Numerical modelling of closed-cell aluminium foams under shock loading

M. A. Kader, M. A. Islam, P. J. Hazell, J. P. Escobedo, M. Saadatfar, and A. D. Brown

Citation: AIP Conference Proceedings **1793**, 120028 (2017); doi: 10.1063/1.4971710
View online: http://dx.doi.org/10.1063/1.4971710
View Table of Contents: http://aip.scitation.org/toc/apc/1793/1
Published by the American Institute of Physics

Numerical Modelling of Closed-Cell Aluminium Foams Under Shock Loading

M. A. Kader[1, a)], M. A. Islam[1], P. J. Hazell[1, b)], J. P. Escobedo[1], M. Saadatfar[2] and A. D. Brown[1]

[1]*School of Engineering and Information Technology, The University of New South Wales, Canberra, ACT-2600, Australia.*
[2]*Department of Applied Mathematics, Australian National University, Canberra, ACT-0200, Australia.*

[b)]Corresponding author: P.Hazell@adfa.edu.au
[a)]Md.Kader@student.adfa.edu.au

Abstract. The present research numerically investigates shock propagation through closed-cell aluminium foam via flyer-plate impact. The mechanics of foam deformation was elucidated using the finite element (FE) software ABAQUS/explicit. X-ray computed micro-tomography was performed to render a full 3D foam geometry mesh for understanding detailed macrostructural response due to shock propagation. Elastic wave propagation and pore collapse mechanism with time were studied. The free surface velocity of the foam was measured at two different flyer-plate impact velocities to observe the profile of the shock wave with time. Good correlations were observed between experimental data and FE predictions for both test conditions.

INTRODUCTION

Closed-cell aluminium foams show promise for extensive use in the automobile, aerospace and military vehicle industries to protect against impact and blast loading. This is principally due to their light weight and high impact energy absorption capacity. However, these stochastic structured foams are susceptible to damage during shock loading that consequently diminishes their strength [1]. To date, researchers have focused their attention on numerically modelling the dynamic characteristics of aluminium foam at low velocity impact using continuum approaches [2,3]. However, numerical modelling of closed-cell aluminium foams subjected to shock loading, with an accurate meso-scale foam geometry, has not been found in the literature. A few research groups [4-6] have investigated the foam behaviour under shock loading experimentally. Detailed analysis of the wave phenomena inside the foam centre is difficult experimentally because high-speed photography can investigate only the side surfaces and everything happens in a transient period. Lopatnikov et al [7] studied the closed-cell aluminium foam behaviour under shock loading with analytical and continuum approaches, but ignored the effect of discrete pores that are chaotically distributed throughout the structure. Shock propagation is affected by the complex geometrical nature of foam and therefore FE modelling developed from a micro-CT analysis is important to understand the foam behaviour under blast and shock loading.

In this study, the numerical simulation of a plate-impact experiment is reported to elucidate the shock propagation through closed-cell aluminium foam and its effect on cell-wall deformation and pore collapse. An X-ray computed micro-tomography approach is adopted to develop the foam geometry. A Mie-Gruneisen equation-of-state (EOS) with linear U_s-u_p and a Johnson-Cook plasticity material model with dynamic failure are used to describe the

Shock Compression of Condensed Matter - 2015
AIP Conf. Proc. 1793, 120028-1–120028-4; doi: 10.1063/1.4971710
Published by AIP Publishing. 978-0-7354-1457-0/$30.00

structural aluminium foam material. The numerical predictions are validated through comparisons with experimental results [5].

METHODOLOGY

Foam Geometry Development

CYMAT foam of density 0.5 g/cc (relative density 0.18) with 82% porosity was considered for the present research. X-ray computed micro-tomography was used to develop the digital foam geometry. It is a non-destructive technique that allows the 3D internal structure of an object to be determined by reconstructing the X-ray absorption coefficients of the materials. A micro-focus X-ray source of 100 kV acceleration voltage and flat panel detector were used for imaging. The foam specimen was placed on a motor controlled rotating stage and radioscope projections of the foam sample were taken after each degree of rotation. Subsequently, the grey projections were converted to binary images and processed to reconstruct a full 3D digital foam geometry. Because of the complexity of the foam structure, tetrahedral elements were used to mesh the geometry.

