Computational simulations of aluminum foam projectile behavior

M. Borovinsek[1,a], M. Vesenjak[1,b], Z. Ren[1,c] and S. Itoh[2,d]

[1]University of Maribor, Faculty of Mechanical Engineering, Slovenia

[2]Kumamoto University, Shock Wave and Condensed Matter Research Center, Japan

[a]matej.borovinsek@uni-mb.si, [b]m.vesenjak@uni-mb.si, [c]ren@uni-mb.si, [d]itoh_lab@okinawa-ct.ac.jp

Keywords: Taylor impact test, computer simulations, FEM, aluminum foam.

Abstract. The results of experimental tests and computer simulations of open-cell aluminum foam behavior under high deformation rates are presented. Experimental Taylor impact tests showed, that the open-cell foam projectile deforms already during its acceleration in the Taylor barrel. This behavior was investigated further by use of computer simulations with the LS-DYNA. The simulations confirmed very high sensitivity of open-cell foam projectile to the acceleration.

Introduction

Lightweight materials, which have an attractive combination of physical and mechanical properties, such as low density and high specific stiffness in relation to their weight, are extremely important for many branches of modern industry. Metallic cellular materials fall into this category and are particularly suitable for use in impact energy absorbers, which are subjected to high strain rate deformations. Since there are only few research results available in this regards, it is particularly important to further study the influence of strain rate on the deformation behavior of metallic cellular materials [4].

Strain rate effects on the behavior of cellular materials under compression have been studied by Rinde and Hoge [11], which analyzed the compressive stiffness of Styrofoam (polystyrene) at room temperature as a function of strain rate. They report that the stiffness of the polystyrene only slightly increases with increased strain rate. Mukai et al. [9] compared the stiffness of the polystyrene and closed-cell aluminum foam (ALPORAS) with the same relative density ρ_r (ratio between the density of cellular material and ρ^* and the density of the base material ρ_s). They proved that increased strain rate influence on the plateau stresses of the aluminum foam is much higher than for the polystyrene. The strain rate dependence (up to 1000 s^{-1}) of material properties of open cell magnesium foams (AZ91) under compressive loading conditions were examined by Mukai et al. [10]. Their results show, that the amount of absorbed mechanical work heavily depends on the applied strain rate, since the energy absorption at a strain rate of 1400 s^{-1} is approximately 100 % higher than the at the quasi-static loading conditions. Christ et al. [3] examined the mechanical properties of closed-cell cellular materials subjected to compressive loading (up to the strain of 80 %) under different strain rates, ranging from $2 \cdot 10^{-4}$ s^{-1} to 2 s^{-1}. The authors concluded that with increased strain rate closed-cell materials lose their characteristic deformation behavior under compressive loading conditions (stress-strain diagram), because increased strain rates also increase the material stiffness. The result of increased stiffness is also the increase of the absorbed mechanical work.

The properties of cellular materials strongly depend on their structure [6, 14], and using only experimental methods to study and understand the behavior of cellular material under deformation is not enough. The structure of open-cell materials is highly irregular, limiting the reproducibility of experimental tests. In addition, the measurements of certain physical properties of cellular materials during experimental tests are very difficult or even impossible. Computer simulations based on the finite element method represent a viable alternative to advance the studies and with that the understanding of cellular materials behavior under impact loading.

Existing constitutive models of cellular materials, which are included in some engineering computer simulation software systems, do not take into account the effects of geometric irregularity and different strain rates under dynamic loading on simulating the macroscopic behaviour of cellular materials. This prompted development of new lattice computational model of irregular open-cell material [2], which is able to account for the effects of structural irregularity and effects of different strain rates on the properties of open-cell materials under large deformations.

The model was validated using experimental quasi-static and dynamic uniaxial compressive experiments of aluminum open-cell foams up to the strain rate of 7 s^{-1} [2]. The Taylor impact tests were carried out to validate the model at higher strain rates and parametric dynamic computer simulations were carried out to better understand this phenomenon.

Experimental Setup

The Taylor impact test was used to study the behavior of open-cell aluminum foam projectile at high strain rates. During the test a specimen of known dimensions is accelerated to the desired velocity and then impacted into a rigid wall. Dynamic properties of the used material can be determined upon plastic deformations of the specimen after the impact in the rigid wall and using the theory proposed by Taylor [8].

