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Surface Topography Measurement by Confocal Spectral Interferometry

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Abstract**—**Confocal spectral interferometry (CSI) is an innovative optical method for determining microtopography of surfaces and thickness of transparent layers, based on the combination of two optical principles: confocal imaging, and spectral interferometry. Confocal optical system images at each instant a single point of the sample. The whole surface is reconstructed by plan scanning. The interference signal generated by mixing two white-light beams is analyzed using a spectrometer. In this work, five 'rugotests' of known standard roughnesses are investigated. The topography is then measured and illustrated, and the equivalent roughness is determined and compared with the standard values.

Keywords**—**Confocal spectral interferometry, Nondestructive testing, Optical metrology, Surface topography, Roughness.

I. Introduction

CONTACTLESS metrology becomes more and more important for all steps of production quality control. Automotive industry, producers of microsystems, and advanced components need fast and accurate measurements of small structures, surface topography, and layer thickness. Normally, a lateral resolution of a few microns is required. The accuracy of the distance measured between the object and a reference plane usually needs to be better than 0.1 µm. Evidently, only optical systems are capable of operating with such needs.

II. Theoretical Background

A. Confocal Imaging

For the most innovative applications, the method of distance detection by chromatic coding has proved to be well appropriate. It benefits from the chromatic aberration of a lens where the axial position of the focal point depends on the wavelength of the radiation (color of light) to be converged [3].

Chromatic aberration results in a more pronounced convergence of blue radiation than red radiation. The other radiations will converge between blue and red in the order observed in the rainbow, as shown in Fig. 1.

Depending on the position of the converging lens (L) with respect to the object surface, a very small area of this surface is illuminated, thus the radiation of wavelength λ_m is focused at the point M of the surface. The other radiations illuminate a wider area of the surface, so they are defocused.

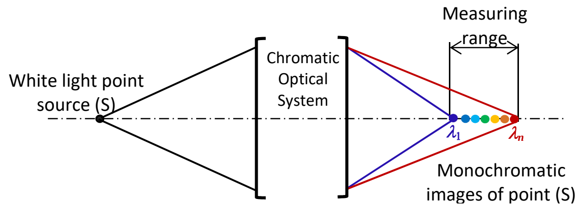

Fig. 1 Principle of chromatic coding

The focusing lens (L) is also used to receive the backscattered light from the object's surface and to focus it into an optical fiber. Due to that confocal arrangement, light with the wavelength λ_m is focused to the front of the fiber and enters it without cutting. All other spectral components are stretched on a much bigger area. As a consequence, the light fed through the fiber to a spectrometer is almost monochromatic, and its wavelength λ_m is a chromatic code about the axial position of the backscattering surface. However, the heights of the asperities of the scattering surface can be translated by the respective positions of the spectrometer frequencies, and thus, a calibration of the spectrometer scale is possible [1], [2]. Then, the key feature of the confocal setup is the fact that, at each instant, the photodetector perceives a single point: the light emitted by surface point located near, above or below the point *M* is not captured since it is spatially filtered by the pinhole. This allows [4]:

- Reconstruction of the image by scanning the surface in the horizontal plane containing the point *M*.
- As the illuminating beam is sharply focused on the observed point, the confocal system is insensitive to ambient lighting. However, a high signal to noise ratio is observed.
- Since the pinhole stops, all the light backscattered from the points on the optical axis outside the observed point, then if a planar scan is made in the (x, y) directions, a clearly focused observation plane is generated.
- The coaxial arrangement of the confocal system has the advantage of removing the shading effect which can disturb the operation of the triangulation devices.
- A lens with large numerical aperture lets a large flux of light accumulate. This allows measuring all kinds of surfaces, whether reflective or opaque.
- A pinhole (P) with sufficiently small size keeps the spot of the focused light very small, which results in a significant increase in lateral resolution.

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B. Spectral Interferometry

The interferometric method is based on spectroscopic analysis of white light fringe pattern, as the principle is shown by Fig. 2. It consists of spectral analysis of fringe pattern created by superposition of two wavefronts in order to determine the optical difference path between them. The two backreflected wavefronts are produced by the two faces of the transparent sample. Alternately, a reference plate may be introduced on the sample when this one is opaque; in this case, one wavefront is engendered by reflection on the sample surface, and the other one by reflection on the plate, which is the reference surface [4].

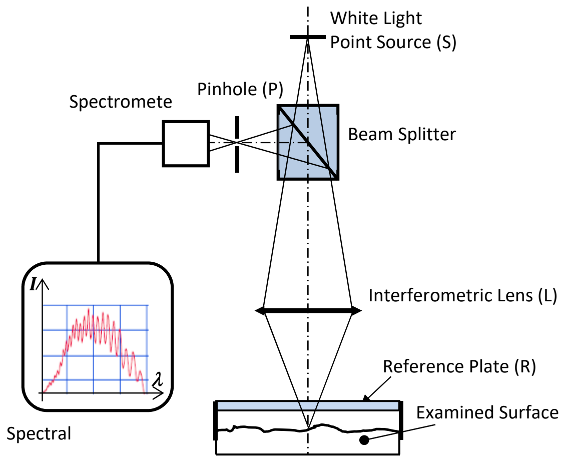

Fig. 2 CSI setup

Interferometric signal is a channeled spectrum, and from this signal, the spectral phase is calculated using a numerical phase shifting algorithm allowing measurement of the local height of the analyzed surface with a sub-nanometric resolution [3].

