IMPROVING MICRO-CT ACCURACY ON FEATURE EXTRACTION THROUGH IMAGE UPSCALING

M. Aurilia[1], M. D'Auria[2], M. Voltolini[3#], L. Mancini[3], L. Sorrentino[1*]

[1]*Institute for Composite and Biomedical Materials, National Research Council, P.le V. Tecchio 80, 80125 Napoli - Italy*
[2]*Department of Materials and Production Engineering, University of Naples "Federico II", P.le Tecchio 80, 80125 Napoli - Italy*
[3]*Sincrotrone Trieste SCpA, S.S. 14 - km 163.5 AREA Science Park, 34149 Basovizza, Trieste - Italy*
[#]*Now at: Department of Geoscience, University of Padova, via G. Gradenigo 6, 35131 Padova - Italy*
**luigi.sorrentino@cnr.it*

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Abstract
X-ray Micro-CT is a technique of choice for the investigation of the internal features of materials. One typical necessary compromise is the choice of the resolution vs the size of the field of view. Cellular morphology analysis of foams can benefit from Micro-CT because both physical (low and high strain rate mechanical properties) and functional properties (fluid transport through cells, thermal and acoustical insulation) are strongly affected by the morphological parameters (strut sections area and shape, degree of cell inter-connections and distribution of cell interconnections diameters). The typical resolution of detectors commonly available is not able to provide an accurate 3D description of the real spatial distribution of the finest structural features. A new approach is proposed based on the up-scaling of reconstructed slices, which is able to recover details from low resolution images and to minimize the morphological feature loss. In order to show the advantages of the proposed method, a phase contrast micro-tomographic acquisition was performed on a 10 mm wide polyurethane foam sample at the SYRMEP beamline at the Elettra - Sincrotrone Trieste (Italy) facility.
Results from the standard workflow (slice stacking, slice filtration, thresholding) were compared to those from the new approach (slice stacking, slice upscaling, thresholding, binary volume comparison). The image upscaling allowed a reduction of the image noise without using heavy noise reduction filters and preserved finer details of the microstructure with respect to those from the conventional procedure.

1 Introduction

X-ray Micro-CT is a non-invasive technique suitable for the investigation of the internal structure of multiphase materials. From Micro-CT data it is possible to extract and quantify the 3D textural features in the material. The results can be used for the modelling and predictions of both physical (mechanical, cushion, impact behavior) and functional (thermal, acoustic or fluid transport behavior) properties of the system. Micro-CT analysis can also be used for failure mechanisms, micro-cracks and internal defects evaluations [1-3].
X-ray Micro-CT has been used in several research fields, from natural systems such as rocks and soils [4-6] to industrial ones like metallic [7], polymeric [8-9] and ceramic [10] foams. In

all these fields the digital image analysis based on X-ray Micro-CT data is able to give both qualitative and quantitative results on the geometrical, topological or morphological configuration of the sample.
The conventional procedure for an analysis based on Micro-CT data consists in few steps: a) slice reconstruction via an inversion algorithm of the acquired sample projections, b) filtering to improve the phase separation (contrast enhancement) and reduce the noise (noise reduction filters, such as a median, or bilateral filter), c) segmentation to identify and separate the different phases in the sample, and d) performing qualitative and quantitative evaluations concerning the structural features.
Image treatments on the slices are needed to remove issues due to the data collection (such as edge and surface irregularities, random Gaussian noise, zingers, etc.) and to equalize the grey scale of all slices in order to allow a homogeneous phase segmentation. The scope of noise-reduction filtering is to replace a voxel grayscale value with another one that is weighted with the neighbours according to a selected algorithm. The median smoothing filter is the most widely used to reduce noise in the images with minimal alteration to the object geometry, unlike averaging or Gaussian filters which tends to blur the boundaries. In case some features need to be highlighted, sharpening (which enhance the edges) or contrast-enhancement (which acts on the grey values distribution) filters are commonly used.
After noise reduction and feature enhancement, the segmentation process is used to detect and separate the different phases of the material. In the case of foams, the purpose of segmentation process is to separate voids from solid. The evaluation of the porosity, as well as other geometrical and morphological parameters, is carried out on a binary datasets where the value of each voxel has been assigned to belong to either one of the two phases.
The binary dataset can be analyzed with appropriate image processing tools for the evaluation of the geometrical and morphological features of the acquired sample. Evaluations are performed on a representative elementary volume, i.e. the smallest volume with a statistical significance, for computational reasons. Anisotropy can be quantified by morphological evaluations along three orthogonal directions. In foams the most significant parameters to obtain are the porosity, the average cell size, the cell size distribution, and the degree of anisotropy in three orthogonal directions. When an estimate of the area of cell interconnections is needed, the conventional image processing technique is not satisfying, because it artificially increases the size of interconnections between foam cells. This can lead to wrong input provided to software aimed at modeling e.g. fluid transport, impact absorption or sound absorption through foams because the 3D virtual volume from Micro-CT overestimate the size of the fluid path through the cellular structure, thus leading to unacceptable errors.
This issue is strongly related to the resolution of Micro-CT datasets, that typically range from tens of micrometers to less than one micron. When the observed sample has a complex morphology, such as in the case of foams, which have large void domains separated by very thin membranes, the effective accuracy depends on the compromise between the number of pixels on the camera sensor and the field of view needed to detect a statistically significant number of features. The mean cell size (usually from 10 μm to 1 mm) and the apparent density affect the static structural properties of foams but their functional (such as the thermal or acoustical insulation) or dynamic mechanical properties (high strain rate applications) are heavily affected by the size distribution of cell interconnections (usually not higher than few micrometers). Because the size of the objects of interest typically differs by an order of magnitude or more, the appropriate selection of the correct field of view, vs resolution compromise, is very challenging. In the case of large samples the effective resolution will be poor. As an example, for a 10 Mpixel camera sensor, the effective resolution for a 10 mm