Taylor impact test was carried out using a device shown in Fig. 1, which consists of a 3 m long barrel, a combustion chamber and a target chamber. A diaphragm is positioned between the combustion chamber and the barrel. The diaphragm keeps the combustion gases in the chamber until it ruptures at a specified pressure. A steel plate with a diameter of 90 mm and a thickness of 2.5 mm was used as a diaphragm in the presented experiments. Both sides of the target chamber have a transparent window region, which allows for optical observations of the experiments. A vacuum pump is attached to the target chamber to remove the air from the target chamber and the barrel, minimizing the air influence on the movement of the projectile and at the same time acoustically isolates the chamber [12].

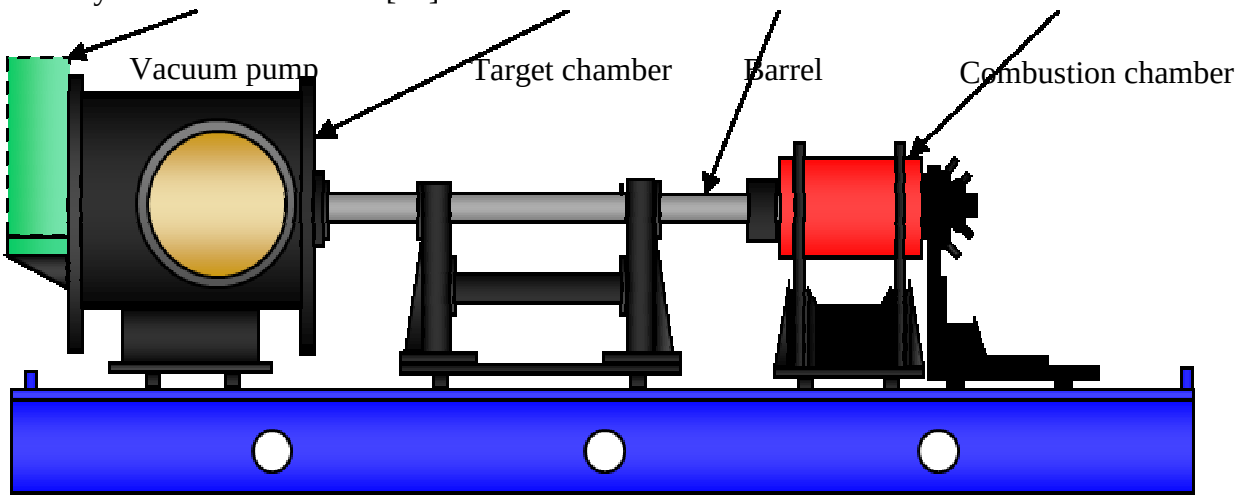

Figure 1: The Taylor impact test device

The projectiles were made from the open-cell aluminum foam produced by m-pore GmbH [7] with a relative density of 6.1 % and a cell size of 20 ppi (mean cell diameter equals 3.8 mm). Pure aluminum EN AW-1070 was used as the base material of the foam. The projectiles were shaped in a cylindrical form with a diameter of 35 mm and height of 35 mm (Fig. 2). The complete Taylor impact test projectiles comprised also a copper plate, with a thickness of 5 mm, which was inserted

into a plastic sabot (Fig. 3). The projectile was placed in the barrel in such way that it was in contact with the diaphragm.

The Taylor impact tests were carried out using nitrocellulose based explosive. The appropriate mass of the explosive 8 grams was determined with preliminary testing. A small amount of the black powder (2 grams) was used for the ignition, which was activated by an electric spark. This combination of explosives accelerated the projectile through the 3 m long barrel to the final muzzle velocity of 400 m/s. A high speed camera Hyper Vision HPV was used for optical observations of projectiles impact into a rigid wall in the target chamber. The recording frame rate of the camera was $1 \cdot 10^6$ FPS with a resolution of 312 x 260 pixels. A pressure generated by the impacting projectile into a rigid wall was measured with piezofilm sensor PVF2.

