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Experimental and Computational Study of Underwater Shock Wave Effect on Aluminum Foam

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ABSTRACT

The behavior of aluminum foam subjected to underwater shock wave loading was investigated both experimentally and computationally. Experimental testing was conducted on an aluminum foam sample submerged in a water tank, where the shock wave was generated with detonation of SEP explosive device at water surface. The shadowgraph method and the high speed video camera were us used to observe the generation and propagation of shock wave and its influence on the aluminum foam. To obtain a better insight into the inner mechanism of aluminum foam deformation pattern during underwater shock wave loading, a follow-on computational study was conducted, where several different coupled ALE modeling approaches and foam models were evaluated and validated. All computer simulations were performed with the finite element explicit dynamic code LS-DYNA, which allows also for finding solutions of coupled problems, such as interaction between the underwater shock wave and aluminum foam investigated in this study. Comparison of the results shows a good correlation between the experimental and some computer simulation results, which in turn validates some proposed modeling approaches.

1. INTRODUCTION

Metal foams have become very popular engineering materials in recent years due to their high applicability and various advantageous mechanical and thermal properties (Banhart 2001, Gibson 1997, Hong 2006, Vesenjak 2009). Metal foam is made of interconnected network of solid struts or plates which form the edges and faces of cells

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(Fig. 1). The advantages of metal foams in general are low density (light-weight structures), high acoustic isolation and damping, high energy absorption capabilities, durability at dynamic loadings and fatigue, recyclability (Banhart 2001). Their micro- and macroscopic properties make them perfect for use in automotive, rail, naval, aerospace and armour industry as heat exchangers, filters, bearings, acoustic dampers, bio-medical implants, blast protectors and especially as elements for crash energy absorption (Gibson 1997, Banhart 2001, Yu 2006).

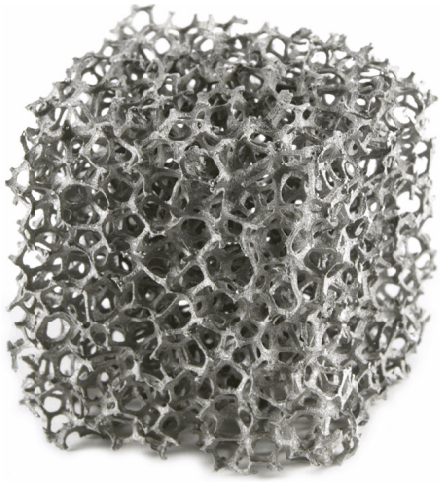

Fig. 1. Open-cell aluminum foam sample

Mechanical behavior of cellular materials mainly depends on their relative density and on their base material. The other important parameters of the cellular structures are morphology (open or closed cell), the geometry and topology (regular or irregular structure) and possible filler type. Cellular materials have a characteristic stress-strain relationship in compression, which can be divided into four main areas: (i) quasi-linear elastic response, (ii) transition zone, (iii) stress plateau and (iv) densification.

Although these materials have been a subject of intense research during past several years, there is still a lack of their mechanical characterization data. The behavior of metal foams under impact loading conditions and especially the shock wave propagation are still not well understood. The shock wave propagation through the cellular material structure under impact loading conditions has a significant effect on its deformation mechanism and is therefore imperative to understand its effects thoroughly.

The paper describes the shock wave propagation effect on aluminum foam with 5% relative density. For this purpose experimental tests and explicit computational simulations of aluminum foam specimens submerged in a water tank and subjected to shock wave loading, initiated by the explosive charge, have been performed.

