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The Effect of Impact Energy Parameters on the Closed-Cell Aluminum Foam Crushing Behavior Using X-Ray Tomography Method

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ABSTRACT: The present study is devoted to the numerical and experimental investigation of the influence of dominant impact parameters, including inertia and impact velocity, on the closed-cell aluminum foam behavior. In order to access 3D modeling of the internal microstructure of the foam samples, a new technique based on computerized tomography (CT) of 2D images is utilized. The influence of the abovementioned influential parameters is studied for three different foam densities. In order to validate finite element results, low-velocity impact tests were conducted. The results demonstrate that for a constant level of impactor energy, two primary impact quantities of interest, i.e. maximum stress and energy absorption, are highly dependent on the values of impactor momentum. In contrast, increasing the value of impactor inertia results in negligible variations of energy absorption for different foam densities. Similarly, increasing inertia at a constant foam density shows no significant variation in peak stress and a slight change in energy absorption. On the other hand, the velocity of impactor at a constant level of impactor energy plays a crucial role such that for all three different foam sample densities, the case of higher impactor velocity causes greater values of peak stress as well as energy absorption.

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1- Introduction

Metal foams are cellular material consisting of solid metal with pores comprising a large portion of the volume. The subject of metal foams receives increasingly more attention from investigators. Due to their remarkable mechanical, thermal and insulation properties, metallic foams are widely used in various engineering and industrial fields, such as bumpers, body implants and sandwich structure cores. Metal foams are generally composed of aluminum. However, other metal foams are possible, as well. Foam materials are typically produced by trapping gas bubbles in a liquid or solid [1-9]. Foams are generally divided into two categories of closed-cell and open-cell. Energy absorption property of closed-cell metallic foams due to the vast plastic deformation in the walls of failed cells, is one of the several properties, which has created numerous applications for its useful structure. The aforementioned feature makes closed-cell aluminum foams used in many applications such as automobiles, trains, airplanes and other vehicles [10-14]. Experimental test are required so as to assess physical features of metallic foam samples. Possible human errors on the one hand and the high cost of such tests on the other hand, however, restrict experimental methods and suggest adopting an alternative approach. Open literature indicates that appropriate numerical schemes are the viable alternative to experimental methods. Rajendran et al. [15] carried out numerical simulation of the closed-cell aluminum foams under axial impact due to free fall of a drop hammer. In order to derive the material properties, quasi-static axial crushing tests were carried out on foams of three different densities. Parametric study was performed on the foams of various densities for different impact velocities. They showed that elastic fraction of the foam deformation energy becomes insignificant as the impact velocity of the hammer increases. Song et al. [16] studied the dynamic crushing responses of three-dimensional cellular foams using the Voronoi tessellation technique. They investigated the effects of the cell shape irregularity, impact loading, relative density and strain hardening on the deformation mode and the plateau stress. They found out that the plateau stress, the densification strain energy and the capacity of foam absorbing energy can be improved by increasing the degree of cell shape irregularity. Liu et al. [17] studied the effect of strain rate and porosity on the dynamic behavior of aluminum foam. They showed that the effect of air pressure on static stress and strain rate is negligible. The effect of the strength of the cell wall and the amount of porosity are effective in the value of energy absorption. Fang et al. [18] numerically investigated the foregoing effects. The proposed model is capable of considering various thicknesses for the walls of a cell. Li et al. [19] investigated one-degree freedom model of impact in order to estimate the amount of the energy absorption of the metallic foams. They stated that the foam behavior in dynamic loading is similar to quasi-static loading provided that the velocity of impactor is lower than the critical velocity. Nayyeri et al. [20] studied compressive behavior of tailor-made metallic foams under quasi-static compressive loading by considering a representative unit cell. Their analysis revealed that the ratio of the wall thickness to the size of cell has the most significant influence on the compressive behavior of tailor-made metallic foams and there was an adequate agreement between the simulation data and the experimental measurements. Wang et al. [21] studied the effects of strain rate and inertia on the deformation behavior of closed-cell aluminum foam under an impact loading. They

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revealed that aluminum foam is sensitive to the strain rate and the effect of axial inertia at high velocities is higher than the effect of strain rate. Birla et al. [22] studied the effect of cenosphere size and relative density on the compressive deformation behavior of hybrid foams. The plastic collapse stress, plateau stress, and energy absorption of hybrid foams increased with the decrease in cenosphere size and increase in relative density. Li et al. [23] performed a numerical study on deformation mode and strength enhancement of metal foam under dynamic loading. In order to obtain reasonable results, a 3D Voronoi model with a uniform cell wall thickness was used. They investigated the effects of strain rate of cell wall material and relative densities of the metal foam on the deformation modes. They found out that under impact condition, the metal foams with a low density exhibit low critical velocities. Their findings show that the strength enhancement is deformation-mode dependent.

In the 3D modeling of the internal structure of the different materials, computerized tomography is an important and useful technique. In this method, the material is scanned as a number of 2D images, and then material microstructure can be extracted. Due to the increasing quality of X-ray imaging and development in the processing of images, the applications of images obtained by CT scan have been expanding during recent years. In view of the quality and high precision of the method, some researchers have used this method [24-32]. Kader et al. [33] studied experimental and numerical simulations of pore collapse mechanisms of closed-cell aluminum foams under quasi-static compression. They used X-ray computed tomography method to generate the 3D structure of the foam. Their study showed that numerical results were in good agreement with the experimental test data. The simulations revealed that deformation evolution of cell-walls during compression is extremely complicated. They also observed that the micro-pores and cracks present within the cell-walls contribute to their deformation. Miedzinska et al. [34] studied the microstructural properties of closed-cell aluminum foams experimentally and numerically. The results of this work showed that by increasing the number of holes per inch, energy absorption increases. Petit et al. [35] characterized aluminum foam microstructure by combining X-ray tomography at different resolutions, image processing, and FE modeling approach. The images obtained from local tomography were processed to create one low-resolution image of the initial sample, including the details of the high resolution. This image was used to generate an FE mesh. This study showed that the presence of inclusions can explain the fracture of structures. Saadatfar et al. [36] carried out the experimental and numerical study on closed-cell aluminum foam subjected to uniaxial compression. X-ray computed tomography was used to access the three-dimensional foam structure. The results showed that strain hardening occurs predominantly in regions with large cells and high anisotropy. Sun et al. [37] investigated the strain-rate effect on the compressive behavior of closed-cell aluminum foam of the type Alporas. In order to access three-dimensional finite element foam model, a computed tomography method was employed. They showed that the numerical prediction of the rate dependence of the compressive strength was in a good agreement with the reported test data. The simulations also showed that the rate dependence of the cell-wall material dominates the macro strain-rate effect on the compressive strength measured at the supporting end, whereas micro inertia had a negligible contribution to Alporas foam. Kadkhodapour and Raeisi simulated the behavior of the closed-cell aluminum foam in micro and macro size. They studied the effect of the relative density on the mechanical features. They compared the achieved results to those of the experimental tests and analytical relations. In the second phase, they simulated foam cellular structure by combination of different kinds of unit cells with different sizes at constant relative density. The results showed that the cell geometry affects the cell's macroscopic behavior which relates to the deformation and local failure in the cells [38]. Low-velocity impact test is also used in other cases to study the behavior of structures such as metal tubes [39-41].

