laser speckle pattern. In the case that laser speckle is considered as a simple light scattering phenomenon, the mean value of light intensity on laser speckle decreases as the surface roughness become larger. On the other hand, in the case that the adjacent micro surface structures have high similarity, the laser speckle patterns formed are diffraction

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doi:10.1016/j.procir.2015.06.045

images from multiple apertures such as diffraction grating. In particular, the optical system satisfies the Fraunhofer condition, the interval of bright lines on the laser speckle patterns can be estimated to be inversely proportional to the period of micro surface structure. In addition, the laser speckle formed by high periodic surface texture is expected to have high similarity between adjacent speckle patterns. For the above reasons, the mean intensity, the interval of bright lines, and the degree of similarity between adjacent speckle patterns can be used for surface texture assessment.

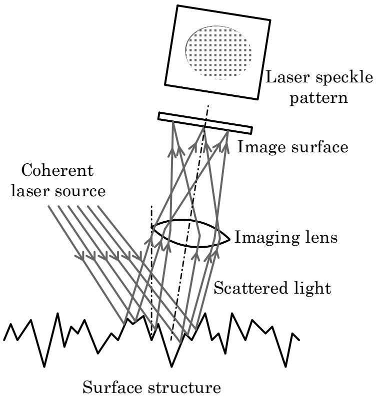

Fig. 1. Laser speckle formed by surface texture.

3. Experimental setup

A laser speckle observation instrument was developed to investigate relation between surface texture and laser speckle pattern, as shown in Figs.2 and 3. The instrument has two laser diodes as laser sources, which irradiate 635nm or 450nm wavelength laser beam. The diameter of laser beams is 5mm at the aperture of the laser source. The light intensity of laser beams is regulated with ND filters, which have 11 transmittance grades areas from 0.1 to 91.2%. In addition, the irradiated area is varied with an iris. The scattered light from the light spot on the sample surface at a given moment could be observed with a CCD camera through a convex lens, and the observing direction was on the specular reflection angle. The sample and the CCD camera were located on the focal distance of the lens to satisfy the Fraunhofer condition. The CCD camera has 1280 × 960 pixels, and the size of each cell is 6.45μm × 6.45μm. Furthermore, a photo diode detects the light intensity reaching sample surface.

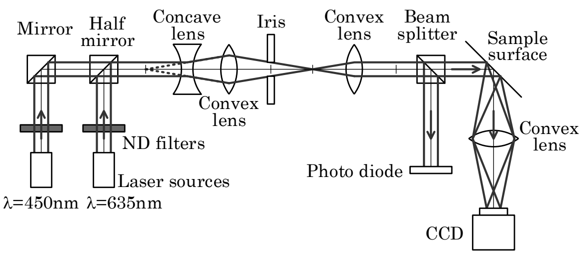

Fig. 2. Optical system for laser speckle observation instrument.

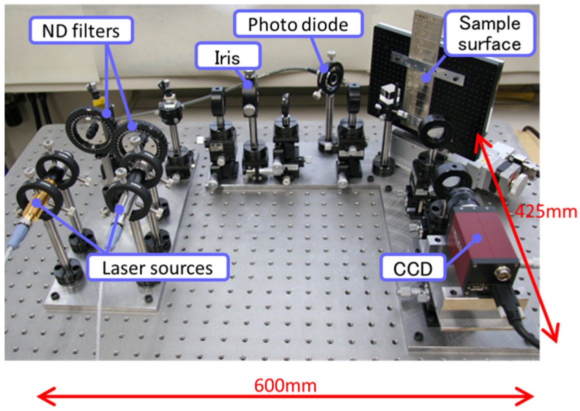

Fig. 3. Laser speckle observation instrument.