Figure 2: Cylindrical foam sample (d = 35 mm; h = 35 mm)

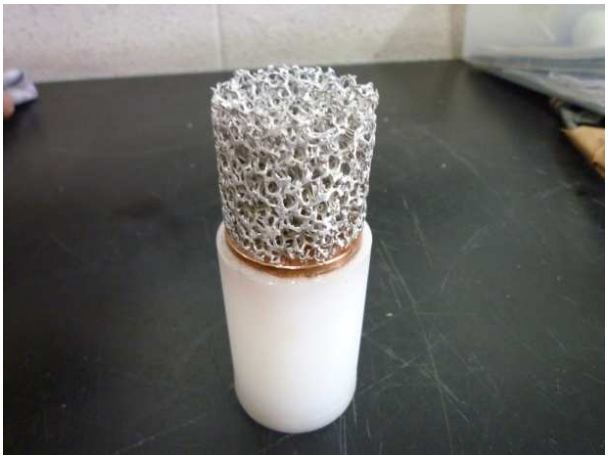

Figure 3: Sample attached to the copper plate and the sabot

Experimental Results

Optical recording of projectile behavior before and upon impact into a rigid wall was used to analyze the deformation behavior of open-cell aluminum foam sample (Fig. 4). Because of the high impact velocity the inertia effects dominate the deformation behavior and the open-cell material deforms only in contact with the rigid wall. These experimental results confirm the predictions based on previous computer simulations of open-cell material behavior under compressive loading conditions [2].

A more in depth analysis of the samples geometry before the impact in the rigid wall (top left in Fig. 4) showed, that open-cell foam deforms already while accelerating through the barrel. This deformation was estimated to be approximately 11.4 %. The reason for this deformation is a very high acceleration, which acts on the specimen immediately after the pressure of combustion gases causes the rupture of the diaphragm. This deformation was even higher during experiments where larger quantities of explosives were used.

Computer Simulations

To analyze the effect of acceleration on the open-cell foam deformation behavior, parametric computer simulations of accelerated irregular open-cell foam were carried out. The purpose of performed computer simulations was primarily to obtain an insight into the events occurring during a Taylor impact test and not a to qualitatively evaluate the simulation results, since the used model of the open-cell foam has not yet been validated at such high strain rates, which occurred during this test.

In general, the time dependence of the acceleration during a Taylor impact test is highly non-linear where the maximum acceleration occurs immediately after the collapse of the diaphragm. Since the time dependence of the acceleration was not measured, a ramp function was used for the accelerations in performed computer simulations. The effect on the acceleration on the deformation of the open-cell foam in computer simulations was studied by parametric simulations varying the value of the acceleration. Computer simulations were done by means of a finite element method using the LS-DYNA software.

