Surface Characterization of optical elements based on monochromatic scattered light techniques

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Introduction

Surface roughness in the nanometric range represents one of the key properties of high quality optical elements (lenses, mirrors, replication tools and molds). Besides the roughness local defects (scratches, abrasions, pits, cracks and chips) influence the optical functionality. Furthermore, in the case of structured surfaces, pattern deviations (e.g., insufficient periodicity) affect the structure function. In general, such surfaces are characterized with conventional measuring devices, like tactile profilometers, white light interferometers, confocal microscopes, scanning force microscopes, or near field acoustic microscopes. They measure the surface topography in detail and calculate roughness parameters from the measuring data. The surface assessment of optical components is also part of the Transregional Cooperative Research Center SFB/TR4 "Process Chains for the Replication of Complex Optical Elements" funded by the DFG (Deutsche Forschungsgemeinschaft). One objective within this research center is to lay the scientific foundations of microtopography characterization for a deterministic and economical mass production of optical elements with a complex geometry. As the elements are used to shape optical beams, the investigations focus on optical measuring methods. In the case of mass production the measuring methods for both the production tools (e.g., molds) and the products should additionally be capable of in-situ measurements or even in-process measurements. Laser measuring principles based on scattered light and speckle correlation processes are suitable for this task. Scattered light techniques are generally parametric, i.e. integral roughness parameters like Ra and Rq (ISO 4287) can be extracted directly from one measurement without reproducing the 3D-topography. The view field dimensions are in the millimeter range. Therefore, scattered light techniques ensure the required short measuring times and high clock rates, i.e. they show in-process capabilities.

This contribution presents a modified angle resolved scattering (ARS) set-up to detect and analyze local defects like scratches, abrasions and pits on optically smooth surfaces. The method of double scattering by speckle pattern illumination quantifies the surface roughness in the range of Ra < 100 nm by an integral parameter.

State of technology

Conventional tactile topography measuring devices are not suitable for measurements near to production processes. Since machine vibrations spoil the measuring process, in-process measurements of moved surfaces are not possible at all. Scattered light techniques generally allow in-process measurements, and were therefore investigated since many years now. A theoretical description of light scattering from rough surfaces is based on the "Physical Optics Approximation", which assumes that the radii of surface curvature are large compared with the wavelength of the light. For surface amplitude fluctuation much smaller than the light wavelength the "Small Pertubation Theory" holds [1][2](BEC63a)(OGI91a).

The method of total integrated scattering (TIS) was introduced in 1961 [3](BEN61a) and enables the characterization of smooth surfaces with roughness Rq < 35 nm. The method compares the diffusely scattered light intensities with the specularly reflected light portion. Two problems arise, which prevent its use in industrial production processes: i) the optical integration of the diffusely scattered light requires a special mirror, e.g. a "Coblentz Sphere", which has to be applied near to the surface; ii) the separation of scattered and reflected light is very sensitive to surface tilts.

Angle resolved scattering (ARS) is based on the fact that the angular distribution of scattered light intensities is proportional to the power spectrum of the illuminated rough surface area [4][5][6] (TWH80a)(VOR93a)(BEN99a). Fourier transformation of the scattered light intensity distribution gives the surface autocorrelation function, the maximum of which is identical with the roughness value Rq. For visible light with a wavelength l = 633 nm the measuring range is limited to roughness values Rq < 100 nm.

Corresponding ARS measurements require the angle resolved detection of scattered light intensities over the complete hemisphere above the surface, which again is a problem in connection with in-process applications. Besides the determination of the power spectrum, ARS allows the detection of local surface defects [7][8](LON91a)(ROT93a).

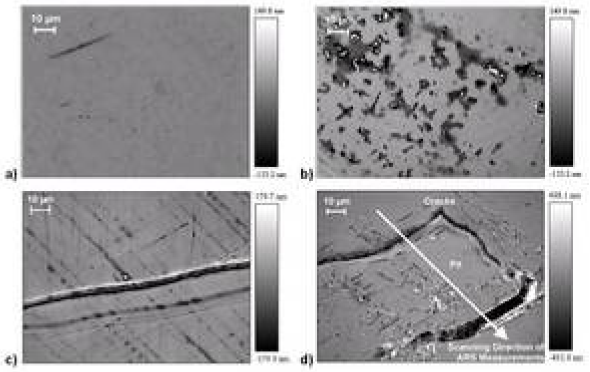

Figure 1: White light interferometer measurements of ball-bearing ball surfaces
a) without significant defects,
b) with an abrasion,
c) with a double scratch and
d) a pit as a result of an impact.

