Advanced Architectural Descriptors in Foams: Novel 3D Computational Methods

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ABSTRACT

This work presents 3D computational strategies aimed at providing foam de-structuration of the basic components of a cellular material (struts and cell walls) offering the possibility of analysing separately the structural elements that play an important role in the physical properties of thee materials. Two different methodologies have been used depending on the topological similarities existing between the struts and cell walls: 3D erosion-dilation procedure (thick struts) and solid classification algorithm (thin struts). In a second step, analysis of cell walls is performed in order to show the advantages of analysing separately the two foams components. Particularly, cell wall thickness distribution reveals differences that could not be found prior to the de-structuration.

1. INTRODUCTION

Foams are two-phase systems constituted by a continuous or discontinuous gaseous phase in a solid continuous network (edges, vertexes and, on occasion, cell walls) . Physical properties of these structures are strongly connected to their microscale morphology. Among some of the morphological features that are linked to properties we can cite porosity, cell size (diameter, volume) and cell orientation (anisotropy). Some other secondary cellular descriptors -more difficult to be calculated- are cell coordination number, sphericity, cell wall thickness, mass fraction in the struts, etc.

Most of these descriptors have been traditionally obtained by imaging constrained to 2D analysis (Glicksman 1994, Kuhn 1992) but, in recent years and thanks to the last advances in X-ray devices, microcomputed tomography (μCT) allows providing accurate 3D results for these materials. However, the morphological analysis of these structures is still typically limited to the calculation of an equivalent 3D descriptor comparable to the 2D one calculated by old-established methods. In this sense, novel advanced architecture descriptors should be explored in order to determine aspects linked to final properties yielding a finer description of these structures.

In general, the analysis of cellular structures is focused on the pore analysis (air-phase) whereas the solid phase is less studied and, as a maximum, analysis on material thickness distribution is carried out. This work proposes a novel strategy for the solid phase analysis, which virtually separates the continuous solid structure into two clearly differentiated parts characterized by shape, local topology and location. We have focused our attention on closed cell foams that are constituted by two solid entities: cell walls and struts. This de-structuration technique offers the possibility of analysing separately structural features of each component. Furthermore we propose a collection of second-order analysis techniques performed at struts and cell walls after the de-structuration step.

2. EXPERIMENTAL

2.1. Materials and X-ray CT

Different polymer foams with a distinctly different material distribution within the solid network have been selected to compute the struts-walls de-structuration. A collection of 5 types of closed cell rigid polyurethane foams (PU, density 52 kg/m^3 and average cell size 800-300 μm) owing a high material fraction in the struts was used for this study. Furthermore, two LDPE foams (28 kg/m^3 density and average cell size of around 1500 μm) with a rather low material fraction in the struts has been analyzed for comparison purposes. This particular type of LDPE foams may present wrinkles in the cell walls and therefore part of the second-order analysis will be focused on this aspect.

Cone-beam tomograms were performed at the Centre for X-ray Tomography at Ghent University (UGCT) (Masschaele *et. al* 2007). The scanner settings used allowed resolutions ranging 3-7 microns for the studied materials. Octopus® 8.6 server/client reconstruction package was used for the reconstruction of the tomogram (Vlassenbroeck *et. al* 2007).

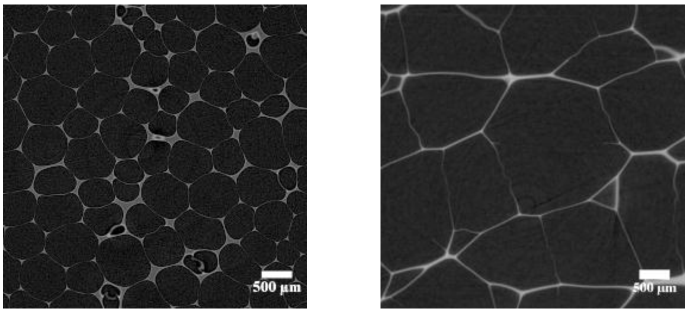

Figure 1: *Tomographic projections of PU foam (left) and LDPE foam (right).*

2.2. 3D De-structuration process

Conventional established methodologies aimed at determining the solid repartition in between the edges-vertexes (f_s) are part theoretical and part empirical. These methodologies are based on 2D micrographies. They make use of manual methods to approximate the projected cross-section of the struts either in an equivalent circle (Kuhn *et. al* 1992)) or triangle -occupying two-thirds area of an equilateral triangle- (Glicksman 1994). Both models later use a dodecahedron model to estimate the final f_s value. This value is of a capital influence for a fine modelling of thermal and mechanical properties.

a) 3D erosion-dilation technique

This procedure is based on the different morphology/topology of the two elements aimed to separate; struts and walls. Iterative erosion-dilation operations allow eliminating the walls whereas struts remain preserved; although they become slightly eroded. Particularly two consecutive 3D erosions followed by three consecutive 3D dilations give as a result a mask containing over-dilated struts (Fig. 2 B) that are subtracted from the original binary stack (Fig. 2 A) to identify struts (Fig. 2 C) and walls (Fig. 2 D). This methodology was applied over a cubic VOI of 1000^3 voxels (representative number of cells). It is important to note that this apparently rough approach is valid for materials with a high fraction of material located at the struts (PU). Materials like the LDPE foams analysed in this work will not fulfil the requirement of sufficient topological differences in between struts and walls.