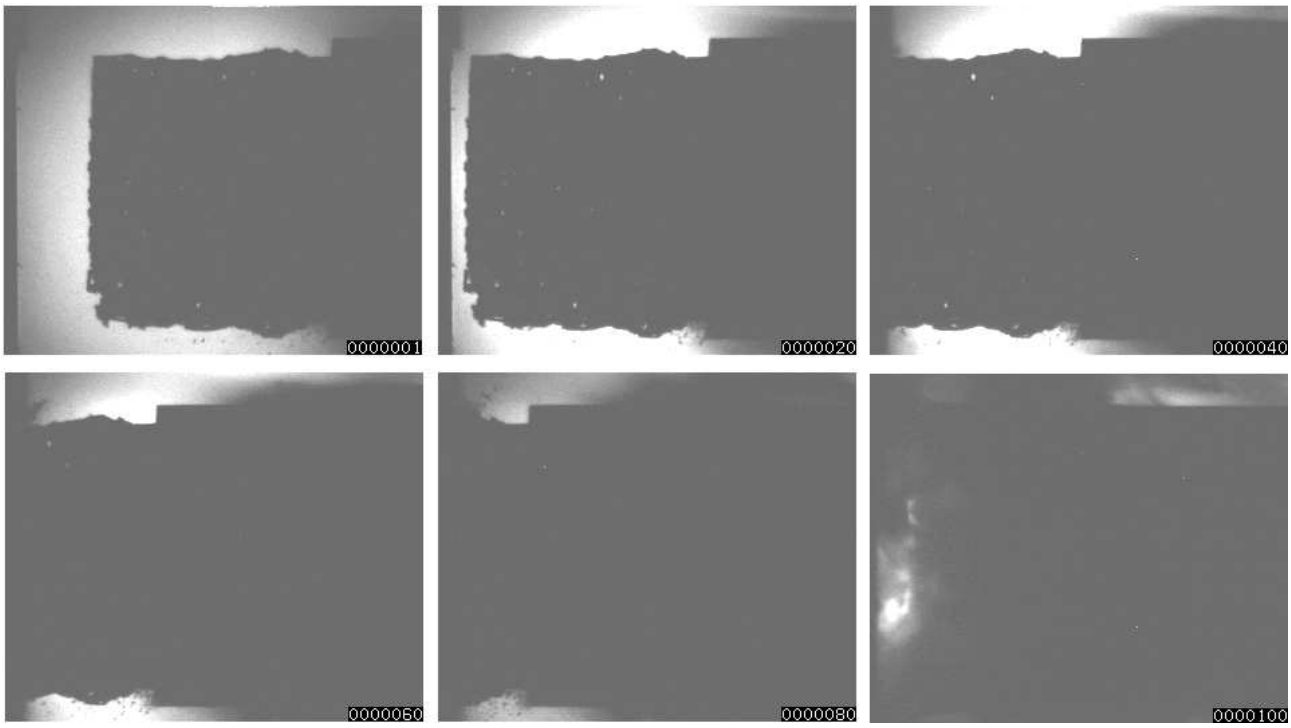

Figure 4: Impact sequence of the open-cell foam projectile into the rigid wall

Numerical model of irregular open-cell material. The open-cell aluminum foam projectiles were modeled by using newly developed lattice type model of irregular open-cell material, based on the equilibrium liquid foam model with Weaire-Phelan cells. Irregularity was introduced into the model with a controlled displacements of Voronoi seed points of the equilibrium model [2], according to the following equation:

$$x_k = x_k^i + a \cdot d_c \cdot \phi_k \,. \qquad (1)$$

x_k^i (k ∈ [x, y, z]) are the spatial coordinates of the seed point in the equilibrium model, d_c is the representative cell size, ϕ_k (∈ [-1, 1]) is a random variable with uniform distribution and *a* (∈ [0, 1]) is the amplitude, which determines the level of irregularity - irregularity parameter.

Voronoi lattice models contain the information about the positions of mesh vertices and their topology, which represents the cell edges of the generated models. Based on the information

contained in the lattice model a numerical model of irregular open-cell material is built, where each cell edge of the Voronoi modeled is replaced with three to five beam finite elements of the Hughes-Liu type. The number of finite elements is determined from the cell edge length. In order to transfer the loads in all six degrees of freedom through the finite element mesh, the nodes of all finite elements sharing the same cell edge joint were merged into a single node [13].

The shape of the cross-section of the beam finite elements was circular and constant along their length. The radius of the cross-section r_b was calculated from the foam relative density ρ_r, from the volume of the whole model V and from the total length of all beam finite elements l_{tot} using the Equation 2.

$$r_b = \sqrt{\frac{[(\rho]_r \cdot V)}{[(l]_{tot} \cdot \pi)}}. \qquad (2)$$

The outer form of the numerical model was cylindrical with a diameter of 35 mm and a height of 35 mm.

Instead of the material properties of the aluminum EN AW-1070 (99.7% purity), which was used in the production of the foam samples, the material properties of the aluminum EN AW-1050 (99.5% purity) were used. The reason is that the aluminum EN AW-1050 in much more common in the industry and hence more accurate data of its dynamic mechanical properties is available and at the same time its mechanical properties are practically the same as those of the aluminum EN AW-1070 [5].

The base material in the developed foam model was modeled using a constitutive model developed by Cowper-Symonds with a bilinear elasto-plastic characteristic based on measurements made by Berski et al. [1]. Young's modulus of elasticity was E = 70 GPa, yield strength σ_y = 59 MPa and tangent modulus E_t = 84 MPa, while the Cowper-Symods coefficients were equal to C = 6500 s^{-1} and p = 4. The density of the aluminum was estimated as ρ_{al} = 2700 kg/m^3.

