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Optical Topometry for Roughness Measurement and Form Analysis of Engineering Surfaces Using Confocal Microscopy

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1 INTRODUCTION TO CONFOCAL METHODS FOR MICROSTRUCTURE ANALYSIS

In recent years the technique of confocal microscopy was established for biological or medicinal texture analysis as well as for analysis of smooth engineering surfaces. These applications are using highly magnifying microscope objectives with high numerical apertures ($0.6<NA<1.4$) which allow only small object volumina. The technique of confocal microscopy also implies the potential for topographic analysis of engineering surfaces on large object volumina. Medium numerical apertures and are needed for these applications.
In confocal microscopy, light emitted from a point light source is focused onto the specimen. For a specimen with exact location in the focus, the reflected light is imaged onto a point detector and therefore the flux of light through the detector pinhole is optimized. Light reflected from defocused object regions is partly suppressed. The detector signal, limited by the pinhole diameter, is reduced strongly by scanning the specimen axialy. This effect named *depth discrimination* allows an accurate determination of the specimens *z*-coordinate.
Different serial *xy*-scanning techniques like the confocal laser scanner have been developed for data acquisition of depth discriminated sections of the specimen. This paper describes two methods of parallel *xy*-scanning video techniques realizing confocal microscopy for ultraprecise optical 3D measurements of engineering surfaces.
The Scanning Confocal Microscope (SCM) is using a rotating Nipkow disk for real-time *xy*-scans of object fields up to $(1\text{mm})^2$. The SCM system allows precise 3D topometry and roughness analysis of complex engineering surfaces like all kinds of sheet metals or papers.
The Microlens Array Confocal Microscopy (MLACM) is suitable for object fields up to $(40\text{mm})^2$. This set-up enables precise optical 3D form and microstructure analysis.

2 DEPTH RESPONSE I(Z) AND FULL WIDTH AT HALF MAXIMUM FWHM

The resulting main advantages of confocal microscopy compared to classical light microscopy are contrast enhancement by confocal depth discrimination which allows optical sectioning, suppression of scattered light and an increase of the lateral resolution of ≈20%.
The detailed description of the theory of confocal microscopy is given in [1,2]. The depth response *I(z)* of a confocal system is proportional to a $SINC^2$ function,

$$I(z) = \left(\frac{\sin(kz(1-\cos\alpha))}{kz(1-\cos\alpha)} \right)^2 I_0 \qquad (1)$$

which is depending on the aperture angle α of the microscope objective, the wavelength of light λ, the wavenumber $k = 2\pi/\lambda$ and the coordinate of defocussing *z*. Significant for the depth response *I(z)* is the Full Width at Half Maximum, which is

$$FWHM = \frac{0.443\,\lambda}{1 - \cos\alpha} \quad . \qquad (2)$$

The half angle of the numerical aperture *NA* gives the maximum surface slope αmax for specular reflection. The wavelength together with the numerical aperture determine the full width at half maximum *FWHM* of the depth response *I(z)* of the detectors intensity. For *NA*=0.45 the maximum surface slope is $\alpha_{max} \approx 14$ deg., the calculated *FWHM* is about 2.3µm.

3 SCANNING CONFOCAL MICROSCOPY (SCM)

For *xy*-scanning of a depth discriminated section we use a Nipkow disk, which consists of an array of pinholes of 20µm diameter, seperated by 200µm and arranged in a spiral shape [3]. The rotating disk is illuminated by a plane wave and acts as a scanning multiple point light source, which is imaged into the object focal plane of the microscope objective MO (Fig. 1). After the reflection of light, each illuminating Nipkow pinhole acts as his own detector pinhole. The depth discriminated *xy* information $I(x,y,z)$ is imaged onto a CCD camera. Thus, during one rotation of the disk, a *xy*-section of the specimen is scanned.

