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Energy Absorption of Reinforced Aluminium Foams

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Foamed materials in general, and aluminium foams in particular, demonstrate a number of interesting properties due to their porous structure, which makes them usable in a wide range of applications. The possibility of absorbing the energy is one of the most interesting properties of foams. The use of lightweight porous materials with high specific strength has attracted much interest in the transportation industry in order to improve safety. Recently, foamed aluminium has frequently been used in various absorbers of kinetic energy (buffers of automobiles, trains, trams). This paper studies the influence of reinforcement in the form of steel rods on compression behaviour of aluminium foams.

Apsorpcija energije ojačanih aluminijskih pjena

Izvornoznanstveni članak

Pjene općenito, kao i aluminijske pjene imaju mnoga povoljna svojstva zahvaljujući njihovoj poroznoj strukturi što ih čini pogodnima za mnoge primjene. Mogućnost apsorpcije energije je jedno od najzanimljivijih uporabnih svojstava pjena. Primjena lakih poroznih materijala visoke čvrstoće u transportnoj industriji je sve zanimljivija u pogledu povećanja sigurnosti. Aluminijske pjene se sve češće koriste kao različiti apsorberi kinetičke energije (odbojnici automobila, vlakova, tramvaja). U ovom radu istraživan je utjecaj ojačanja u obliku čeličnih šipki na ponašanje pri tlačnom opterećenju.

1. Introduction

Foams and other highly porous materials with a cellular structure are known to have many interests in combinations of physical and mechanical properties, such as high stiffness in conjunction with very low specific weight or high gas permeability combined with high thermal conductivity. For this reason, nature frequently uses cellular materials for constructional or functional purposes (e.g. wood or bones). Among man-made cellular materials, polymeric foams are currently the most important ones with widespread applications in nearly every sector of technology. Less known is that even metals and alloys can be produced as cellular materials or foams and that these materials have such interesting properties that exciting new applications are expected in the near future [1].

At this point in time most commercially available metal foams are based on aluminium or nickel. Methods exist for foaming magnesium, lead, zinc, copper, bronze, titanium, steel and even gold, available on custom order. At present metal foams are incompletely characterized, and the processes used to make them are imperfectly controlled, resulting in some variability in properties. But even the present generation of metal foams have property profiles with alluring potential, and the control of processing is improving rapidly [2].

Although many years have passed since the first patents concerning the manufacture of metallic foams appeared, the material has not been put into large-scale commercial production yet. This discouraging fact can be attributed to inadequate design of components, low reproducibility of properties, a lack of testing procedures and calculation approaches, absence of concepts for secondary treatment, as well as the production technologies being too complicated and relatively expensive [3]. By improving technology, production become faster and the product has better quality and low price [4].

Foamed aluminium is, principally, a composite material consisting of aluminium or aluminium alloy matrix and of pores filled up with a gas distributed throughout the matrix. This unique structure possesses an unusual combination of properties, such as low thermal conductivity, high impact energy absorption capacity, very high specific toughness and good acoustic properties, especially in the case of interconnected porosity. Moreover, this exceptionally lightweight material is nonflammable, ecologically harmless and easily recyclable [5].

Symbols/Oznake

E	- Young modulus, N/mm^2 - Youngov modul	σ	- stress, N/mm^2 - naprezanje
F	- Force, N - sila		**Subscripts/Indeksi**
W	- absorbed energy, J - apsorbirana energija	D	- nominal - nominalno
	Greek letters/Grčka slova	pl	- plateau - plato, konstantno
δ	- displacement, mm - skraćenje	m	- maximum - maksimalno
ε	- strain, % - deformacija	V	- per unit volume - po jedinici volumena
ρ	- density of foam, g/cm^3 - gustoća pjene		

The design of optimal foam for wanted mechanical and electrical properties requires a sound knowledge of the relation between microstructural parameters like density or number of cells or struts per unit volume and the effective properties. These properties turn out to be strongly anisotropic and this anisotropy is mainly due to material processing. The deformation of heterogeneous highly porous materials is often associated with the development of non-homogeneous deformation patterns like strain localization, in the form of bands during the compression of aluminium foams for instance [6].