4. Characteristic parameters proposition for surface texture assessment

Laser speckle patterns obtained from several machined surfaces were observed to identify characteristic parameters of laser speckle for surface texture assessment. As the samples, roughness standard specimens made of magnesium and aluminium alloy shown in Fig.4 were used. The arranged samples were lapped, ground, and milled surfaces, and each sample contained several areas which had different roughness. The surface textures of the samples were measured with both a stylus profilometer (Taylor Hobson, Form Talysurf PGI820) and an optical profilometer (WYKO, RST-Plus Optical Profiler). Then, the laser speckle patterns observed with the instrument were compared with the surface texture, and the relation between them was investigated. In addition, the measured surface texture was evaluated with two surface texture parameters defined in ISO4287-1997; the arithmetical mean deviation of the assessed area (Ra) and the mean width of profile elements of the assessed profile (RSm). Table 1 shows the evaluation results by the stylus profilometer and the optical profilometer. In this study, the X and Y directions indicate the tool mark direction and the perpendicular direction against tool marks, respectively.

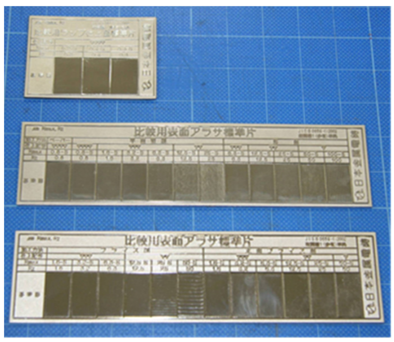

Fig. 4. Roughness standard specimens.

Table 1 Surface texture parameters of experiment sample surfaces.

	Roughness [nmRa]	Mean width [μmRSm]	
		X-direction	Y-direction
Lapped-A	32.6	22.5	9.5
Lapped-B	59.8	24.5	30.1
Lapped-C	110.4	28.9	65.3
Ground-A	169.3	18.3	19.9
Ground-B	288.7	39.0	46.8
Ground-C	577.0	18.3	53.5
Ground-D	891.3	39.2	40.1
Milled-A	340.1	137.0	397.4
Milled-B	627.0	85.1	588.2
Milled-C	963.1	99.4	518.2
Milled-D	1250.0	99.5	852.1

4.1. Laser speckle patterns of machined surfaces

Figure 5 shows typical examples of the surface texture and the obtained laser speckle patterns. As the authors investigated in the previous study [5], the lapped surfaces, which had almost no tool marks and smaller roughness than laser beam wavelength, projected the laser speckle patterns which were aperiodic and gradual intensity distributions. Meanwhile, the ground surfaces had periodic tool marks, so that they projected banded laser speckle patterns in the same direction. The milled surfaces also had tool marks and they were higher periodic than that on the ground surfaces. In these cases, the laser speckle patterns became also high periodic. In consequence, laser speckle patterns are estimated to provide valuable information on surface texture.

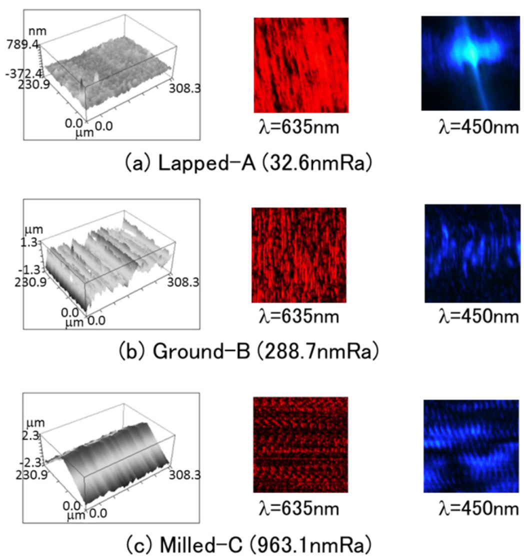

Fig. 5. Typical examples of surface texture and laser speckle patterns.

4.2. Mean value of speckle intensity

Figure 6 shows the relation between the mean value of speckle intensity on the entire observed area and surface roughness, which is the arithmetical mean deviation of the assessed area (Ra) evaluated with an optical profilometer. The measured data were on a characteristic curve in a range of Ra < 1500nm regardless of machining method under the condition of each laser beam wavelength. Similar relation between the surface roughness and the reflecting light intensity has been pointed out in conventional studies [6]. However, the value of the intensity of laser speckle obtained with 450nm wavelength laser was almost twice larger than that obtained with 635nm wavelength laser. This is because the diffraction angle of 450nm wavelength laser is smaller than that of 635nm wavelength laser, thus the scattered light was concentrated in the observed area. As mentioned above, the mean value of speckle intensity on entire observed area can be used as a characteristic parameter for evaluating Ra.

