Surface roughness parameters measurements by Digital Holographic Microscopy (DHM)

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ABSTRACT

Digital Holographic Microscopes (DHM) allows the capture of all the information necessary to provide 3D phase measurements with a nanometer vertical resolution in a single image acquisition. DHM images provide measurements of the surface topography which can be used for surface analysis, roughness measurements for example. In this paper we present roughness measurements on micro-balls of different sizes for which numerical procedures are applied for form factor and waviness removal. DHM thus permits quantitative measurements of the roughness on a 2 dimensional area allowing enlarged information compared to common profilometers. Mean roughness of 5 to 30 nm are measured and compared to values obtained by a profilometer.

Keywords: digital holography, roughness measurements, surface measurements, 3D optical topography

1. INTRODUCTION

Surface roughness parameters are most of the time measured using scanned contact stylus probe based instruments. International standards and norms are based on those instruments. For small scale roughness, smaller then a few tenths of micrometers, such measurement becomes difficult: ambient vibration amplitudes can be of order of magnitude of the roughness itself and contact with the sample may damage it. For such application range, Digital Holographic Microscopes provides an ideal alternative as they provide interferometric resolutions with extremely short acquisition time.

The strength of DHM as implemented in the frame of this paper lies in particular on the use of the so-called off-axis configuration, which enables to capture the whole information by a single image acquisition within a few microseconds. These important features make out of DHM a unique tool for surface roughness parameters measurements:

- The extremely short acquisition time makes DHM systems insensitive to vibrations. They can operate without vibration insulation means, making them a cost effective R&D solution and enable their implementation on production lines.

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- 3D and real time measurements enable control of entire samples.
- Lateral resolution is smaller that most of the conventional stylus. By proper convolution of the measurements with the stylus shape, any geometrical shape of stylus probes can be simulated.
- The measurements are possible on a large variety of surface shapes

2. DHM PRINCIPLES

Light interaction with a sample modifies both intensity and phase of the illuminating wave. Any available supports for image recording are sensitive only to intensity. Denis Gabor invented in 1948 a way to encode the phase as an intensity variation: the "hologram" [1]. Digital Holographic Microscopy (DHM) implements digitally this powerful concept of holography (Figure 1). With the present performances of computers and the developments of digital cameras, holograms can be numerically interpreted within a tenth of second to provide simultaneously: (1) the phase information, which reveals object surface with vertical resolution below 1° of the wave phase (the nanometer scale for homogeneous samples), and (2) intensity images, as obtained by conventional optical microscope. Both images are defined with a diffraction limited resolution in the transverse (0xy) plane and are "reconstructed" from the hologram in real time (more than 15 reconstructions per second for 512x512 holograms).

The strength of DHM lies in particular on the use of the so-called off-axis configuration [2], which enables to retrieve the 3D phase and intensity images of the observed object by numerical reconstruction of a single hologram, which comprises the whole information, and which can be acquired within a few microseconds only.