wide sample is not better than 5 µm. As a result, it is not possible at the same time to evaluate with a statistical significance both small and large size morphological details.
In this work a new approach is proposed for the digital image processing of micro-CT datasets based on image upscaling. This procedure artificially increases the resolution from conventionally reconstructed slices, improving the accuracy of the thresholding procedure and the quantitative morphometric analysis. Furthermore, it makes possible to avoid a heavy filtering procedure, which would result in the loss of the smallest features.

2 Materials And Testing Methods

The foam used for the investigations is the Confor Foam CF45Blue from EAR Specialty Composites (Indianapolis, IN, USA), with a measured density of 0.102 g/cm^3. Scanning electron micrographs were acquired to evaluate the morphology of foams with a resolution of 0.1 micrometers by using a Quanta 200 FEG from FEI (Eindhoven, The Netherlands). Microtomographic acquisitions and reconstructions were carried out to evaluate the 3D morphology of samples. Tomographic images were acquired through the SYRMEP beamline at the Elettra – Synchrotron and 3D volumes were reconstructed with a specifically developed software available at the SYRMEP beamline. Digital image processing was performed by using the software ImageJ from National Institute of Health (USA, http://rsb.info.nih.gov/ij/).

3 Results And Discussion

The upscaling method consists in rescaling all slices by using a bicubic algorithm and selecting an integer scaling factor equal to 2 or more. The new dataset is used to perform the subsequent image processing steps (from equalization to the segmentation). In the Figure 1, a flow diagram of the conventional and new Micro-CT processing methods is represented. In table 1, a comparison of 8 bit and 16 bit datasets at different upscaling factors is shown.

Figure 1. Flow diagram of the conventional and the proposed Micro-CT processing routes

Upscaling factor	*8 bit [GB]*	*16 bit [GB]*	*Teoretical Resolution [µm]*
1	1.25E-01	2.50E-01	9.00
2	1.00E+00	2.00E+00	4.50
4	8.00E+00	1.60E+01	2.25
8	6.40E+01	1.28E+02	1.13
16	5.12E+02	1.02E+03	0.56

Table 1. Dataset size as function of the upscaling factor and gray scale depth (assuming a dataset size of 500^3 voxels)

The dataset size grows exponentially but the feature detail potentially recovered can be worth the increase of computational resources, also considering that the application of upscaling could potentially allow to avoid the application of noise reduction filter. In order to show the detail increase, upscaling factors 2, 4 and 8 were used and a 500x500x250 vx subset of the original dataset was considered. Furthermore, in order to reduce the size of the dataset, a preliminary comparison between 8 bit and 16 bit images was performed. Their histograms, evaluated on the same slice, did not show any shape or feature difference, and 8 bit datasets were used for the investigations.

In Figure 2, a comparison between the unscaled slice (US), the unscaled-filtered slices (UFS1 and UFS2) and upscaled slices (xS, where x stands for the upscaling factor) is shown. The UFS1 and UFS2 images were obtained from the US sample by using the median filter with a radius equal to 1 and 2. The median filter allows for a reduction of the noise both in the solid and in the void with respect to the untreated and the upscaled samples, but the application of a threshold (Fig. 3) evidences its negative effect on the preservation of details, in particular on small parts such as the wall edge.