Another measuring method very similar to ARS determines the width of the scattered light cone, which is proportional to the standard deviation of the microtopographical surface slopes [9][10](BRO84a)(BRO85a). For some surface topologies (e.g., ground surfaces) this measure correlates with the standard deviation of the surface heights Rq, which often is the parameter of interest [11]. However, in most cases the interpretation of the measuring data is ambiguous.

The coherent optical method of double light scattering was first introduced to characterize the roughness of transmitting surfaces [12][13][14](YOS90a)(NAK93a)(BAS95a). Here, a speckle pattern with a well-defined mean speckle diameter illuminates the surface. The transmitted scattered speckle pattern shows a roughness dependent intensity modulation. This method can be extended to reflecting surfaces and enables roughness measurements in the range below Rq = 100 nm [15][16](LEH99a)(LEH00a).

Angle resolved scattering using CMOS technology

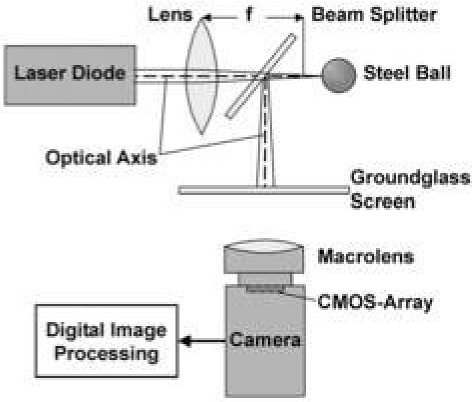

Figure 2: Experimental arrangement for the investigation of smooth surface defects on ball-bearing balls.

Figure 1 shows topography plots of ball-bearing ball surfaces, which are measured with a white light interferometer. The smooth surface area in Figure 1.a has no significant defects. Typical defects are abrasions (b), scratches (c) and pits (d). The latter originate from impacts, e.g., at the end of the production process, when the ball drops into a storage box and collides with other balls. As there were no pits on the ball under investigation, it was prepared by an impact generated at a defined force by a smaller ball. Figure 1.d reveals that the resulting pit is surrounded by three cracks. Furthermore, the beginning of the slide trace to the lower left corner is visible, where the smaller ball slided sideways after the collision.

The parametric optical measurements of these surface defects were carried out with a modified ARS set-up according to Figure 2. A double convex lens focuses the parallel monochromatic beam of a laser diode module with the wavelength $\lambda = 670$ nm. The optical axis is radially to the ball. A beam splitter deviates the reflected and scattered and/or diffracted light to a groundglass screen in the Fresnel region (near field). A CMOS camera (512 x 512 pixel) with a macrolens observes the intensity distribution. The image is digitized as a gray scale data set with 10 bit resolution and evaluated with image processing and correlation algorithms in order to recognize the surface defect. The use of a modern CMOS-based camera with a large dynamic intensity range overcomes the blooming effect, which formerly represented a problem in connection with conventional CCD-devices and resulted in a crosstalk of pixel intensities to neighbored pixels in the case of an overexposure.

For the detection of abrasions (Figure 1.b) and scratches (Figure 1.c), the ball surface is scanned with a focused laser beam. If there is no significant defect on the surface, the detected image shows a specularly reflected light spot surrounded by some diffraction fringes due to the convex ball shape (Figure 3.a). An abrasion as a local roughness enhancement leads to scattered light intensities, which in the case of coherent light emerge as speckle (Figure 3.b). The scratch of Figure 1.c behaves under coherent illumination like a slit: The diffraction pattern extends orthogonally to the scratch (Figure 3.c).

Figure 3: ARS measurements of the surface areas shown in Figure 1:
a) Without significant defects,
b) an enhanced roughness due to an abrasion causing speckle,
c) a vertical scratch leads to a horizontal diffraction pattern.

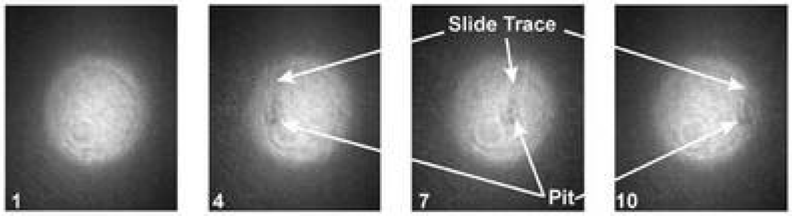

Figure 4: Four CMOS images out of twelve from the scanning ARS measurement of the pit presented in Figure 1.d.

