Surface morphology characterization of a paraffin film used as an optical diffuser

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1. Introduction

There are many applications, such as different lighting applications that need uniform light over large areas like electronic displays and signs, LED-based lighting systems, fluorescent-based lighting systems, and printed signage that need to use optical diffuser. Moreover, uniform illumination for lens-less single-exposure 3D imaging [1] requires uniform illumination, as is also the case with colorimetric analysis for detection of various substances by using hand-held devices [2]. Furthermore, in laser safety systems it is also necessary – except of special glasses and beam dumpers, to have optical diffusers as supplementary shields against high power laser beams. Other applications include mimicking of a dynamic scattering medium generating variable speckle [3]. Such mimicking could help for testing different image recovery algorithms used for extracting image from a light beam traveling through a scattering medium prior to test them on the real system (for example, biological samples). These diffusers are designed to break up and distribute light evenly. There are several working principles for such optical diffusers. For example, two such techniques are scattering, which is also referred to as the bulk diffusion, and, respectively, refraction. The latter one is considered to be an optically active surface type of light diffusion since refraction takes place only at the entrance and, respectively, exit surfaces of the material.

In the scattering technique, a scattering additive is incorporated within the diffuser. There are many additives that are used today to manufacture such type of light diffusion panels. Usually, clear particles having a different refractive index than the surrounding host material can be obtained, the scattering properties being determined by several factors such as size and shape of the particle, material used for making the particle (refractive index contrast). In this way it is much easier to achieve a better scattering effect. This type of optical diffuser is described for example in [4], [5] and [6].

The refraction technique is mainly used for polymer made panels that have an irregular structure of their surface. Each time when light reaches a surface inclined at an angle, it will be refracted. The change of direction due to refraction is equivalent to a scattering process (for random slopes on the surface). It should be taken into account that the boundary between air and polymer sheet (especially when it has a wrinkled surface at wavelength and sub-wavelength scale) also causes a change in the reflective index.

Usually, the fabrication of these optical diffusers, either scattering or refractive, requires several fabrication steps and use of materials that can be costly and not environmentally-friendly. Moreover, if lithographic fabrication techniques are used, the resulting diffuser is a pseudo-random one, since the scatterers / surface irregularities are put according to a mathematically specified position. Even if a software-based pseudo-random number generator is used, their positions on the surface or within the material are still deterministic. It is the aim of this paper to present an environmentally-friendly, cost-effective route for making such optical diffusers that have truly random patterning.

The paper is organized as follows. Chapter 2 describes the preparation and surface morphology characterization of the paraffin film, with the emphasis put on the characterization part. Chapter 3 is a discussion section and contains also the concluding remarks.

2. Preparation and characterization

We have used a liquid bed for making the paraffin film. The paraffin was molten and then placed onto the liquid bed. We used a different route than in [7], since they were oriented towards obtaining wax drops of different shapes. We let the paraffin film to solidify naturally, without forcing its cooling. The obtained film had a surface in excess of 10 cm2. This initial, large area film was broken into several smaller parts with the help of a tweezers.

In order to determine its surface morphology, we used two methods: optical microscopy and, respectively, Atomic Force Microscopy (AFM). We have used two such different techniques in order to check the surface morphology at different length scales.

First, the film was examined with the naked eye in order to qualitatively determine its optical transmission. A photo image is presented in figure 1, where we have used a pencil for checking how images are transferred.

It can be observed from figure 1 that the film is translucent and the image of the object is blurred. This is a first test showing the diffuser properties of the film.

The optical microscopy images are shown in figures 2a-2f.

As can be seen from figures 2a-2f, the surface is extremely irregular. Practically, we cannot identify two regions having the same pattern of the surface. Even if the general aspect is similar between different regions, the concrete geometry of each region is individual and represents a fingertip of that precise region. We have measured the thickness of the paraffin film by optical microscopy of its section, as presented in figure 3.

