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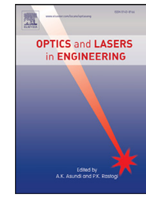

Roughness measurement of oriented surface by depolarization of scattered light

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ABSTRACT

In this work we present a study of light depolarization by an oriented rough surface. A polarized laser beam shines samples with different roughness in two different ranges and the intensity of depolarized light at normal direction is monitored. We show the applicability of Cross–Polarization Ratio (CPR) analysis, previously applied to random rough surfaces, for oriented rough surface. In addition, we observed a clear dependence of the depolarized light intensity by respect the sample's mean roughness (R_a) for both analyzed roughness range. Our results consist in a proof of principle for indirect roughness measurement of metallic samples and intend to be a potential application in industrial production line, once R_a can be related directly with an intensity measurement in a fast way.

1. Introduction

In material research, surface roughness is an important parameter to be controlled. For film deposition the final average roughness plays a crucial role for many applications [1–3]. Substrate's roughness can affect structure and morphology of thin films[4]. For industrial material, such as surfaces of ammonia [5] and spray-dried dairy powders [6], surfaces properties have extreme relevance. In the more traditional and older industrial production, such as metallic plates, the surface's roughness affects the attrition and adhesion, and must be controlled in order to cope with the surface use [7–9].

Average roughness (R_a) is the main parameter studied for surface characterization. Profilometry is the established method in engineering process. However, the contact principle is responsible by surface damage and non contact techniques are constantly developed [10]. The main approach for non-contact surface's measurements is through optical methods [11]. By means optical profilometer it is possible to recover the stylus technique without damage and also increase resolution [12]. New approaches such as composite interferometry have enabled the creation of a hight sensitive method immune to vibration [13]. By using optical fiber, an optical profilometer was developed for hard-to-access areas [14].

Speckle patterns are observed in the scattering of light in rough surfaces [15]. By using speckle's properties several methods were proposed. Correlation between speckle patterns produced by different incidence angle was used to propose surface roughness measurement [16–18]. Digital speckle patterns opened a very powerful strategy: image processing. The ratio B/D of the number of bright (B) and dark (D) pixels both in specular [19] and normal [20] direction were related to surface roughness. Statistical properties of digital speckle patterns were also explored to evaluate metallic surfaces such as fractal dimension [21], image threshold [22], and lacunarity [23]. It was also introduced the Hurst exponent of digital speckle patterns to study roughness of metallic surfaces [24] and monitoring moving surface quality [25]. It was showed that speckle patterns produced by the incidence of laser beams containing orbital angular momentum improve the sensitivity of the Hurst exponent technique [26].

Beyond speckle patterns analysis, light scattering is used in the investigation of surface properties with different approaches [28,29]. Statistics estimation of roughness of surface was obtained from light scattering measurements [27]. Another very powerful analysis of scattered light is by means depolarization [30–32]. Scattering of electromagnetic field in rough surface was carefully studied in [33] leading Liu, Li, and Nonaka [34] to introduce the Cross-Polarization Ratio (CPR) to evaluate random rough surface.

The orientation of rough surfaces has a great importance for contact and adhesion applications [35,36]. Concerning roughness measurement, a random surface can be studied in any direction and only the amplitude of the profiles are important for the measurement [10]. On the other hand, in an oriented surface the direction should be taken into account. For profilometry, the profile should be lifted in a direction orthogonal to

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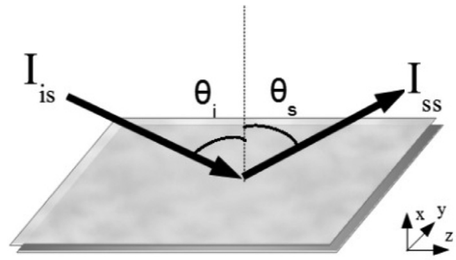

Fig. 1. Reflection of a beam light on a smooth surface.

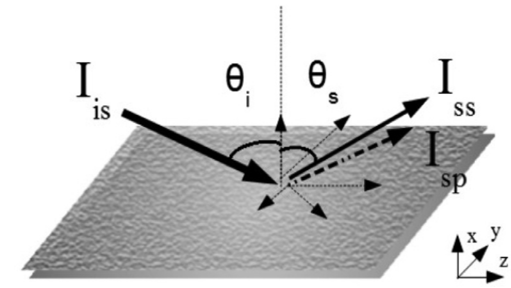

Fig. 2. Depolarization of a beam striking a rough sample.

the orientation of the surfaces. Considering laser based measurements [37], for random surfaces only random speckle patterns are expected while oriented surface can given rise to non random speckle patterns, presenting some structures in the scattered light. Considering the CPR technique, developed for random surfaces, does it also apply to oriented surfaces?