The foamed panels can be reinforced by metallic wires or nets like concrete. In this case, the reinforcing components (made of steel) are inserted in the mould together with foamable PM-precursor before foaming [7].

2. Energy Absorption

Lightweight porous materials with high specific strength have attracted much interest in the transportation industry where they have been used for improving safety [8]. In recent years, foamed aluminium has been frequently used in various absorbers of kinetic energy (buffers of automobiles, trains, trams) [9], Figure 1.

The way the cells are formed in metal foams allow energy absorption in all directions. The tetrakaidecahedron shape of the cell makes it insensitive to direction or isotropic (ideally speaking); this geometry allows the foam to absorb energy from any direction and it also allows heat transfer, thermal resistance and fluid flow from all directions as well. It is important to state that foams of uniform periodic cell distribution and porosity can ideally be labeled as isotropic; however, when foams are processed, imperfections always arise in cell distribution and the cells themselves, normally, are slightly sheared to one direction; usually that would be the direction the foaming agents or bubbles rose to and furthermore the cell pores vary in size [10].

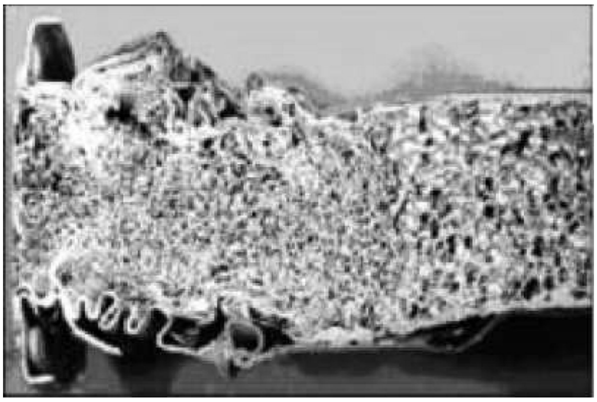


Figure 1. The motor carrier filled with aluminium foam after frontal impact [11]

Slika 1. Nosač motora ispunjen aluminijskom pjenom nakon čeonog udara [11]

The absorbed energy per unit volume (W_V) in a certain strain interval (ε_1, ε_2) is equal to the area below the stress-strain curve (figure 1) and can be expressed as:

$$W_V = \int_{\varepsilon_1}^{\varepsilon_2} \sigma(\varepsilon)\mathrm{d}\varepsilon. \qquad (1)$$

Ideal energy absorbers have a long flat stress–strain (or load-deflection) curve like those of Figure 2.

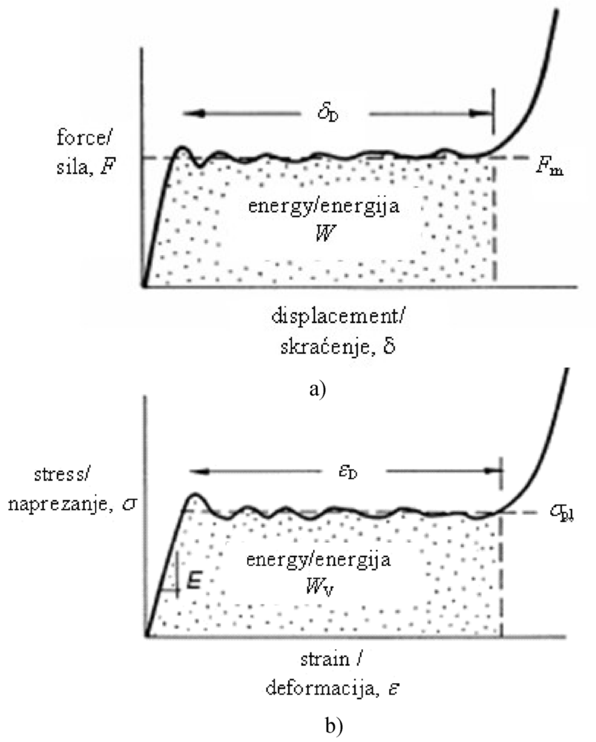


Figure 2. a) a load-deflection curve and (b) a stress–strain curve for an energy absorber [2]