Finite Element Simulation

Numerical simulations were carried out to offer an inexpensive and reliable method for predicting the shock response with the finite element software ABAQUS/Explicit. The experimental schematic and FE assembly of flyer-plate (Cu/Al) and target foam, both 8 mm thick, are shown in Figures 1 and 2, respectively.

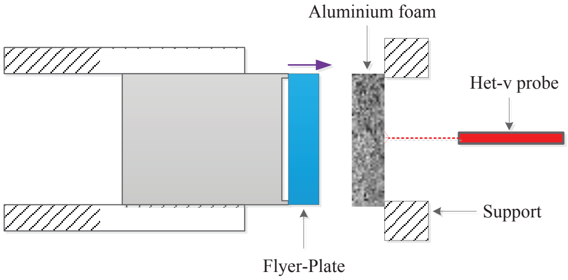


FIGURE 1. Schematic of the flyer-plate experiment [5]

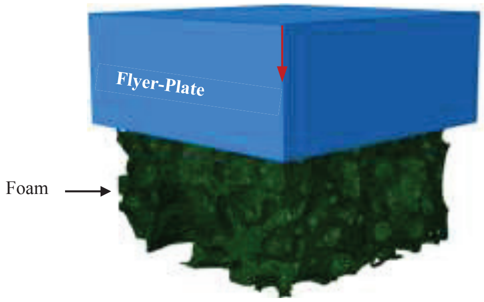


FIGURE 2. FE model of the flyer-plate experiment

The Mie-Gruneisen EOS (equation 1) with linear U_s-u_p was used to describe the base material of the foam.

$$P = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2}\left(1 - \frac{\Gamma_0 \eta}{2}\right) + \Gamma_0 \rho_0 E_m \tag{1}$$

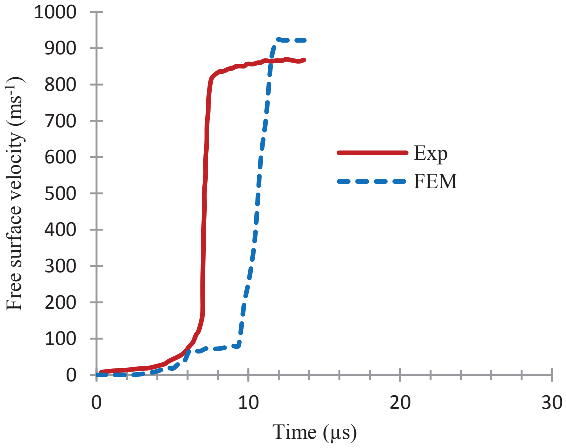
The constants used were $\rho_0 = 2700$ kg m^{-3}, $c_0 = 5.24$ mm μs^{-1}, s =1.40 and $\Gamma_0 = 1.97$ [8]. An elastic, Johnson-Cook plasticity (equation 2) material model with Johnson-Cook dynamic failure criteria for the structural material (Al) was applied to simulate the plastic response [9].

$$\sigma^0 = [A + B(\bar{\varepsilon}^{pl})^n]\left(1 - \hat{\theta}^m\right) \tag{2}$$

Where $\bar{\varepsilon}^{pl}$ is the equivalent plastic strain and A, B, n and m are material parameters measured at or below the transition temperature [8]. $\hat{\theta}$ is the non-dimensional temperature expressed as a ratio between the current, transition, and melting temperatures of the material [8]. Linear elastic material properties were used for the flyer plate models. The impact velocity was applied to the flyer and a boundary condition was applied to the target's perimeters to mimic confinement. All degrees of freedom of the flyer-plate are restrained except the velocity direction. The general contact option of ABAQUS/Explicit was used for interactions between the flyer and target and for all interior contacts of the foam structure.

