Multi-dimensional assessment of nano/micro scale surface texture using laser speckle pattern analysis

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Abstract
Nano/micro scale surface structure on precision machined parts dominates the various product functions such as friction, wear resistance, corrosion, fatigue, and wetting. This paper presents a multi-dimensional surface texture assessment using laser speckle pattern analysis. From the observation result of laser speckle in precision machined surface, the probability density distribution of light intensity on laser speckle changes with the surface roughness. In addition, the autocorrelation function of speckle intensity distribution changes with the periodicity of micro surface structure. By analyzing the relation between surface texture and laser speckle pattern, characteristic parameters of laser speckle reflecting surface texture properties are identified; i.e. the mean light intensity, the deviation of the probability density distribution of light intensity, the autocorrelation length of intensity distribution, and the degree of dissimilarity between adjacent speckle patterns. The proposed parameters can evaluate the roughness, the period, and the degree of dissimilarity in periodic micro surface structure. Furthermore, the surface texture distribution and the anisotropy of micro surface structure can be assessed by detecting the variation of the proposed parameters. In consequence, the proposed method can quantitatively assess the nano/micro scale surface texture.

Key words: Measurement, Optical measurement, Nano & micro machining, Surface roughness, Surface texture, Anisotropy of surface structure, Multi-dimensional assessment, Laser speckle, Characteristic parameter

1. Introduction

Surface texture on precision machined parts may have great significance on providing various functions to product surfaces, such as friction, wear resistance, corrosion, fatigue, and wetting. For instance, J. Bico et al. (2002) pointed out that the contact angle of a water drop is altered with surface roughness, and N. Moronuki et al. (2007) showed the relation between surface structure and coefficient of friction. Therefore, surface texture with nano-meter scale height and micro-meter scale period plays an important role in product development, and the surface texture assessment in a large area at a high speed without damage is required in a variety of industries. A laser speckle pattern analysis is one of the most useful methods which meet such demands, because it is a non-contact measurement method with high efficiency. Thus, several surface texture assessment methods using laser speckle have been proposed. A speckle contrast method is the surface roughness evaluation method, which uses the relation between contrast of laser speckle pattern and surface roughness (Ohtsubo and Asakura, 1978, Leonard and Toal, 1998). An angular speckle correlation method (Toh, et al., 2001) and a polychromatic speckle correlation method (Patzelt, et al., 1998) also evaluate surface roughness from the correlation coefficient between two speckle patterns obtained by different conditions. The co-occurrence matrix of laser speckle pattern (Lu R., et al., 2006) and the speckle interferometry (Dhanasekar B., et al., 2008) were also proposed to evaluate surface roughness. However, most of the conventional laser speckle methods can
evaluate only surface roughness by describing complex speckle patterns with one parameter, which means that these methods may ignore much information contained in laser speckle patterns.

A purpose of this study is to propose a new multi-dimensional surface texture assessment method which can evaluate multiple properties of surface texture using laser speckle pattern analysis. From the observation result of laser speckle obtained from precision machined surfaces, this study proposes several characteristic parameters obtained by laser speckle pattern analysis representing the properties of surface texture such as roughness, period, and degree of dissimilarity in periodic micro surface structure. In addition, both the surface texture distribution and the anisotropy of micro surface structure can be assessed by using the proposed characteristic parameters.

2. Theoretical description

A coherent laser beam irradiated onto a machined surface is reflected and scattered by the nano/micro structures on the surfaces, as shown in Fig.1. The scattered light forms a resultant light distribution on the image surface, i.e. laser speckle pattern. Laser speckle patterns obtained from precision machined surfaces are characterized by two aspects; i.e. statistical and diffraction phenomena.