By an additional *z*-scan of the specimen, a stack z_1 to z_n of depth discriminated CCD cameraframes is acquired, from which a 3D topography can be constructed with an resolution of about 1% of the FWHM. In figure 2, a measured depth response $I(x_i,y_j,z)$ and the mode of evaluation of the height coordinate $h(x_i,y_j)$ as the centre of $I(x_i,y_j,z)$ is presented. A well formed depth response according to Eq. 1 is decisive for accurate confocal 3D topometry especially for applications using microscope objectives of medium numerical aperture *NA*.

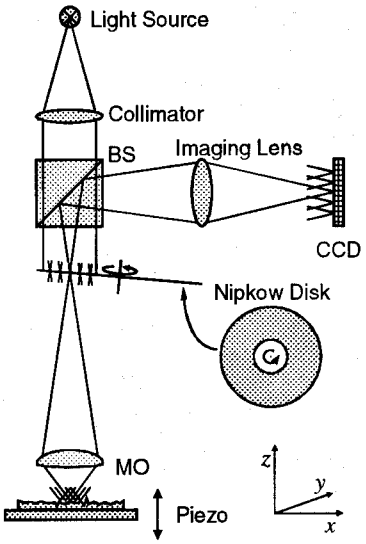
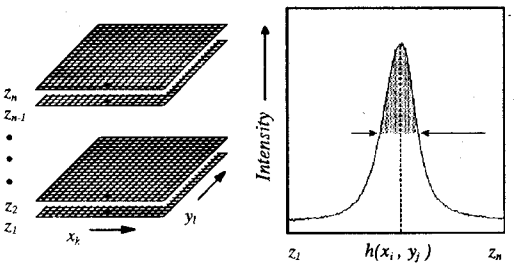


Fig. 1 (left): SCM set-up, using a rotating Nipkow disk.

Fig. 2 (bottom): The evaluation of the topography: Calculation of the height coordinate $h(x_i,y_j)$ as the centre of the depth response $I(x_i,y_j,z)$ for each pixel of the stack z_1 to z_n.



To check the quality of the SCM output the topographic data of the SCM set-up have been compared to those obtained with the PTBs stylus instruments (Rank Taylor Hobson NANOSTEP, 0.1µm tip radius) using the PTB roughness standards. This standards have been designed and calibrated by the Physikalisch Technische Bundesanstalt PTB in Braunschweig / Germany. They are periodic and one dimensional rough, that means the surface profile varies only in one direction with a period of 4mm. The upper part of figure 3 shows a stylus profile record of the PTB. The confocal profile record was construced from a set of 3D topographies. After each confocal measurement the standard was laterally displaced less than the width of the field of view. The single topographies were then summarized to one longer line profile, neglecting the overlapp between neighboured topographies. The lower part of figure 3 shows this summarized line profile. The deviation of roughness parameters calculated from this confocal profile record compared to those calculated from the stylus profile record was in the order of less than 1%. As can be seen from figure 3, the confocal profile record compares well to the stylus profile record. That means the SCM set-up is suitable for precise 3D topometry of rough engineering surfaces, with resolution and accuracy in the 10nm range.

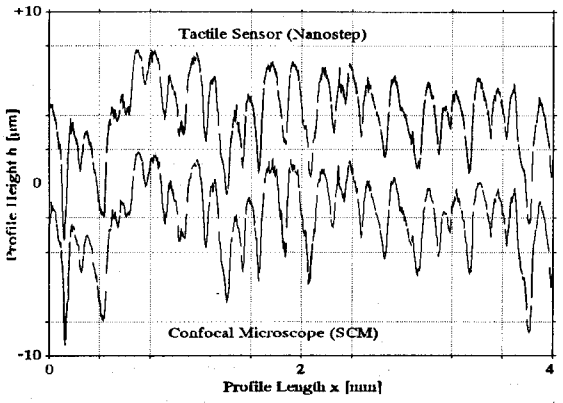


Fig. 3: Comparison of an unfiltered stylus profile record (NANOSTEP, 0.1µm tip radius) and an unfiltered confocal profile record (SCM, 20×/0.45 MO) using a PTB standard with roughness parameters (DIN 4768):

R_a = 1.45µm ± 4%
R_q = 7.24µm ± 4%
R_{max} = 9.6µm ± 4%

As an example for 3D analysis of engineering surfaces showing roughness as well as a complex form, a high resolved topography of a LASERTEX sheet is presented in figure 4. Although this specimen has very steep slopes, the backscattered light - due to the microroughness of highest spatial frequencies - was sufficient for accurate topometry. It should be notized, that no spike filtering was applied to all the result presented in this paper.

