Assessment of Energy Absorption in Styrene Acrylonitrile Foams at Different Strain Rates

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Abstract: Thorough work is done on investigating the strain-rate dependent behaviour of Styrene Acrylonitrile foam under compression loads. Quasi-static and dynamic compression tests ($10^{-3}s^{-1}$ up to $10^{2}s^{-1}$) were carried out on foams with three different nominal densities, and Finite Element Method (FEM) simulation was developed using a 3D foam volume reconstruction to compare with the experimental results. A remarkable improvement at the energy absorption capacity occurred in foams with higher density related to the cellular topology. On the other hand, simulation results show close correlation with the failure mechanism registered by micrographs.

Key words: Densification, energy absorption, microstructure, plateau region, relative density.

1. Introduction

Rigid polymeric foams are widely used in several engineering applications due to their higher energy absorption capabilities especially in the event of impact loading [1], [2]; e.g. core sandwich structures, crash mitigation, packaging, cushioning, etc. Most of the load cases are applied at high strain rates. Therefore, characterization of the mechanical response of foams under compression load has been investigated in last decades [3], [4]. The structural response of polymer foams strongly depends on foam density, solid material properties and cellular structure such as cell size and shape, open or closed cell grade [5], [6]. Due to the complexity of cellular structure and the effect it represents on the macroscopic constitutive behavior, it is fundamental to characterize the microstructure of polymeric foams [7]. Furthermore, strain-rate dependent behavior is strongly related to the viscoelastic nature of the solid polymer.

Characterization of foam mechanical response under dynamic loading at high strain rates represents some challenges such as the delayed stress equilibrium and mechanical impedance mismatch [8]. Nevertheless, those can be overcome implementing polymeric bars in the SHPB test and implementing the Iterative Deconvolution Algorithm (L-SIDA) [9].

Based on the ideas aforementioned, it can be inferred that a previous investigation is required to get a better understanding of the strain rate dependent behavior in polymeric foams, as well the influence of cellular microstructure into the macroscopic mechanical behavior with the purpose to optimize the design of foam-based equipment submitted to compression loads.

In the presented work, microstructural characterization is carried out using optical stereoscopy and X-ray computed tomography, Moreover, characterization of mechanical response under compression load from low strain rates up to high strain rates is performed with the purpose to analyze the influence of density change into the macroscopic constitutive behavior, along with the material strain rate dependence. Eventually, a 3D foam volume reconstruction based on CT images is developed to compare experimental data with the FEM simulation results as well as the mechanic failure mechanism.

2. Material and Methods

2.1. Specimen Material

Styrene Acrylonitrile foam supplied by Gurit® Corecell™ is selected for the presented study. This material is selected due to the inadequately PVC core technology in marine sandwich. Three different foams with nominal densities of 116.5, 150 and 210 kg/m^3 known commercially as SAN A600, A800 and A1200 were chosen. Some previous studies have explored the mechanical properties of SAN foams [5], [10]-[12].

2.2. Microstructural Characterization

A first approach to visualize the microstructure of SAN foams is carried out using optical stereoscopy equipment (Olympus SZX9), at resolutions of: 30X and 96X. Due to the difficulty of identifying the microstructural topology, X-ray computed tomography is used in a specimen of size 10 mm x 10 mm x10 mm that was machined with a diamond cut saw disk to decrease the possible damage in the cellular structure.

2.3. Quasi-static and Dynamic Compression Testing

Low strain rates from $10^{-3}s^{-1}$ up to $10^{-1}s^{-1}$ are achieved through the electro-mechanical Instron 3376 test system. Specimen size and cross-head displacement speed are established following the norm ASTM D 1624-94 titled as "Standard Test Method for Compressive Properties of Rigid Cellular Plastics" [13]. Furthermore, Optimum specimen aspect ratio was determined through qualitative FEM analysis [11]. It was found more homogeneous state of strain for higher aspect ratio [14], [15]. Thus, an aspect ratio of 0.5 was selected, obtaining specimen dimensions of 59.51 mm × 59.41 mm × 30 mm.

A controlled drop tower apparatus is used to accomplish medium strain rates. The machine has a mass of 13.2 kg, which is dropped at the maximum height of 680 mm. Moreover, the aspect ratio of specimen is changed to 1 with the purpose to achieve the densification regimen. On the other hand, the impact is recorded using a high-speed camera at 5000 frames per second to observe the failure mechanism presented in the different foams.