In previous studies, micro CT imaging technique was used to access the microstructure of the foam samples. Micro CT imaging method considers more details compared to simulation requirements, and to cover the details, so smaller mesh size is required which leads to a very high solving time. It will be then very difficult to use more cells for the numerical analysis. Moreover, there is also no straightforward access to the Micro CT device. The technique used in this study needs a common CT scan device used in medical science. This method is more optimal and has a better accuracy and lower solution time, as well as better convergence. In the present work, the influence of energy parameters, including impactor velocity and inertia on the crushing behavior of closed-cell aluminum foams of Alporas type under impact loading is studied. The impact load is of the low-velocity type created by drop test setup. The foam behavior was investigated based on both experimental and numerical analysis and the results are compared with each other. CT scan method is employed to 3D-model foam structures. Impact energy parameters are studied for three different densities of the foam samples.

2- Material and Methods

2- 1- Foam sample fabrication

In order to fabricate the required test samples, the aluminum foam of the type Alporas [42-44] was produced. Aluminum foam is made from molten aluminum by stabilizing bubbles in the melt which consists of several steps, namely thickening, foaming and cooling. Initially aluminum is molten and then the blowing agent (TiH_2 powder) is added. After stirring, the molten material expands and fills up the mold. In the last step, the material is cooled by the use of blower and water. The foam density in different heights in foaming direction was different. Thus, in order to analyze the effect of density parameter on the foam behavior under impact loading, the foam block was divided into three groups of low density, moderate density, and high density. Foam sample fabrication and cutting process are depicted in Figure 1. Samples with approximate dimensions of 40 * 40 * 40 mm^3 were produced. The exact dimensions and density of all samples are shown in Table 1. The closed-cell aluminum foam is made up of aluminum 1100 and has a brittle structure. The average cell size is about 5 mm.

2- 2- Low-velocity impact test

The falling weight impact test is one of the methods used to assess the impact properties of the materials. The foam sample used for the test was placed on a flat fixed plate and impacted centrally by a vertically falling weight. The drop

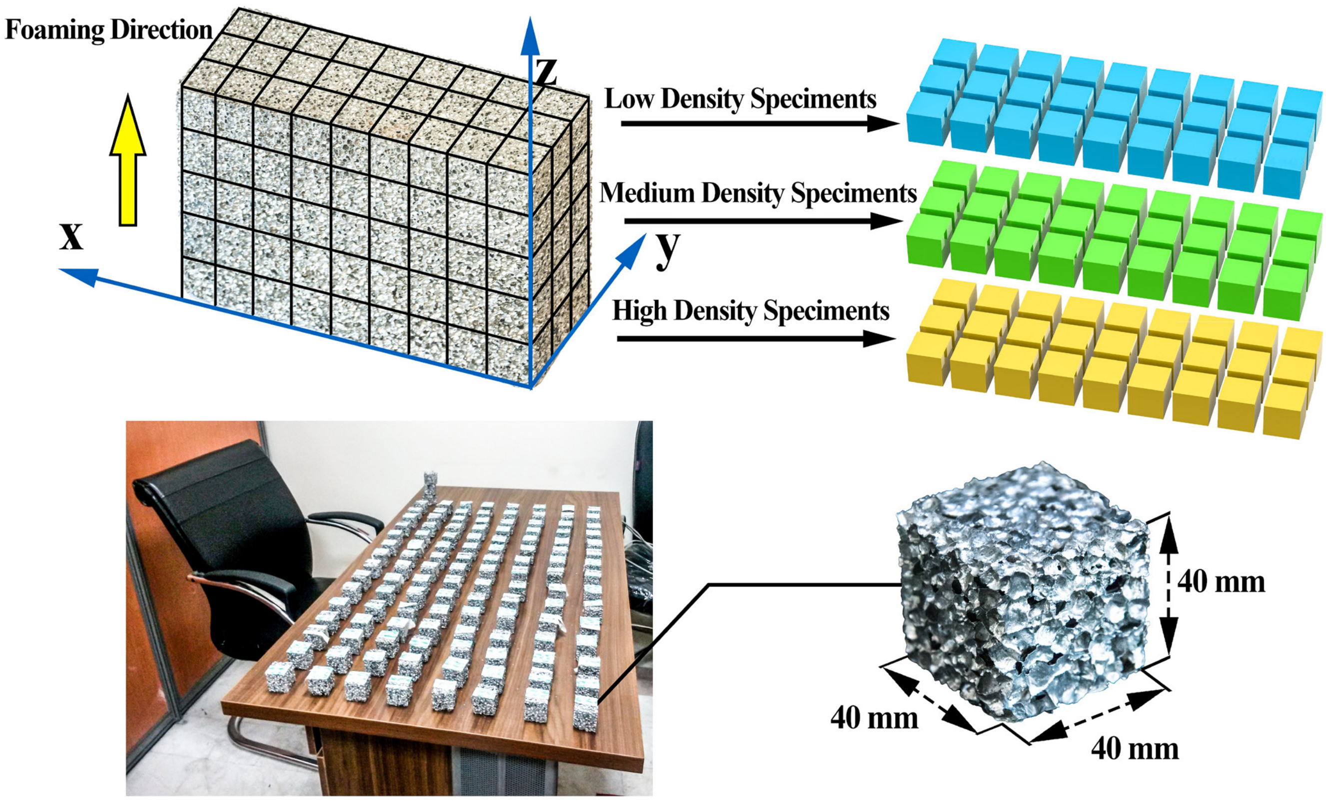

Fig. 1. Closed cell aluminum foam samples fabrication steps

Table 1. Experimental test foam samples specifications

ID	Mass, gr	Length, mm	Width, mm	Height, mm	Initial Velocity, m/s	Foam density, kg/m3
A1	13.5	39.19	38.97	39.48	3.7	224
A2	19.4	38.91	38.75	40.33	3.7	319
A3	33.3	38.76	38.48	40.11	3.7	557
B1	12.2	38.56	38.01	38.65	-	215
B2	19.4	38.88	38.72	39.5	-	326
B3	32.2	38.57	38.37	41.61	-	523

test device mainly consists of the main body, adjustable impactor, extra weights, acceleration sensor and data acquisition system. After locating the sample and loading the weights depending on the impact energy, the height of the impactor can be adjusted. By releasing the impactor, the data acquisition system saves the acceleration sensor data. Figure 2 shows the drop weight impact test setup.