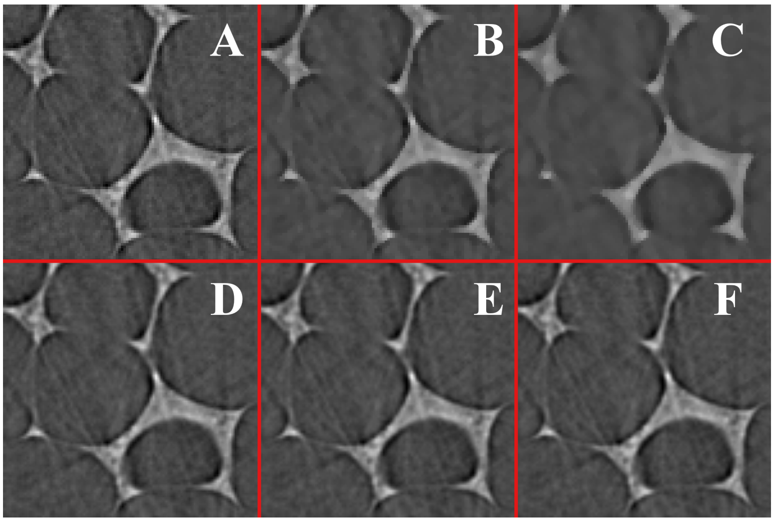

Figure 2. Comparison of the same region in a slice: A) untreated image, B) image after the application of the median filter with radius=1, C) image after the application of the median filter with radius=2, D) 2x upscaled image, E) 4x upscaled image, F) 8x upscaled image

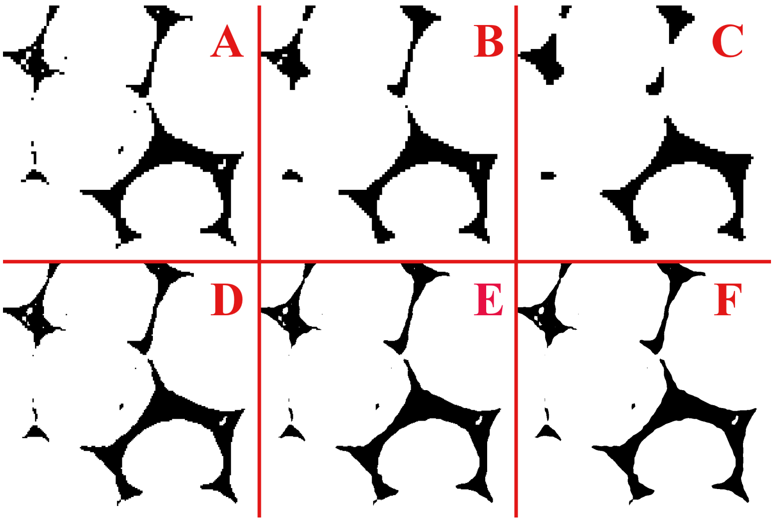

Figure 3. Comparison of the same region in a slice after thresholding (threshold value equal to 96): A) untreated image, B) image after the application of the median filter with radius=1, C) image after the application of the median filter with radius=2, D) 2x upscaled image, E) 4x upscaled image, F) 8x upscaled image

An increase of the median filter radius reduces the noise in the voids, but increases the small features loss, such as the walls between upper left cells or the voids in the upper left polymer section (Fig. 3). All upscaled images maintain both type of features and show a strong reduction of the digital noise. With the increase of the upscaling factor (from 2x to 8x, respectively in Fig. 3D to 3F) an increase of the qualitative perception of the features is obtained, and all calculations can be performed with higher accuracy. It is evident that the median filter, even reducing the noise, induces a loss of fine details in the cell walls. This can lead to significantly wrong estimations of the interconnections between cells.

In Fig. 4 a qualitative comparison of reconstructed volumes with a SEM image, taken in a random position of the sample, reproducing the real cell morphology in the foam has been proposed. The advantages of the upscaling technique with respect to the conventional one in recovering fine details are clear. In Fig. 4A the untreated sample shows cell walls and struts not well defined. The application of the median filter (Fig. 4B and 4C for radius equal to 1 and 2, respectively) improves the image but reduces the struts section and increases the interconnection between adjacent cells. These features are better reproduced in the upscaled samples (Fig 4D and 4E for 2x and 4x upscaling factors, respectively), which allow a better estimation of cell strut sections and of the interconnections.