Compression tests at high strain rates are conducted using a split Hopkinson pressure bar. A well-aligned striker bar was launched from a gas gun to hit the incident bar producing a stress wave, which propagates along the bars. Before the testing development, an experiment design is performed to guarantee a good quality experimentation. This is divided in four steps: (i) Striker calibration, (ii) Bar alignment, (iii) Specimen size, (iv) Permissible fire range. Bar deformations are acquired using gages positioned at the middle of the bars, obtaining value information, which is implemented to reconstruct the stress-strain curve of the specimen using the iterative deconvolution algorithm known as L-SIDA [9].

2.4. Finite Element Method Setup

The computational foam model behaviour under compression load it is described using the constitutive model of Johnson-Cook [11], which relates the hardening effects, strain rate and temperature with the yield strength. A modification over the Johnson-Cook model is applied, assuming a rigid material-perfectly plastic-densification (RPPD) behaviour. As a first step, different simulations were carried out using the using Marc Mentat® software varying the type of element (Solid-7, Solid-21, Solid-127 and Solid-134). Secondly, mesh sensitivity is analysed using different mesh densities. FEM simulations are performed implementing the properties of foam base material without the inclusion of air in cells [16]. Simulations were run up to deformation of 40% due to the presence of cell wall buckling and self-faces contact

3. Results

3.1. Foam Microstructure

It can be noted that the foam presents a close cell grade due to the presence of membranes covering cell faces at deepest layers (Fig. 1- a -middle and bottom row). On the other hand, cell geometry is associated with tetrakaidecahedron polyhedral cell or most commonly known as Kelvin cell [17], constituted by 14 faces (*f*), 36 edges (*n*) and 24 vertices (*v*).

Because of large variation in cell size, at least 250 measurements of cell diameter and 100 wall thickness measurements are taken in randomly selected areas. However, the standard deviation are large compared to the average cell size value. This is because cell sizes are significantly varying. Moreover, a general trend in the average values is observed, which is reflected in the density of foam specimens [18].

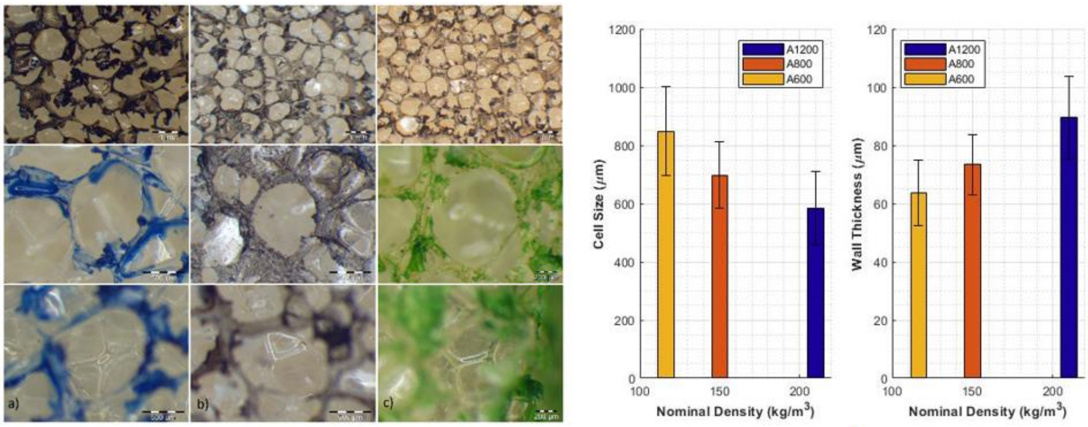

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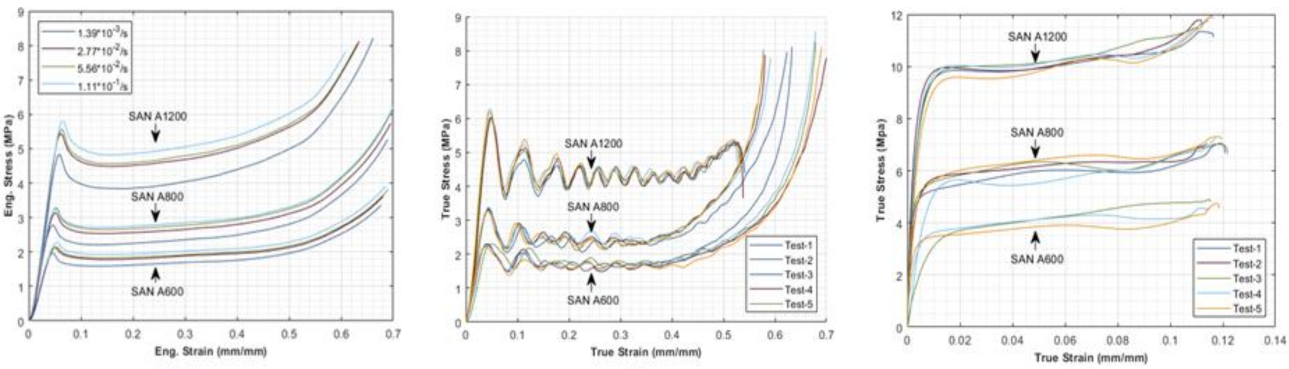
Fig. 1. a)- Micrographs of Styrene Acrylonitrile foams a) A600, b) A800 and c) A1200 at resolutions 30X and 96X. b) - Measurement of cell diameter and cell wall thickness in SAN A600, A800 and A1200 foams.

