Roughness analysis of the “invisible” surface by means of X-ray micro-CT

Magdalena Rajczakowska¹, Damian Stefaniuk¹, Maciej Sobótka

¹Wrocław University of Technology, Wybrzeże Wyspianskiego 27, 50-370 Wrocław, magdalena.

Aims
A solid material's surface is characterized by a complex structure. Its properties depend on many factors e.g. the nature of the material, the method of surface preparation as well as the interaction between the surface and the environment. Those properties are crucial to surface interaction because they affect the important parameters such as real area of contact, friction, wear and lubrication [1]. Surface roughness represents significant information both for scientific and industrial purposes. In science, the assessment of the surface roughness is especially useful when performing surface measurements, e.g. hardness test, in nano or micro scale. For these kind of tests, the surface of the material needs to be polished in a specific way, allowing the roughness to be the lowest possible in order to guarantee a satisfying result. There are also many areas of industry where surface roughness information is needed to ensure proper function of the end products. Fast and accurate measurement and monitoring of surface roughness is crucial to safeguard product quality of automotive applications such as brake shoes and pads, friction plates, or sealing shafts, as well as electronics and semiconductor applications such as lead frames or copper panels [2]. In civil engineering, there are also materials where surface roughness plays a crucial role and has an effect on their final properties. One of those materials are the drywalls, also known as the gypsum board. They can be defined as panels made of gypsum plaster pressed between two thick sheets of paper. They are widely used to make interior walls and ceilings. During production of this material, the interface between the paper and gypsum is a critical feature. A certain bonding between the cover sheets and the gypsum core is necessary for the material to have required properties. However, the surface of the gypsum is hidden under the paper and classical methods of measuring its roughness are not possible to apply without destruction of the product. Now, the question arises: how can one analyze the surface roughness without having an access to the surface itself? This paper presents a method of a 3D analysis of the “invisible” surface with the use of X-ray micro-CT scanner.

Method
The sample under investigation was a piece of a drywall acquired from a manufacturer. A cuboid specimen of dimensions 10 x 10 x 15 mm was cut out of the gypsum board in order to grant a reasonable resolution of the images. Firstly, the sample was analyzed with the use of Scanning Electron Microscope (SEM). Hitachi Analytical TableTop SEM TM3030 was employed. Different magnification levels were chosen to allow a better insight into materials microstructure. Next, the sample was scanned with the use of Skyscan 1172 X-ray Micro-CT system. Several trial scans were necessary in order to visualize all the components of the material. Furthermore, due to the high porosity of the material and the pore sizes reaching several micrometers, a high resolution was needed for a detailed material analysis. Finally, the 0.5 mm aluminum filter was utilized and the scanning voltage and power were set to 100 kV and 10 W, respectively. The scanning resolution was 4.8 µm with the unit angle 0.05 deg. Skyscan NRecon software based on the Feldkamp algorithm was applied for the image reconstruction. The acquired images were processed and analyzed with the use of CTAn software and the calculation were performed in Wolfram’s Mathematica.
Results
The results from the SEM analysis are presented in Figure 1b and 1c. The porous microstructure of the gypsum plaster can be easily noticed in the images. A relatively uniform pore system is visible with pore diameters ranging from 20 to 800 µm. Nevertheless, the aim of this article was to identify the roughness of the paper-gypsum interface.

![Figure 1: a) Micro-CT cross-section of the material, b) SEM image of the material's surface, c) SEM image of the gypsum-paper sheet interface.](image)

It is obvious that the paper sheet is present in the SEM images, however, due to its irregular fibrous microstructure it is extremely difficult to distinguish the border between the gypsum and paper. Thus, calculation of the gypsum-paper interface profile was impossible. What is more, SEM images contain only a small part of the material hence the result of the surface roughness would be partial and not sufficient for this analysis.

