Impact test deformations of polypropylene foam samples followed by microtomography

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Cellular material behavior is intensely studied for a few years. The use of these new materials in safety applications requires a better knowledge of their mechanical response to dynamic loading. The stress-versus-strain curve comprises three stages under compression loading (axis $\vec{z}$): an elastic portion followed by a plastic plateau (stress σ_{pl}) characteristic of the material's progressive damage. The final stage corresponds to the porous material densification [1]. If a large number of works currently relates to the identification of the material elastic response in correlation with microstructure, impact engineering is more particularly concerned by the plastic behavior characterization since, during this phase, the material is able to dissipate a significant shock energy.

The material considered in this work is a multi-scale polypropylene foam composed of agglomerated grains (diameter of 2 mm). The grain wall thickness is about 10 microns. Each grain is composed of randomly distributed small closed cells. Cell diameters are variable (from 10 to 60μm) but the cell wall thickness is almost constant (less than 1μm). Previous works [2] on this material have shown that the plastic plateau corresponds to the buckling of the cell walls and of the much thicker (and rigid) grain walls. In complement to these studies, it seems interesting to examine the influence of grain buckling on the material global response; the grain wall thickness being significant, their deformations dissipate an important energy. The main objective of this work is thus the characterization of the expanded grain deformation during an impact.

3D characterization of foam deformation and damage propagation by buckling required the development of a specific dynamic test methodology. This article presents this procedure and the first obtained results.

Until now, it was impossible to analyze within the sample the buckling phenomena of foam structure without a preliminary cutting, often cause of damages as significant as those to be estimated. Microtomography is a new imaging technique allowing 3D reconstruction of inhomogeneous material structure. This technique has already been used to characterize porous material structure [3]. However, it does not yet allow a real-time structure reconstruction during its compression, and even less under dynamic loading.

To be compatible with microtomography requests the selected experimental method consists in carrying out interrupted impact tests followed by microtomographic synchrotron measurements. First, a microtomographic record of the initial foam structure (not impacted) is performed. This sample is then impacted with a drop tower. During this loading, the deformation amplitude is limited to a determined value. The sample is kept in compression and placed again in the microtomographic setup in order to carry out a second record. These operations (impact and X-rays scan) are repeated until the complete densification of the sample. The cellular material deformation can then be evaluated from the series of 3D reconstructions at different steps of the dynamic test.

The foam microstructure characterization after each dynamic compression requires obviously carrying out the impact tests near the microtomographic setup. It was then necessary to develop a portative drop tower able to carry out interrupted impacts. This specific experimental setup includes two subsets: a loading module and a measurement set (Fig. 1). The loading module consists of a Plexiglas cylindrical projectile (diameter 30 mm, length 200 mm, mass 0.37 kg) guided in a rectified metallic tube of height H=1.6 m. The projectile and punch speeds have been measured, giving values of 5 m/s. This set is placed above the measurement module constituted by an aluminium base, a die and a punch. The punch is guided in the internal diameter of the die with a fitting of ϕ10h7G6. The sample is positioned inside the die.

The successive compressions are carried out using punches of different lengths (l = 16, 18, 20, 22, and

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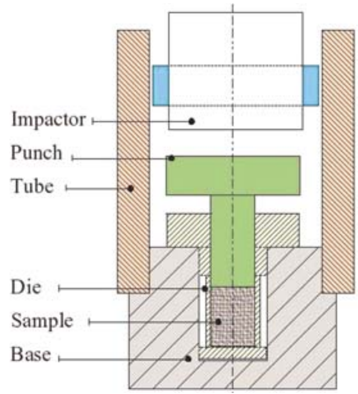

Figure 1 Drop tower scheme.

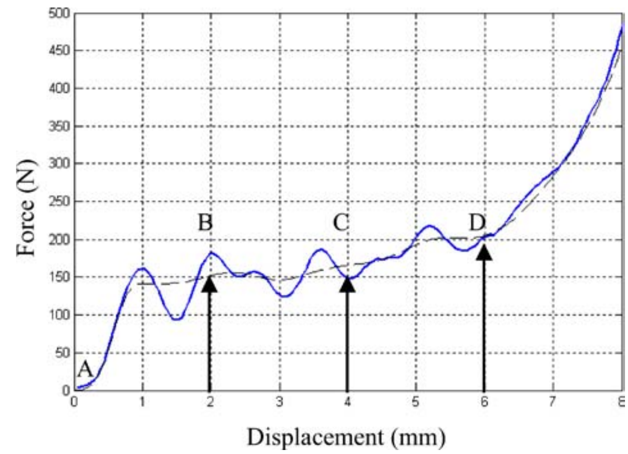

Figure 2 Force-Displacement curve. Raw measurement (*solid line*) and filtered result (*dashed line*).