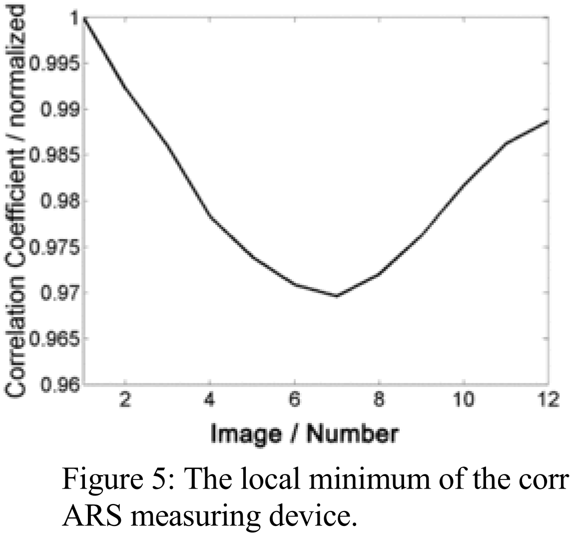

Figure 5: The local minimum of the correlation coefficient indicates a defect in the view field of the ARS measuring device.

Each kind of local defect leads to a characteristic light intensity distribution. A corresponding ARS scanning measurement of the pit in Figure 1.d would show diffraction fringes, if the beam focus illuminates the cracks, and a speckled scattered light cone, if the beam is focused to the rough center of the pit. However, an important question is, whether the beam has to be focused to the surface, or not. A larger view field of the ARS set-up significantly decreases the time needed for a measurement of the complete ball surface. Therefore, the surface area containing the pit was scanned along the white arrow in Figure 1.d with a beam diameter of nearly 2 mm. Figure 4 shows four out of twelve images. As the defect enters the view field, both the indentation as well as the slide trace cause diffraction fringes. For evaluation the individual digitized intensity distributions are correlated with a reference image, which is in this case the first one of the image series, i.e. the CMOS image of the undamaged region next to the pit. Figure 5 shows the resulting correlation coefficients of the twelve measurements (images). The local minimum of the curve indicates that the pit is in the center of the view field or the illuminated surface area, respectively.

Hence, it is possible to detect micro defects on curved smooth surfaces even if the diameter of the illumination spot is about twenty times larger than the one of the defect. However, it is still a problem to characterize the kind of defect, which is quite easy for a human being because of his experience, but represents an extensive task to develop corresponding automatic image processing tools.

Doubly scattered light

The method of roughness characterization by double scattering is applicable to specularly reflecting surfaces. It is based on the statistical properties of speckle patterns emerging from an optical smooth surface, which is illuminated with a fully developed static speckle pattern. The measuring effect results in a roughness-dependent intensity modulation of the scattered speckle field. Yoshimura et al. [12] (YOS90a) introduced the theoretical background of the measuring principle and performed experiments with transmitting isotropic surfaces. Basano et al. [14](BAS95a) described the detection of the resulting speckle pattern by use of an intensified CCD camera. Lehmann [15](LEH99a) gives a theoretical extension of the method for reflecting and possibly anisotropic surfaces.

Since the method is based on statistical optics, the corresponding roughness parameters used within this context should be of statistical relevance. Therefore, the surface description is based on the rms-roughness Rq or the arithmetical mean deviation Ra, respectively:

$$Rq = \sqrt{\frac{1}{L}\int_0^L h^2(x)dx} \qquad Ra = \frac{1}{L}\int_0^L |h(x)|dx \qquad (1)$$

For a Gaussian height distribution *h*(*x*) the relation

$$Rq = \sqrt{\pi/2}\,Ra \qquad (2)$$

between Rq and Ra is valid.

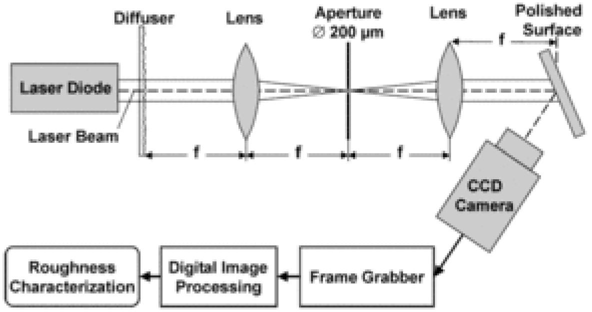

Figure 6: Experimental arrangement for roughness characterization using doubly scattered light.

Figure 6 shows the experimental set-up for roughness measurements according to the double scattering principle. A laser diode module with an anamorphotic optical system emits a Gaussian shaped 60 mW beam at 813 nm of about 3.8 mm diameter. A rough diffuser plate scatters the beam. By optical low-pass filtering using a 4-f-arrangement including an aperture, which is adjusted in the back focal plane of a Fourier transforming lens, a grainy structure, i.e. a speckle pattern, of well defined extension and speckle diameter is generated on the investigated surface. A conventional monochrome CCD-array with 768 x 576 pixel detects the scattered light intensity distribution in the Fresnel region. The image is stored for digital evaluation as a gray scale data set with 8 bit resolution.