2. EXPERIMENTAL SETUP

The experimental tests of aluminum foams samples have been performed at the Shock Wave and Condensed Matter Research Center, Kumamoto University, Japan

(Irie 2010). The experimental setup is shown in Fig. 2. The aluminum specimens, measuring 40 mm x 40 mm x 40 mm, were submerged at the bottom of a water filled reservoir with clear PMMA walls with following dimension: 200 mm x 200 mm x 135 mm. The SEP explosive set (mass: 50 g, detonation velocity: 7000 m/s, density: 1310 kg/m3) in the PVC pipe was positioned 110 mm above the foam specimen at the water surface. It was used as booster explosive for shock wave generation and was initiated by an electric detonator. A PMMA plate was positioned on top of the aluminum foam sample to transfer the shock wave pressure forces to the open-cell foam sample. Otherwise the propagating shock wave would have very little influence on the foam sample.

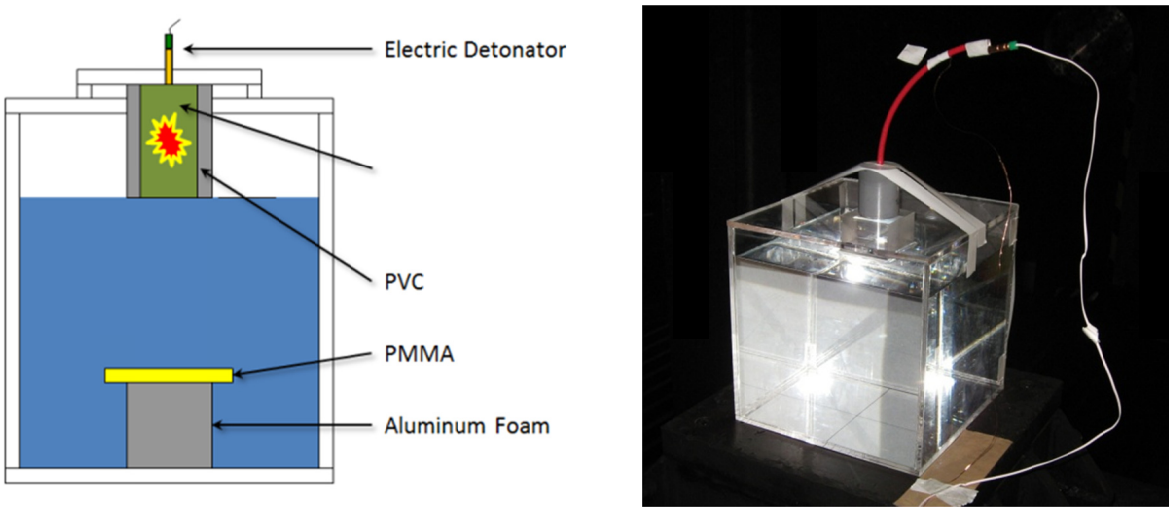

Fig. 2. Underwater shock wave experimental setup

The shadowgraph method was used to observe the generation and propagation of shock wave and its influence on the aluminum foam (Fig. 3). This method is used to observe and project the shadow of the light by density change on a screen or the film of a camera, and it is also called the direct projective technique (Settles 2001).

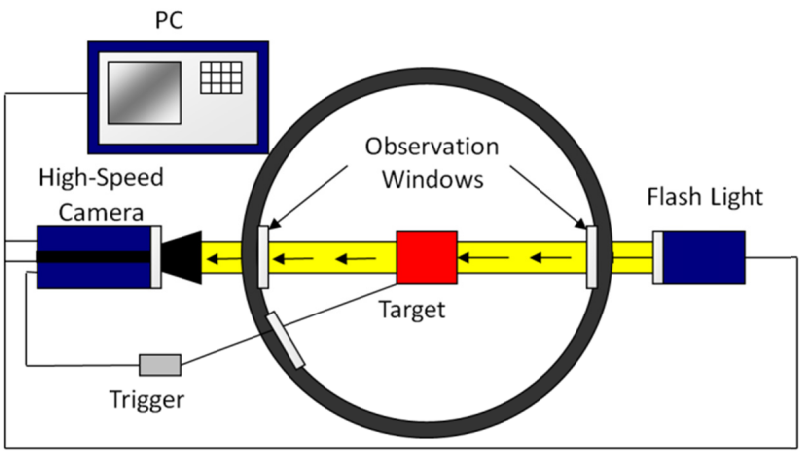

Fig. 3. The shadowgraph method

The high speed video camera HPV-1 (Shimadzu Corporation) with a frame rate of 500.000 FPS and an image resolution of 320 x 260 pixels was used to visualize the shock wave propagation during the experiment (Fig. 4).

