

# Rough Surfaces Profiles and Speckle Patterns Analysis by Hurst Exponent Method

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**Abstract:** In this work, a conventional surface roughness comparator is used to perform an analysis of different textures. The Hurst exponent method for the characterization of optical profiles and speckle digital patterns obtained from the comparator was used. By implementation of a simple experimental setup with minimum alignment, information about specific points on the comparator for different roughness was obtained. The processing and analysis of optical signals and images obtained by reflection allowed calculation of Hurst coefficients, revealing a relation between surface roughness, optical profiles and speckle patterns. The setup simplicity and Hurst analysis suggest their combined application on surface metrology.

**Key words:** Roughness, optical data processing, Hurst exponent, speckle patterns.

## 1. Introduction

Most of ordinary mechanical processes are manifested on material surface; such an important fact is an absolute singular element to be considered on surface engineering studies [1]. From a basic point of view, its importance is over emphasized for technological materials as mostly of them modified their properties due to complex superficial processes. Although superficial finishing touch and its integrity (determined by inherent manufacturing processes) are able to produce higher quality surfaces than others, economical cost of processing is increased with superficial finishing improvement [2].

On the other hand, surface roughness is a measurable

characteristic which may be defined as a set of irregularities determined on a real surface section, where shape and undulation mistakes have been eliminated [3]. Standard techniques based on profile registering are used to quantify roughness through a height function  $z(x, y)$ , which contains information about a superficial profile of interest. Such a profile is usually obtained by means of a mechanical profile meter; however precision, scanning time and surface deterioration become disadvantages for direct contact systems used to obtain information about roughness and surface shape. Additionally, it is well known that several non-contact methods have been developed for superficial roughness quantification, such as capacitive [4], ultrasonic [5], atomic force microscopy (AFM) [6, 7] and optical [8, 9]. AFM is widely used for topographic studies in material surfaces [10, 11],

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although it might be consider as a sub-micrometric resolution profile meter, i.e., a contact method able to operate in a non-contact mode [12].

Nowadays, optical methods are still the most widely used; on such a context, the optical interferometry technique has been used to measure surface characteristics under 0.1  $\mu\text{m}$  range without physical contact [13]; also light scattering techniques have been used for superficial roughness measuring at 0.1-3  $\mu\text{m}$  range [14-19]. Recently however, laser speckle techniques have been applied on different science and engineering areas, such as angular speckle correlation (ASC) [20, 21], autocorrelation of speckle patterns (ASP) [22-25], speckle contrast method (SCM) [26-28] and spectral speckle correlation (SSC) [29, 30], as the most commonly used technique for surface engineering evaluations at 1.6-50  $\mu\text{m}$  interval [31].

Regarding surface roughness characterization, the statistical data processing is used for certain parameters determination such as RMS roughness ( $R_{rms}$ ) and average roughness ( $R_a$ ), defined as:

$$R_a = \frac{1}{L} \int_0^L |z(x)| dx \quad (1)$$

$$R_{rms} = \sqrt{\frac{1}{L} \int_0^L z^2(x) dx} \quad (2)$$

where,  $L$ ,  $R_a$  and  $R_{rms}$  represent sampling length, arithmetic average of the absolute values of heights  $z(x)$ , and quadratic shifts average value with respect to average height, respectively. However, as such values depend on the analyzed characteristic length, it is necessary another method to avoid this dependence such as the self-affinity analysis. This method is usually used for interface roughness and material surface studies, and consists on determining the Hurst exponent ( $H$ ), also known as roughness exponent.

For Hurst exponent calculation, one of the most commonly used methods is the rescaled range analysis, also known as  $R/S$  method, defined as:

$$R/S = \frac{1}{N} \sum_{i=1}^N (R_i/S_i) \quad (3)$$

where  $R$  represents the maximum and minimum

variable values, and  $S$  is the time series standard deviation. A detailed description of the method can be found on specialized literature [32]; it has been shown that relation between  $R/S$  and  $H$  is:

$$R/S \propto \tau^H ; \quad H = \frac{\log(R/S)}{\log(\tau)} \quad (4)$$

where  $\tau$  is the measured period time, and  $H$  is obtained as the slope in a logarithmic graphic  $R/S(\tau)$  vs.  $\tau$ , which determines how rough is an interface. Unlike former  $R_a$  and  $R_{rms}$  parameters,  $H$  is ideally independent from sampling size being  $H = 1$  for a fully smooth profile (straight line).