2- 3- Numerical modeling

For finite element analysis of the impact test, 3D model of the foam structure has been developed. First, 2D images of all foam samples were taken layer by layer using multi-slice CT scan device. The CT scan device takes an image every 0.1 mm in each three main directions (*x,y,z*). Thus, for each sample, about 1200 images are extracted which are observed in Fig. 3 (b). Then CT images imported into Mimics software. Using CT images, 3D model of close-cell aluminum foam was constructed (Fig. 3(c)) and the foam volume was meshed. The steps of this procedure are depicted in Fig. 3. Then, 3D finite element model of the foam was imported into commercial LS-DYNA software. In order to analyze the nonlinear behavior of aluminum foams under intense dynamic loadings precisely, the PLASTIC KINEMATIC model, material type 3 in LS-DYNA, is employed to simulate the cell-walls, aluminum alloy. This model is suitable to model isotropic and kinematic hardening plasticity with the option including rate effects. Standard computational parameters are as follows: mass density ρ = 2700 kg/m^3, Young's modulus E = 70 GPa, Poisson's ratio ν = 0.3. On the other hand, PLASTIC KINEMATIC model also requires a yield stress as well as tangent modulus as input parameters. In this regard, a uni-axial tension static test was performed and the following numerical values of required parameters are extracted: yield stress SIGY = 150 MPa, tangent modulus ETAN = 1.724 GPa. In order to incorporate the strain rate sensitivity of the base material, the well-known Cowper–Symonds relation

$$\sigma_y = \sigma_0 \left[1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{P}} \right] \tag{1}$$

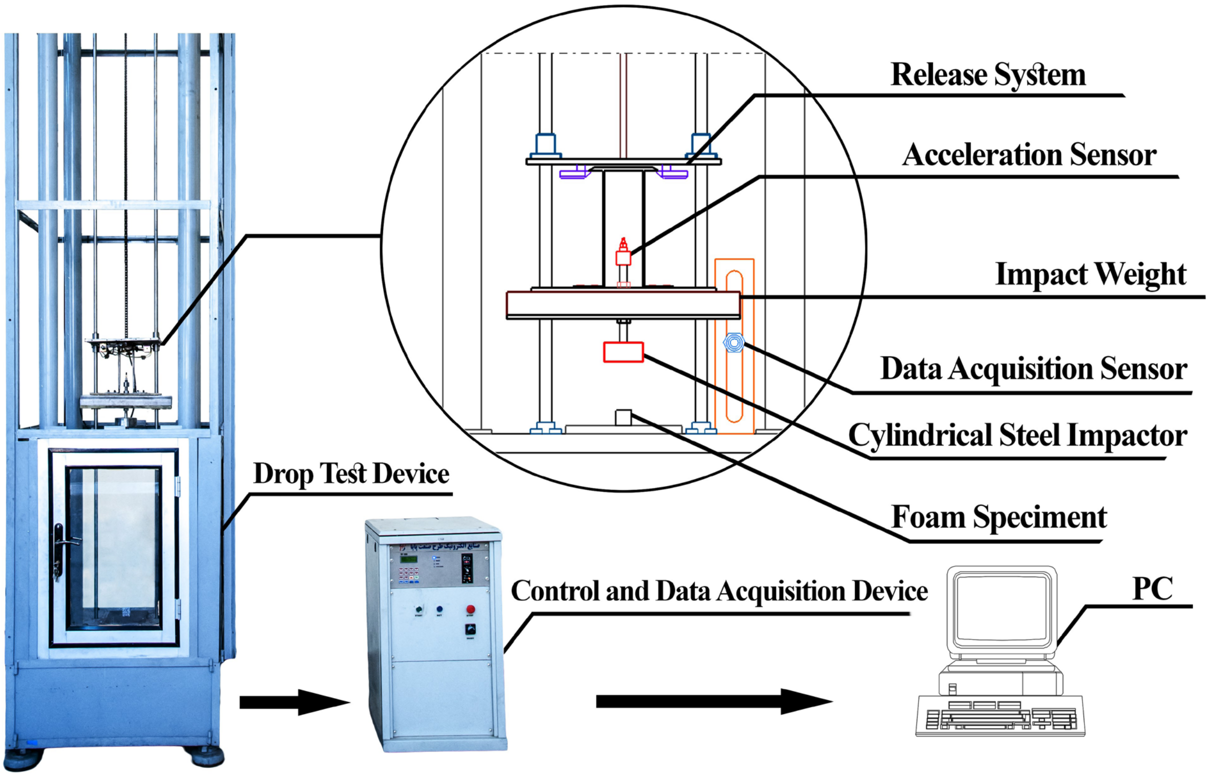

Fig. 2. Drop weight low-velocity impact test setup

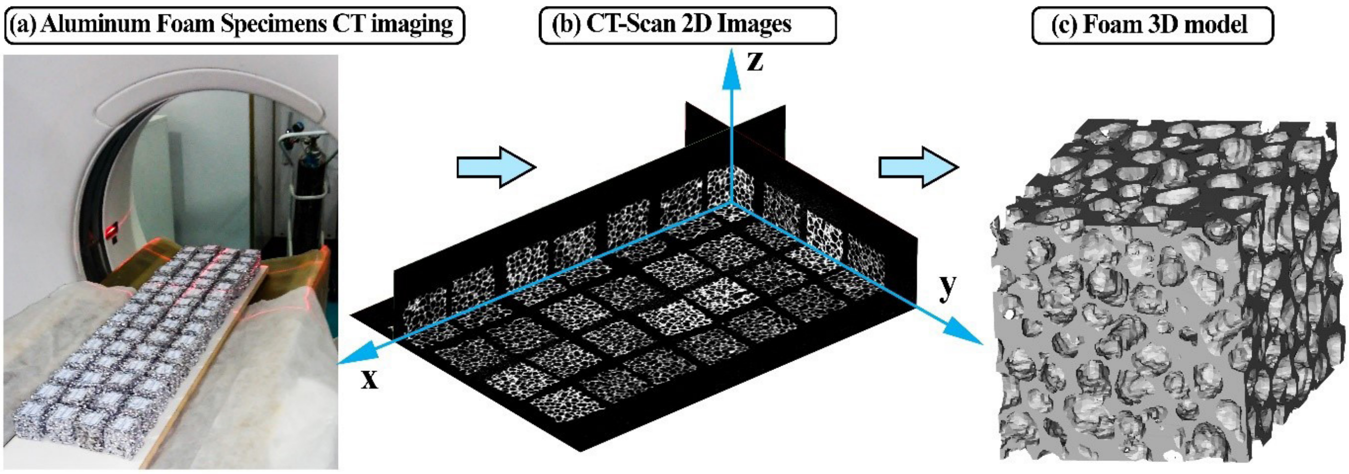

Fig. 3. 3D modeling of the closed-cell aluminum foam samples: (a) CT scan device and foam samples, (b) extracted CT scan 2D images of the foam samples, (c) 3D modeling of the foam sample from 2D images using Mimics software