Boundary conditions. Numerical model of the irregular open-cell foam was placed on a rigid support plate, modeled by shell finite elements. This plate had a similar role as the copper plate during the experiment, namely to transfer the loads of the combustion gases to the foam. These loads were transferred through a contact, which was defined between the plate and the foam model. Since the contact between cell edges of the open-cell material is essential mechanism of load transmission by larger deformations of the material, another contact definition was used for the contact between the beam finite elements of the foam model. The load was prescribed as an acceleration of the support plate, acting normal to the plane of the plate in the direction of the foam model. Eleven different accelerations between $1 \cdot 10^5$ and $9 \cdot 10^5$ m/s^2 were used for the conducted parametric study. Twenty simulations with differently generated models of irregular open-cell foams were carried out for each of the selected accelerations, in order to exclude from the results the impact of randomness, which was used in the preparation of the geometry (Equation 1).

The engineering deformation was calculated as $\varepsilon_e = \frac{\Delta h}{h_0}$, where Δh represents the change in the height of the specimen, and h_0 represents the initial specimen height. The change of the specimen height was calculated from the difference between the position of the support plate and the average displacement of all nodes on that surface of the foam model, which is opposite from the support plate.

Computational Results

Deformation behavior of one open-cell foam model, accelerated with an acceleration of $3 \cdot 10^5$ m/s^2 is shown in Fig. 5. For easier comparison between the different deformation stages, the images were rotated in such way, that the support plate is always above the foam model (the

direction of the motion is therefore downward). It is seen from the figure that the deformation of the open-cell foam occurs only at the contact with the support plate. This is due to the distribution of inertia force within the material, which increases linearly in the direction towards the plate. This means that on the layer closest to the support plate acts the inertia force of the whole foam mass, while on the cell layer in the middle of the foam only the inertia force of the half of the foam mass act. As the maximum load in the foam occurs right at the support plate, this is also the place where the largest deformations occur and where the foam failure starts.