III. Experiment

Non-contact sensors called “Micromesure 2” of STIL [5], is used; a picture is shown in Fig. 3. This device allows acquiring roughness profiles much faster than a classical tactile probe, and without any risk of marking the surface. This sensor measure the altitude (*z*-coordinate) of the sample point located on its optical axis. It can also measure the thickness of transparent samples. It consists of (1) a controller CHR 150 with tungsten halogen light source, (2) an “optical pen” CL-MG (optical probe), including a chromatic lens and a magnifier lens, (3) a fiber optic cable, and also, (4) a motorized table which is used as sample holder allowing accurate micro-displacement in the plane (x, y).

The topography is carried out by scanning the probe on a surface of 3×0.4 mm^2 with a step of sampling of 0.01mm and 0.02 mm on x-axis and y-axis respectively, and a rate of 1.0 mm/s for the both directions in the horizontal plane (x, y). The depth of field is about 300 µm.

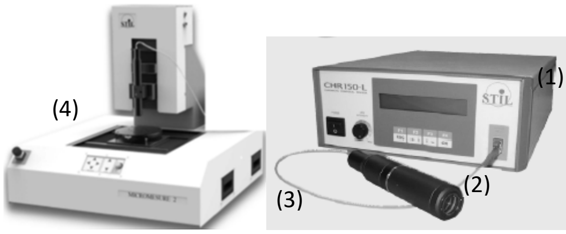

Fig. 3 Micromesure 2 with CHR controller and Optical pen

The work consists of performing the topography of five surface comparators called "rugotests", as shown in Fig. 4, with the roughness characteristics indicated as presented in Table I.

These comparators are used to compare the profile of a surface with the various reference surfaces of the comparators by means of view or touch.

Fig. 4 The rugotests

TABLE I
RUGOTESTS CHARACTERISTICS

Rugotest	*Rz* (µm)	*Rt* (µm)	*Ra* (µm)	*Rp* (µm)
1	1,70	2,1	0,18	0,31
2	3,50	4,0	0,40	0,80
3	7,50	8,0	1,10	2,10
4	9,00	11,5	1,40	2,90
5	19,00	23,0	3,00	5,50

Rz: Maximum roughness, *Rt*: Total roughness, *Ra*: Arithmetic roughness, *Rp*: Height of maximum peak.

Fig. 5 exposes the investigative results for three rugotests surfaces: the left column illustrates the 2D-Intensity distribution as result of CSI, with a line profile intensity in the top, the middle one concerns with the 3D-Intensity distribution, and the right column displays the surface topography. This task is performed with appropriate software under LabVIEW environment. In addition, the software allows access to the values of the heights of the surface asperities. From these data, the mean arithmetic and quadratic roughness are calculated by using the equations below.

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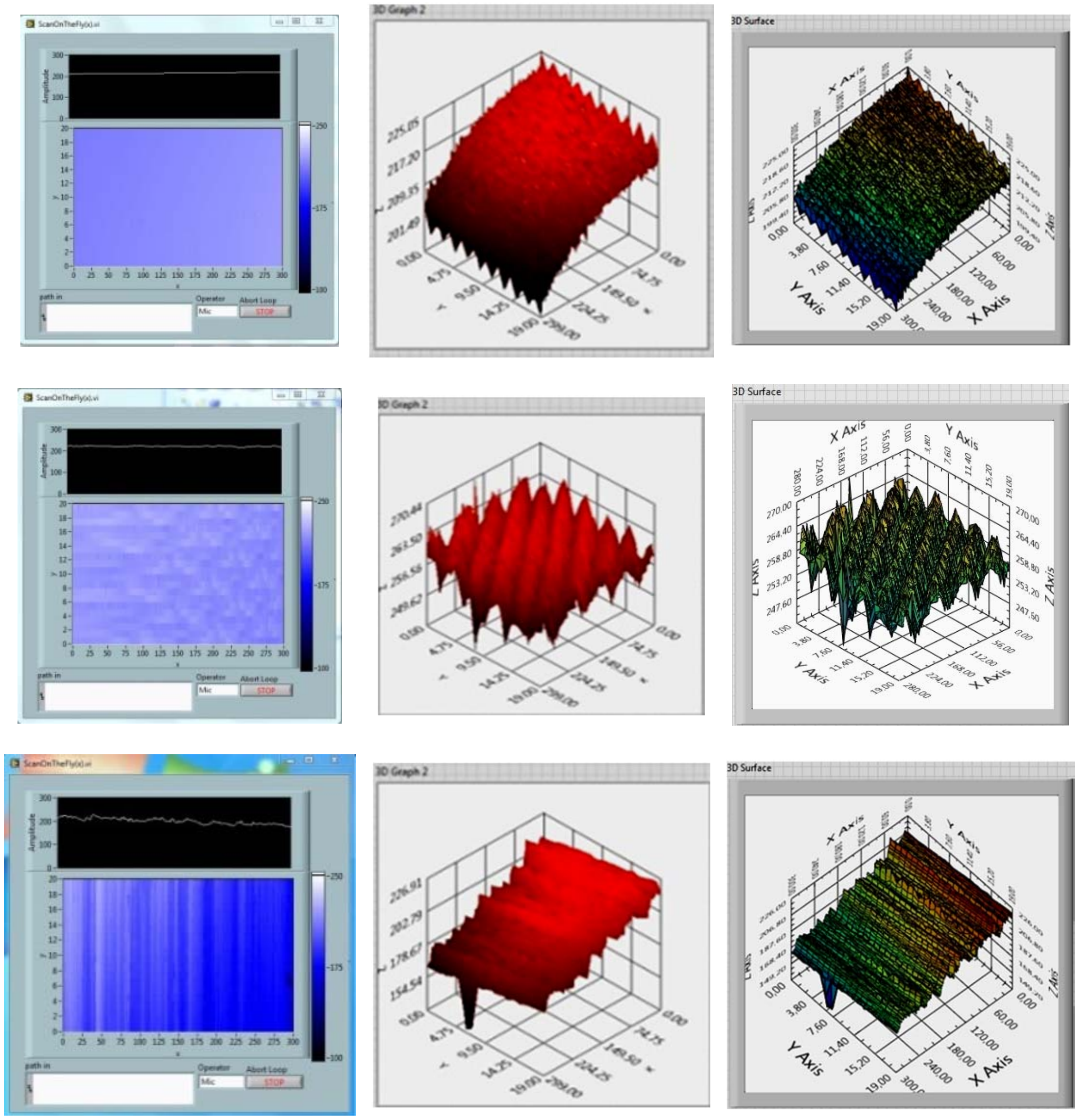
$R_z = 1.6\mu m$