RESULTS

The comparison of free surface velocity between experimental outcome and FE prediction for flyer-plate impact velocities 845 ms^{-1} and 480 ms^{-1} are shown in Figure 3 and 4, respectively. As is shown from Figure 3, the free surface velocity predicted by FEM increases steadily up to 5 μs and then gradually rises to plateau at around 90 ms^{-1} (precursor wave). After that the velocity increases dramatically (shock formation) similar to the experimental outcome and peaks at around 900 ms^{-1}. Petel et al [4] carried out plate-impact experiments with open-cell aluminium foams and found a precursor wave at the beginning similar to the present FE prediction. However, the experimental results of Islam et al. [5], shown in Figure 3, contain no significant precursor. The experimental specimen studied by Islam et al. [5] contained a distribution of ceramic particles and microporosity from the manufacturing process, possibly resulting in some dispersion of the precursor wave. Pure aluminium (with no porosity or ceramic particles) was considered for modelling as the structural material with the absence of a constitutive model for CYMAT.



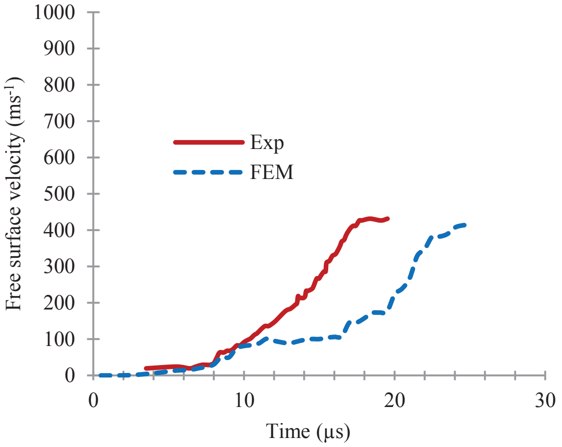


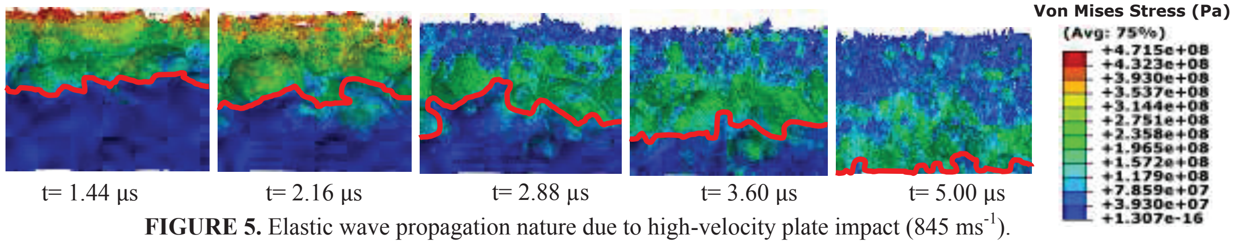
FIGURE 3. Comparison of velocity-time curve between experiment and finite element for 845 ms^{-1} Cu flyer plate velocity.

FIGURE 4. Comparison of velocity-time curve between experiment and FE for 480 ms^{-1} Al flyer plate velocity.

As can be seen from Figure 4, the predicted free surface velocity (impact velocity 480 ms^{-1}) increases gradually up to 13 μs and agrees with experimental result. After a short plateau at 100 ms^{-1} the velocity again increases with almost the same rate as the experiment. It should be pointed out that in our computations the thickness of the target was 8 mm, whereas in the experimental work [5] the thickness of the target was 10 mm. For this reason a small deviation was found between FE predictions and experimental results, however; the overall prediction of the present simulation is reasonably good.

DISCUSSION

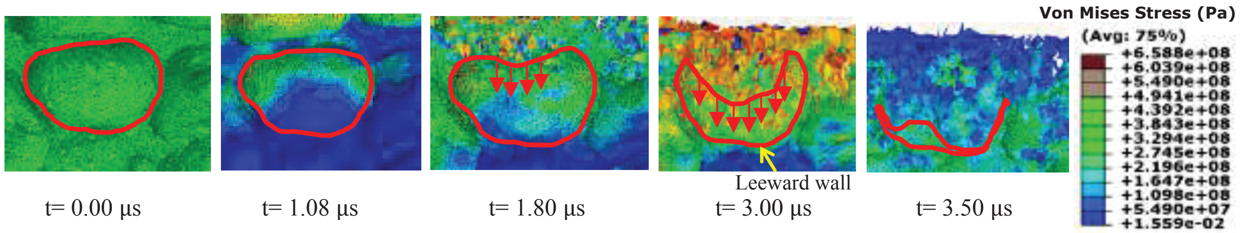
The micro-tomography based foam geometry allows one to observe the internal wave propagation during impact. At the beginning of loading, an elastic wave propagates through the cellular material due to elastic compression. Figure 5 shows the elastic wave propagation through the aluminium foam with time for a plate impact velocity of