Slika 2. a) krivulja sila-skraćenje i (b) krivulja naprezanje-deformacija pri apsorpciji energije [2]

The absorber collapses plastically at a constant nominal stress, called the plateau stress, σ_{pl}, up to a limiting nominal strain, ε_D. Energy absorbers for packaging and protection are chosen so that the plateau stress is just below that which will cause damage to the packaged object; the best choice is then the one which has the longest plateau, and therefore absorbs the most energy before reaching ε_D. The area under the curve, roughly $\sigma_{pl} \cdot \varepsilon_D$, measures the energy the foam can absorb, per unit initial volume, up to the end of the plateau. Foams which have a stress–strain curve like that shown in Figure 1 perform well in this function. The area under the flat part ('plateau') of the curves is the useful energy, W, or energy per unit volume, W_V, which can be absorbed [2].

3. Experimental Part

For the production of foamed aluminium, Al powder is mixed with a blowing agent which releases gas at higher temperatures, and then the mixture is compacted by using extrusion technologies. This precursor is placed into a mould form and heated up until the agent starts to foam. Immediately thereafter the mould is taken out of the furnace and cooled off, so the aluminium foam part is frozen in shape, Figure 3. The outcome of this process is a closed-cell aluminium foam showing a thin casting skin on the surface [12], Figure 4.