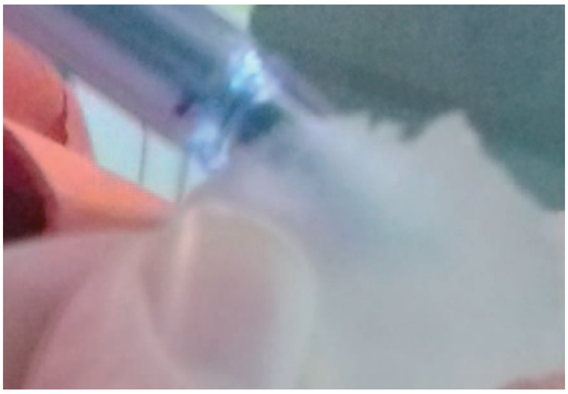

Figure 1. Photo image of the paraffin film showing its optical transmission.

The thickness was measured in several regions along the thickness. The average value is 89 microns with a deviation of not more than 2 microns.

There are several scales of irregularities, as can be noticed from figures 2a-2f. First, there are parts of the images that are unfocused. These regions are at a different height than the clear part of image, showing a large scale patterning of the film on lengths of hundreds of microns to millimeters. Secondly, there are the patterns as those shown in the clear part of figures 2a-2f, with a specific size in the few tens of microns length scale.

These second scale patterns have a finer structure. These finer scale patterns, not accessible to optical microscopy because of refraction, are revealed by AFM images, as presented in figures 4a-4c. AFM measurements were achieved in semi-contact (tapping) mode using a Ntegra Aura SPM (NT-MDT Spectrum Instruments).

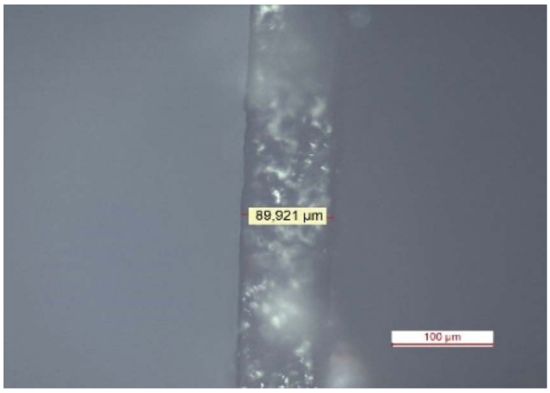

Figure 3. Optical microscopy image of the paraffin film thickness.

As can be noticed from figures 4a-4c, at this scale the patterns are in the micron-to-submicron range. It must be mentioned the fact that we have made detailed measurement (i.e. scan range of 10 microns) in several places on the surface and each region showed a different kind of surface pattern. The one presented in figure 4c seems to indicate trapping of some gas bubbles at the interface between liquid bed and molten paraffin layer. It must be noted that the bubble-shaped patterns appear only on one face of the paraffin film, indicating the fact that the film was quite viscous when these bubbles were trapped at the liquid-paraffin interface. Some of these bubbles may be embedded inside the paraffin layer, since paraffin is able to