An evident cell size decrease is evidenced as the foam nominal density increments. Hence, an augment of material into the cell walls should be present to maintain a material porosity relation. Due to the reduction of the cell wall thickness from the cell junctions up to ligament middle section, it is expected that the deformation and failure will start at the weak points in the material. This point is usually at the center of the cell walls or ligaments.



a b c

Fig. 2. Stress-strain curves under compression load at strain rate of: a) $10^{-3}s^{-1}$ up to $10^{-1}s^{-1}$ b) $129s^{-1}$ c) $839s^{-1}$ in SAN Foams A600, A800 and A1200.

3.2. Compressive Response

Force and displacement are obtained in quasi-static and dynamic compression tests, which are converted into stress-strain curves (Fig. 2). The behaviour presented exhibits a good agreement with the literature related to elasto-plastic foams, presenting three characteristic regions: (i) linear elastic regimen, (ii) plateau regimen and (iii) densification regimen [6], [19], [20]. On the other hand, despite the material is exposed under dynamic compression tests, styrene acrylonitrile foams show a good repeatability since the stress-strain curves presents a tendency in the mechanical behavior. Similarly to the quasi-static compression response, foams with higher density present a faster densification point attributed to the lower porosity. In reference to the SHPB results, it has been found that the maximum strain obtained in the three different foams presents a relation with the speed wave and specimen length, obtaining a similar value. This idea is supported with the high speed camera videos, where multiple compressions were detected, concluding that the information obtained during the experimentation belongs of a portion of the first compression due to the high front wave speed and long specimen length.

The increment of performance in the energy absorption under quasi-static and dynamic loads can be noticed from strain rates of $10^{-3}s^{-1}$ up to $10^{-1}s^{-1}$. In foams with higher density, the improvement is more evident, and it could be associated with the fact that those foams presents more material located into the cell walls, exposing greater resistance to bending failure. The aforementioned idea is based on the fact that the three different foams have the same base material and only present different cell size. The energy absorbed at high strain rates was not calculated because the information acquired belongs to a portion of the total deformation. Nevertheless, through the plastic collapse strength it can be noted the performance of the foams is remarkable at high strain rates.

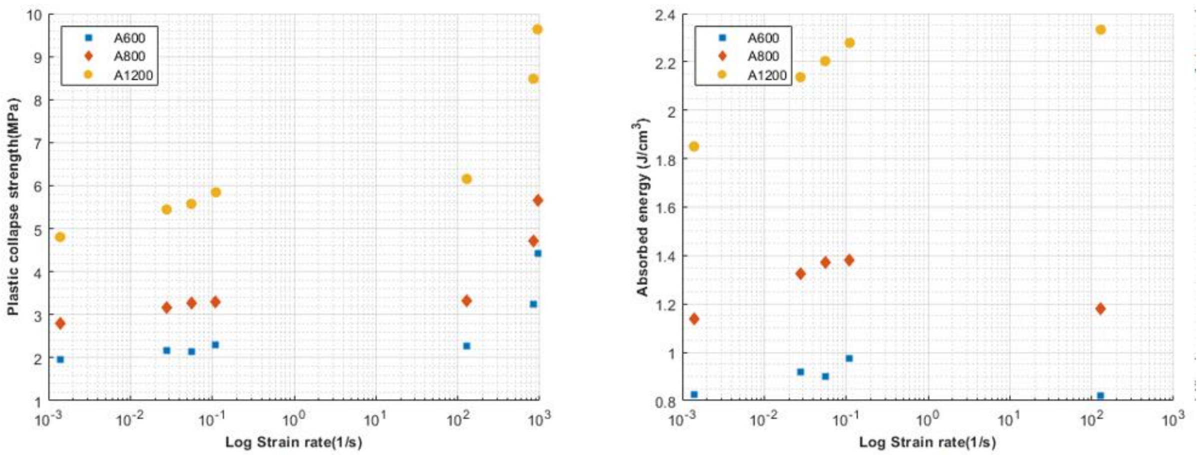


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Fig. 3. a) Plastic collapse stress at different strain rates in SAN A600, A800 and A1200 foams. b) Energy absorption at different strain rates in SAN A600, A800 and A1200 foams.