2.1 Statistical phenomenon aspect of laser speckle pattern

According to Uozumi J. et al (1980), the probability density distribution of complex amplitude of laser speckle intensity changes with the surface roughness in the case that the surface roughness is smaller than the laser wavelength. The coupling probability density distribution of the real and imaginary parts of the complex amplitude on laser speckle intensity can be given by Eq.(1),

$$P_{r,i}(A_r, A_i) = \frac{1}{2\pi\sigma_r\sigma_i(1-\rho^2)^{1/2}} \exp \left[ -\frac{1}{1-\rho^2} \left( \frac{(A_r-\langle A_r \rangle)^2}{\sigma_r^2} + \frac{2\rho(A_r-\langle A_r \rangle)(A_i-\langle A_i \rangle)}{\sigma_r\sigma_i} + \frac{(A_i-\langle A_i \rangle)^2}{\sigma_i^2} \right) \right]$$

(1)

where $\sigma_r$ and $\sigma_i$ are the standard deviations of the distributions of the real and imaginary parts, $\langle A_r \rangle$ and $\langle A_i \rangle$ are the mean value of the distributions of the real and imaginary parts, and $\rho$ is the correlation coefficient between $A_r$ and $A_i$. Both the mean values decrease to close to zero and the two standard deviations get closer as the surface roughness becomes larger. Ultimately, the coupling probability density distribution is asymptotic to Eq.(2) as the surface roughness is larger than the laser wavelength.
\[ P_s(A_r, A_i) = \frac{1}{2\sigma^2} \exp \left( -\frac{A_r^2 + A_i^2}{2\sigma^2} \right) \] (2)

where \( \sigma \) is the standard deviation of the distributions of the real and imaginary parts. The light intensity is the sum of squares of the real and imaginary parts, thus the probability density distribution of light intensity is given by Eq.(3), which is a negative exponential function,

\[ P(t) = \frac{1}{2\sigma^2} \exp \left( -\frac{t}{2\sigma^2} \right) \] (3)

In consequence, the mean value and the deviation of the probability density distribution on laser speckle intensity can be used for evaluating the surface roughness.

2.2 Diffraction phenomenon aspect of laser speckle pattern

In the case that the optical system for observing laser speckle satisfies the Fraunhofer condition; i.e. both the sample surface and the image surface are located on the focal distance of the imaging lens, the laser speckle pattern becomes the Fourier transform image of the micro surface structure. Thus, if the adjacent micro structures have high similarity on the sample surface, the observed laser speckle pattern becomes a diffraction image from multiple apertures such as a diffraction grating. In other words, the interval of bright lines on the laser speckle pattern is expected to be inversely proportional to the period of micro surface structure. T. Miyoshi et al. (1987, 1992) proposed to estimate the surface roughness and the structure period on ultra-precision surface based on the point of view assuming that the surface structure is chopping waves or rectangular grooves. However, the micro surface structures on an actual machined surface are not completely the same one, and the similarity between adjacent speckle patterns of a machined surface is considered to decrease compared with that of a diffraction grating. Thus, this method can be applied to only ultra-precision surface with low roughness and high-aligned periodic structure. Inversely, the surface roughness measurement of random rough surface based on Fraunhofer diffraction was also proposed (Y. Takaya et al., 1990) by assuming that the ultra-precision polished surface has random roughness following a Gaussian distribution. However, the detection range of this method is limited to below 120nmRq theoretically. This study investigates the relation between the interval of bright lines on the laser speckle pattern and the period of micro surface structure on various types of machined surfaces. In addition, the similarity between adjacent speckle patterns is used for evaluating the similarity between adjacent micro surface structures. In this study, the period on a laser speckle pattern and the similarity between adjacent speckle patterns are detected from the autocorrelation function of speckle intensity distribution.

3. Experimental setup

A laser speckle observation instrument was developed to characterize laser speckle patterns obtained from precision machined surfaces, as shown in Figs.2 and 3. A laser beam irradiates a sample surface and then the scattered light on the specular reflection angle at a given moment can be observed with a CCD camera through an imaging convex lens. As laser sources, two laser diodes, which irradiate 635nm or 450nm wavelength laser beam, are used and the diameter of laser beams is 5mm at the aperture of the laser source. The light intensity of two laser beams is regulated independently with ND filters, which have 11 transmittance grades areas from 0.1 to 91.2%, located on the optical paths, and the light intensity reaching sample surface is detected with a photo diode. On the other hand, the diameter of the irradiated area is varied with the collimating optical system consists of an iris and several lenses. To satisfy the Fraunhofer condition, the sample and the CCD camera are located on the focal distance of the convex lens. The CCD camera used for observing laser speckle has 1280 × 960 pixels, and the size of each image cell is 6.45\( \mu \)m × 6.45\( \mu \)m.