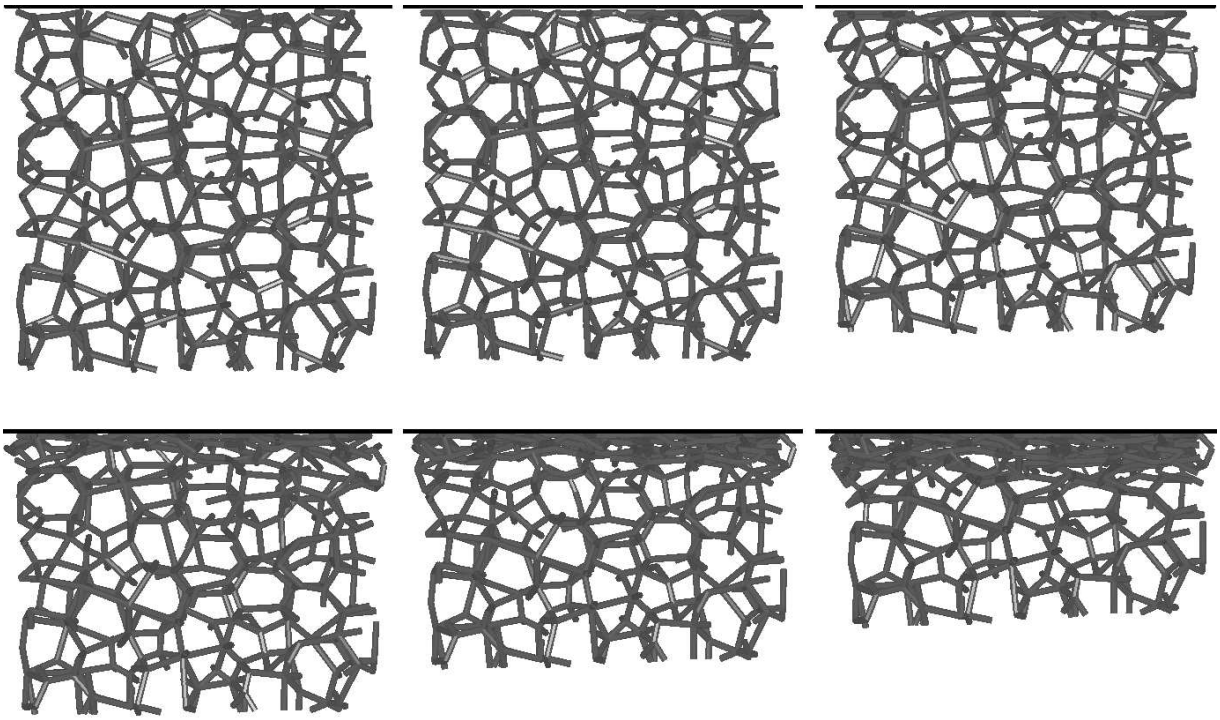

Figure 5: Deformation behavior of the open-cell foam at an acceleration of $3 \cdot 10^5$ m/s^2

The engineering strain of the open-cell foam was first computed for each of the twenty computer simulations with the same acceleration individually and then the average strain values were calculated. The time and acceleration dependence of the average engineering strain is shown in Fig. 6. The calculated dependence shows that the average strains increase with time up to the point, where the system reaches a dynamic equilibrium. At the state of equilibrium the average strains range from 1.7 % at the minimum acceleration up to 85.3 % at the maximum acceleration. Interpolation of the results shows that the acceleration of $1.52 \cdot 10^5$ m/s^2 is needed in order for the foam model to reach the deformation of 11.4 %, which is the deformation that was measured during the experimental Taylor impact test.

Analysis of the acceleration effects on the average strain of the open-cell foam shows significant differences between the strains at the accelerations between $1.0 \cdot 10^5$ and $3.0 \cdot 10^5$ m/s^2, while by higher accelerations the differences in strain become much smaller. The cause for these large differences is the behavior of the open-cell foam under compressive loading conditions. Namely, open-cell materials reach a plateau stress region after the initial elastic and transition region [2]. In this stress region a small increase in load, in this case the acceleration, greatly increases the strain of the open-cell material. Further increase of the load causes the open-cell material to transition from the plateau region to the region of increased stiffness, where the voids in the cells of the material are filled up and contacts between cell edges occur. The results are smaller differences between the deformations at higher accelerations.