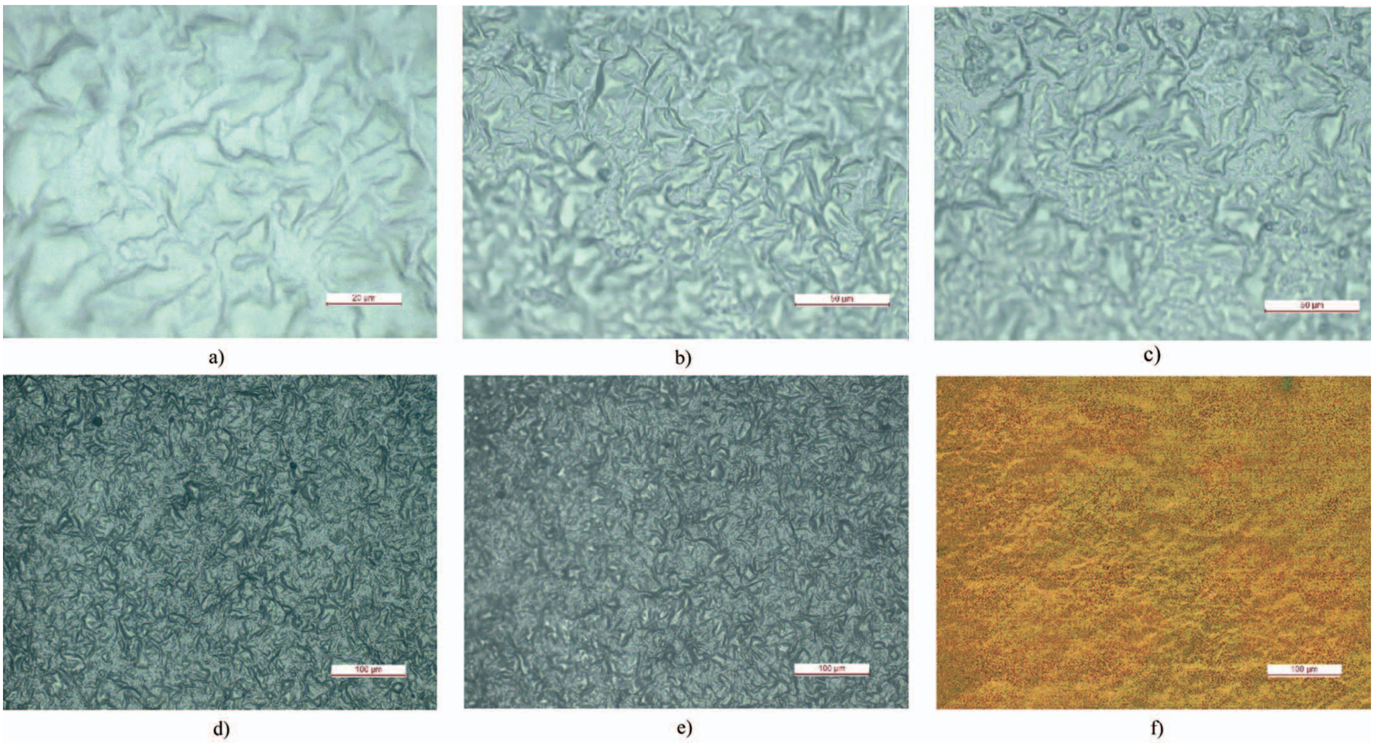

Figure 2. Optical microscopy images (in reflection mode) of the paraffin film. a) bright field, bar 20 microns; b) bright field, bar 50 microns, same region as a); c) bright field, bar 50 microns, another region on the film's surface; d) bright field, bar 100 microns, same region as in c); e) bright field, bar 100 microns, another region on the film's surface; f) dark field image of the paraffin film, bar of 100 microns.

absorb gases [8]. In this case, light travelling through paraffin and hitting such inhomogeneities will be either scattered or diffracted (or both) according to the size of bubble. The height variation in figures 4a-4c ranges from sub-micrometer to few microns scale while the rms roughness is of the order of 0.5 microns on array of 90 microns x 90 microns.