As objective surfaces for observation, the roughness standard specimens made of magnesium and aluminium alloy shown in Fig.4 were used. The arranged samples were three types of machined surfaces, which were lapped, ground, or milled surfaces, and each sample contained several areas which had different roughness. The surface texture of the samples was measured with both a stylus profilometer (Taylor Hobson, Form Talysurf PGI820) and an optical profilometer (WYKO, RST-Plus Optical Profiler). Furthermore, the measured surface texture was evaluated with three
surface texture parameters defined in ISO4287-1997; the arithmetical mean deviation of the assessed area (Ra), the mean height of profile elements of the assessed profile (Rc), and the mean width of profile elements of the assessed profile (RSm). The evaluated results are shown in Table 1. In this study, the X and Y directions indicate the tool mark direction and the perpendicular direction, respectively. Then, the laser speckle patterns obtained from these specimens were observed with the instrument as mentioned above. The relation between the surface texture and the laser speckle pattern was also investigated.

![Optical system for laser speckle observation instrument.](image1)

![Appearance of the developed laser speckle observation instrument.](image2)

![Roughness standard specimens.](image3)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Roughness[nmRa]</th>
<th>Mean height[nmRc]</th>
<th>Mean width[μmRSm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X-direction</td>
<td>Y-direction</td>
</tr>
<tr>
<td>Lapped-A</td>
<td>32.6</td>
<td>61.4</td>
<td></td>
</tr>
<tr>
<td>Lapped-B</td>
<td>59.8</td>
<td>95.3</td>
<td>128.5</td>
</tr>
<tr>
<td>Lapped-C</td>
<td>110.4</td>
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<td>484.3</td>
</tr>
<tr>
<td>Ground-A</td>
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<td>Ground-C</td>
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<td>1042.9</td>
<td>1458.1</td>
</tr>
<tr>
<td>Ground-D</td>
<td>891.3</td>
<td>489.1</td>
<td>3961.6</td>
</tr>
<tr>
<td>Milled-A</td>
<td>340.1</td>
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<tr>
<td>Milled-B</td>
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<td>2748.3</td>
</tr>
<tr>
<td>Milled-C</td>
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<tr>
<td>Milled-D</td>
<td>1250.0</td>
<td>547.3</td>
<td>6128.8</td>
</tr>
</tbody>
</table>
4. Characteristic parameters proposition for surface texture assessment

4.1 Laser speckle patterns of machined surfaces

Figure 5 shows typical examples of the surface texture measured with the optical profilometer and the obtained laser speckle patterns of machined surfaces. Laser speckle patterns obtained with 450nm wavelength laser were concentrated in a small area compared with the laser speckle patterns obtained with 635nm wavelength laser because of its small diffraction angle. However, overall characteristics of laser speckle patterns obtained with two laser beams were basically similar. The surface texture of Lapped-A had no tool marks, and the roughness was about 1/10 of the wavelength of laser beams. In this case, the laser speckle patterns were aperiodic and gradual intensity distributions. Meanwhile, the surface texture of Ground-B had periodic tool marks, and the roughness was larger than that of lapped surfaces. In particular, the mean height in the perpendicular direction against tool marks was larger than the laser wavelength. This type of surfaces projected banded laser speckle patterns in the same direction as tool marks. However, in the case that the mean height on the tool mark direction became larger, banded laser speckle pattern separated shorter. For this reason, the surface texture of Milled-C, which had periodic tool marks and large mean height on the tool mark direction, formed a short separated banded laser speckle pattern. In addition, the periodic micro surface structure on Milled-C was high-periodic and the mean width was large on the perpendicular direction, so that the banded pattern of laser speckle became high-periodic in short spacing. In consequence, laser speckle patterns can provide valuable information on surface texture, such as roughness, periodicity, and a tool mark direction.