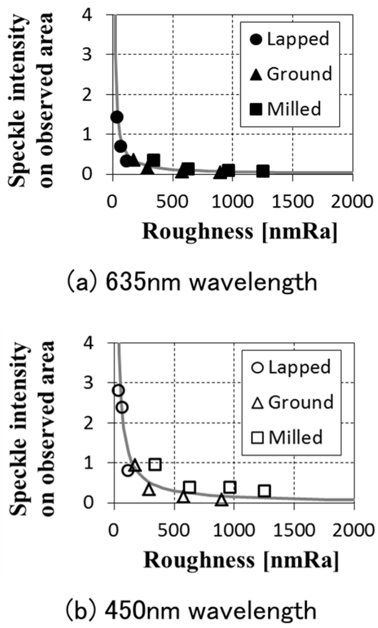

Fig. 6. Relation between mean value of speckle intensity on entire observed area and surface roughness.

4.3. Autocorrelation length of speckle intensity distribution

Figure 7 shows typical examples of the surface profile on the perpendicular direction against tool marks measured with the stylus profilometer and the autocorrelation function of a speckle intensity distribution on one line, which describes the degree of similarity of laser speckle pattern with shifted itself. This figure shows that the autocorrelation function of a speckle intensity distribution has some peaks at a constant interval in the case that the surface profile has periodic structure. This is caused by the diffraction phenomenon aspect of laser speckle. In other words, the interval of the peaks on the autocorrelation function can indicates the period of micro surface structure. In this study, a shifted length giving the maximum autocorrelation value in a range above the sifted length giving the first minimal autocorrelation value was defined as the autocorrelation length of speckle intensity distribution.

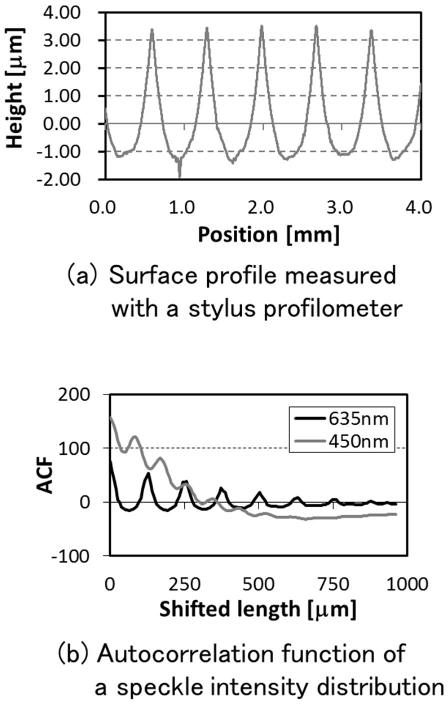

Fig. 7. Surface profile and autocorrelation function of a speckle intensity distribution on one line (Milled surface, 963.1nmRa).

Figure 8 shows the relations between the autocorrelation length of speckle intensity distribution on one line (AL_{line}) and the mean width of profile elements of the assessed profile (RSm) in the corresponding direction. In the case of using 635nm wavelength laser, the parameter decreased with the increase of RSm in a range of RSm > 50μm, whereas it had no tendency in a range of RSm < 50μm. Meanwhile, in the case of using 450nm wavelength laser, the parameter decreased with the increase of RSm in a range of RSm < 50μm. The reason for the difference is that the detectability for structure period is limited by two conditions; the period of laser speckle intensity distribution corresponding to the structure period is included in the half size of observed area, and the autocorrelation function peak corresponding to the structure period is separable with the peak on the shifted length 0. Thus, because of the large diffraction angle of 635nm wavelength laser, short structure-period could not be detected due to the limit of the observed area size. Meanwhile, because of the small diffraction angle of 450nm wavelength laser, long structure-period could not be detected due to the limit of peak separability.