is employed for the plastic deformation of the base material in the adopted 3D model in which C and P are the Cowper-Symonds coefficients, $\dot{\varepsilon}$ is the strain-rate, σ_y is the dynamic stress or strength and σ_0 is the quasi-static stress or strength. Aluminum alloys generally manifest weak rate dependency. The Cowper-Symonds parameters for aluminum alloys are considered to be $C = 6500$ and $P = 4$ [45]. The steel impactor and bottom plate are treated as a rigid body in the model. According material parameters are: mass den sity $\rho = 7800$ kg/m^3, Young's modulus $E = 200$ GPa, Poisson's ratio $\nu = 0.3$. Element type used for the foam was of the type solid 4-point tetrahedral and for the bottom plate and impactor the solid 8-point hexahedral elements were considered. To get closer to the real conditions of loading and boundary conditions in impact test, the foam sample was placed between a rigidly fixed plate and a cylindrical rigid impactor and the initial velocity was attributed based on the initial velocity of the impactor in drop test experiment, as shown in Fig. 4. The contact constraint was of the type automatic single surface for closed-cell foam sample and the contact between impactor and the fixed base with the foam was selected as automatic surface to surface.

3- Results and Discussion

Prior to the low-velocity impact test, in order to evaluate overall behavior and densification strain of the closed-cell

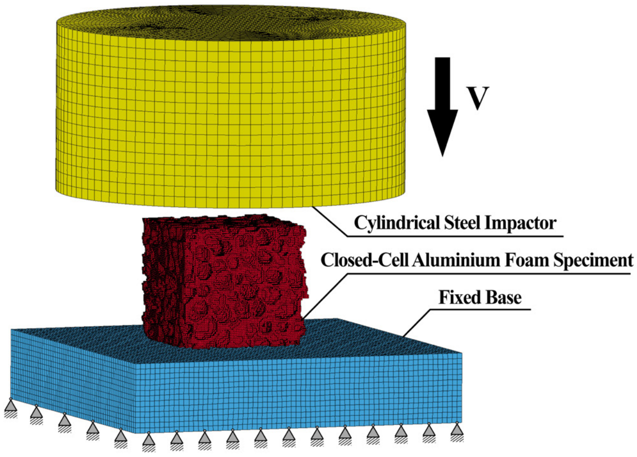

Fig. 4. Boundary conditions of finite element modeling of closed-cell aluminum foam

aluminum foam samples, three compressive quasi-static tests for three different foam densities were conducted (samples B1-B3). From the results of the static tests and the limitations of the low-velocity impact test device, the mass of 14 kg and impactor height of 70 cm (initial velocity of 3.7 m/s) were considered. Fig. 5 indicates how the low-velocity impact test is done numerically and experimentally. Figure 5 also shows the deformation and failure of the foam specimen for impact velocity of 3.7 m/s. There are two important points in how the foam sample is deformed. The first point is the cell failure start region, which for impact velocity of 3.7 m/s starts from top and bottom at the same time, and the rate of progression of cell failure is higher at the top of foam specimen, which is according to the cell failure pattern in the experimental test. The second point in the figure is how the cells break down and the dominant mode of the cell collapses. Due to the fact that the main material of the cells is pure aluminum, considering the percentage of elements found in the foam structure used in the experimental test, it has a brittle structure, and the dominant fashion in the collapse of cells is a brittle fracture. This is also evident in the oscillatory nature of the stress-strain graphs in the impact test. For the validation of the results obtained from numerical analysis, some experimental tests were conducted for three different foam densities at constant impact velocity (samples A1-A3). The results of the experimental impact tests are compared with the similar results from finite element analysis. Fig. 6 states that the curves obtained from the experimental tests were in a good agreement with the results of the finite element solutions. The amount of the energy absorption depends on the impactor energy and the density of the foam. Therefore, impact velocity, impact inertia and foam density are effective parameters in impact response which here the effect of each is analyzed. First, the effect of inertia on the impact response was studied. To this end, a constant velocity of the impactor (10 m/s) and four different impactor weights (14, 30, 60, 120 kg) for three different foam densities (0.2, 0.3, 0.5 gr/cm^3) were considered. Results of Figure 7 and Table 2 revealed that for a constant density, increasing impact inertia had no effect on the peak stress but slightly increased energy absorption. By increasing the impactor weight from 14 to 120 kg, the energy absorption increased 0.89%, 1.45% and 1.75% for foam densities of 0.2, 0.3 and 0.5 gr/cm^3, respectively.

At the next section, the impact response of the foam at constant energy will be studied. The aim of this analysis is to evaluate the effect of impact velocity and inertia as impact energy parameters on the impact response of aluminum foam behavior. The impactor kinetic energy right before the impact occurs is equal to 1/2 the product of the mass and the square of the speed. In order to evaluate the effect of mass and velocity on stress-strain impact curve, the mass of 15 kg