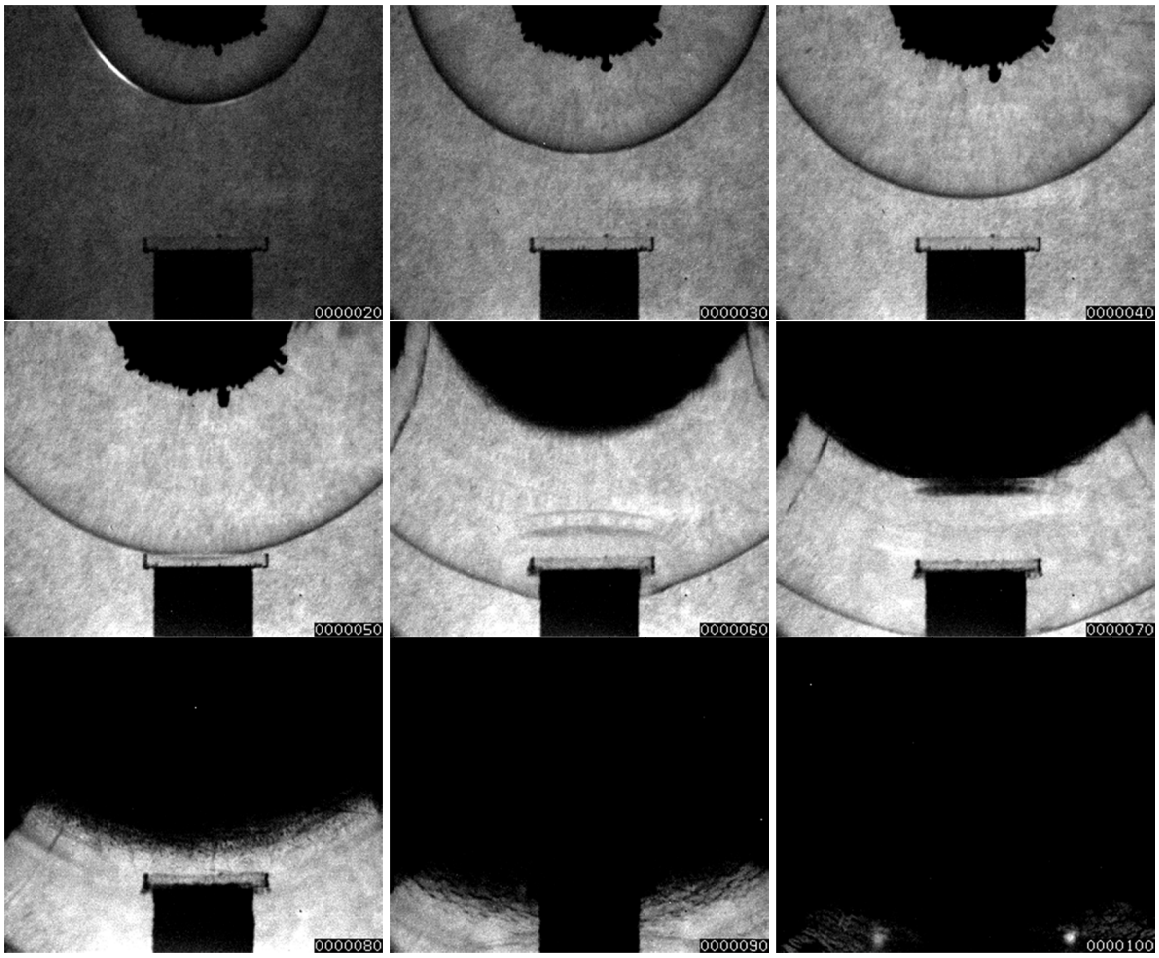

Fig. 4. The shock wave propagation (20 - 100 μs after detonation)