On the other hand, Hurst coefficient  $H$  is a quite versatile and simple concept, as it has been used as a control parameter in roughness studies using speckle digital patterns obtained in return from the laser beam scattering on a metallic rough surface [33], as well as surface roughness determination on polymers [34, 35]. Therefore this work is focused on determination of the method sensitivity for different roughness scales corresponding to different industrial manufactures, where Hurst coefficient is obtained from optical profiles and digital speckle patterns acquired from scattered light coming from a known rough surface.

## 2. Materials and Methods

### 2.1 Optical Equipment and Surface Roughness Comparator.

A ~50 mW power laser beam at 533 nm wavelength is used as illumination source. A 40 $\times$  microscopic objective and a focal length  $f = 50$  mm biconvex lens are used for expanding and collimating the laser beam. An Alfa a 200 CCD camera with  $3,872 \times 2,592$  pixels resolution and a  $6.093 \times 7.253$  pixel size is used for speckle patterns registration. A Microfinish conventional manufactured comparator is used to obtain the optical profiles and speckle patterns corresponding to surface roughness into the following intervals: 0.1-0.2  $\mu\text{m}$  (lapping), 0.4-0.8  $\mu\text{m}$  (rectified) and 1.6-12.7  $\mu\text{m}$  (profiled).

## 2.2 Optical Characterization

For optical profiles obtaining, experimental setup consisted on illuminating with a laser beam an specific point in the center of every analyzed section of the comparator (Fig. 2a). A translational mechanic system allowed longitudinal displacement through every section and also to perform the optical scanning; the scattered light containing information of surface irregularities and variations is collected through a biconvex lens ( $f = 200$  mm) and focused on a power detector coupled to a data acquisition, connected in turn to a PC for later analysis. On the other hand, for digital speckle patterns acquisition, the laser beam is amplified to a  $\sim 10$  mm diameter with a  $40\times$  microscope objective and another biconvex lens ( $f = 50$  mm), to illuminate a  $78.53$  mm<sup>2</sup> surface section, and the obtained speckle pattern is registered with the CCD camera (Fig. 2b).

## 2.3 Storage and Optical Data Processing

A HP Benchlink Data Logger data acquisition and a Newport power detector coupled to a PC are used for time series registering, where  $\sim 6,500$  data were registered at a  $100$  ms/datum velocity sampling. Scattered beam power coming from the sample is used as a time series monitoring parameter. Hurst exponent analysis of roughness optical patterns registered as time series is performed through an application

software where  $R/S$  algorithm was implemented, as defined by Eq. (3). For digital processing of images an application software was used; each speckle pattern is processed to obtain intensity profiles ( $1 \times 1,616$  pixels vectors) corresponding to  $78.53$  mm<sup>2</sup> of transverse section illuminated by the laser beam. The resultant vector represents the total image average which contains the variations and irregularities information of analyzed sections. Profiles (vectors) are used for surface characterization through Hurst exponent method.

## 3. Results and Discussion

### 3.1 Optical Patterns

In Fig. 3, three analyzed surfaces corresponding to



Fig. 1 Microfinish surface roughness comparator.

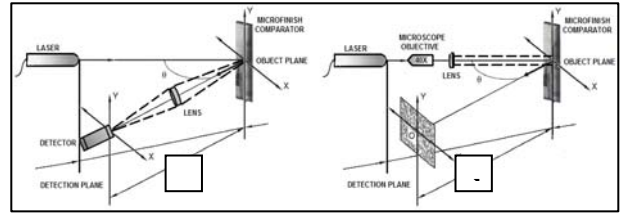


Fig. 2 Experimental setup. (a) optical profiles registering and (b) speckle patterns registering.