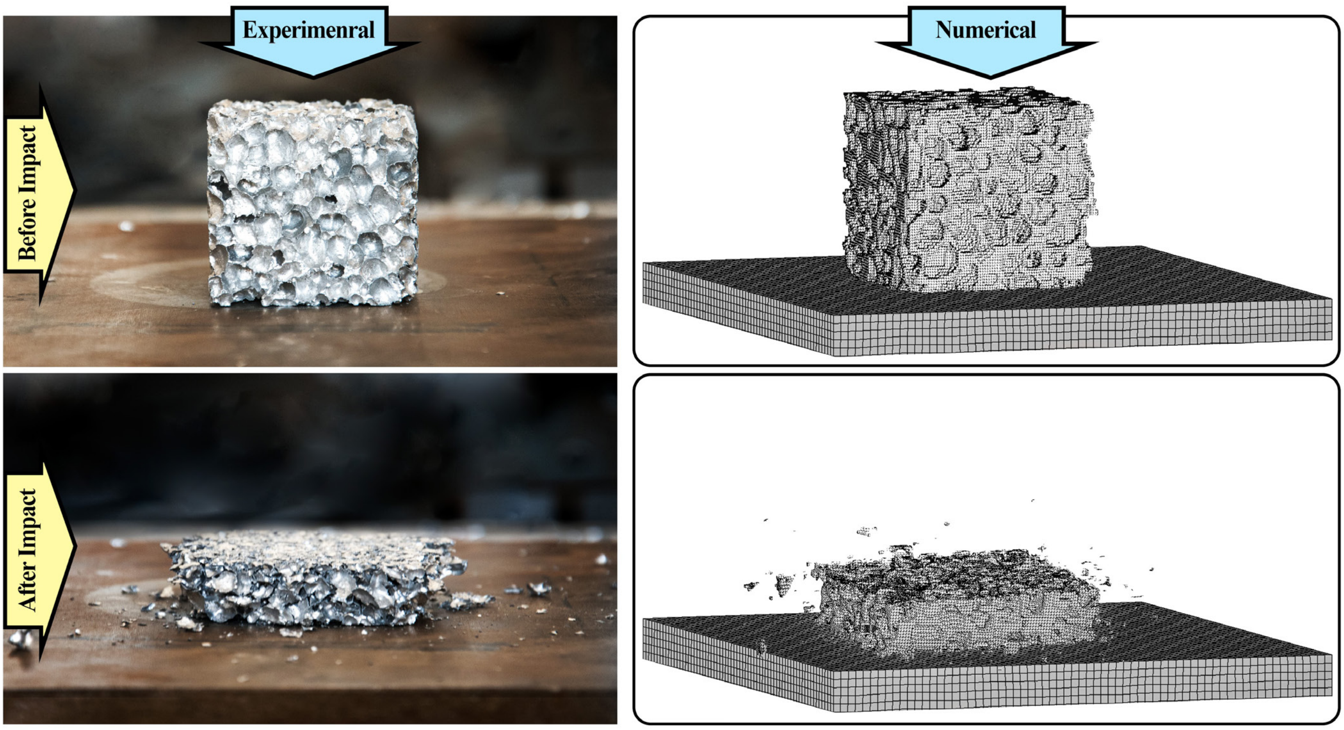

Fig. 5. Experimental and numerical modeling of low-velocity impact test

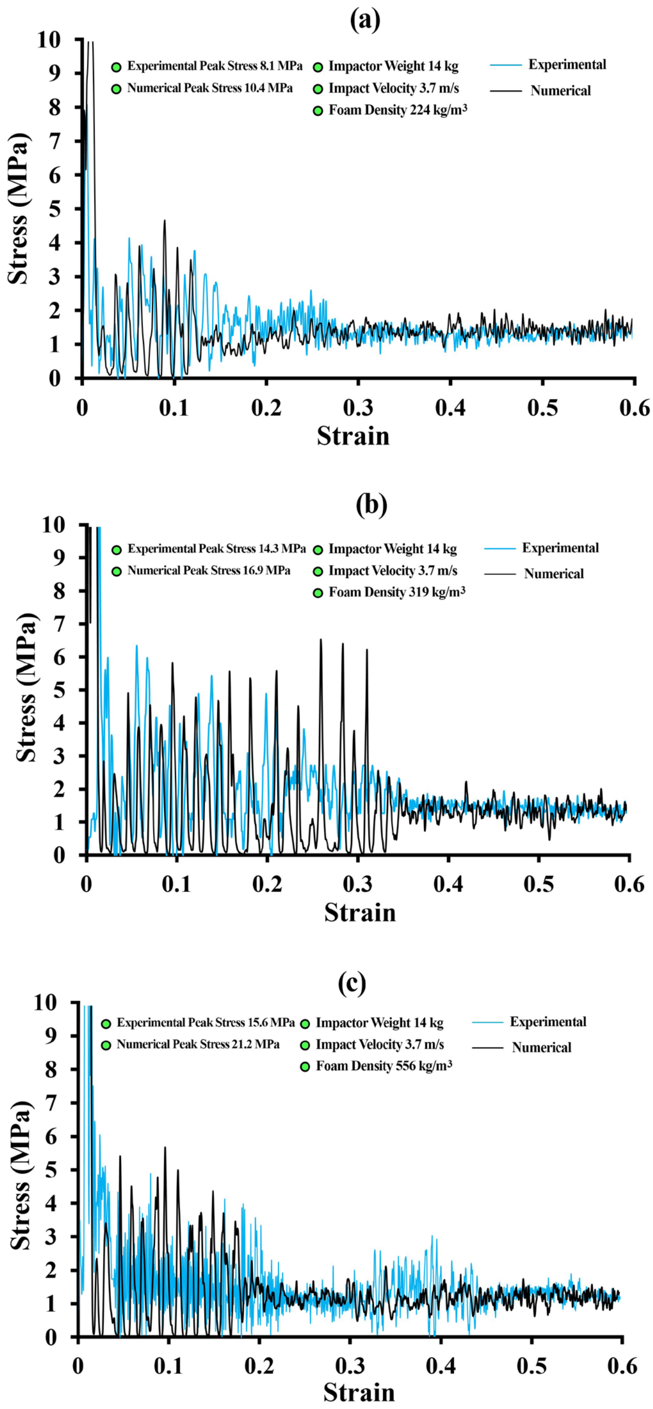

Fig. 6. Experimental and numerical results related to low velocity impact test for three different foam densities: (a) 224 kg/m³ (b) 319 kg/m³ (c) 557 kg/m³

with the impact velocity of 20 m/s and the mass of 60 kg with the impact velocity of 10 m/s for constant kinetic energy was considered. Table 3 indicates the values of peak stress and energy absorption for three different impactor densities for constant impact energy. An important point which is inferred from the Fig. 8 and Table 3 is that increasing the velocity had a considerable effect on the peak load and energy absorption in a way that by increasing the velocity from 10 to 20 m/s the value of the peak stress increases between 160 to 190% and energy absorption between 50 to 75%. Thus,