From Fig. 4 it can be seen that the shock wave reaches the top PMMA plate around 50 μs after detonation of the SEP explosive set. Thereafter a reflection of the shock wave from the PMMA plate can be observed, which later interferes with the blast wave front at approximately 70 μs after detonation. Only a very small deformation effect of shock wave loading on aluminum sample could be observed, which could not be quantified precisely enough due to fuzzy pictures with low resolution. This indicates that the shock wave energy was too small to cause optically measurable deformation. Approximately 90 μs after detonation the blast wave reached the sample, which was thereafter completely destroyed along with the PMMA plate and reservoir.

The variation of the shock wave speed was determined by analyzing the images taken during the experiment (Fig. 4) and is shown in Fig. 5. The accuracy was limited by the pixel size and is approximately ± 250 m/s.

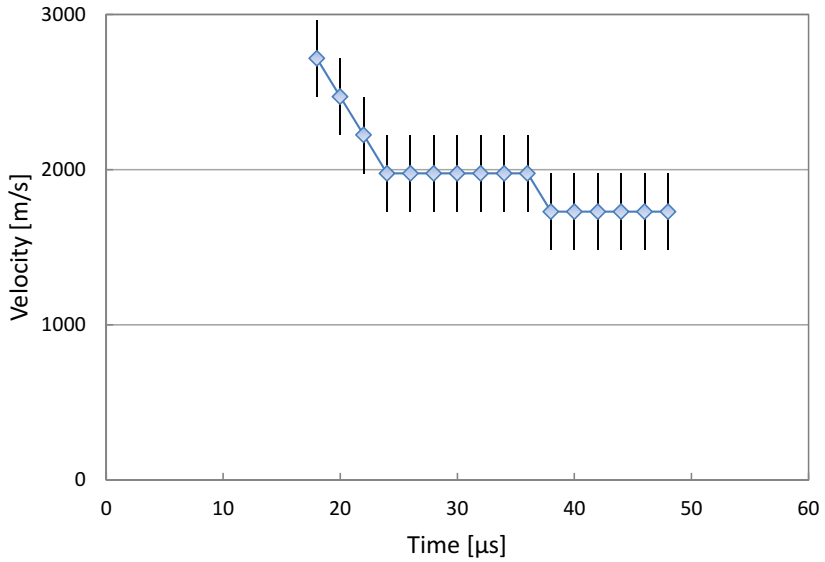

Fig. 5. Shock wave propagation speed variation during the experiment

3. COMPUTATIONAL SIMULATIONS

The finite element explicit dynamic code LS-DYNA was used to further investigate the behavior of open-cell aluminum foams under shock and blast wave loading conditions by means of computational simulations.

3.1. Shock wave propagation speed

First a simulation of the shock wave propagation through water without a foam sample model was performed. The computational model (Fig. 6) consisted of different parts with their own set of equations and discretization frameworks. The behavior of SEP explosive was described with the Jones-Wilkins-Lee (JWL) equation of state, the water with the Mie-Gruneisen equation of state, the air with the linear polynomial equation of state, and all these parts were discretized with an Eulerian framework mesh. The Lagrangian mesh was used for discretizing the PVC pipe and PMMA container, where behavior of both was described with the piecewise-linear plasticity constitutive model with failure. Due to the double symmetry of the problem only a quarter of the problem volume was modeled in computational simulations. The fluid-structure interaction interface was prescribed on the boundaries of the PVC and PMMA meshes.