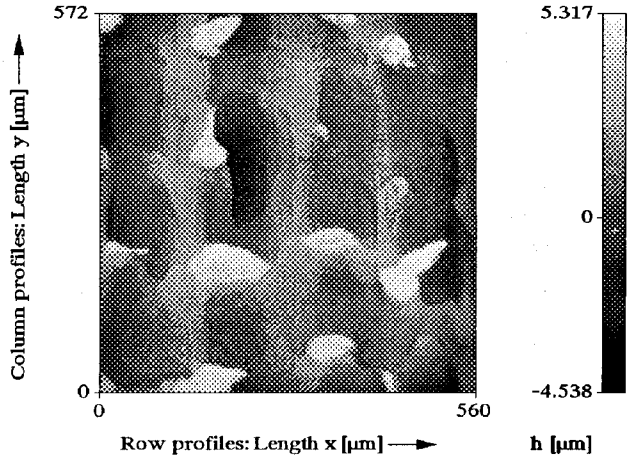


Fig. 4: Top of view greyscale presentation of an unfiltered 3D topography (raw data) of a LASERTEX sheet.

The topography was obtained using the 20×/0.45 microscope objective of the SCM set-up.

The field size was 560µm×572µm, the measured height range is ≈ 10µm.

In the SCM set-up we developed, the measured field size is limited by the magnification respectively by the numerical aperture of the microscopes objective to be less than (1 mm)^2 using a 20× microscope objective with *NA*=0.45. To overcome the limitation in the field size another approach of the confocal technique was developed using microlens arrays.

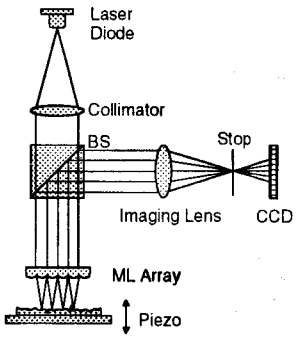


Fig. 5: MLACM set-up

4 MICROLENS ARRAY CONFOCAL MICROSCOPY (MLACM)

In co-operation with the imaging lens, each microlens of the ML array in figure 5 acts as a single confocal microscope [4]. Thus the confocal technique is parallelized using an ML array. The depth response *I(z)* and the *FWHM* of the MLACM are determined by the *NA* of a single microlens and are furthermore given by equation 1 and equation 2. But the object field size is now limited by the size of the microlens array, object fields up to (40mm)^2 have been realized.

As an example figure 6 shows a 3D form analysis of a Canadian 10 cent coin. Even fine details like single ropes of the shrouds have been resolved.

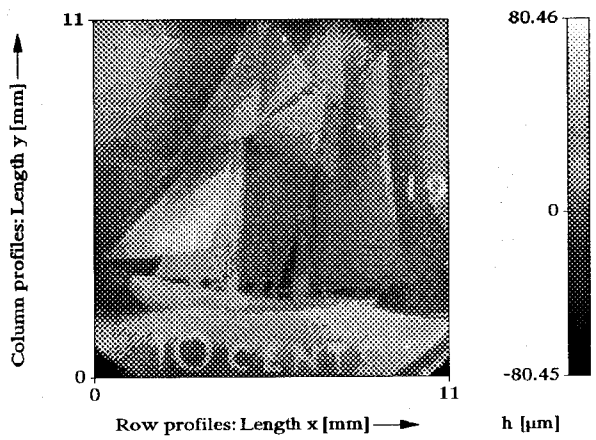


Fig. 6: Top of view greyscale presentation of an 3D topography of an Canadian 10 cent coin.

The topography was obtained using a microlense array of *NA*=0.3.

The field size was 11mmx11mm, the measured height range is ≈ 161µm.

5 CONCLUSIONS

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