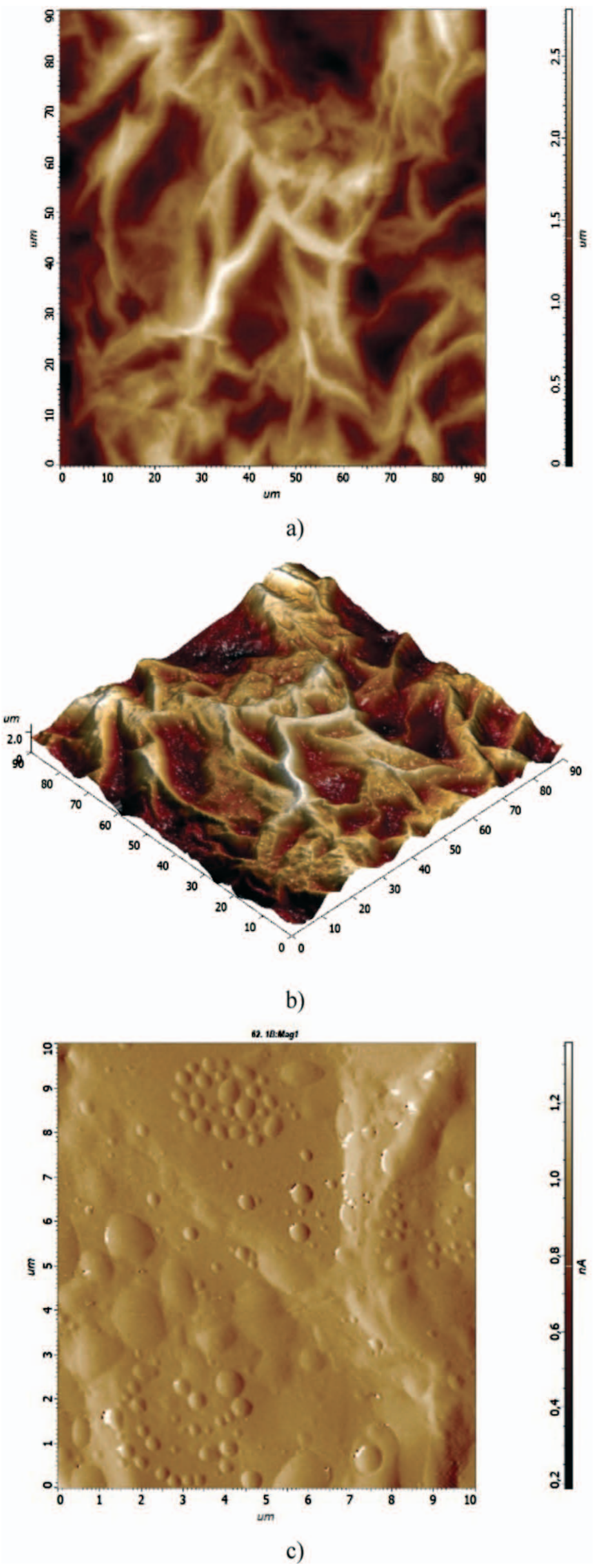

Figure 4. AFM images (AC mode) of the paraffin film surface. a) 2D AFM image of the surface morphology (90 μm scan size); b) 3D rendering of the area imaged in a); c) amplitude (error) signal revealing fine details in a) (10 μm scan size).

3. Discussions and Conclusions

As can be seen from the previous section, the surface of the paraffin film optical diffuser presents highly irregular, on multiple scale lengths, patterns in the form of wrinkles and, sometimes, of bubbles.

The first reason for obtaining such a surface is the thermal contraction during cooling. As mentioned in [8], the relative volume variation during solidification may have values of 10% - 15%. The initial smooth liquid (molten) film contracts during cooling and solidification giving rise to these wrinkles. These wrinkles form a truly random network according to the local thermal and mechanical conditions and this is why we consider these wrinkles as being truly random patterns that cannot be reproducibly repeated if we let the film solidify naturally. Every time we will make a paraffin-based optical diffuser we will obtain a different geometry of the wrinkles. While the overall behaviour will be identical on average, each diffuser will have its own specific pattern and way of encoding the incident lightwave.

While someone may be tempted to consider the film morphology as a fractal one, this is not the case since there is no self-similarity, i.e. a pattern that repeats itself at different length scales. Because of that we call it (highly) irregular.

What is important for the application as optical diffuser is the fact that the surface topography manifests also on a range of a few microns, which is comparable to the visible light wavelength. This means that the ligthwave passing through such a diffuser is acquiring a significant scrambling of its phase within its section and within its coherence area. The different slopes of the wrinkles will randomly orient the exiting light beam to various directions because of refraction, while the wavelength-scale irregularities will give rise to diffraction of the incoming light. Because of all these, the working principle of this type of diffuser is a combination of several mechanisms, namely the two ones mentioned at the beginning (scattering and refraction) as well as diffraction. This will be precisely determined by detailed optical measurements, which are the subject of a forthcoming paper.

The fabrication of the film took several minutes, with low energy consumption (1000 Watts for 10 minutes). The method for obtaining such films is clean, is making use of substances that do not pose a significant hazard to the medium and are low cost. Large area thin films can be obtained. More important, the paraffin film can be recycled as many times as desired.

The truly random surface pattern of the film, the environment friendly character and cost effectiveness of the fabrication technique and of the materials used to produce this type of optical diffusers make them a very interesting candidate in the field and a subject of further research interest.

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Authors' contribution

GMP and AP prepared the paraffin film, GMP and CT made optical microscopy measurements, RG made the AFM measurements, GMP led the work and developed the concept for application. The authors contributed equally to the preparation of the manuscript.

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