The shock wave propagation speed in the computer simulation was determined from observing the pressure variations at a series of 10 measurement points positioned every 10 mm from the water surface to the bottom of the container (Fig. 6). The accuracy of this calculation was limited by the time sampling interval of 0.15 µs.

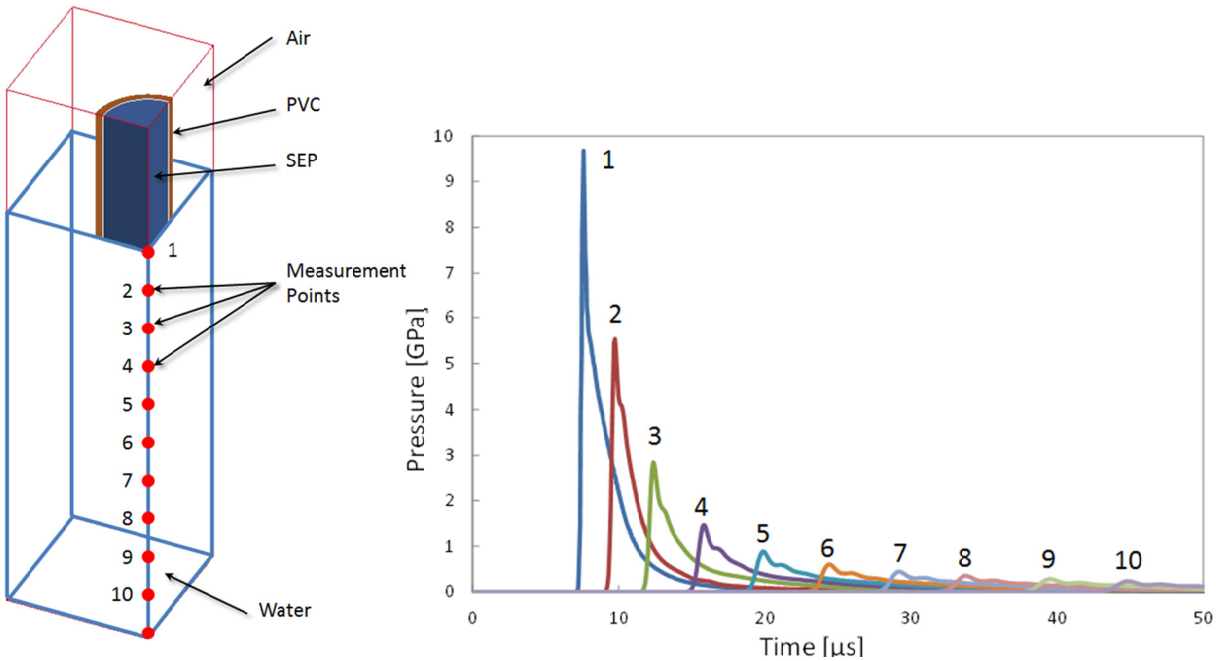

Fig. 6. Computational model (left) and pressure history at selected points (right)

Fig. 7 shows a comparison of experimental and simulation results of the shock wave propagation speed variation where good correlation of results can be observed. This validates the computational model as suitable for the following computational simulations of the shock wave effects on the submerged aluminum foam sample.