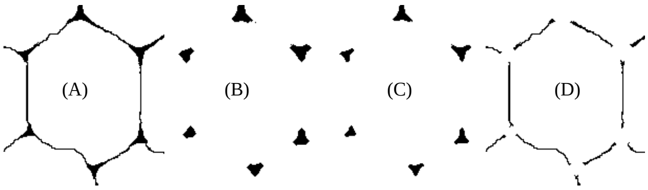

Figure 2: *Sequence of erosion-dilation procedure:(A) original binary pore, (B) overdilated mask (C) resulting struts (D) resulting cell walls.*

b) Solid classification algorithm

This approach is the finest method for materials with low f_s. It is based on propagation growth computation technique (Brun 2009). The algorithm (implemented in Imorph software) performs an iterative analysis of elongation inertial moment at every voxel within the selected phase. Voxels showing unidirectional continuity are identified as struts (uniaxial oriented), whereas those showing 2D or 3D connectivity constitute either walls or vertexes (biaxial or triaxial oriented). Once the struts and vertexes have been identified, the remaining steps are refinements based on dilation operations. The mask containing those over-dilated struts projections is subtracted from the original binary image containing both struts and walls. In this case this procedure was applied over a 500^3 voxels containing approx. 110 cells (110x12 walls, 110x30 edges) that are enough to obtain representative results of the solid phase of analysed foams. This technique requires high computing capabilities and was only applied for the LDPE foams although it works well in the case of PU foams.

2.3. Cell wall analysis

Foam de-structuration procedures described allowed for a separate analysis of cell walls that can be now analysed as individual objects. In our case we decided to comparatively analyze the cell wall thickness and wrinkles for two apparently similar LDPE foams since no significant differences were observed in the typical morphological parameters (cell size, cells surface, cells sphericity, anisotropy, etc.). The thickness histogram analysis of the cell walls is done by the local thickness plugin for ImageJ (Hildebrand et *al*. 1996). A further study on the cell wall wrinkles present in the cell walls will be done but results are not present in this paper.

3. RESULTS AND DISCUSSION

The two procedures used to segment the struts and cell walls result in two image stacks containing separately the struts and the cell walls. Figure 3 shows the two combined colour-labelled (red→ struts, green → cell walls). The two de-structured elements can be clearly visualized. A 3D rendering over a representative pore for the two types of materials provides a better visualization of the success of the de-structuration. It can be observed that even the finest struts are identified in the case of LDPE foams.

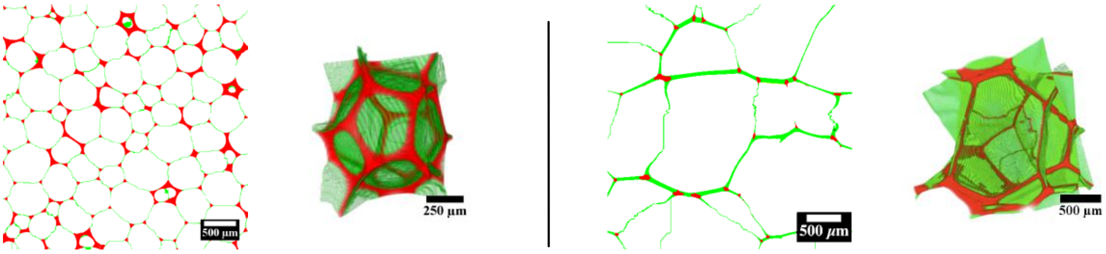

Figure 3: *Results of segmentation and single cell 3D rendering of PU (left) and LDPE (right) foam.*

3.1. Material distribution

A direct result from the de-structuration methodology is the determination of the material fraction in the struts (f_s) by calculating the ratio of the total number of pixels in these components and the total amount of pixels in the solid network. Preliminary results for three selected materials are shown in Table 1. The results are congruent with the observed images in Figure 3. PU foam presents rather thick struts in comparison to thin cell walls, while the struts of LDPE foams are of a similar thickness in comparison to the cell walls. Further results will be reported after analysing the full collection of the samples under study.

Table 1: *Material volume fraction at struts for different investigated materials.*

Sample	f_s (%)
PU	66
LDPE 1	28
LDPE 2	30

3.2. Cell walls analysis

The analysis of cell walls thickness distribution has been done over two samples of LDPE foams. The results indicate clear differences among samples which were not identified by conventional morphology analysis.

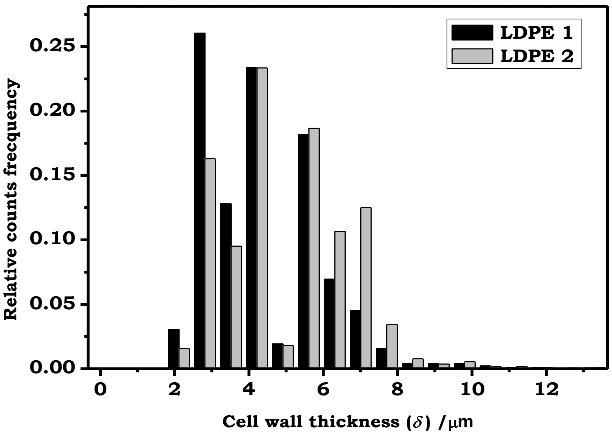

Figure 4: *Cell wall thickness distribution in de-structured walls.*

4. CONCLUSIONS

CT and advanced 3D computation algorithms allowed a new approach in the analysis of cellular materials thanks to the chances of de-structure the continuous solid network in its constituents: struts and cell walls. The separation of this components permits to calculate the material distribution at the walls, edges and vertexes across the solid skeleton that can be translated into valuable information for modelling and understanding cellular structures and physical properties.

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