3.3. Finite Method Analysis

It was found that the stiffness value predicted using hexahedral elements, which conforms the cubic voxel mesh, is lower in comparison to the tetrahedral mesh. This could be related to the relative density difference presented in the meshes since the step-wise surfaces in cubic voxel mesh leads to a decrease in the effective thickness of cell walls. A difference of 3.165% is obtained by the higher and medium refinement meshes.

It is evident through Fig. 4 that the computational model cannot replicate the presence of the critical peak stress due to the constitutive model implemented. On the other hand, the difference value presented at the plateau region between the experimental and simulation curve is associated to the fact that the gas capsuled into the cells has not been considered. However, the failure mechanism exhibited by the 3D foam presents an accordance with the micrographs captured after compression tests, where the failure begins at the middle of the cell ligaments where the presence of material is minor, undergoing a failure by buckling.

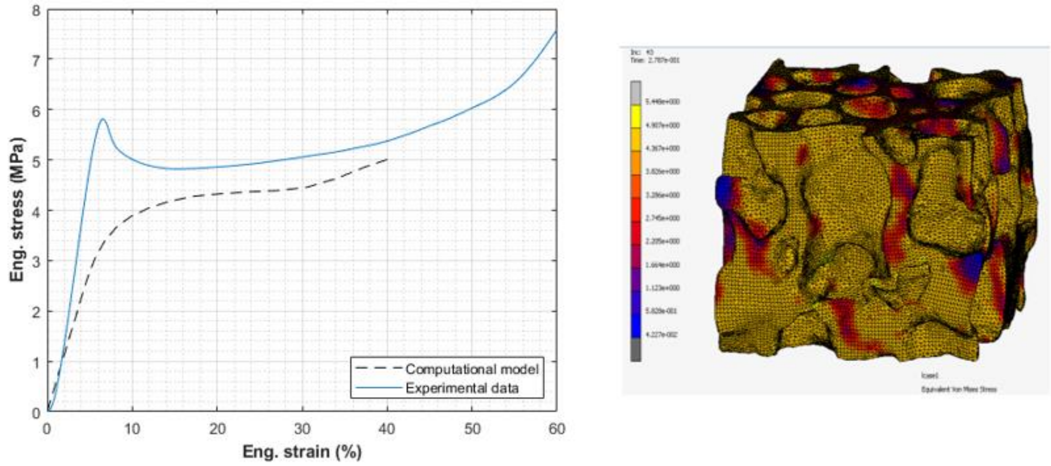

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Fig. 4. a) Comparison of computational model results and experimental data obtained by quasi-static test at cross-head speed of 200 mm/min. b) Deformed 3D foam volume reconstruction at strain of 40%.

4. Conclusions

Microstructural characterization was carried out using optical stereoscopy and X-ray compute tomography technique. It was found that the geometry cell-shape could be approximate to the tetrakaidecahedron polyhedral cell, presenting an elongation in the growth direction. Furthermore, it has been determined that the change of nominal density is reflected on the average diameter cell and cell wall thickness. Foams with higher nominal density presents lower porosity due to the size of the cell and the large amount of material lodged inside the cell walls.

Through experimental test performed at low, medium and high strain rates, it was found that the Styrene Acrylonitrile foam exhibits an energy absorption improvement at high strain rates. However, a better performance is more remarkable on foams with higher nominal density. Signals at the specimen/bar interface are retrieved using an iterative deconvolution algorithm (L-SIDA) obtaining the stress-strain curve. Nevertheless, it was observed that a pulse reconstruction is not enough to obtain a complete information about the physical phenomenon presented during the experimentation. Hence, a multiple pulse reconstruction is required.

Finally, 3D volume reconstruction is performed using image operations as: binarization, dilatation and erosion with the purpose to eliminate image noise and repair broken filaments. Computational model of size 2.5×2.5×2.5 mm is meshed implementing solid element type 134. Johnson-Cook constitutive model is used on the foam SAN A1200 assuming a RPPD behaviour. The result obtained cannot replicate the presence of critical peak stress due to the constitutive model applied. Furthermore, different values presented in plateau regimen are attributed to the absence of air into the cells. Failure mechanism is presented at the middle of cell walls where the presence of material is minor leading a failure by buckling.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The author David Gutiérrez was in charge of carrying out the experiments, as well as data analysis and simulations. Juan Casas was in charge of supervision as a master thesis advisor.

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