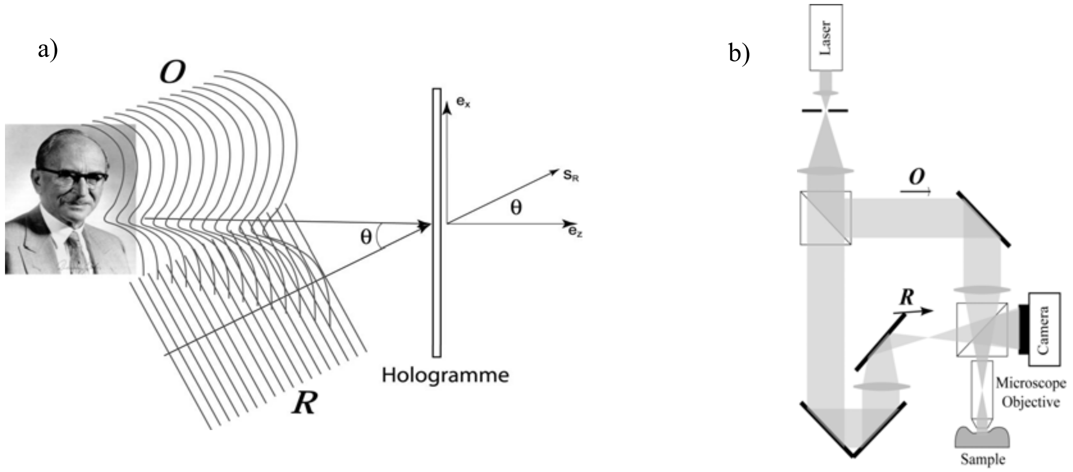


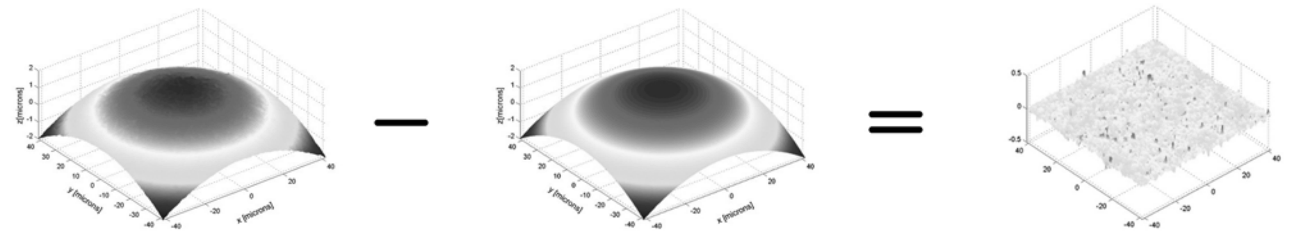
Figure 1: (a) Recording principle of off axis holograms. There are a few degrees (angle θ) between the reference (R) and the object beams (O). This enables to reconstruct the information using a single hologram acquisition. On-axis holography (i.e. θ=0) requires acquisition of several holograms. The portrait is the one of Dennis Gabor, Nobel Price of physics for its discovery of Holography. (b) Optical set up for reflection DHM: the source beam is first separated into two parts: a reference beam and an object beam. The object beam illuminates the sample. The light diffracted by the sample is collected by the microscope objective and is combined with the

reference beam to form a hologram on the camera. In this paper, the wavelength of the laser is 682 nanometers.

The numerical access to the phase allows numerous facilities among others phase aberration corrections and form factor removal [3]. A fit of the phase surface can be performed and then subtracted to the phase surface itself, leaving a residual shape. This allows either characterization of surfaces comparatively to a given or a theoretical one. But it also allows to perform roughness measurements on any shaped surface.

3. ROUGHNESS MEASUREMENT PRINCIPLES

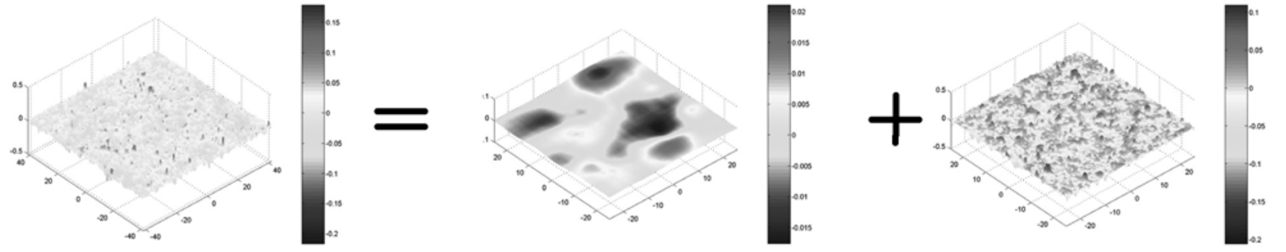
The samples characterized were metallic micro-balls with diameters of 0.5, 0.7, 0.8, 0.99, 1.0 and 1.2 mm. A hologram is recorded from the ball surface and the complex wave front is then reconstructed. The used instrument is a DHM R1000 from Lyncée Tec with a 50x (NA=0.8) objective. A least square fit is then performed to determine the radius and the center of the sphere. Finally the flatten surface (residue) is obtained by the difference of the two surfaces (Figure 2).



Measured Sphere fit Residue

Figure 2: Form factor removal principle: a spherical fit is subtracted to the measured surface to obtain the residual surface.

Two contributions remain in the residual surface: the waviness and the roughness. Both are differentiated in the frequency domain. A cut-off frequency has been taken to suppress forms with sizes of about 1/5th of the field of view (figure 3).