t= 1.44 μs t= 2.16 μs t= 2.88 μs t= 3.60 μs t= 5.00 μs

FIGURE 5. Elastic wave propagation nature due to high-velocity plate impact (845 ms^{-1}).

845 ms^{-1}. From the observation of elastic wave propagation, it is found that the main elastic wave front propagates at a velocity of 1600 ms^{-1}. This is far lower compared to wave propagation through its parent material (~6400 ms^{-1}). Petel et al [4] found the elastic wave velocity was about 1500 ms^{-1} from shock experiments with open-celled aluminium foams, in agreement with the velocity reported here. Possible underlying reasons behind this are (i) actual distances travelled by the wave through the structure is larger than the linear distance, (ii) microporosity exists within the struts, reducing the stiffness of the material and (iii) the energy of the elastic wave is lost to the surrounding pores.



t= 0.00 μs t= 1.08 μs t= 1.80 μs t= 3.00 μs t= 3.50 μs

FIGURE 6. Pore collapse mechanism at high velocity (845 ms^{-1}) plate impact with time.

Figure 6 shows the details of a pore collapse mechanism with time due to shock loading for the impact velocity 845 ms^{-1}. It can be seen from the sequence of pore state that the collapse begins from the top surface and proceeds over time to consolidate the pore within 3.5 μs. This sequence reveals that the crushing of pores takes place due to transmitted compressive load through adjacent cell walls with complex movements. During compression the pore collapsed by the movement of damaged cell wall into its inner void space.

CONCLUSIONS

The micro-computed tomography based 3D foam geometry facilitates the FEM to observe the real-time foam collapse mechanism during shock loading. The experimental results and FE simulations show similar free surface velocities except for an initial precursor found in the simulation. The FE simulation results clearly reveal that the initial precursor wave appeared when the elastic wave reached the free surface, travelling at ~1600 ms^{-1}. The pore collapse mechanism initiates at the top surface and propagates due to complex deformation of neighboring pores.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the laboratory facility provided by Department of Applied Mathematics, Australian National University. We also gratefully acknowledge the UNSW Canberra Defence Related Research Program that part-funded this work.

REFERENCES

1. I. Ivanez, C. Santiuste, E. Barbero and S. Sanchez-Saez, Compos. Struct. 93, 2392-2399 (2011).
2. D. Karagiozova, G. S. Langdon and G. N. Nurick, Int. J. Impact Eng. 62, 196-209 (2013).
3. M. Peroni, G. Solomos and V. Pizzinato, Int. J. Impact Eng. 53, 74-83 (2013).
4. O. E. Petel, S. Ouellet, D. L. Frost and A. J. Higgins, Journal of Physics: Conference Series 500, 112050, (2014).
5. M. A. Islam, M. A. Kader, J. P. Escobedo, P. J. Hazell and G. J. Appleby-Thomas, 19th Biennial APS Conference on Shock Compression of Condensed Matter, Tampa, Florida (2015).
6. P.J. Tan, S.R. Reid, and J.J. Harrigan, Int. J. Solids and Struct., 49, 2744-2753, (2012).
7. S. L. Lopatnikov, B. A. Gama, M. J. Haque, C. Krauthauser, J.W. Gillespie Jr., Int. J. Impact Eng. 30, 421-455 (2004).
8. ABAQUS Technology Brief, Simulation of the ballistic perforation of aluminium plates with Abaqus/Explicit, Dassault Systemes (2012).
9. G. R. Johnson and W. H. Cook, Eng. Fract. Mech. 21, 31-48 (1985).