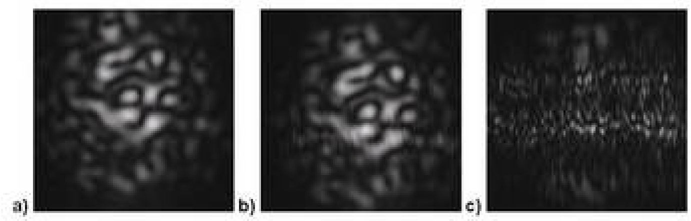

Figure 7: Doubly scattered speckle pattern emerging from polished surfaces with
a) Ra = 5 nm,
b) Ra = 82 nm and
c) Ra = 127 nm.

The investigated surfaces are diamond turned electroless nickel platted steel substrates (100Cr6), which are (chemical-)mechanical polished with different parameters (time, velocity, force). The resulting roughness is in the range between Ra = 5 nm and Ra = 127 nm. In the case of the smoothest specimen the illumination speckle pattern is nearly specularly reflected to the CCD-array (Figure 7.a). The rougher surface with Ra = 82 nm slightly modulates the speckle intensities. The mean speckle diameter decreases, but the original speckle pattern is still recognizable (Figure 7.b). The surface with Ra = 127 nm completely modulates the original speckle pattern. The resulting speckle are much smaller (Figure 7.c).

This leads to different widths of the corresponding two-dimensional discrete speckle intensity autocorrelation functions (ACF, Figure 8). The ACF width is a measure for the mean speckle diameter in the scattered light distribution and, therefore, decreases with increasing roughness. Furthermore, due to the anisotropic polishing process the ACFs become asymmetrical with increasing roughness, because in the rotation direction of the polishing felt-tool the surface is smoother than perpendicular to this direction.

In Figure 9 the optical roughness value Ropt is plotted as a function of the Ra roughness. Ropt is based on the estimation of the ACF-widths, i.e. of the mean speckle diameters, in the x-direction, which is perpendicularly to the polishing direction. A suitable measure for the ACF-width is the ACF-gradient in the corresponding direction near to the ACF-maximum [17](PAT02d). The sensitivity of the method of double scattering decreases with increasing roughness. As mentioned before, the measuring range is between Ra = 1 nm and Ra = 100 nm. For the characterization of engineered surface, which show pure diffuse scattering, the method of polychromatic speckle autocorrelation is suitable [18].(LEH99b)

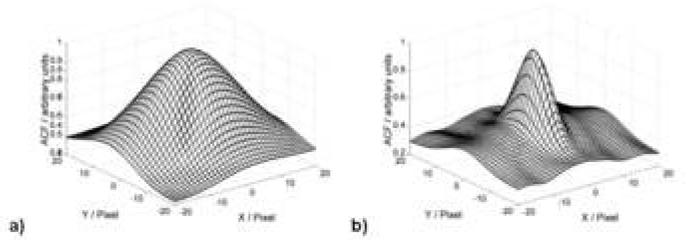

Figure 8: The width of the two-dimensional speckle intensity autocorrelation function (ACF) decreases with increasing surface roughness:
a) ACF of Figure 7.a (Ra = 5 nm),
b) ACF of Figure 7.c (Ra = 127 nm).

Prospects

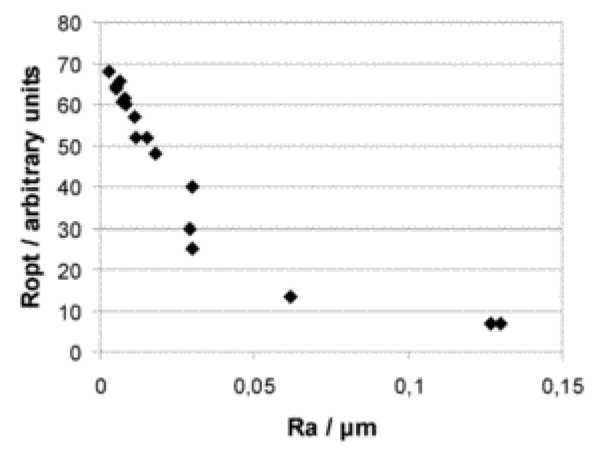

Figure 9: The parametric optical roughness parameter Ropt correlates with the arithmetical mean roughness Ra.

The methods of doubly scattered laser light and CMOS-based ARS are promising techniques to investigate surfaces of optical parts near to or even within the production process. In the case of smooth engineered surfaces, these parametric optical methods enable the characterization of roughness and the detection of defects. Future investigations concentrate on the development of suitable image processing algorithms in order to characterize and quantify surface defects with respect to the surface functionality.

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