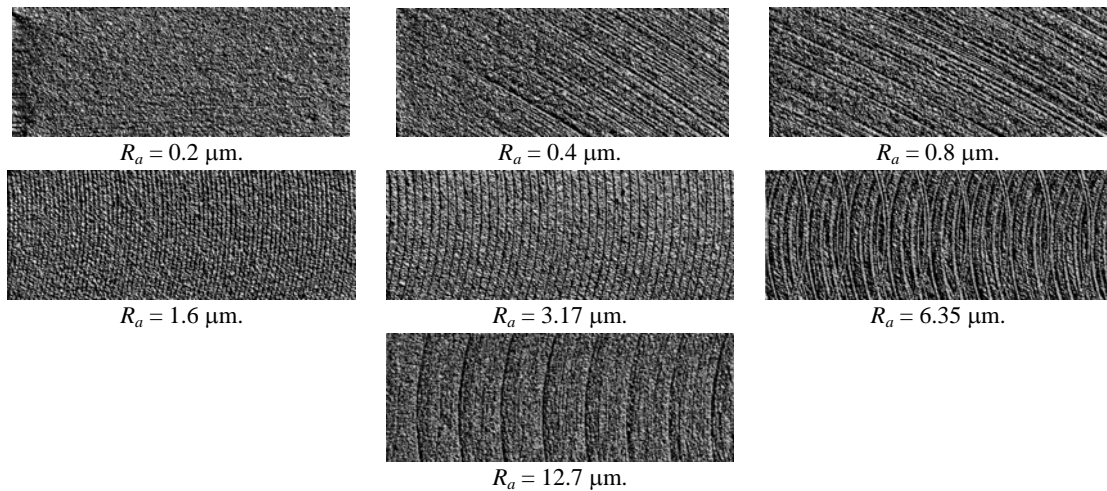


Fig. 3 Surface roughness corresponding to different conventional manufactures.

different conventional manufactures at surface roughness range  $R_a = 0.2$ - $12.7$  are shown.

At Fig. 4, digital images associated with speckle patterns obtained for each analyzed sections are shown. Every registered image presents  $1,616 \times 1,080$  pixels resolution corresponding to a  $\sim 78.53 \text{ mm}^2$  section area.

It is clearly observed how roughness has an effect on speckle pattern formation, because as  $R_a$  roughness parameter increases, it generates high contrast fluctuations on speckle patterns intensity distribution. On the other hand on sections with relatively uniform distribution intensity, low contrast regions on speckle patterns are generated, which do not depend on the manufacture process. Fig. 5 shows 5 of 7 different optical profiles registered for different conventional manufactures presented above in Fig. 3.

For optical scanning, laser intensity was adjusted to a fixed value for each comparator manufactures, as well as longitudinal displacement on central part of

each different surface section, obtaining as a result the optical roughness profiles. In Fig. 5, it is clearly seen how as surface roughness increases, optical profiles height fluctuations are highlighted.

### 3.2 Hurst Exponent

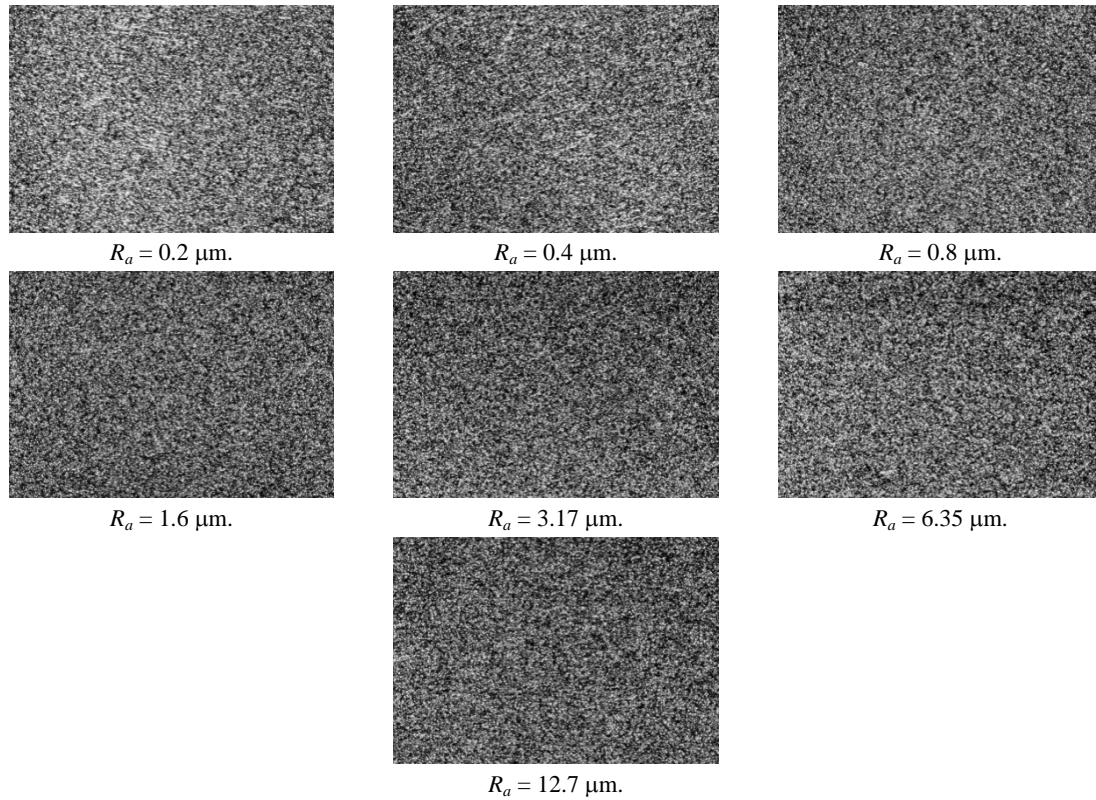
Using the method explained above (Subsection 2.2), Hurst exponent is calculated for each digital speckle patterns associated to surface roughness of different conventional manufactures presented in Fig. 3. Figs. 6a and 6b represent Hurst exponent as a height absolute values arithmetic average function ( $R_a$ ), where red solid lines are corresponding data fittings, obtaining exponential decaying curves:

*Speckles:*

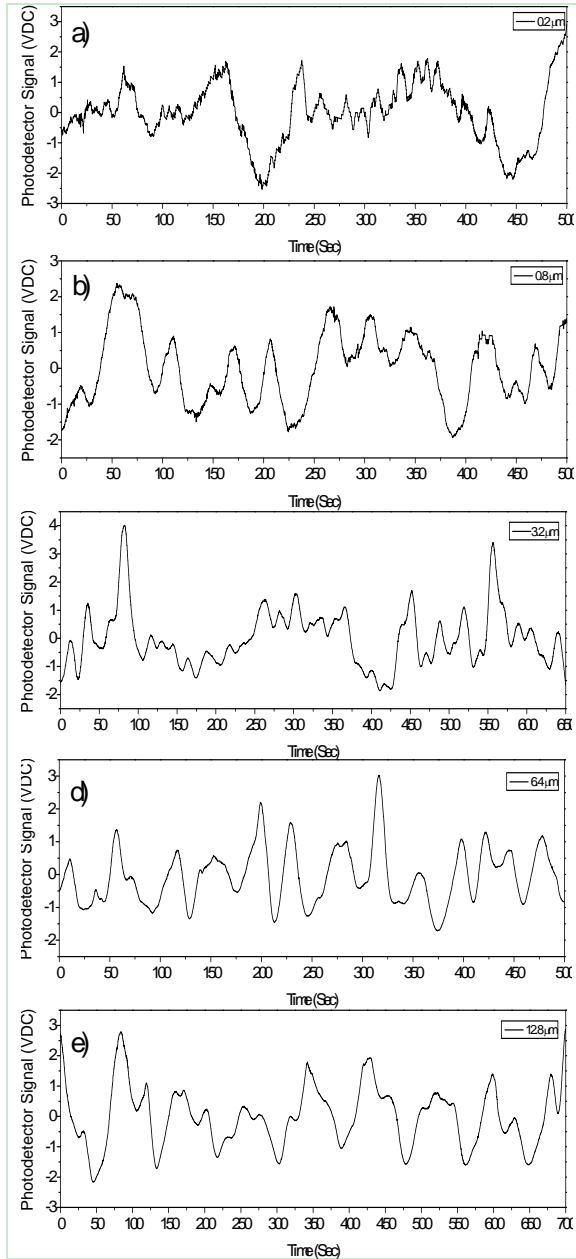
$$H(R_a) = 0.10516e^{-0.47254R_a} + 0.58221e^{-4.60871R_a} + 0.45392 \quad (5)$$

