Three-dimensional characterization of polymer foams using X-ray dark-field imaging

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Abstract

Due to the low cost, the ease of processing, and excellent material properties, polymer foams are used in various applications, e.g. packaging, building and construction, furnitures and bedding, and the automotive and aerospace sector.

The mechanical response of polymer foams is primarily influenced by density and morphology. While foam density can be determined with high precision, cell morphology is more difficult to determine since the size distribution of foam cells differs in three dimensions. However, using conventional methods, e.g. light optical microscopy or scanning electron microscopy, it is very difficult to obtain three-dimensional information and to differentiate between the strut system and cell walls. An alternative for the three-dimensional characterization of foam morphology is micro-computed tomography (XCT). But even non-destructive techniques like XCT are not able to characterize anisotropic foams if the thickness of single struts and cell walls is below the physcial resolution of the respective XCT system.

In this contribution we therefore investigate different polymeric foam samples using a Talbot-Lau grating interferometer XCT (TLGI-XCT) system. We show that the obtained darkfield contrast images show a high contrast and a strong signal at struts and cell walls, improving the segmentation of foam cells in various examples.

Keywords: foam, micro-computed tomography, Talbot-Lau grating interferometer XCT, dark-field imaging

1 Introduction

Synthetic foams play an universal role in a wide field of applications ranging from packaging, lightweight structures to thermal insulation [1]. Modern technologies enable the production of foamed polymers in a wide range of densities. Cellular polymers vary in relation to their density from light (0.003 to 0.05 g / cm3) to high (> 0.7 g / cm^3) density foams [2]. Various polymers have been used for foam applications including polyurethane (PU), polystyrene, polyethylene, and polypropylene [3].

However, foams of the same density that show different cell size distributions show different mechanical properties. Primary factors influencing the mechanical deformation behavior are foam density, cell size and diameter, foam hardness, and deformation rate. For closed- and open-cell foams, numerous geometric parameters must be determined in addition to the relative density and stiffness of the polymer phase in order to determine the foam modulus. To this end, the spatial distribution of matrix material in the cell walls must be accurately described [4].

In polymeric foams, the low density in addition to the small wall thickness poses a major task in the three-dimensional materials characterization using conventional and absorption-based micro-computed tomography (XCT) systems [5], in particular at low physical resolutions. A method to overcome these shortcomings is Talbot-Lau grating interferometer XCT (TLGI-XCT) that has a big potential in the non-destructive testing of materials since it provides complementary information to standard absorption-based methods (AC) in the form of differential phase contrast (DPC) and dark-field contrast (DFC) [6]. In particular dark field imaging reveals information undisclosed by both AC and DPC imaging since dark field contrast delivers morphological information in the sub-pixel regime depending on the local scattering power [7, 8]. In addition, dark field images yield a high contrast and a strong signal of interfaces. This improves segmentation and the subsequent computation of pore size distributions of polymeric foams, even if the sample was scanned at a relatively low physical resolution [9].

2 Material and methods

In the last decade, one of the most important innovations in X-ray technology has emerged by the introduction of the Talbot–Lau grating interferometry [10]. This method provides three complementary characteristics in a single scan of the specimen: (1) attenuation contrast (AC), (2) differential phase contrast (DPC) due to refraction, (3) dark-field contrast (DFC) due to scattering. AC provides information on the attenuation of the X-ray beam intensity through the specimen and it is thus equivalent to conventional X-ray imaging. DPC is related to the index of refraction and image contrast is thus achieved through the local deflection of the X-ray beam. DFC reflects the total amount of radiation scattered at small angles, e.g. caused by microscopic structures in the sample represented by particles, pores, fibers, struts, or cracks. Depending on the micro-structure, the scattering has a preferred direction perpendicular to the local orientation, which is reflected by the measured

dark-field signal [11]. This immanent physical property of grating-based dark-field imaging can be used to extract directional information about the angular variation [12].
TLGI-CT scans have been performed on open-cell PU based foams with a density between 0.037 – 0.085 g/cm^3 produced by Greiner Foam International GmbH. The specimens tested in this study are rectangular samples of dimensions 5×5×10 mm. Scanning parameters for TLGI-CT scans using a Skyscan 1294 (Bruker microCT) are 35 kV, 1000 µA, 1700 ms integration time, 900 projections, 0.25 mm Al filter at an isometric voxel size of 5.7 µm, resulting in a total scan duration of 491min. Reference scans with a voxel size of 3.5 µm and 1.5 µm are performed using a Nanotom 180NF (GE phoenix | X-ray).