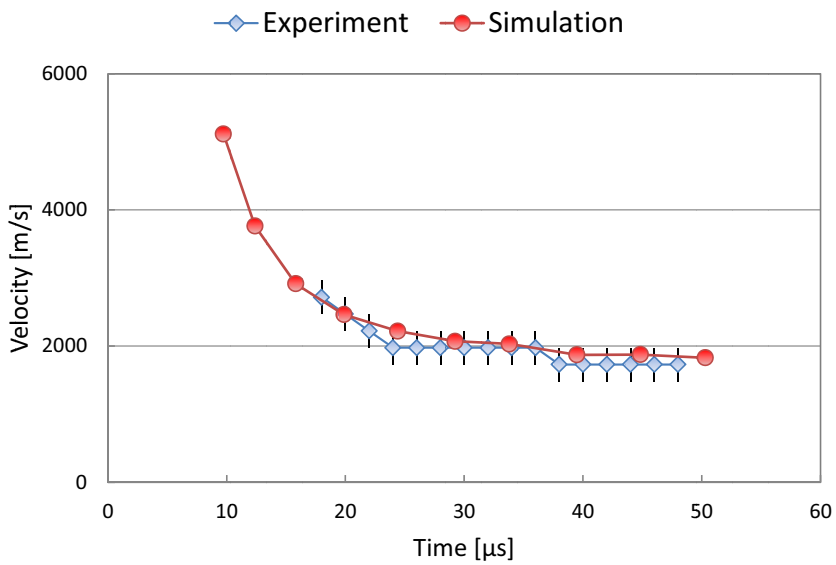

Fig. 7. Comparison of experimentally and computationally determined shock wave speed variation

3.2. Homogenized model of the aluminum foam

A homogenized aluminum foam model was added to the simulation model to evaluate the explosion effects on deformation behavior of the open-cell aluminum foam. The constitutive parameters of the homogenized aluminum foam model used in these simulations were determined in a previous study (Loehnert 2010).

Three different modeling approaches were evaluated:

- Model 1: The foam was modeled with the Lagrangian mesh and a piecewise-linear plasticity constitutive model. The water domain was modeled also inside the foam;
- Model 2: The foam was modeled with the Lagrangian mesh and a piecewise-linear plasticity constitutive model. The air domain was modeled also inside the foam;
- Model 3: The foam was modeled with the Eulerian mesh and a piecewise-linear plasticity constitutive model.

The resulting deformation behavior of three differently modeled homogenized foam models is shown in Fig. 8. It can be observed that the Model 1 exhibits the stiffest behavior, while the Model 3 sustains the largest deformation.

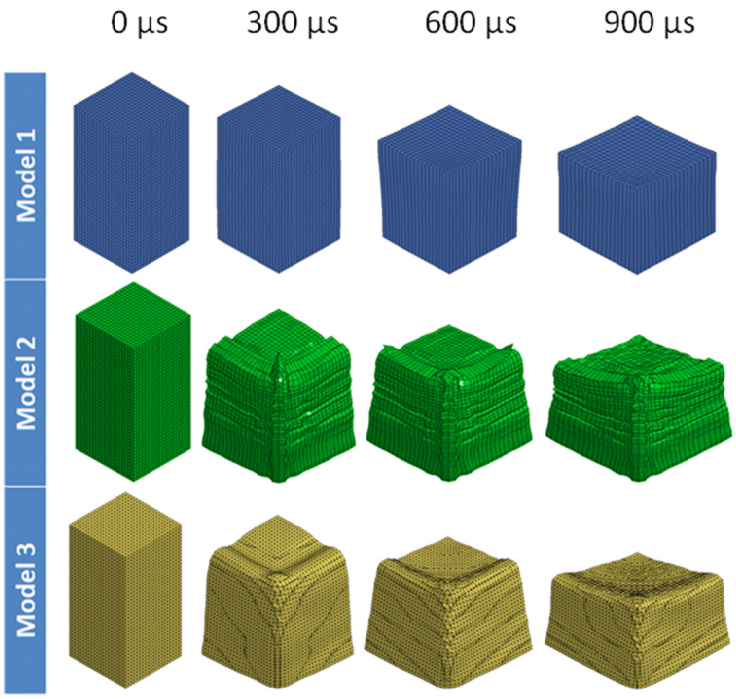

Fig. 8. Deformation pattern of the homogenized aluminum foam models

Fig. 9 shows the average variation of the top surface displacement of the aluminum foam for all three models evaluated. For Lagrangian Models 1 and 2 the average of all nodes displacements at the top surface was taken into account while for the Eulerian Model 3 only displacement at 4 positions on the top surface was considered.