In consequence, RSm can be evaluated from the autocorrelation length of a speckle intensity distribution on one line by using appropriate wavelength laser beam.

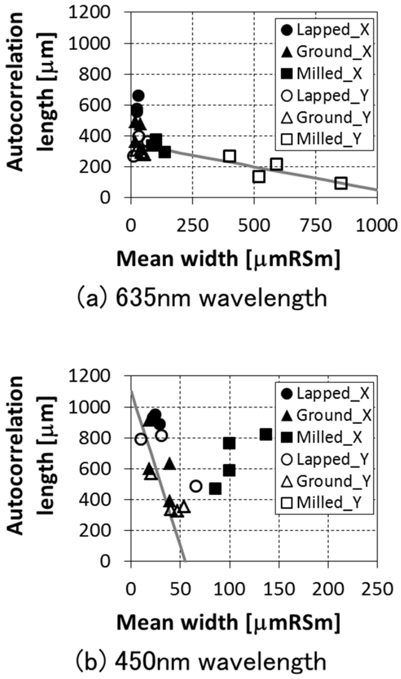

Fig. 8. Relations between autocorrelation length of speckle intensity distribution on one line and RSm.

4.4. Degree of similarity between adjacent speckle patterns

The autocorrelation function of a speckle intensity distribution is considered to express not only the structure period of surface texture but also the similarity in periodic micro surface structure, because the autocorrelation value at the autocorrelation length becomes larger with the increase of the similarity between adjacent surface structures. Thus, the similarity between adjacent speckle patterns is expected to be proportional to the similarity between micro surface structures. However, there is no standard that expresses the degree of similarity in periodic micro surface structure. Therefore, this study evaluated it from the autocorrelation function of a surface profile. In addition, the degree of similarity in speckle pattern was also evaluated from the autocorrelation function of a speckle intensity distribution in the same way. Equation (1) indicates the degrees of dissimilarity between adjacent surface structures or speckle patterns.

$$\delta = \log \frac{a_0 - a_{\min}}{a_{\text{acl}} - a_{\min}} \quad (1)$$

where a_{acl} , $a_{\min}$, a_0 are the autocorrelation value at the autocorrelation length, the shifted length giving the first minimal autocorrelation value, and the shifted length 0, respectively. The proposed parameter δ becomes smaller when the adjacent surface structures or speckle patterns are similar, and it becomes 0 if the adjacent surface structures or speckle patterns are completely same.

Figure 9 shows the relation between δ of surface structure and δ of laser speckle pattern. The figures indicate that the δ of laser speckle pattern was in direct proportion to the δ of surface structure in the case of using 450nm wavelength laser. However, the data were dispersed in the case of using 635nm wavelength laser, because structure-period shorter than 50μm cannot be evaluated properly by using 635nm wavelength laser as mentioned in the previous section.

From the above, the degree of similarity in micro surface structure can be estimated by the proposed parameter δ of laser speckle pattern in the case of using 450nm wavelength laser.

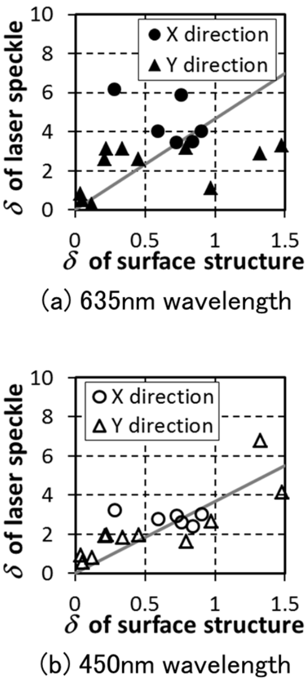

Fig. 9. Relations between δ of laser speckle pattern and δ of surface structure.