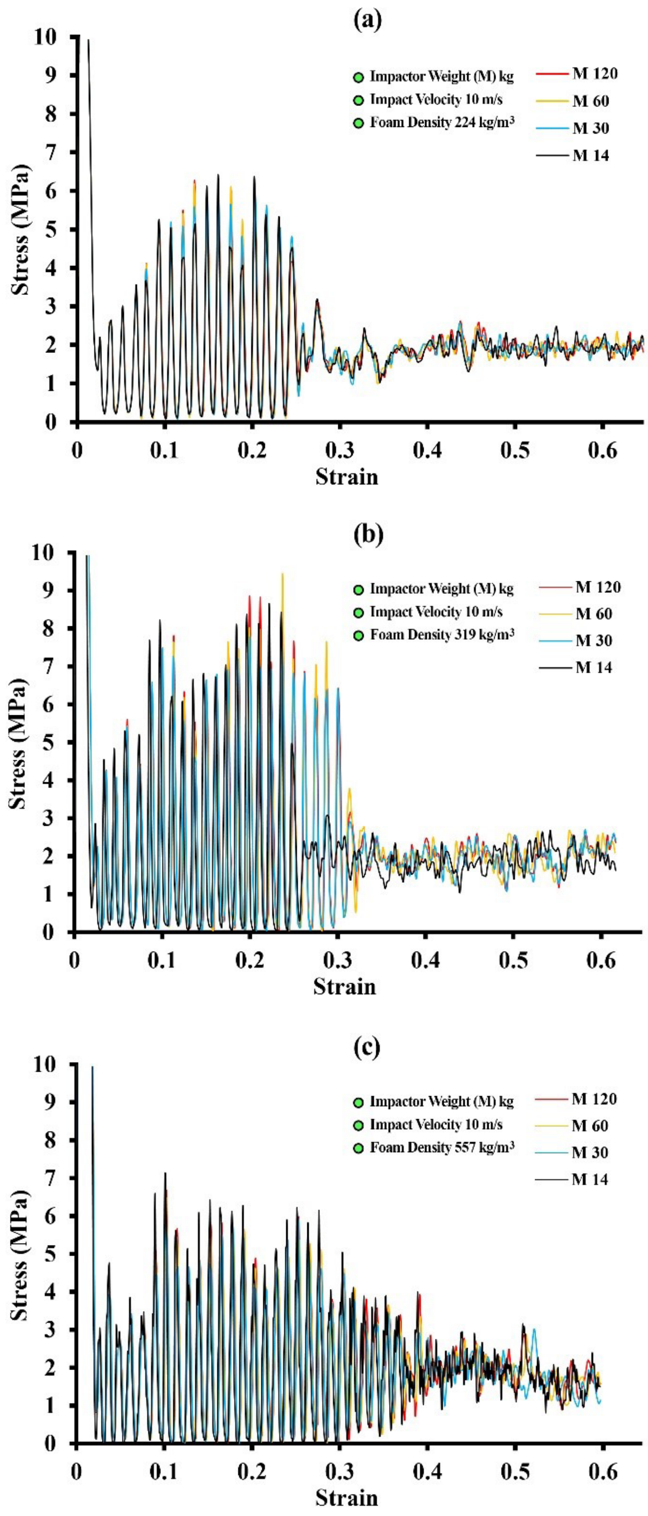

Fig. 7. The effect of impact inertia at constant velocity for three different foam densities: (a) 224 kg/m³ (b) 319 kg/m³ (c) 557 kg/m³

it is obvious that velocity changes had much more effect on energy absorption and peak stress than increasing impact inertia. In other words, low-velocity impact on the closed-cell aluminum foam is a displacement dominated phenomenon not an inertia dominated phenomena. It is probably because the weight of the cell walls is negligible against the weight of impactor, hence increasing the impact inertia would not have

Table 2. The effect of impact inertia on the impact response of closed-cell aluminum foam

Density, kg/m^3	Impactor Weight, kg	Peak Stress, MPa	Energy Absorption, kJ/m^3
224	14	13.75	1585.2
	30	13.75	1594.4
	60	13.75	1594.0
	120	13.76	1599.3
319	14	21.62	1553.9
	30	21.94	1555.4
	60	21.95	1559.6
	120	21.95	1563.2
557	14	25.56	1534.6
	30	25.98	1534.2
	60	25.99	1550.8
	120	25.99	1561.5

Table 3. The effect of inertia and impact velocity on the impact response of closed-cell aluminum foam at constant energy

Foam Density, kg/m^3	Energy Parameters		Peak Stress, MPa	Energy Absorption, kJ/m^3
	Initial Velocity, m/s	Impactor Weight, kg		
224	10	60	13.75	1594.0
	20	15	36.47	2480.5
			Δ_1 =165.2%	Δ_2 =55.6%
319	10	60	21.95	1559.6
	20	15	46.27	2650.0
			Δ_1 =110.8%	Δ_2 =69.9%
557	10	60	25.99	1550.8
	20	15	74.16	2665.8
			Δ_1 =185.3%	Δ_2 =71.9%

a considerable effect on energy absorption and peak stress. It is also clear that the foam density had no remarkable effect on the energy absorption but in both cases, the increase in foam density led to the increase in the peak stress.

$$\Delta_1 = \frac{\text{Peak Stress}\big|_{V=20\ m/s} - \text{Peak Stress}\big|_{V=10\ m/s}}{\text{Peak Stress}\big|_{V=10\ m/s}} \times 100 \;\&\; \Delta_2 = \frac{\text{Energy Absorption}\big|_{V=20\ m/s} - \text{Energy Absorption}\big|_{V=10\ m/s}}{\text{Energy Absorption}\big|_{V=10\ m/s}} \times 100 \tag{2}$$