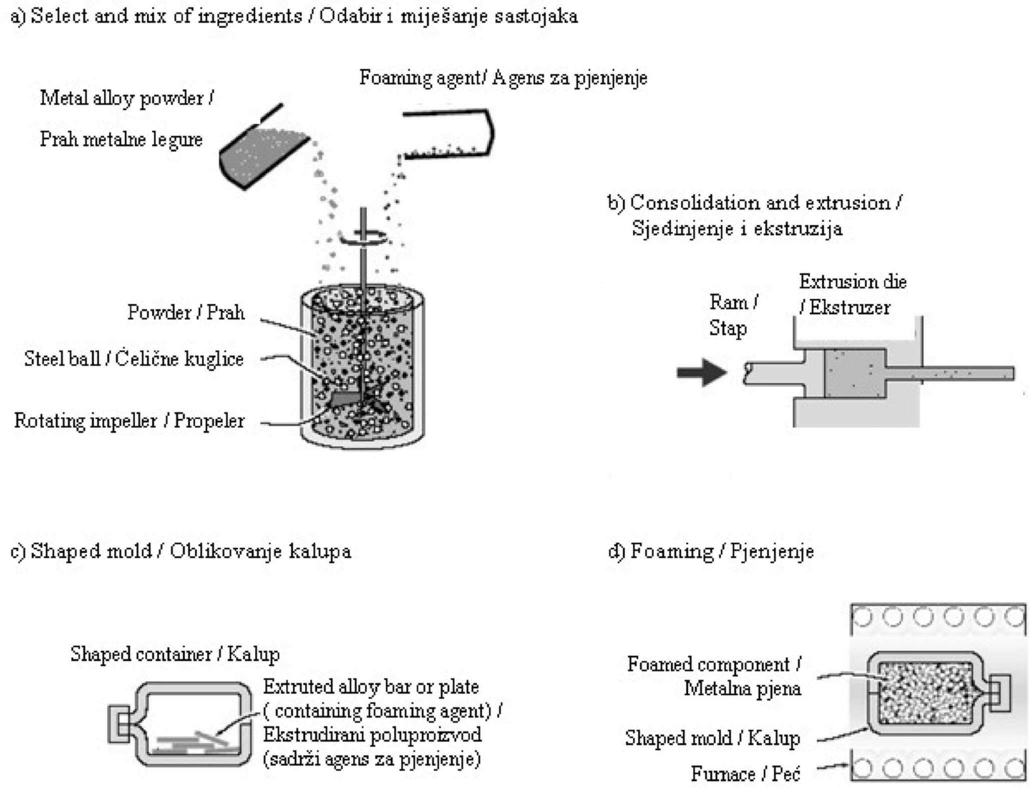


Figure 3. The sequence of powder metallurgy steps used to manufacture metal foams by gas-releasing particles in semi-solids [2]

Slika 3. Slijed koraka metalurgije praha pri proizvodnji metalnih pjena tehnologijom plinom oslobođenih čestica otopljenih u polučvrstoj fazi [2]

Figure 4. Closed-cell aluminium foam [13]

Slika 4. Aluminijska pjena zatvorenih ćelija [13]

Six samples of aluminium foams (dimension 74 x 74 x 100 mm, density of foam ρ = 0,27 g/cm^3) were produced from an Alulight AlMgSi 0,6 TiH_2 - 0,4 precursor. Three samples had reinforcement from steel rods (square profile 6×6 mm) in the form of double letter "H", welded together, Figure 5.

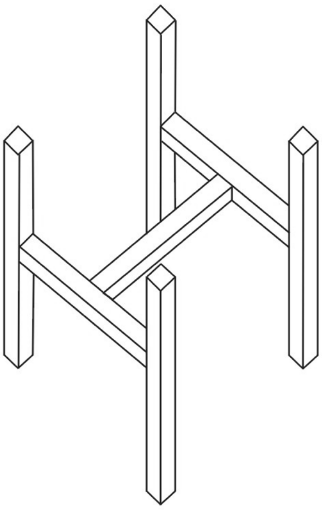


Figure 5. Shape of reinforcement

Slika 5. Oblik ojačanja

Steel reinforcement was inserted in the mould together with precursor, figure 6. An electric resistance furnace with a power of 7,5 kW (situated in the Non-metal Laboratory at the Faculty of Mechanical Engineering and Naval Architecture) was used. Figure 7 presents the process of producing aluminium foam samples.

Determination of energy absorption was carried out in the Laboratory for Mechanical Properties Testing at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. A WPM universal test machine, model EU 40, with a maximum compressive force of 400 kN was used. The feed rate was 60 mm/min. Figure 8 shows start of testing and Figure 9 compression of samples.