$R_z = 6.3\mu m$

$R_z = 20\mu m$



(a) (b) (c)

Fig. 5 Surface topography of rugotests (a) 2D-Intensity distribution, (b) 3D-Intensity, c) Surface topography

For a set of $N \times M$ data of Z_{ij} (Z_{ij} are heights of the surface), one calculates $\overline{Z}$, the average value of Z_{ij}, and then determines R_a and *rms*.

- Mean surface:

$$\overline{Z} = \frac{1}{N \times M} \sum_{i=1}^{N} \sum_{j=1}^{M} Z_{ij} \tag{1}$$

- Arithmetic roughness:

$$R_a = \frac{1}{N \times M} \sum_{i=1}^{N} \sum_{j=1}^{M} \left| Z_{ij} - \overline{Z} \right| \tag{2}$$

- Quadratic roughness:

$$rms = \sqrt{\frac{1}{N \times M} \sum_{i=1}^{N} \sum_{j=1}^{M} \left(Z_{ij} - \overline{Z} \right)^2} \tag{3}$$

To exclude non-representative points, we calculate the deviation of each of the values of Z_{ij} with respect to the mean value $\overline{Z}$ and verify if it is greater than four times the average roughness, i.e. $4 \times R_a$, so Z_{ij} is eliminated and $\overline{Z}$ is computed for the remaining Z_{ij} values, then *rms* is corrected [6].

The results are shown in Table II.

For comparison, Fig. 6 display the values for the arithmetic roughness obtained by CSI and indicated on the rugotests. The results show that they are little different. This justifies the reliability of that the CSI technique for measuring roughness.

TABLE II
ARITHMETIC ROUGHNESS AND RMS DETERMINED BY CSI

Rugotest	*Ra* (µm)	*rms* (µm)
1	0.238	0.101
2	0.467	0.404
3	1.017	0.815
4	1.230	0.912
5	4.306	3.403

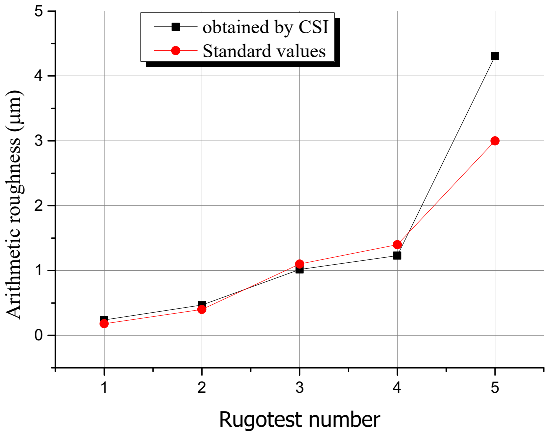


Fig. 6 Arithmetic roughness R_a obtained by CSI and the standard values

IV. CONCLUSION

In this work, we used a non-invasive optical method to generate the topography of rough surfaces, which is the CSI.

To verify the ability of this technique in order to evaluate the roughness, we investigated five surface comparators of known standard roughnesses called "rugotests". The results are in good agreement. Furthermore, the *rms* which is a strong and significant parameter for characterizing surface roughness can be determined by this technique.

The advantage of the CSI is to give both the topography and the roughness parameters of a surface.

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