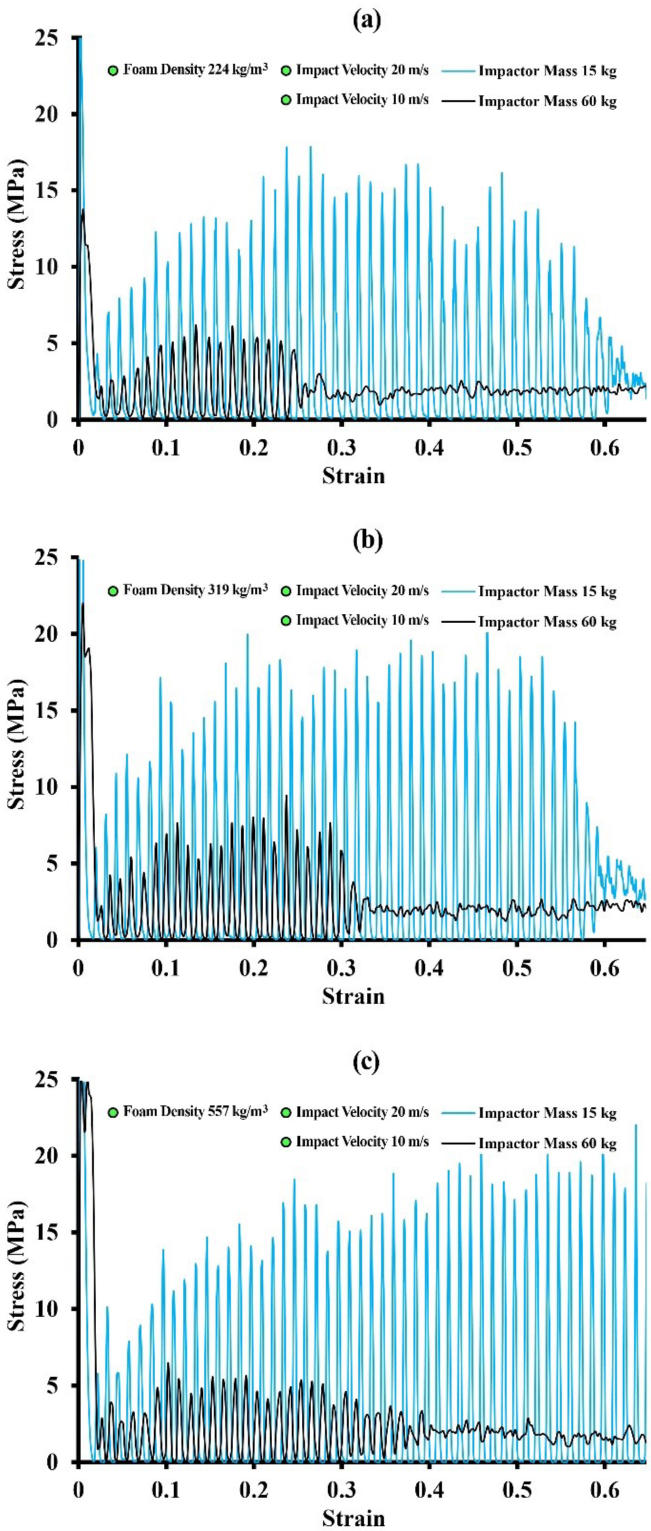

Fig. 8. The effect of impact inertia versus impact velocity for three different foam densities: (a) 224 kg/m^3 (b) 319 kg/m^3 (c) 557 kg/m^3

4- Conclusion

In this paper, the effect of inertia and impact velocity as energy parameters on the closed-cell Alporas aluminum foam behavior are investigated. First, the three-dimensional models of the aluminum foam were created via the CT scan method. Then, the model was analyzed under low-velocity impact test via LS-DYNA software. The results of the finite element method are compared with the experimental results and it is concluded that the numerical method shows a high accuracy. After that, the effect of important parameters, including the inertia, velocity of impactor and foam density on the impact response is investigated. The results show that at a constant level of impact velocity, increasing inertia has no effect on peak stress and also slightly increases energy absorption.

It is also observed that at a constant impact energy, impact velocity has considerably more effect on energy absorption and peak stress compared to inertia. For every three different foam densities at constant impact energy, increasing velocity causes greater values of peak stress and energy absorption than increasing inertia. The peak stress value is higher for greater foam densities in constant impact inertia. Furthermore, foam density has no remarkable effect on energy absorption.

References

[1] T. Miyoshi, M. Itoh, S. Akiyama, A. Kitahara, ALPORAS Aluminum Foam: Production Process, Properties, and Applications, *Advanced Engineering Materials*, 2(4) (2000) 179–183.

[2] S. Akiyama, H. Ueno, K. Imagawa, A. Kitahara, S. Nagata, K. Morimoto, T. Nishikawa, M. Itoh, Foamed metal and method of producing same, *US Patent* 4.713.277, 1987.

[3] S. Akiyama, K. Imagawa, A. Kitahara, S. Nagata, K. Morimoto, T. Nishikawa, M. Itoh, *European Patent Application* 0.210.803 A1, 1986.

[4] J.C. Elliot, *US Patent* 2.983.597, 1961.

[5] W.S. Fiedler, *US Patent* 3.214.265, 1965.

[6] P.W. Hardy, G.W. Peisker, *US Patent* 3.300.296, 1967.

[7] J. Bjorksten, E.J. Rock, *US Patent* 3.707.367, 1972.

[8] C.B. Berry, *US Patent* 3.669.654, 1972.

[9] J. Weber, *German Patent Application* 3.516.737, 1986.

[10] M. Peroni, G. Solomos, V. Pizzinato, Impact behaviour testing of aluminium foam, *International Journal of Impact Engineering*, 53 (2013) 74–83.

[11] J. Banhart, Manufacture, characterisation, and application of cellular metals and metal foams, *Progress in Materials Science*, 46(6) (2001) 559–632.

[12] M.F. Ashby, A. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, H.N.G. Wadley. *Metal foams: a design guide*, 1st edition, Butterworth-Heinemann, 2000.

[13] A.G. Evans, J.W. Hutchinson, N.A. Fleck, M.F. Ashby, H.M.G. Wadley, The topological design of multifunctional cellular metals, *Progress in Materials Science*, 46(3-4) (2001) 309–327.

[14] R. Singh, P.D. Lee, T.C. Lindley, C. Kohlhauser, C. Hellmich, M. Bram, T. Imwinkelried, R.J. Dashwood, Characterization of the deformation behavior of intermediate porosity interconnected Ti foams using micro-computed tomography and direct finite element modeling, *Acta Biomaterialia*, 6(6) (2010) 2342–2351.

[15] R. Rajendran, A. Moorthi, S. Basu, Numerical simulation of drop weight impact behaviour of closed cell aluminium foam, *Materials and Design*, 30 (2009) 2823–2830.

[16] Y. Song, Z. Wang, L. Zhao, J. Luo, Dynamic crushing behavior of 3D closed-cell foams based on Voronoi random model, *Materials and Design*, 31 (2010) 4281–4289.

[17] Y. Liu, W. Gong, X. Zhang, Numerical investigation of influences of porous density and strain-rate effect on dynamical responses of aluminum foam, *Computational Materials Science*, 91(2014) 223-230.

[18] Q. Fang, J. Zhang, Y. Zhang, J. Liu, Z. Gong, Mesoscopic investigation of closed-cell aluminum foams on energy absorption capability under impact, *Composite Structures*. 124 (2015) 409-420.

[19] B. Li, G. Zhao, T. Lu, Low strain rate compressive behavior of high porosity closed-cell aluminum foams, *Science China Technological Sciences*, 55(2) (2012) 451-463.