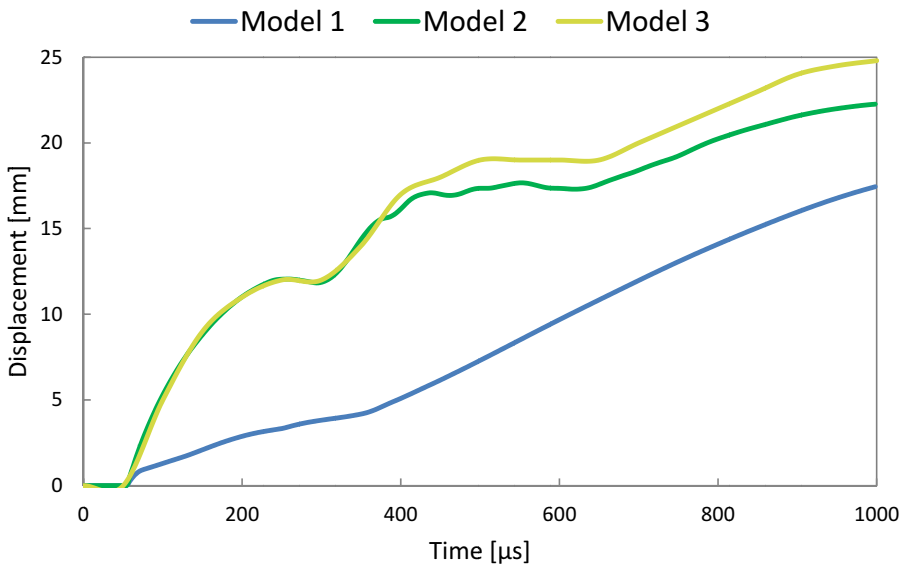

Fig. 9. Average vertical displacement of the aluminum foam top surface for different modeling approaches

3.3. Lattice model of the aluminum foam

In the following simulations the homogeneous aluminum foam model was replaced with a lattice model to represent the true irregularity of the reconstructed open-cell aluminum foam structure. The foam cell edges were modeled with beam finite elements and their topology was created using a developed algorithm based on Voronoi 3D regions (Borovinšek 2008). Three different relative densities of the aluminum foam were considered: 5, 10 and 15 %. Since the lattice foam model is not symmetric the whole simulation domain had to be modeled for these simulations. The PMMA plate on top of aluminum foam sample was modeled using an Eulerian mesh with a piecewise-linear plasticity constitutive model. A fluid structure interaction interface was used to transfer the pressures between the water and the PMMA plate.

The resulting deformation of the lattice model for the 5% relative density is represented in Fig. 10. It can be observed, that due to the high velocity loading of the PMMA plate, the foam material primarily deforms at the upper part where the shock and blast waves impact the plate.

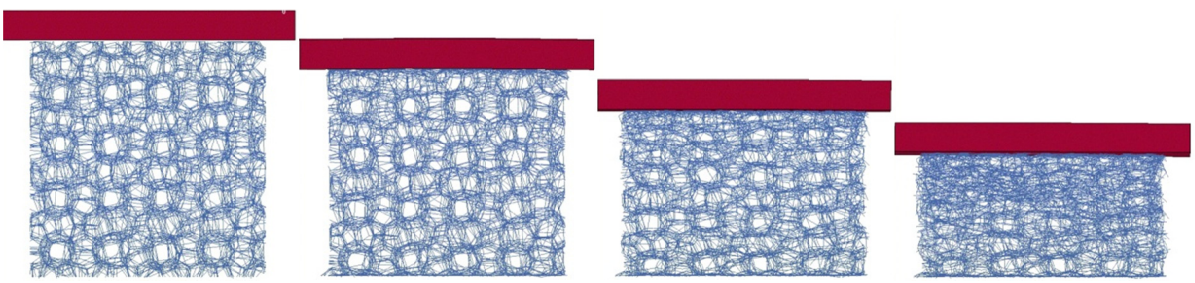

Fig. 10. Deformation of the lattice aluminum foam model with 5% relative density

The diagram in Fig. 11 shows the average displacement of the top surface of the aluminum foams for different relative densities. The blue curve in the diagram represents the simulation results obtained with a model without the aluminum foam, where only the freely floating PMMA plate movement through the water was taken into account. As expected, the foam with the lowest relative density experiences the highest displacements (deformations). Increasing the relative density of the foam also increases the macroscopic stiffness of the foam and at the same time decreases the displacements (deformations).