24 mm) imposing a maximum deformation of 2 mm at each impact. This die-punches set was designed to apply a uni-axial compression on the foam sample. It can be easily dissociated from the drop tower and directly placed on the microtomographic setup without inducing a large attenuation of the X-ray beam. After an impact, the punch shoulder stays against the die, keeping the sample compressed during the tomographic measurement.

This compression device is instrumented to measure compression force and punch displacement during the test. The displacement is optically measured using a high-speed cam Phantom V4. A sensor measures the force; it was made from an aluminium tube instrumented by four gages connected in Wheastone bridge.

The first series of experiments was carried out on polypropylene foams of different densities. Results presented here concern the foam having a density ρ equal to 80 kg/m^3.

The material behavior depends on the strain rate [4]. During the impact loading (axis z), the punch speed is 5 m/s and, since the initial sample height is 10 mm, the initial axial strain rate $\dot{\varepsilon}_z$ is then 500 s^{-1}. A first test has been performed to validate the results given by the specific impact setup. This test was not interrupted in order to show the three stages of the material behavior (Fig. 2). One finds firstly the foam elastic behavior limited by the plastic strain σ_{pl}. The second stage is a long plastic plateau during which the material is damaged, a light increase in the stress is then noted. Finally, compression ends with the rise in stress during the foam densification. This result can be compared with those obtained in dynamic compression on a flywheel and for close strain rate [4]. One observes a similar force-displacement curve and the same plastic stress close to 1.5 Mpa.

The curve obtained from this drop tower (Fig. 2, solid line) shows strong oscillations. This phenomenon, inherent in impact loading and already observed on other machines such as flywheel, is due to the impact wave propagation through the sample and the compression device. These oscillations are not representative of the foam behavior and can be eliminated (Fig. 2, dashed line) by using a 4th order Butterworth low pass filter (cut-off frequency 2500 Hz).

Microtomography measurements were carried out on each sample before any loading and after each impact. The complete data treatments (artefact corrections and filtering) and 3D reconstruction of sample structure requires a long computing time. Partial 3D reconstructions have been done on a small cubic sub volume of the sample to quickly obtain a preliminary view of the results. A cube of 2 mm height was then extracted to visualize, *for the first time*, the deformation mechanisms at the expanded grain scale. Its location was selected in the lower part of the sample to follow as well as possible the deformation evolution of the foam structure embedded in the cube after each impact.

The first 3D image (Fig. 3a) shows clearly the foam structure, before impact, at the different scales. The grain walls are highlighted by darker lines; one finds the same thickness of these walls determined by other optical techniques (SEM, optical microscopy). Inside the grains, it is harder to distinguish the material cellular structure; some macro defaults of significant sizes can be correctly observed, but foam cells (with sizes close to 60 μm) cannot be accurately represented. Their walls are very thin (thickness 0.5 μm). One obtains by consequence a blurred image of the grain structure.

The Figs. 3b, c, d present the 3D reconstruction results carried out after the third first impacts. On Fig. 3b, the grain wall buckling is not visible, one can only observe the structure displacement (in comparison with the Fig. 3a) and, if there exists some buckling for this impact, it occurred in another zone. This hypothesis will be verified on the complete 3D sample reconstruction. In Fig. 3c, the buckling of grain walls appears clearly in the loading direction (vertical axis). This deformation mode is not evidently observed on the walls along other directions. The last reconstruction (Fig. 3d) obtained after the third impact, confirms these observations; strong localizations of buckling are highlighted on the grain walls. One can observe the inhomogeneous evolution