5. Assessment of surface texture anisotropy by the proposed parameter

Machined surfaces have anisotropy caused by tool motion, e.g. tool marks. Thus, the surface structures have some difference according to direction even if the roughness has same value. This study investigated the variation of AL_{line} with the assessed direction. Fig.10 shows the variation of the parameter of laser speckle in the case that the samples were rotated at every 15 degrees. To evaluate short period micro surface structure, 450nm wavelength laser beam was used for laser speckle observation. The lapped and the ground surface samples were fixed on a rotating stage under the condition that the assessed direction at the initial position (0°) corresponded with the perpendicular direction against tool marks, while the milled surface samples were fixed under the condition that the assessed direction corresponded with the tool mark direction. From these figures, the parameter became smallest on the perpendicular direction against tool marks on the ground and the milled surfaces. On the Milled-D surface, the parameter also became smaller on the tool mark direction. This could be because there were waves on tool marks due to cyclic oscillation of tool motion. On the other hand, the lapped surface was isotropic as shown in Fig.5, thus the parameters had almost same value on the all directions. The decrease of the value of the parameter around 120° could be caused by rough tool marks.

As a result, the direction which has periodic surface structure can be detected from the variation of AL_{line} with the assessed direction.

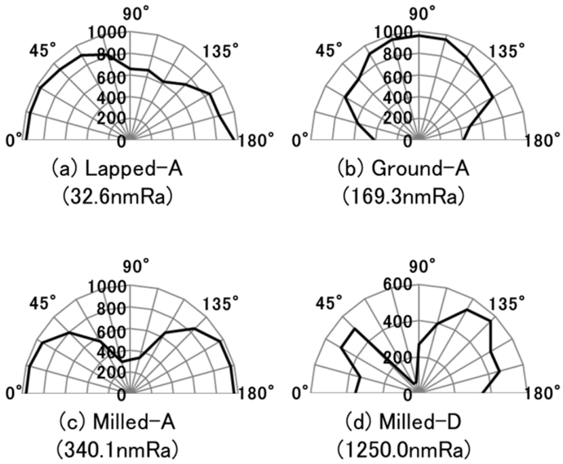

Fig. 10. Variation of AL_{line} with assessed direction on machined surfaces.

6. Conclusions

This paper proposed a novel surface texture assessment method based on laser speckle pattern analysis. By observing laser speckle patterns which were obtained from precision machined surfaces, i.e. lapped, ground, and milled surfaces, the relation between the characteristics of laser speckle and surface texture was confirmed. As a result, the arithmetical mean deviation of the assessed area (Ra), the mean width of profile elements of the assessed profile (RSm), and the degree of dissimilarity in micro surface structure could be evaluated by characteristic parameters of laser speckle pattern. The laser beam wavelength affects the range of evaluation especially for RSm and the degree of dissimilarity in micro surface structure. In addition, by using the proposed characteristic parameters of laser speckle pattern, the surface texture anisotropy, such as tool marks, was assessed. From these results, the proposed method can quantitatively assess precision machined surface texture.

Acknowledgements

This study was financially supported by the Japan Society for the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research (S) No.24226004 and Grant-in-Aid for JSPS Fellows No.25007543.

References

[1] Ohtsubo J., Asakura T. Measurement of surface roughness properties using speckle patterns with non-Gaussian statistics. Optics Communications 1978; 25; 3; 315-319.
[2] Leonard L.C., Toal V. Roughness measurement of metallic surfaces based on the laser speckle contrast method. Optics and Laser in Engineering 1998; 30; 433-440.
[3] Toh S.L., Quan C., Woo K.C., Tay C.J., Shang H.M. Whole field surface roughness measurement by laser speckle correlation technique. Optics & Laser Technology 2001; 33; 427-434.
[4] Patzelt S., Ciossek A., Lehmann P., Schöne A., Parametric optical surface roughness measurement by means of polychromatic speckle autocorrelation. Proc. SPIE 1998; 3426; 124-133.
[5] Shimizu M., Sawano H., Yoshioka H., Shinno H., Surface texture assessment of ultra-precision machined parts based on laser speckle pattern analysis, Precision Engineering 2014; 38; 1; 1-8.
[6] Sakai I., Sawabe M. A method for surface roughness measurement by means of light reflectance, Bulletin of the Japan Society of Precision Engineering 1982; 16; 2; 123-124.