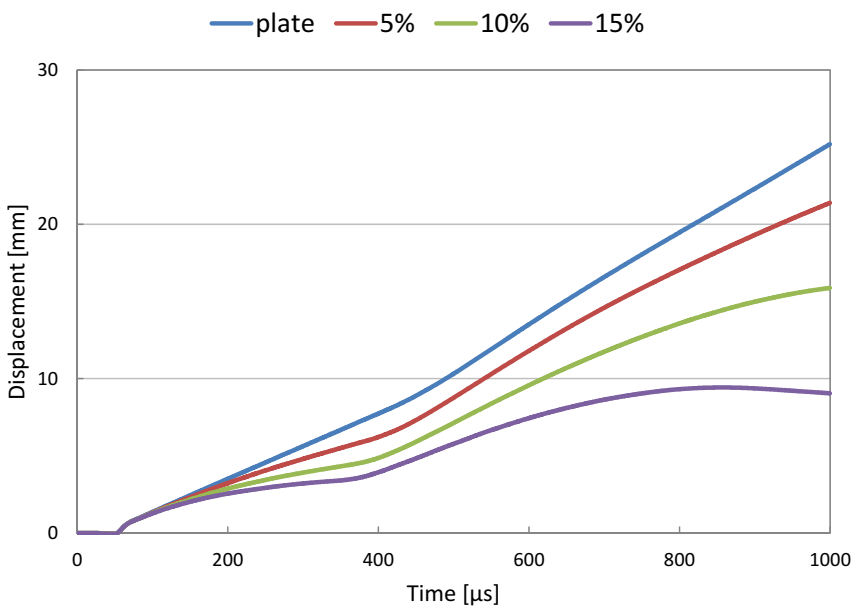

Fig. 11. Comparison of displacements for aluminum foams with different relative densities

By comparing the computational results shown on Fig. 9 and Fig. 11 it can be observed that the homogeneous Model 2 is best corresponding to the results obtained with the lattice model with 5% relative density. However, the lattice type model shows more constant deformation pattern than the homogeneous model, which is rather unexpected.

4. CONCLUSIONS

The paper presents the study of underwater shock wave propagation effect on open-cell aluminum foam. For this purpose experimental tests and computational simulations have been performed. The subject of investigation were the aluminum specimens, submerged at the bottom of a water filled reservoir and subjected to shock and blast wave effects, initiated with detonation of the SEP explosive set, positioned above the foam specimen at the water surface. A PMMA plate was positioned on top of the aluminum foam sample to transfer the shock wave pressure forces to the open-cell foam sample. The shadowgraph method was used to determine the shock wave

propagation speed variation and the shock wave effect on the aluminum sample. Only a very small deformation effect of shock wave loading on aluminum sample could be observed, which could not be quantified precisely enough due to fuzzy pictures with low resolution. This indicates that the shock wave energy was too small to cause optically measurable deformation.

Computational simulations were used to evaluate appropriateness of several different computational models for simulating the conducted experiments. Different ALE modeling approaches and foam models (homogenized and reconstructed irregular lattice) were evaluated and their results compared and validated with the experimentally determined data. Comparison of the results shows rather good correlation between the experimental and simulation results.

Further experimental and computational studies are being planned to achieve better characterization of open-cell aluminum foam subjected to underwater shock wave loading.

ACKNOWLEDGMENTS

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