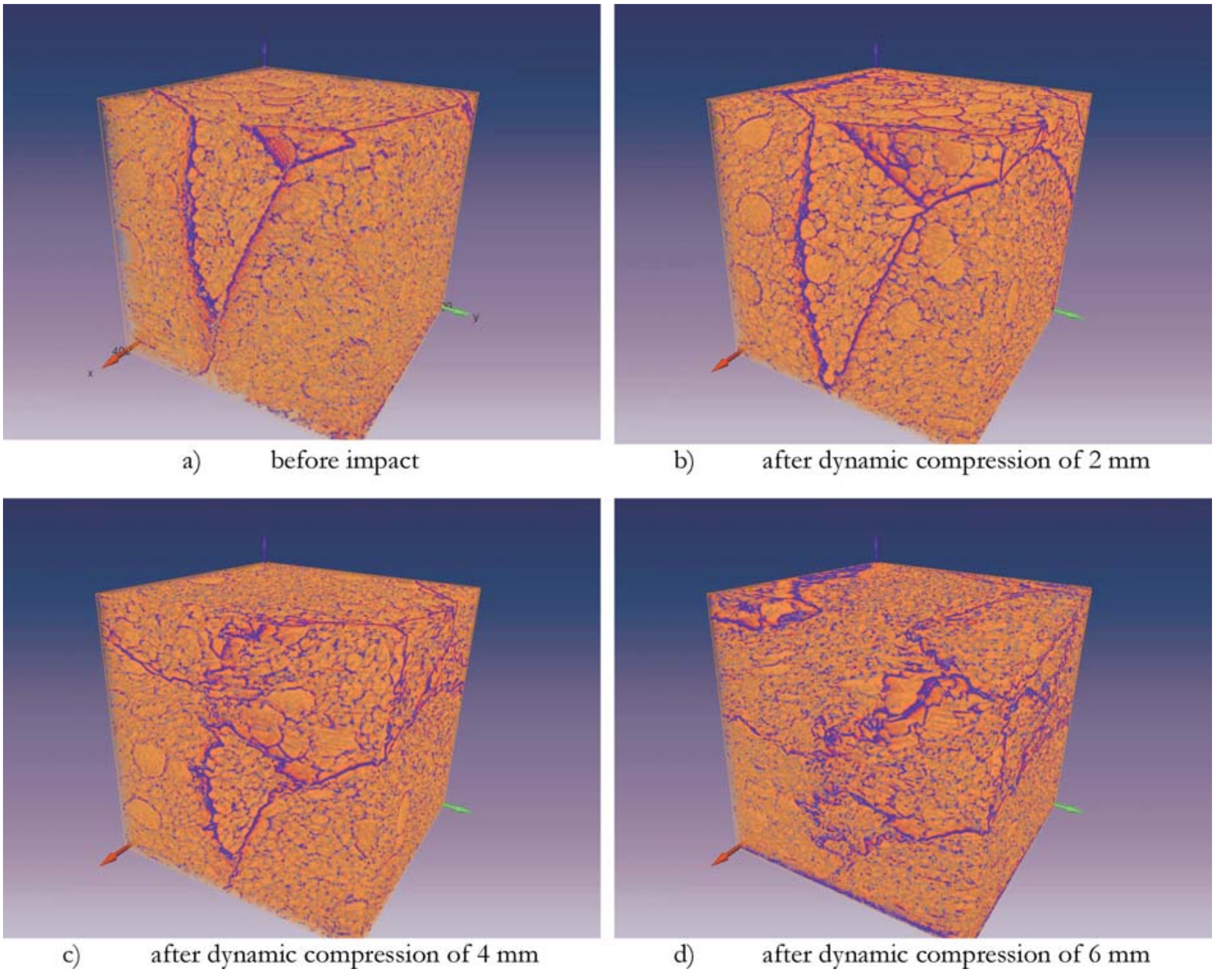

Figure 3 Evolution of the structure deformation after several dynamic loading. (a) Before impact. (b) After dynamic compression of 2 mm. (c) After dynamic compression of 4 mm. (d) After dynamic compression of 6 mm.

of the cellular mesostructure. Some grains seem to be completely densified (in the low part of the cube).

Compression dynamic tests were carried out on polypropylene foam. Microtomography was used to image the 3D microstructure evolution within the samples. A small cubic sub volume ($2 \times 2 \times 2$ mm^3) has been extracted allowing, *for the first time under dynamic loading*, the visualization of the grain wall buckling phenomena within the cellular material.

These preliminary results are promising since one can observe at a finer scale the macro default deformations. This 3D reconstruction work will be continued in order to extract from these data the grain shapes before and after impacts, and more precisely, the wall geometries and their thickness. These final results would be exploited to better understand the correlation between the structure deformation and the material response under shock.

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