![Fig.5 Typical examples of surface texture, laser speckle pattern obtained with 635nm wavelength laser, and laser speckle pattern obtained with 450nm wavelength laser.](image)
4.2 Probability density distribution of light intensity

Figure 6 shows typical examples of the probability density distributions of light intensity on laser speckle obtained with 635nm wavelength laser. In the case that the roughness of the surfaces was similar, the probability density distributions indicated similar shape regardless of machining methods. Judging from the observations, the probability density distribution was being condensed around zero as roughness became larger. In addition, the shape of probability density distribution was also changing with roughness. The peak of the distribution was in the high-intensity area in the case of low-roughness surface, whereas that was in the low-intensity area in the case that the surface roughness was larger than the laser beam wavelength. In the case that the surface roughness was between 50 and 600nmRa, there were two peaks on the distribution. This shape-changing of probability density distribution is considered to be based on the statistical phenomena mentioned in Chapter 2. When the center of probability density distribution given by Eq.(1) is far from the origin of the coordinate axes, the peak of the probability density distributions of light intensity appears around \( \{ \langle A \rangle, \langle A^2 \rangle \} \). While, when the center of probability density distribution of complex amplitude is close to the origin, the probability density of laser speckle intensity in a low-intensity area get larger, and the distribution ultimately becomes a negative exponential function given by Eq.(3). From these results, two parameters can be used for evaluating the surface roughness; the mean value and the deviation of the probability density distribution of laser speckle intensity. On the other hand, in the case of using 450nm wavelength laser, all of the probability density distributions of light intensity on laser speckle were similar shape, which had a peak in around zero and another in large intensity area, as shown in Fig.7. This could be because the dark areas were too large in observed laser speckle patterns obtained with 450nm wavelength laser due to a small diffraction angle of blue light.

Figure 8 shows the relation between the mean value of speckle intensity on an entire observed area and Ra evaluated with an optical profilometer. Regardless of machining methods, the measured data were on inverse proportional characteristic curves in a range of Ra < 1500nm under the condition of each laser beam wavelength. Similar relation between the surface roughness and the reflecting light intensity has been pointed out in the conventional studies (Sakai and Sawabe, 1982). In addition, the mean intensity value of laser speckle patterns obtained with 450nm wavelength laser was 2.5 - 3 times larger than that of laser speckle patterns obtained with 635nm wavelength laser. It is assumed that the mean speckle intensity is inversely proportional to the cube of the laser wavelength because the light energy is inversely proportional to the wavelength and the light energy density is in roughly inverse proportion to the square of the diffraction angle. Fig.9 (a) shows the relation between the ratio of amount of pixels which had smaller intensity than the 20% of maximum intensity on laser speckle and Ra in the case of using 635nm wavelength laser. The ratio of amount of smaller intensity pixels increased with Ra linearly in a range of Ra < 1500nm. However, in the case of using 450nm wavelength laser, the relation between the two parameters had no definite tendency as shown in Fig.9 (b) because of the above mentioned reason. In consequence, the Ra of machined surfaces can be evaluated from the deviation of the probability density distribution of laser speckle intensity by using two independent methods.

The interrelation between the mean value of speckle intensity and the surface roughness can be applied to the limited area of observed speckle pattern as the authors investigated in the previous study (shimizu, et al., 2014). Fig.10 shows the relation between the mean value of speckle intensity on one line of the obtained pattern and the mean height (Rc) in the corresponding direction. In a range of Rc < 500nm, the measured data were described by same inverse proportional characteristic curve regardless of machining methods and estimated directions. The characteristic curves depend on the laser beam wavelength, and the value is inversely proportional to the cube of the laser wavelength because of the above-mentioned reason. In addition, the data spread widely in the case of using 450nm wavelength laser compared with using 635nm wavelength laser because of the large dark area. As a result, the mean value of speckle intensity on one line of the obtained pattern can be used as a characteristic parameter for evaluating Rc.
Fig. 6 Probability density distributions of light intensity on laser speckle (635nm wavelength).

Fig. 7 Probability density distributions of light intensity on laser speckle (450nm wavelength).