*Profiles:*

$$H(R_a) = 0.07456e^{-3.2150R_a} + 0.33809e^{-0.05377R_a} + 0.4583 \quad (6)$$

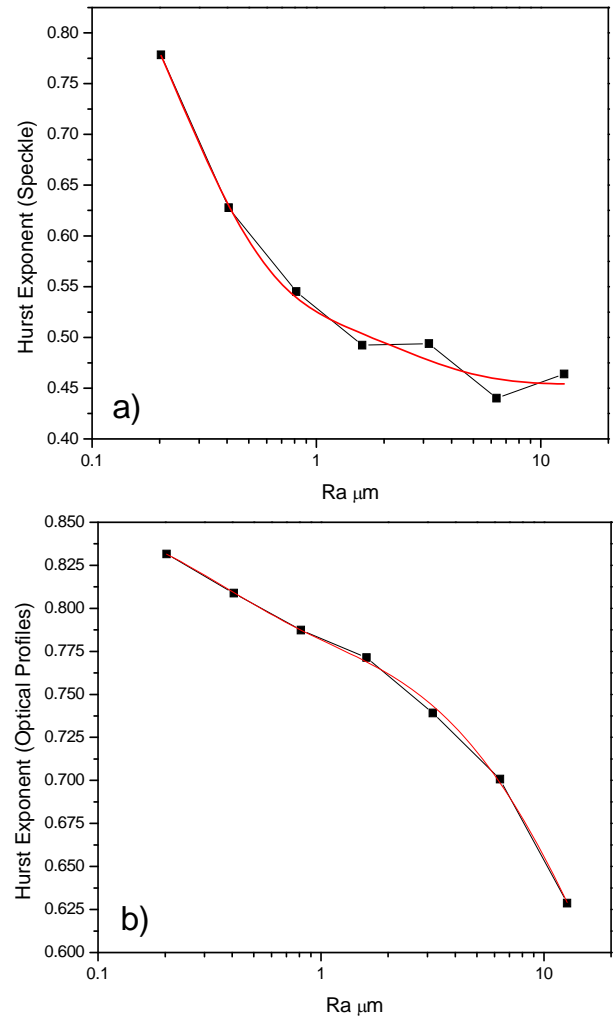


**Fig. 4** Digital speckle patterns associated to surface roughness of each analyzed section.



**Fig. 5 Optical profiles. (a) lapping (0.2 μm), (b) rectified (0.8 μm), (c-e) profiled (3.2-12.7 μm).**

Correlation coefficients of previous equations are quite acceptable (speckle:  $R^2 = 0.98934$ ; profiles:  $R^2 = 0.99902$ ). A brief analysis of Eqs. (5-6), allow us to observe how as  $R_a$  parameter approaches zero value,  $H$  exponent approaches to 1, corresponding to a smooth surface; otherwise, if  $R_a$  parameter increases away from 0, surface becomes rougher and  $H$  exponent approaches to 0.



**Fig. 6 Hurst exponent as a function of  $R_a$ : (a) speckle patterns, (b) optical profiles.**

On the other hand, an input image texture may be characterized using entropy, understood as a random statistical measure [36], where for an  $X$  image quantified at  $M$  levels, entropy  $H_x$  is defined as:

$$H_x = \sum_{i=0}^{M-1} \left( p_i \log_2 \left( \frac{1}{p_i} \right) \right) = - \left( \sum_{i=0}^{M-1} (p_i \log_2 p_i) \right) \quad (7)$$

where,  $p_i$  ( $i = 0 \dots M - 1$ ) is the probability of  $i^{th}$  used pixel level (obtained from an intensities histogram). For grayscale images,  $M$  obtained value is 256.

In Fig. 7, the entropy calculated from digital speckle patterns (Fig. 4) is shown. The  $H_x$  red solid line entropy represents data fit corresponding to an exponential decaying function as depending on surface

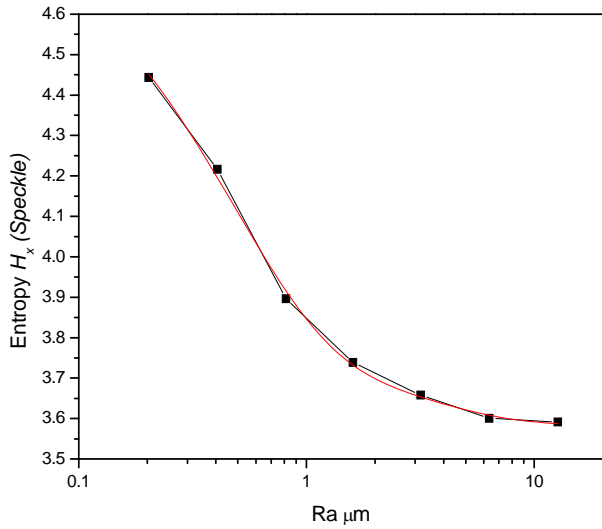


Fig. 7 Speckle patterns entropy as function of  $R_a$ .

roughness  $R_a$ :

$$H(R_a) = 1.06413e^{-2.1680R_a} + 0.19449e^{-0.33370R_a} + 3.58483 \quad (8)$$

here, estimated correlation coefficient is also quite acceptable ( $R^2 = 0.99845$ ), being such a fit a fine model to predict entropy values for speckle patterns, considering  $R_a$ .