In this work we study the intensity of the depolarized light scattered by metallic oriented rough surface, typical finishing in the industries of metallic plates. This study is performed in a very simple and cheap setup. We showed that the CPR approach for random rough surface is also applicable to oriented one. In addition, our results show that, for the studied case, the depolarized light intensity can be used itself for inverse evaluation of the roughness, avoiding an extra data processing in the CPR calculation, giving a more fast answer about roughness. This result has a potential interest for real-time roughness control of metallic surfaces. The article is presented as follows: In section II we summarize the CPR calculation; Section III is devoted to present the sample preparation and characterization beyond the setup for depolarized light intensity measurement; Results and discussions are presented in Section IV. We summarize the main results of our work in Section V.

2. Light depolarization in rough surfaces

When an initially polarized beam strikes a surface its polarization can be modified. This change can be originated by both optical activity of the material, which is the heart of the ellipsometry technique [38], as well as due to surface roughness [34]. For ellipsometry purposes, the roughness is an undesirable property because it is expected that polarization changes are due material optical properties. However, for metallic surface possessing typical industrial roughness, the scattering can be the main source of the polarization changes, or depolarization. In our work, we are interested in the second case and by this reason we consider only the depolarization due to surface roughness.

We start this discussion with an illustration of an idealized case. A *S*-polarized beam of light striking on a flat metallic surface. Let us first consider a smooth surface with no roughness. Fig. 1 illustrates this situation. The incident beam, with intensity I_{is}, is of an angle of θ_i with respect to the sample's normal. Then the incidence plane is the plane *XY*. In this case, there is a specular reflection, with an angle of $\theta_s = \theta_i$ and the reflected intensity I_{ss} (reflected light intensity with *S*-polarization). The specular reflection in super smooth surfaces does not change the polarization state of light. Thus, the *S* polarization (electromagnetic field oscillating in the plane *XY*) remains, mostly on the same plane when reflected. In other words, light has not depolarized.

Let us consider now the illustration of the case of a *S*-polarized incident beam on a surface having some roughness. Fig. 2 illustrates this situation. In this case, in addition to specular reflected beam the light is scattered in many others directions [34], some of then represented by the small arrows. In this process occurs the depolarization, causing cross components to appear, that is, orthogonal to the polarization of the incident beam, for the discussed case, *P*-polarization (the electromagnetic field oscillates in the plane *XZ*). In the illustration, the incident beam has polarization *S* with intensity I_{is}. In any direction we can observe the scattered light we can observe light intensity that has not being depolarized (I_{ss}) and the intensity of the light with cross-polarization (I_{sp}), that is, orthogonal to the polarization of the incident beam (I_{is}). In Fig. 2 we can see the illustration of the change of direction of propagation due to the scattering, beyond the polarization. In this way, the incident beam polarized in the plane *XY* is also scattered in other planes and it is possible to detect orthogonal polarization *P* (plane *XZ*). We then have light intensity scattered in both polarizations: *P* and *S*.

An elegant and accurate way of studying the degree of depolarization of incident light with polarization *S* on a rough surface, in a given direction of observation,has been introduced by Liu, Li, and Nonaka[34]. This is called the Cross-Polarization Ratio (CPR). This ratio is defined as the percentage of the intensity of the polarization *P* in the scattered light relative to the total initial intensity.

$$CPR(\%) = \frac{I_{sp}}{I_{sp} + I_{ss}} \times 100, \tag{1}$$

the intensities defined above,I_{sp} and I_{ss} means the intensities scattered with polarization *P* and *S*, respectively, for an incident beam with *S* polarization. For this reason *CPR* can be measured for any direction of observation. For the purposes of this study, we have analyzed only the intensity scattered in the normal direction of the sample surface.

3. Materials and methods

3.1. Sample production and characterization

In order to produce the samples of rough surfaces we used commercial Dural aluminum. For metallic surfaces, that present some reflectivity, this technique could be more suitable once can offer a better signal to noise ratio for the scattered intensity. So, in principle, it could be used in a broad spectrum industrial metallic surfaces production. The samples surfaces, which were only about 2.0 × 3.0 cm in size, were prepared by using sandpapers with different grits, being sanded until it has a uniform profile of roughness. The process consisted in first sanding all the samples always in the same direction under a constant pressure. This procedure produces oriented rough surfaces with regular grooves in a preferential direction, similar to finishings such as milling and griding, largely used in the industry. We start with the roughest sandpaper (grit 80 MESH), and then separating one of them which became the first (rougher) ready sample. The remaining three samples were sanded again with 150 MESH sandpaper and the second sample was ready (the second rougher). Similarly, the four samples were made successively with the grit sands of 80, 150, 400 and 600 MESH, thus making the four samples from the roughest to the smooth.

Through the Leica DCM3D confocal microscope, 3D profiles of the surface of each sample were obtained. Fig. 3 presents the images of the profiles of the surfaces of four used samples. These images are in agreement with the expected once the rougher sandpaper (80 MESH) generates the rougher surface (Fig. 3-d). The confocal microscope takes 35 associated profiles and each one represents the equivalent to a "slice" of the sample with its height in function of the position. The roughness