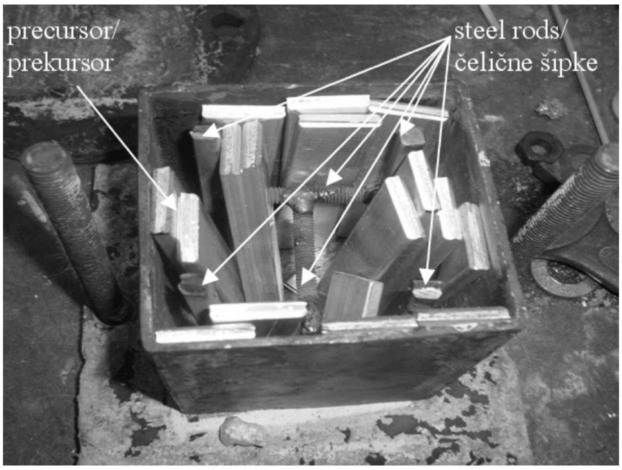


Figure 6. Reinforcement in aluminium foam

Slika 6. Ojačanje u aluminijskoj pjeni

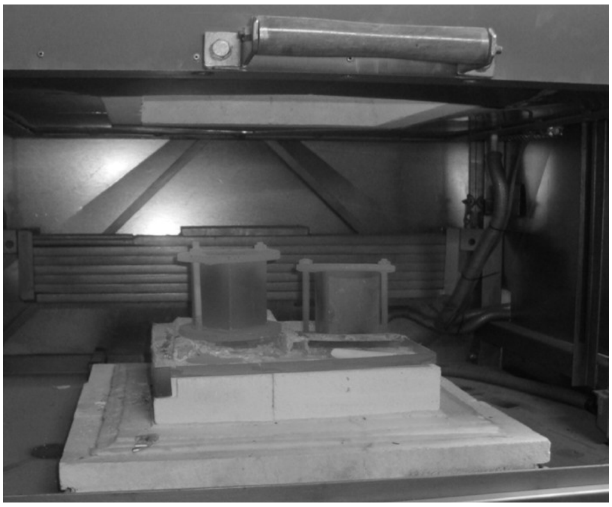


Figure 7. The process of producing aluminium foam samples

Slika 7. Izrada uzoraka aluminijskih pjena

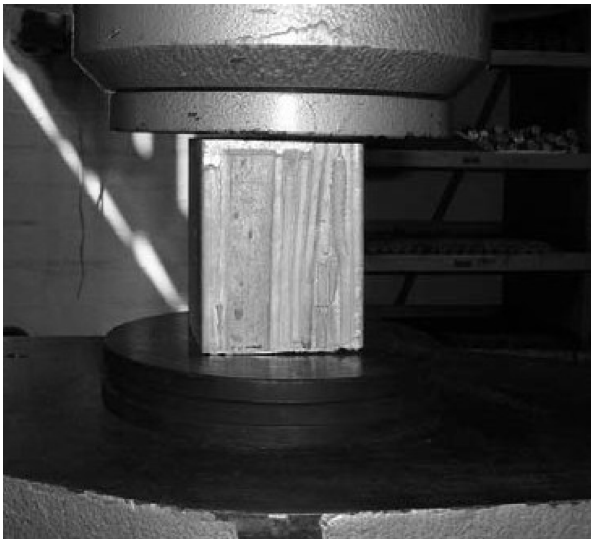
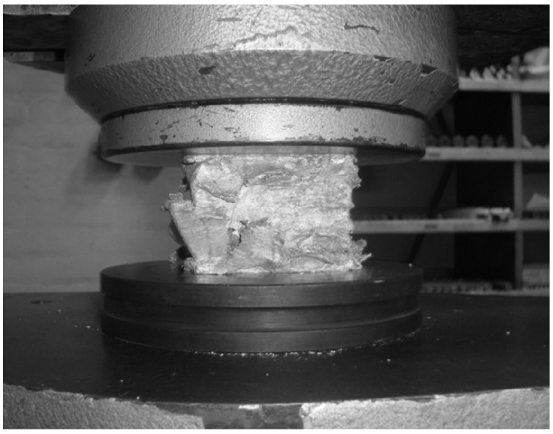
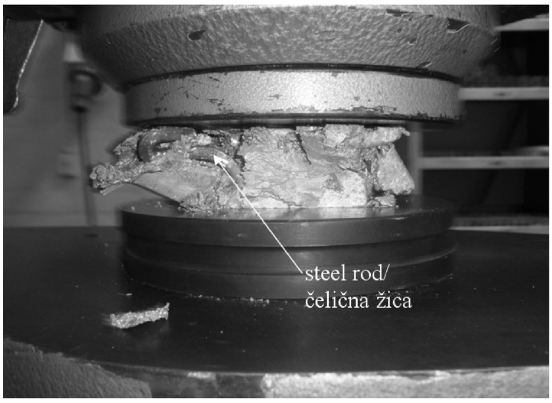


Figure 8. Start of the test

Slika 8. Početak ispitivanja



a)