[20] M.J. Nayyeri, S.M.H. Mirbagheri, D.H. Fatmehsari, Compressive behavior of tailor-made metallic foams (TMFs): Numerical simulation and statistical modeling, *Materials and Design*, 84 (2015) 223–230.

[21] P. Wang, S. Xu, Z. Li, J. Yang, C. Zhan, H. Zheng, S. Hu, Experimental investigation on the strain-rate effect and inertia effect of closed-cell aluminum foam subjected to dynamic loading, *Materials Science and Engineering: A*, 620 (2015) 253-261.

[22] S. Birla, D.P. Mondal, S. Das, A. Khare, J. P. Singh, Effect of cenosphere particle size and relative density on the compressive deformation behavior of aluminum-cenosphere hybrid foam, *Materials and Design*, 117 (2017) 168–177.

[23] L. Li, P. Xue, G. Luo, A Numerical Study on Deformation Mode and Strength Enhancement of Metal Foam under Dynamic Loading, *Materials and Design*, 110 (2016) 72–79.

[24] H. Toda, T. Ohgaki, K. Uesugi, K. Makii, Y. Aruga, T. Akahori, M. Niinomi, T. Kobayashi, In situ observation of fracture of aluminium foam using synchrotron X-ray micro tomography, *Key Engineering Materials*, 297-300 (2005) 1189-1195.

[25] H. Toda, M. Takata, T. Ohgaki, M. Kobayashi, T. Kobayashi, K. Uesugi, K. Makii, Y. Aruga, 3-D image-based mechanical simulation of aluminium foams: effects of internal microstructure, *Advanced Engineering Materials*, 8(6) (2006) 459-467.

[26] H. Toda, I. Sinclair, J.Y. Buffière, E. Maire, K.H. Khor, P. Gregson, T. Kobayashi, A 3D measurement procedure for internal local crack driving forces via synchrotron X-ray microtomography, *Acta Materialia*, 52(5) (2004) 1305-1317.

[27] A. Sassov, E. Cornelis, D. Van Dyck, Non-destructive 3D Investigation of Metal Foam Microstructure, *Materialwissenschaft and Werkstofftechnik*, 31(6) (2000) 571-573.

[28] T. Ohgaki, H. Toda, M. Kobayashi, K. Uesugi, T. Kobayashi, M. Niinomi, T. Akahori, K. Makii, Y. Aruga, In-situ High-resolution X-ray CT Observation of Compressive and Damage Behaviour of Aluminium Foams by Local Tomography Technique, *Advanced Engineering Materials*. 8(6) (2006) 473-475.

[29] Y. Liu, W. Gong, X. Zhang, Numerical investigation of influences of porous density and strain-rate effect on dynamical responses of aluminum foam, *Computational Materials Science*. 91 (2014) 223-230.

[30] A. Elmoutaouakkil, L. Salvo, E. Maire, G. Peix, 2D and 3D Characterization of Metal Foams Using X-ray Tomography, *Advanced Engineering Materials*, 4(10) (2002) 803-807.

[31] C. Veyhl, I. V. Belova, G. E. Murch, T. Fiedler, Finite

element analysis of the mechanical properties of cellular aluminium based on micro-computed tomography, *Materials Science and Engineering: A*, 528(13-14) (2011) 4550-4555.

[32] J.F. Ramírez, M. Cardona, J.A. Velez, I. Mariaka, J.A. Isaza, E. Mendoza, S. Betancourt, P. Fernández-Morales, Numerical modeling and simulation of uniaxial compression of aluminum foams using FEM and 3D-CT images, *Procedia Materials Science*, 4 (2014) 227-231.

[33] M.A. Kader, M.A. Islam, M. Saadatfar, P.J. Hazell, A.D. Brown, S. Ahmed, J.P. Escobedo, Macro and micro collapse mechanisms of closed-cell aluminium foams during quasi-static compression, *Materials and Design*, 118 (2017) 11–21.

[34] D. Miedzińska, T. Niezgoda, R. Gieleta, Numerical and experimental aluminum foam microstructure testing with the use of computed tomography, *Computational Materials Science*, 64 (2012) 90-95.

[35] C. Petit, E. Maire, S. Meille, J. Adrien, Two-scale study of the fracture of an aluminum foam by X-ray tomography and finite element modeling, *Materials and Design*, 120 (2017) 117–127.

[36] M. Saadatfar, M. Mukherjee, M. Madadi, G.E. Schröder-Turke, F. Garcia-Morenoc, d, F.M. challere, S. Hutzlerb, A.P. Shepparda, J. Banhartc, d, U. Ramamurty. Structure and deformation correlation of closed-cell aluminium foam subject to uniaxial compression, *Acta Materialia*, 60(8) (2012) 3604‒3615.

[37] Y. Sun, Q.M. Li, T. Lowe, S.A. McDonald, P.J. Withers, Investigation of strain-rate effect on the compressive behaviour of closed-cell aluminium foam by 3D image-based modelling, *Materials and Design*, 89 (2016) 215–224.

[38] J. Kadkhodapour, S. Raeisi. Micro–macro investigation of deformation and failure in closed-cell aluminum foams, *Computational Materials Science*, 83 (2014) 137–148.

[39] H. Hatami, M. Damghani Nouri, Experimental and numerical investigation of lattice-walled cylindrical shell under low axial impact velocities, *Latin American Journal of Solids and Structures*, 12 (2015) 1950-1971.

[40] H. Hatami, M. Shokri Rad, A. Ghodsbin Jahromi, A theoretical analysis of the energy absorption response of expanded metal tubes under impact loads, *International Journal of Impact Engineering*, 109 (2017) 224-239.

[41] A. Ghodsbin Jahromi, H. Hatami, Energy absorption performance on multilayer expanded metal tubes under axial impact, *Thin-Walled Structures*, 116 (2017) 1-11.

[42] T. Miyoshi, M. Itoh, S. Akiyama, A. Kitahara, ALPORAS Aluminum Foam: Production Process, Properties, and Applications, *Advanced Engineering Materials*, 2(4) (2000) 179-183.

[43] S. Akiyama, K. Imagawa, A. Kitahara, S. Nagata, K. Morimoto, T. Nishizawa, M. Itoh, *US Patent* 4.713.277, 1987.

[44] T. Miyoshi, S. Hara, T. Mukai, K. Higashi, Development of a closed cell aluminium alloy foam with enhancement of the compressive strength, *Materials Transactions*, 42(10) (2001) 2118-2123.

[45] X.Y. Su, T.X. Yu, S.R. Reid, Inertia-sensitive impact energy absorbing structures part II: effect of strain rate, *Int. J. Impact Eng*, 16(4) (1995) 673–689.

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