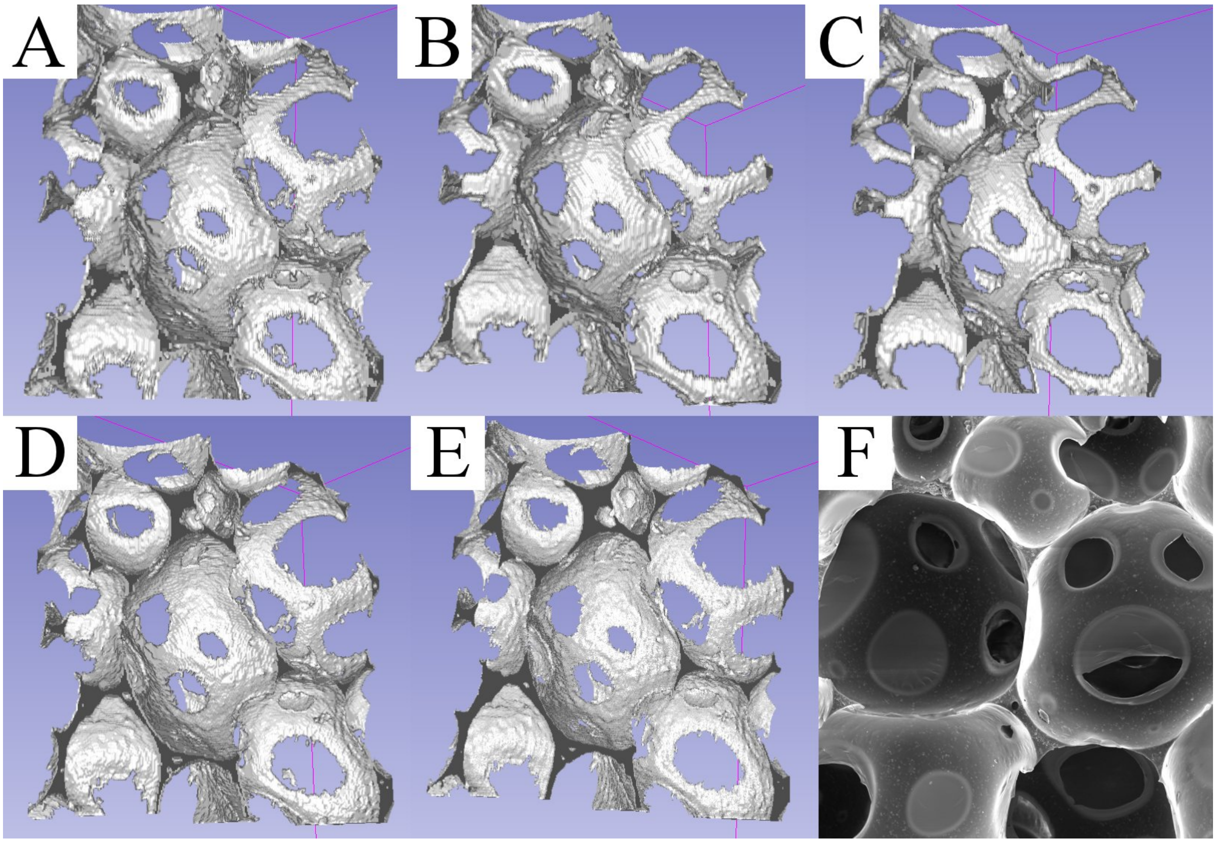

Figure 4. Comparison of the same reconstructed volume with a SEM micrograph randomly taken on the foam sample: A) unscaled sample, B) unscaled and median filtered sample (filter radius = 1), C) unscaled and median filtered sample (filter radius = 2), D) 2x upscaled sample, E) 4x upscaled sample, F) SEM micrograph

4 Conclusions

A Micro-CT analysis was performed on a commercial PU foam at the Elettra synchrotron light facility (Sincrotrone Trieste S.C.p.A. - Trieste). Slices were obtained from tomographs by using a proprietary software developed at the SYRMEP Beamline. The conventional procedure for the binarization of the dataset was used and its results were compared to a new one in which the filtering/noise removal step was replaced by the image upscaling. Different upscaling factors were used to investigate the improvements of details recovered.

The image upscaling intrinsically increases the amount of data to be processed, by a cubic power of the upscaling factor, potentially resulting in a huge need for memory, but it is able to improve the pixel resolution and to recover fine details by using 8bit, low resolution slices. The image upscaling also reduces the need for noise reduction treatment, which is the main

responsible for the loss of details and, in complex structures such foams, the loss of fundamental informations regarding structural and morphological features.
The qualitative comparison of 3D binary volumes coming from the conventional procedure (filtering by means of the median filter) and the proposed one (filtering replaced by upscaling) puts in evidence the clear advantage of the image upscaling, which, starting from the 4x factor, is able to give a foam structures quite equivalent to the real one.

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