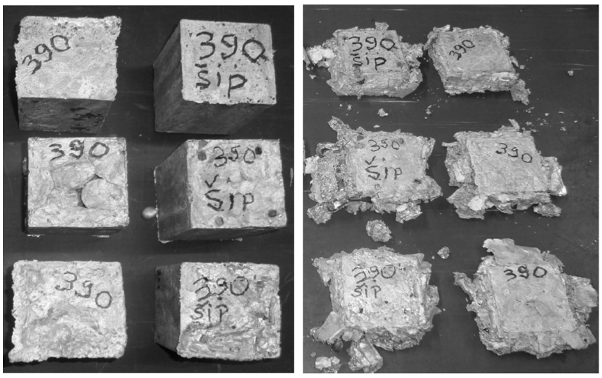


b)

Figure 9. Compression of aluminium foam samples, a) without reinforcement b) with reinforcement

Slika 9. Tlačno ispitivanje uzoraka aluminijske pjene, a) bez ojačanja b) s ojačanjem

Figure 10 shows aluminium foam samples before and after the test.



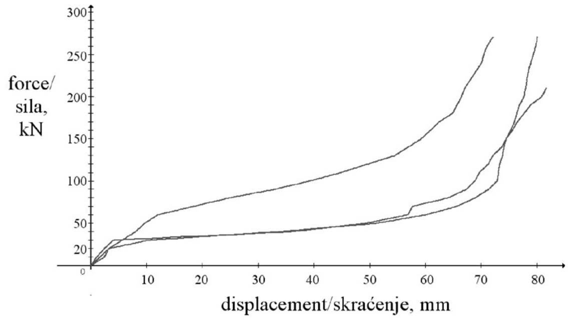
a) b)

Figure 10. Aluminium foam samples, a) before the test, b) after the test

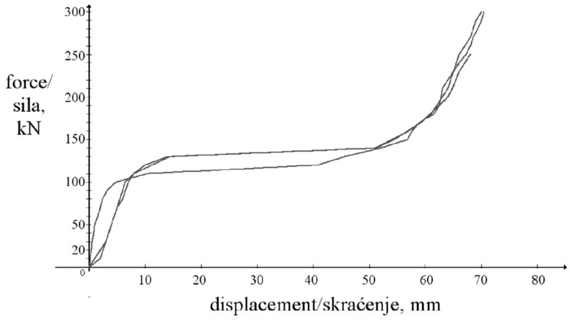
Slika 10. Uzorci aliminijske pjene, a) prije ispitivanja, b) nakon ispitivanja

Figure 11 present approximated "force – displacement" diagrams.

From Figure 11 it can be seen that the aluminium foam samples with reinforcement have better reproducibility of properties. Also they have more expressed and high value of the plateau force.



a)



b)

Figure 11. Approximated"force – displacement" diagrams, a) aluminium foam samples without reinforcement b) aluminium foam samples with reinforcement

Slika 11. Aproksimirani dijagram "tlačna sila – skraćenje", a) za neojačane aluminijske pjene b) za ojačane aluminijske pjene

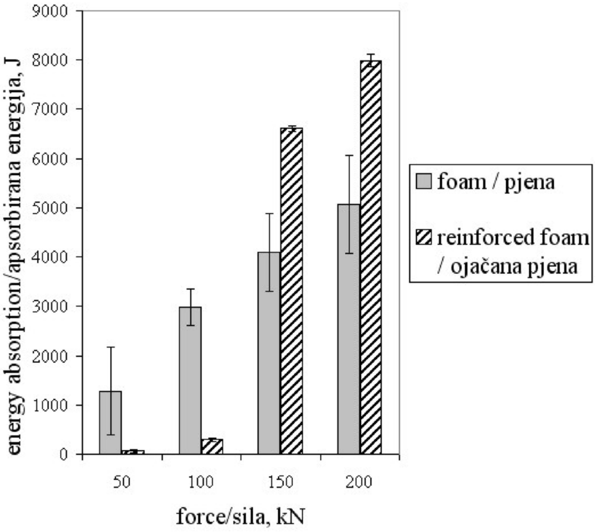


Figure 12. Energy absorption at different compressive forces

Slika 12. Apsorbirana energija pri različitim tlačnim silama

In order to compare the results obtained for different samples, the dependence of absorbed energy on the compressive force is shown in Figure 12.