Fig. 8a presents Hurst exponent  $H$  and entropy  $H_x$  as  $R_a$  functions; on Fig. 8b  $H$  exponent as depending on  $H_x$  entropy is shown, where the following relation is obtained:

$$H(H_x) = -0.80469 + 0.34904H_x \quad (9)$$

Usually entropy is used as a surface roughness measuring, which has a low value when fluctuations or variations (heights, in our particular case) have similar values; on the other hand when fluctuations are significantly variable, entropy has a high value. Although on Fig. 7 entropy has high values for  $R_a$  close to zero (smoother surfaces), for rougher surfaces ( $R_a$  far from 0), lower entropy values are obtained. As it has been explained, such behavior might be caused by high contrast fluctuations on the speckle patterns distribution and, on sectors where intensity distribution is relatively uniform, low contrast regions are generated; additionally, surface height fluctuations represent a Gaussian process for speckle patterns.

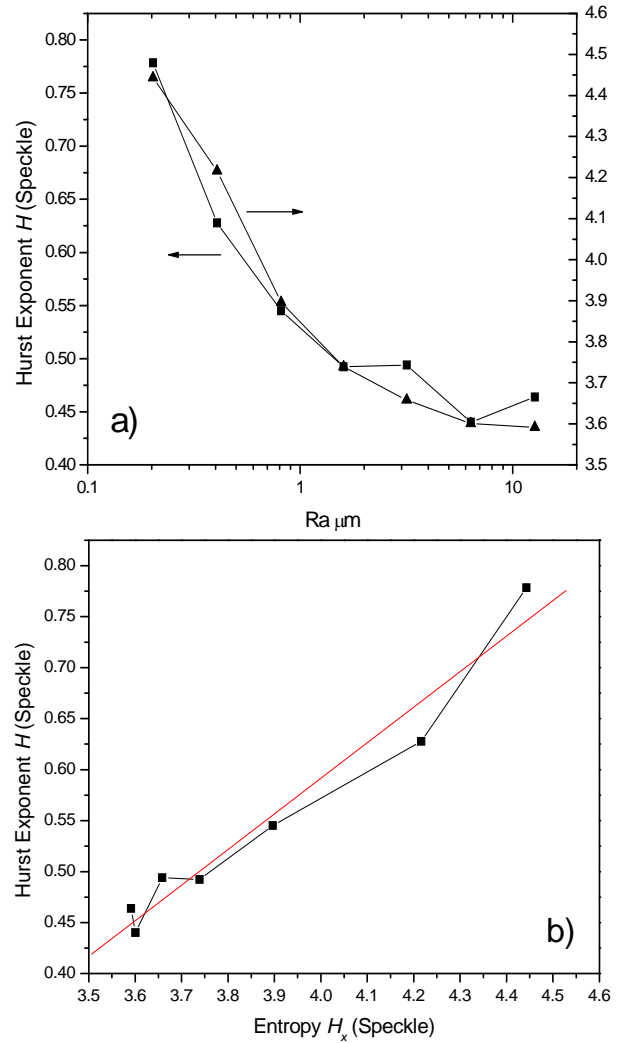


Fig. 8 (a) Hurst exponent and speckle patterns entropy as functions of  $R_a$ . (b) Hurst exponent as a function of  $H_x$ .

At Fig. 8b, a linear correlation is also shown ( $R^2 = 0.95748$ ), which represents  $H$  as a function of  $H_x$ , where for high entropy values (i.e.,  $R_a$  close to 0),  $H$  approaches to 1, which corresponds to a smoother surface, and for low entropy values  $H$  approaches more to 0 value (rougher surface).

#### 4. Conclusions

The sensitivity of the method was determined for different roughness scales corresponding to different industrial manufactures. Hurst exponent was obtained from optical profiles and speckle digital patterns, acquired in turn from scattered reflected light coming from a known rough surface. An evident dependence of



Hurst exponent on surface roughness was demonstrated. The simplicity of experimental optical setup combined with Hurst method, may suggest its application on surfaces metrology.

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