Residue Waviness Roughness

Figure 3: Roughness surface determination: the residual surface is decomposed in two parts in frequency: the waviness is composed of the low frequencies and the roughness of the high ones.

The roughness parameters can then be determined on the surface allowing a better statistical sampling (about 500’000 points) than on a single profile. The parameters of interest here are the mean roughness (Ra) and the maximum roughness (Rt). Ra is defined as the average of the absolute values and Rt as the highest peak to peak value.

4. MEASUREMENTS

The measures presented here are the 1 mm diameter balls. Figure 4 shows the 3D representation of a roughness surface. The field of view is 100 µm x 100 µm. The Ra determined on this surface is 14.2 nm and the Rt is 270 nm.

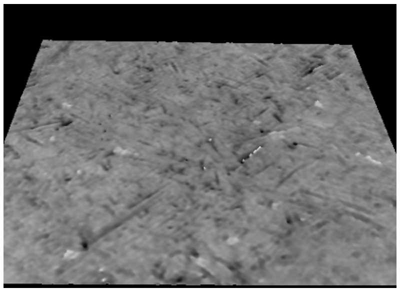


Figure 4: 3D representation of the roughness surface of a 1 mm diameter micro-ball. The field of view is 100 µm x 100 µm. Measured values: Ra= 14.2 nm, Rt= 270 nm.

15 identical micro-balls with a diameter of 1 mm have been measured by DHM and compared to measurements done with a TalySurf profilometer from Taylor-Hobson. Figure 5 resumes the measurements. The average Ra of these balls is 19.9 nm and the standard deviation is 3.36 nm.

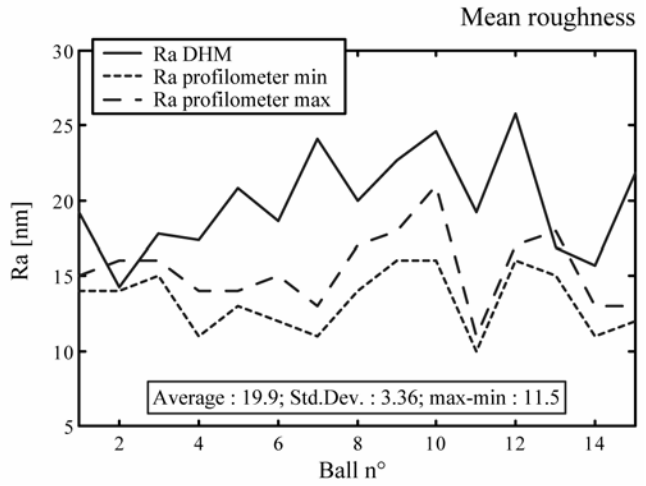


Figure 5: Mean roughness (Ra) measurements on 15 micro-balls of 1 mm diameter. Comparison with maximum and minimum values provides by the profilometer.

The profilometer measures several profiles of the surface and returns an average. The two curves for the profilometer represented in Figure 5 are those giving the minimum and the maximum value for Ra in the average. The results obtained by DHM are a little bit higher than those given by the profilometer.

The repeatability and reproducibility have also been tested. The repeatability has been verified performing 25 times the same measurement on the same surface (Figure 6). The standard deviation of Ra was found to be 0.11 nm and the one of Rt 17.7 nm.

The reproducibility has been tested to know if the roughness was uniform on one ball. 25 measurements have been performed on different areas of the ball surface. The measured Ra and Rt are given in Figure 6. The standard deviation of Ra was found to be 1.26 nm and the one of Rt 34.4 nm.