![Figure 2: a) 2D cross-section of the material, b) image histogram with paper and gypsum peaks, c) gypsum-paper interface detail, d) binarized profile of gypsum core (inverted colors)](image)

The Micro-CT imaging results are presented in Figure 2. An exemplary cross sections is shown (Fig. 2a) with corresponding image histogram (Fig. 2b). It is noticeable that two main
peaks can be distinguished: one for paper and one for gypsum, respectively. The images were binarized with double threshold, allowing to segment only gypsum from the image and put away the paper cover. After series of different image processing steps, e.g. to close the pores etc., a proper binarized gypsum profile was obtained (Fig. 2d)

![Figure 3: Surface profile.](image)

Table 1: Results of the surface analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Formula</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_a$</td>
<td>arithmetic average</td>
<td>$R_a = \frac{1}{n} \sum_{i=1}^{n}</td>
<td>y_i</td>
</tr>
<tr>
<td>$R_q$</td>
<td>root mean squared</td>
<td>$R_q = \frac{1}{n} \sum_{i=1}^{n} y_i^2$</td>
<td>0.018</td>
</tr>
<tr>
<td>$R_v$</td>
<td>maximum valley depth</td>
<td>$R_v = \min_{i} y_i$</td>
<td>-0.148</td>
</tr>
<tr>
<td>$R_p$</td>
<td>maximum peak height</td>
<td>$R_p = \max_{i} y_i$</td>
<td>0.038</td>
</tr>
<tr>
<td>$R_t$</td>
<td>Maximum Height of the Profile</td>
<td>$R_t = R_p - R_v$</td>
<td>0.186</td>
</tr>
<tr>
<td>$R_{sk}$</td>
<td>skewness</td>
<td>$R_{sk} = \frac{1}{nR_q^3} \sum_{i=1}^{n} y_i^3$</td>
<td>-2.315</td>
</tr>
<tr>
<td>$R_{ku}$</td>
<td>kurtosis</td>
<td>$R_{ku} = \frac{1}{nR_q^4} \sum_{i=1}^{n} y_i^4$</td>
<td>15.065</td>
</tr>
</tbody>
</table>

Based on the binarized image it was possible to calculate the surface roughness diagram (Fig. 3). In the plot, the dotted line 0.0 indicated the average value of the surface height. The orange line, on the other hand, represents the vertical distance from the mean line in each point of the surface $y_i$. In addition, the 2D commonly used parameters describing surface roughness were calculated. The results are listed in Table 1.

The major advantage of the Micro-CT analysis is the opportunity to analyze the surface not only in 2D but also 3D. In Figure 4, a 3D reconstruction of the sample as well as the segmented 3D model of the inner surface of the gypsum core are shown.
In order to acquire the value of the surface area roughness $S_a$, which corresponds to $R_a$ in 3D [3], the procedure presented for the exemplary image is repeated for all the slices of the scanned object. The surface area roughness $S_a$ can be defined by the following formula:

$$S_a = \frac{1}{kn} \sum_{i=1}^{k} \sum_{j=1}^{n} |y_{ij}|$$

where $i$ and $j$ depict rows and columns of pixels, respectively. For the chosen material the calculated $S_a$ value was equal 0.019 mm. When compared with the 2D value for the exemplary image, it can be concluded that the surface profiles are similar for all the locations, hence the surface is relatively homogeneous.

**Conclusion**

The paper presented the roughness analysis of the surface that was inaccessible with any other methods. The gypsum board fragment was the material under investigation. The aim of the study was to analyze the interface between gypsum and paper sheet and obtain the surface profile. This procedure was performed both in two and three dimensions. Basic surface roughness parameters were calculated based on the profiles acquired. The methodology presented proved to be efficient and useful. Undoubtedly, micro-CT is a useful technique for surface roughness calculation, especially for the situation presented in the paper. However, it is noteworthy that the procedure is highly dependent on the segmentation process. If the material covering the surface has the relatively the same density as the surface material, the analysis might be difficult to perform. What is more, the accuracy of the calculation is determined by the possible resolution of the image. In a need of very detail measurements, e.g. in nano scale, the micro-CT system might not be sufficient.

**References:**