From Figure 12 it is obvious that the aluminium foam samples with reinforcement have better energy absorption at higher forces (150 and 200 kN) and the aluminium foam samples without reinforcement have better energy absorption at lower forces (50 and 100 kN).

4. Conclusion

The aluminium foam can be reinforced by metallic wires or nets like concrete. In this case the reinforcing components (made of steel) are inserted in the mould together with foamable PM-precursor before foaming. By a static compression test, it was determined that aluminium foams and aluminium foams with reinforcement from steel rods exhibit good absorption of energy. The aluminium foam samples with reinforcement have better reproducibility of properties. Also they have more expressed and high value of the plateau force. The aluminium foam samples with reinforcement have better energy absorption at higher forces and the aluminium foam samples without reinforcement have better energy absorption at lower forces.

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REFERENCES

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

[2] ASHBY, M.F.; EVANS, A.G.; FLECK, N.A.; GIBSON, L.J.; HUTCHINSON J.W.; WADLEY, H.N.G.: *Metal Foams: A Design Guide*, Butterworth-Heinemann,Boston-Oxford-Auckland-Johannesburg-Melbourne-New Delhi, 2000.

[3] DEGISCHER, H.P.; KRISZT, B.: *Handbook of Cellular Metals*, Wiley-Vch Verlag GmbH, Weinheim, 2002.

[4] FRANZ, M.: *The analysis of criteria for selection of material in engineering practice*, Strojarstvo 30 (1988) 2, 91-95.

[5] SIMANCIK, F.; DEGISCHER H.P.; WÖRZ H.: *Foamed Aluminium - Light Structural and Insulation Material*, Euromat ‘95, Associazione Italiana di Metallurgia, Venice/Padua, Italy, 1995.

[6] BADICHE, X.; FOREST, S.; GUIBERT, T.; BIENVENU, Y.; BARTOUT, J.D.; IENNY, P.; CROSET, M.; BERNET, H.: *Mechanical properties and non-homogeneous deformation of open-cell nickel foams: Application of the mechanics of cellular solids and of porous materials*, Materials Science and Engineering A289 (2000) 276–288.

[7] SIMANCIK, F.; RAJNER, W.; JERZ, J.: *Alulight - Highly porous foamed aluminium panels with outstanding properties at low density*, European Automotive Congress, Bratislava, 2001.

[8] KIM, S.Y.; HUR, B.Y.; KWON, K.C.; CHO, S.H.; LIM, C.Y.; YOO, Y.M.; LEE M.H.: *Mechanical and sound absorption properties of closed cell Al foam by pot furnace method*, International Conference on Cellular Metals and Metal Foaming Technology METFOAM 2003, Berlin, 2003.

[9] LEBEDEV, V.I.; KOMOV, V.I.; ANDREEV D.A.: *Ability of constructions from foamed aluminium to absorb different konds of energy*, International Conference on Cellular Metals and Metal Foaming Technology METFOAM 2003, Berlin, 2003.

[10] AZZI W.E.: *A systematic study on the mechanical and thermal properties of open cell metal foams for aerospace applications*, Ph.D. Thesis, North Carolina, 2004.

[11] SIMANCIK F.: *Metallic foams – ultra light materials for structural applications*, Inzynieria Materialova 5 (2001) 823-828.

[12] http://www.alulight.com/en/downloads/ alulight_datasheets_en2006.pdf

[13] GIBSON, L.J.; ASHBY, M.F.: *Cellular Solids-2 Edition*, Cambridge University Press, New York, 1997.