Fig. 8 Relation between the mean value of speckle intensity on entire observed area and Ra.

Fig. 9 Relation between the ratio of amount of smaller intensity pixels and Ra.
4.3 Autocorrelation function of speckle intensity distribution

Figure 11 shows typical examples of the surface profile on the perpendicular direction against the tool marks measured with the stylus profilometer and the autocorrelation function of a speckle intensity distribution on one line on the corresponding direction, which describes the degree of similarity of laser speckle pattern with shifted itself. This figure indicates that the autocorrelation function of a speckle intensity distribution has some peaks with a constant interval when the micro surface structure has periodic patterns. This is because the laser speckle pattern has a diffraction phenomenon aspect stated in Chapter 2. Thus, the interval of the peaks on the autocorrelation function indicates the period of micro surface structure. In this study, the peaks interval is represented by the shifted length giving the maximum autocorrelation value in a range above the sifted length giving the first minimal autocorrelation value, which is defined as the autocorrelation length of speckle intensity distribution (\(ACL\)).

The relations between the autocorrelation length of speckle intensity distribution on one line and the mean width of profile elements of the assessed profile (RSm) in the corresponding direction is shown in Fig.12. In the case of using 635nm wavelength laser, the autocorrelation length of speckle intensity distribution decreased with an increase of RSm in a range above 50\(\mu\)m, whereas there was no correlation between two parameters in a range below 50\(\mu\)m. Meanwhile, in the case of using 450nm wavelength laser, the parameter decreased with the increase of RSm in a range below 50\(\mu\)m. The difference of the results is estimated to be because of the detectability for structure period limited by two conditions; the interval of laser speckle pattern 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. In the case of using 635nm wavelength laser, the short structure-period could not be detected due to the limit of the observed area size because the diffraction angle of the laser was large. On the other hand, the diffraction angle of 450nm wavelength laser was small, thus the long structure-period could not be detected due to the limit of peak separability.

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 values at its peaks become larger with an increase of the similarity between adjacent surface structures. Thus, the similarity between adjacent speckle patterns is expected to be proportional to the similarity between surface structures. However, there is no common standard that expresses the similarity or dissimilarity in periodic micro surface structure. For this reason, this study defines the degrees of dissimilarity between adjacent surface structures or speckle patterns using the autocorrelation function of a surface profile or a speckle intensity distribution by Eq.(4),

\[
\delta = \log \frac{a_{acl} - a_{min}}{a_{acl} - a_{max}}
\]

where \(a_{acl}\), \(a_{max}\), \(a_{min}\) 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 \(\delta\) is a useful standard because similar pattern continuous makes it smaller and the parameter ultimately become 0 if the adjacent patterns are completely same. Fig.13 shows the relation between \(\delta\) of surface structure and \(\delta\) of laser speckle pattern, and it indicates that the \(\delta\) of laser speckle pattern formed by 450nm wavelength laser was in proportion to the \(\delta\) of...
surface structure. Meanwhile, the data were dispersed in the case of using 635nm wavelength laser. This is because structure-period shorter than 50μm cannot be evaluated properly by using 635nm wavelength laser as mentioned in Fig.12.

In consequence, RSm and the similarity in a periodic micro surface structure can be evaluated using the autocorrelation function of a speckle intensity distribution on one line by using an appropriate wavelength laser beam.

Fig.11 Surface profile and the autocorrelation function of a speckle intensity distribution (Milled surface: 963.1nmRa).

Fig.12 Relations between the autocorrelation length of speckle intensity distribution on one line and RSm.