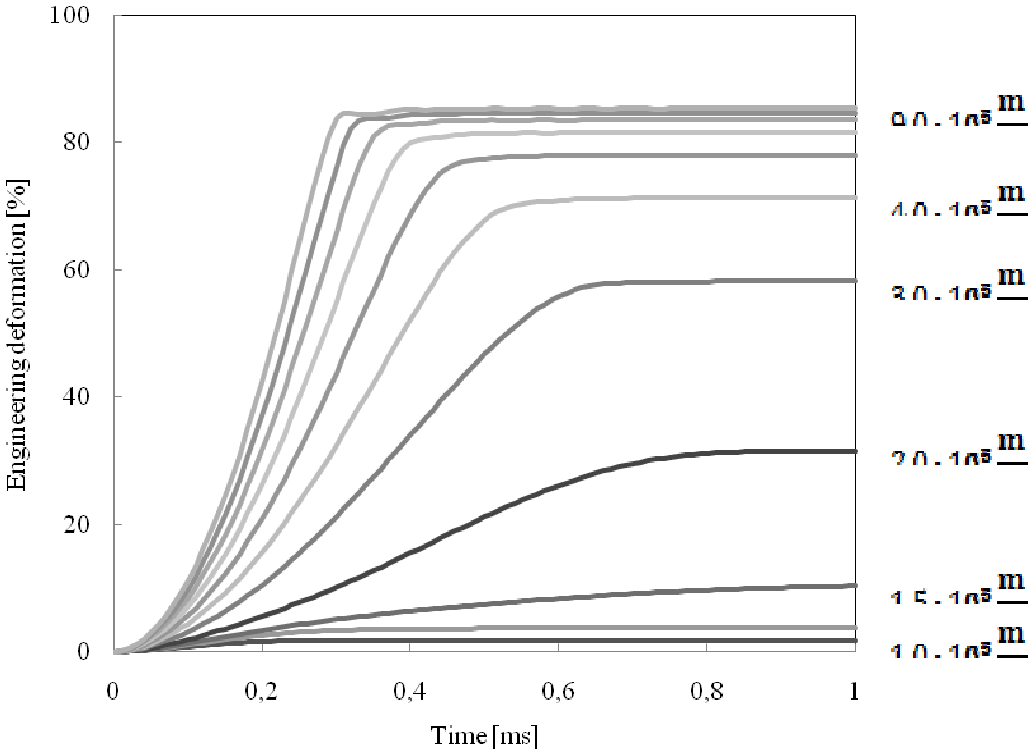

Figure 6: The effect of the acceleration on the foam deformation

Summary

Performed Taylor impact tests showed that the open-cell foam projectile deforms even before the impact in a rigid wall. These deformations are the result of high accelerations, which act on the projectile during the test. Computer simulations of the open-cell foam behavior under different accelerations show that the acceleration of approximately $1.52 \cdot 10^5$ m/s^2 is needed to deform the open-cell foam to the same engineering deformation as was measured during the experiment. The simulations also confirmed the assumption that the material collapse only in the vicinity of the rigid plate is the result of the uneven distribution of the mass inertia force. A high sensitivity of the strain of open-cell material from the accelerations in the area of plateau stresses was also confirmed. Future Taylor impact tests, where the accelerations of the projectile during the tests will be measured, will enable a more detailed analysis of the foam behavior during a Taylor impact test and allow a validation of the developed open-cell material models at high strain rates.

References

[1] S. Berski, H. Dyja, A. Maranda, J. Nowaczewski, G. Banaszek, *Analysis of quality of bimetallic rod after extrusion process*, Journal of Materials Processing Technology 177, 582 - 586, 2006.

[2] M. Borovinšek, *Računalniško modeliranje celičnih gradiv neurejene strukture*, Univerza v Mariboru, Fakulteta za strojništvo, 2009.

[3] H. J. Christ, U. Krupp, A. Ohrndorf, P. Schmidt. *Mechanische Untersuchungen eines geschlossenporigen Aluminiumschaums*, Proceedings zur Werkstoffprüfung, Bad Nauheim, Germany, 7. - 8. 12. 2000.

[4] L. J. Gibson, M. F. Ashby, *Cellular solids: structure and properties - 2nd edition*, Cambridge, Cambridge University Press, 1997.

[5] G. J. Kaufman, E. L. Rooy, *Aluminum alloy castings properties, processes and applications*, Cleveland, Ohio, ASM International, 2004.

[6] K. Li, X. L. Gao, G. Subhash, *Effects of cell shape and strut cross-sectional area variations on the elastic properties of three-dimensional open-cell foams*, Journal of the Mechanics and Physics of Solids 54, 783-806, 2006.

[7] *m-pore*. http://www.m-pore.de/index.html, 2009.

[8] M. Mahnič, *Optimiranje parametrov za razvojno napovedovanje zdržljivosti pri povišanih hitrostih*, Univezra v Ljubljani, Fakulteta za strojništvo, 2007.

[9] T. Mukai, H. Kanahashi, T. Miyoshi, M. Mabuchi, T. G. Nieh, K. Higashi, *Experimental study of energy absorption in a close-celled aluminum foam under dynamic loading*, Scripta Materialia 40, 921-927, 1999.

[10] T. Mukai, H. Kanahashi, Y. Yamada, K. Shimojima, M. Mabuchi, T. G. Nieh, K. Higashi, *Dynamic compressive behavior of an ultra-lightweight magnesium foam*, Scripta Materialia 41, 365-371, 1999.

[11] J. A. Rinde, K. G. Hoge, *Time and temperature dependence of the mechanical properties of polystyrene bead foam*, Journal of Applied Polymer Science 15, 1377-1395, 1971.

[12] Seiichi, G. Kennedy, Z. Ren, S. Itoh. *The Dynamic Property of Aluminium Foam*, Multiphysics, Lille, France, 9. - 11. 12. 2009.

[13] M. W. D. Van der Burg, V. Shulmeister, E. Van der Geissen, R. Marissen, *On the linear elastic properties of regular and random open-cell foam models*, Journal of Cellular Plastics 33, 31-54, 1997.

[14] H. X. Zhu, A. H. Windle, *Effects of cell irregularity on the high strain compression of open-cell foams*, Acta Materialia 50, 1041-1052, 2002.