3 Results

Figure 1 shows an absorption contrast (AC) and dark field image (DFC) of the first sample, an open-cell PU based foam with a density of 0.050 g/cm^3. The results illustrate that dark field imaging provides sub-pixel information in relation to the detection of the strut and cell wall network. While thin walls of the polymeric foam cannot be resolved in the AC image, the dark field image delivers information that is otherwise inaccessible using conventional XCT at a voxel size of 5.7 µm.

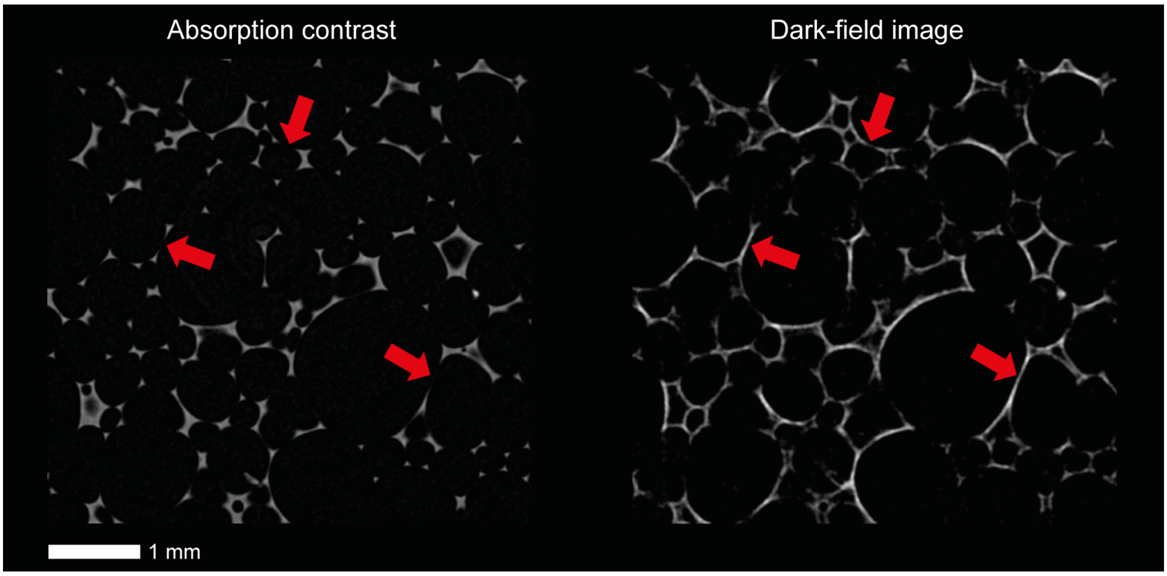

Figure 1: Axial slices (left: absorption contrast and right: dark-field image) of a polymeric foam sample (voxel size: 5.7 µm). The contrast in the AC image is high but thin walls cannot be resolved whereas in the DFC data even thin walls can be detected (see red arrows).

4 Discussion

In many applications it is essential to understand how the foams´ microstructure influences the physical properties of cellular materials like permeability, thermal insulation, and stiffness. Imaging solutions that are able to track the geometric features, e.g. strut length, window and cell shape distributions, are therefore a powerful tool to investigate the three-dimensional morphology in close- and open-cell foams. We showed that dark field imaging reveals information undisclosed by conventional XCT imaging since dark field contrast delivers sub-pixel information. Cell walls are visible more distinct but some parts of the cell walls are nevertheless missing. Detailed analysis, including scans at different orientations of the sample, will show if the cells are partly open or if the resolution of DFC imaging is not sufficient for detecting these very thin walls. The obtained volume data can subsequently be used for the computation of the pore size distribution in polymeric foams. Furthermore, DFC data is an additional basis for three-dimensional models that can be used in numerical simulations like finite element analysis and computational fluid dynamics that are essential for reliable and faster product development.

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