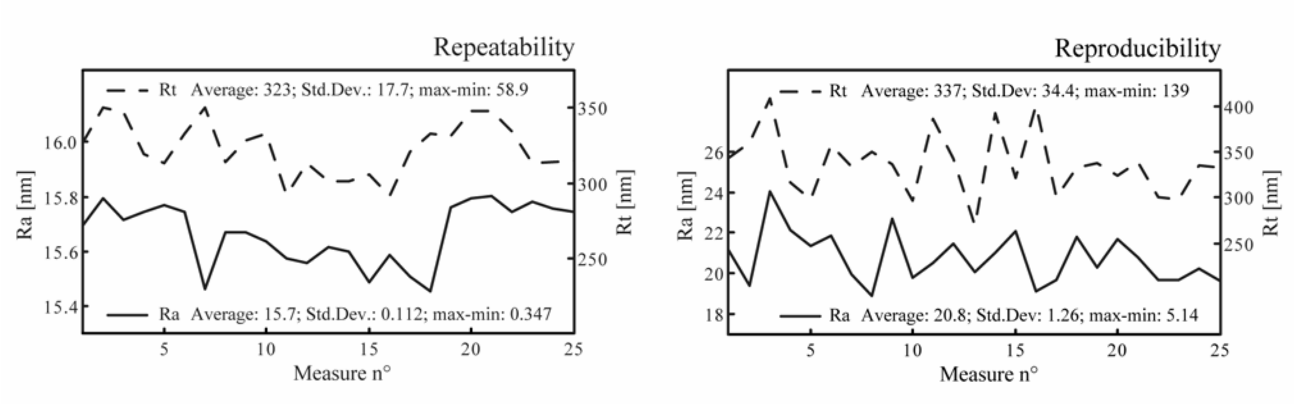


Figure 6: Repeatability and reproducibility tests. The repeatability is performed by 25 measurements on the same surface and the reproducibility by 25 measurements on the different areas of a same micro-ball.

These results show that the measurement incertitude is far under the variations of the roughness to measure, establishing the pertinence of the measurement technique.

The roughness values for the balls of other diameters measured by DHM and profilometer are summarized in Figure 7. Measurements on the 0.5 mm ball were not possible with the profilometer.

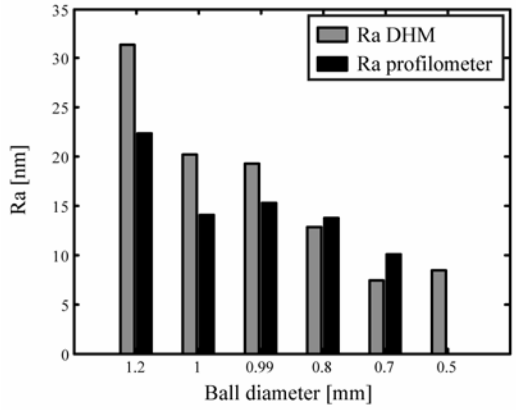


Figure 7: Comparison between DHM and profilometer measurements for different ball sizes. Profilometer measurements on the smallest balls were not possible.

5. DISCUSSION

The contact profilometer measurement technique is basically different from the optical DHM one. Due to its contact principle, the profilometer provided data results of the convolution of the sample profile with the tip radius of instrument. The profilometer thus provides correct information on sharp hills, but does not detect narrow valleys. DHM does not suffer from this asymmetry, but might be limited in light collection of some samples.

Both measurement techniques show an increase of the roughness with the diameter of the ball. In high roughness, DHM values are higher than those provided by the profilometer. On the contrary, for small roughness, DHM provides lower values. Different causes are possible. Due to the radius of the tip (2µm), the sensitivity of the profilometer is lower for narrow valleys. On the other hand the profilometer has a higher sensitivity on sharp bumps. Nevertheless, the sample surface observed here is major formed of valleys, which leads to a higher sensitivity for DHM. Thus the Ra given by DHM is higher than the one of the profilometer. For the small roughness values, the profilometer is limited by noise. It is sensitive to external vibrations, which is not the case for DHM. In addition, here the balls have to be rotated under the profilometer tip, and the measurements are thus more delicate for small balls. These reasons lead to the higher values provided by the profilometer compared to those of DHM, for the smallest radius, which corresponds to the balls of finer surface quality.

6. CONCLUSION

We showed that DHM allows precise and robust roughness measurements. A standard deviation of 0.11 nm was obtained over 25 identical measurements. The measurements were performed on balls of 6 different diameters. The results are reliable for all the tested diameters and correspond to values obtained by a profilometer. DHM thus allows a complete surface texture analysis in terms of form, waviness and roughness quantification.

7. ACKOWLEDGMENTS

The development of the technology has been supported by Swiss government through CTI grants TopNano 21 #6101.3 and NanoMicro #6606.2 and #7152.1. Systems are commercialized by Lyncée Tec SA (www.lynceetec.com).

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