Fig.13 Relations between δ of laser speckle pattern and δ of surface structure.
5. Surface texture assessment by the proposed parameter
5.1 Surface texture distribution assessment

By using the proposed parameters, surface texture distribution of machined surfaces could be successfully assessed. The milled surface shown in Fig.14 was used as an assessed sample. The sample has five areas, which were processed with different tool-diameter endmills under the same feed pick. Thus, Rc in the five areas were different, whereas RSm were almost the same. Fig.15 shows the comparison between Rc in the five areas measured with the stylus profilometer and that estimated from the mean value of speckle intensity on one line of obtained pattern ($I_{aw}$). The parameter was converted to Rc by Eq.(5),

$$Rc = \frac{a}{I_{aw}} + b + c$$

(5)

where the coefficients $a$, $b$, $c$ were chosen so as to meet the experimental results in Fig.10. In Fig.15, the Rc distribution assessed by the proposed method agreed with the measured data except for in area D. This result indicates that the proposed method cannot estimate Rc larger than 1000nmRc, because the sensitivity of the characteristic curve in Fig.10 becomes low in high-roughness area. In the case of using 635nm wavelength laser beam, the estimated value around the boundary between two areas became intermediate value of the two because the spot diameter of red laser was slightly larger than that of blue laser.

The comparison between the RSm measured with the stylus profilometer and that estimated from the proposed parameter is shown in Fig.16. RSm of the sample was less than 50µm on all areas, thus 450nm wavelength laser beam was used for estimation. Autocorrelation length of speckle intensity distribution on one line ($AL_{aw}$) was converted to RSm by Eq.(6),

$$RSm = -AL_{aw} \cdot d + e$$

(6)

where the coefficients $d$, $e$ were chosen to meet the experimental result in Fig.12. Fig.16 shows that the RSm distribution estimated by the proposed method was almost all the constant value in five areas, which was same as the measured result. However, it was 10µm to 20µm larger than the measured data. From this result, more appropriate approximation for expressing the relation in Fig.12 is needed to evaluate RSm quantitatively.

![Fig. 14. Measurement sample for Surface texture distribution assessment.](image-url)
5.2 Surface texture anisotropy assessment

The surface structures on the machined surfaces have some difference according to directions even if the surface roughness has same value, because the surfaces have anisotropy caused by tool motion, e.g. tool marks. Thus, the characteristic parameters of laser speckle are considered to vary with the direction. This study investigated the variation of $A_{L_{\text{ave}}}$ on every 15-degree direction. Fig. 17 shows the variation of the parameter of laser speckle obtained with 450nm wavelength laser. In this study, 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 the tool marks, while the milled surface samples were fixed under the condition that the assessed direction corresponded with the tool mark direction. On the ground and the milled surfaces, the parameter $A_{L_{\text{ave}}}$ became smallest on the perpendicular direction against the tool marks. In addition, the parameter also became smaller on the tool mark direction on Milled-D. This could be because there were waves on tool marks due to the cyclic oscillation of tool motion. Meanwhile, the parameter $A_{L_{\text{ave}}}$ had almost same value on all directions on the lapped surface, which has an isotropic surface structure as shown in Fig. 5. The decrease of the value of the parameter around 120° could be caused by rough tool marks. In consequence, the direction which has periodic surface structure can be detected from the variation of $A_{L_{\text{ave}}}$ with the assessed direction.

Fig. 15. $R_c$ distribution assessment with the stylus profilometer and the proposed laser speckle method.

Fig. 16. $R_{Sm}$ distribution assessment with the stylus profilometer and the proposed laser speckle method by 450nm wavelength laser beam.
6. Conclusions

This paper presented a multi-dimensional surface texture assessment method using laser speckle pattern analysis. First, laser speckle patterns obtained from machined surfaces, i.e. lapped, ground, and milled surfaces, were observed. Then, the probability density distribution of light intensity and the autocorrelation function of speckle intensity distribution were investigated by analyzing the laser speckle patterns. From the analyzed result, the characteristic parameters of laser speckle describing the surface texture were proposed. The proposed parameters can evaluate the arithmetical mean deviation of the assessed area (Ra), the mean height of profile elements of the assessed profile (Rc), the mean width of profile elements of the assessed profile (RSm), and the degree of dissimilarity in a micro surface structure. The laser beam wavelength affects the range of evaluation especially for RSm and the degree of dissimilarity in the micro surface structure. By using the proposed parameters, the distribution of Rc less than 1000nmRc was estimated properly, and the surface texture anisotropy was also assessed. In consequence, the proposed method can quantitatively assess precision machined surface textures.

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References


Fig. 17. Anisotropy assessment of machined surfaces.


