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ALUMINIUM FOAMS IN THE DESIGN OF TRANSPORT MEANS

ABSTRACT

The requirements for weight reduction and improvement of performances in the design of transport means are often in contradiction to the requirements for increased safety. One of the possible ways of meeting these requirements is the application of metal foams. Thanks to cellular structure of aluminium foam along with low weight, the capability of noise and vibration damping, they feature also excellent capabilities of absorbing impact energy. Their application in the production of impact-sensitive elements of mobile or stationary transport means has significantly contributed to the reduction of the impact or collision consequences.

The focus of this paper is on improving the energy absorption characteristics of aluminium foams considering the significance of their application for the technology of traffic and transport.

The paper analyzes the influence of the chemical composition and density on the compression behaviour of aluminium foam. The aluminium foam samples were produced from Alulight precursor. The capability of samples to absorb mechanical energy has been estimated according to the results of compression tests. The tests were performed on a universal test machine. The test results showed that aluminium foams feature good energy absorption and the absorption capability decreases with the foam density. The Alulight AlMgSi 0.6 TiH_2 - 0.4 foam can absorb more energy than Alulight AlSi 10 TiH_2 – 0.8 foam.

KEY WORDS

aluminium foam, energy absorption, impact resistance, collisions

1. INTRODUCTION

How to reduce the number and severity of road collisions is one of the most important issues of technical and technological research and considerations of traffic and transport profession as well as the society in general. Because of the complexity of human-vehicle/environment interaction, capacity-limited traffic flows and constant increase in the number and frequency of traffic means, they have simply become inevitable. Regardless of the improvements in the traffic safety in the EU countries, their number does not show the desired tendency of decline.

According to the report of the European Commission the number of victims in 2009 in road traffic amounted to 1,500,000, out of which about 35,000 were fatalities, along with material damage of ca. 130 billion euro (based on HEATCO study: 6^{th} Framework Programme for Research and Technological Development) [1].

A significant contribution to the technical and safety parameters of the vehicles was made by the introduction of safety devices such as ABS systems, airbags, safety belts, then technologies of electronic warning/control of movement and adaptable headlamps, etc.

However, in the overall balance it is still impossible to quite clearly determine their share in the reduction of the number and severity of accident situations. The electronic safety technologies are of a later date so that they are mainly implemented in higher-class vehicles [2]. High expectations are directed to the development of ITS (Intelligent Transport System). ITS technologies are based on the integration of several "cooperative systems" in which vehicles exchange information in interaction with other vehicles, infrastructure and environment and the traffic flows in order to provide information to the motorists. The real effects of these solutions will come to the fore only in the following decades [3, 4].

These are then the reasons why great efforts are invested in finding design solutions that might improve the safety aspects. The improvement of deformation (crumpling) or crushing mechanics both of mobile and of stationary transport means at impact form the basis for the considerations done in scientific and professional circles. The main issue is how to find a safe vehicle deformation (crumpling) model with the ability of the vehicle structure to disperse the impact energy or to absorb it by the deformation of material which surrounds the passenger space and thus to provide protection [16, 17, 20].

One of the possible solutions is the use of materials that feature high impact energy absorption power in the production of target components with strategic arrangement in the vehicle structure. In this way the destructive action of impact forces would be limited by controlling their acceleration/deceleration [5, 6]. Metal foams, especially aluminium foams, feature excellent capability of energy absorption [7, 8, 9]. In comparison with polymeric foam, aluminium foam is more suitable since it features plastic deformation due to impact and there is almost no return back, preventing in this way further damage [10].

Deformation elements made of metal foams convert impact energy into plastic deformation retaining the peak force on the protected object below the level that causes damage. The thin walls of metal foam pores start to buckle (ductile alloys) and fracture (brittle alloys) at relatively low stresses, which remain almost constant until substantial foam densification is achieved. The extensive compression of the foam absorbs large amounts of kinetic energy and allows for an adequate deceleration path. Practically all impact energy is used for plastic deformation or for cracking, i.e. this energy cannot be released in rebound.

Compared with other impact energy absorbers, metallic foams allow that the energy absorption capacities are matched to the limiting stress level by simple altering of density. If the density is too low, the foam crushes before the energy has been sufficiently absorbed. If the density is too high, the stress exceeds the critical value at low absorbed energy [11].

An illustrative example of a possible application of aluminium foams are the protective bumpers in heavy-duty vehicles. Head-on collisions involving heavy-duty vehicles (with mobile or stationary means) are the most destructive ones and most fatalities occur in collisions with passenger cars [12]. High ratio of mass of the heavy-duty vehicle to passenger car in combination with high stiffness of the structure results in the structure of heavy-duty vehicle absorbing little energy [13].

The rear and side underrun protection prevents cars from running under the truck in car-truck collisions. Rigid underrun protection is a step in the right direction; however, since these collisions usually take place at higher relative speeds at which the energy absorption is necessary on the truck, ECE-Regulation 93 should be expanded with energy absorbing front underrun protection systems and should be compulsory within the European Union. The studies performed by EEVC WG 14 (European Enhanced Vehicle-Safety Committee) have shown that passenger cars can "survive" a frontal truck collision at a relative speed of 75km/h if the truck is equipped with the underrun protection system which absorbs energy [12].

The rigid rear underrun protective systems are highly effective for speeds of up to 60-70km/h since they then engage cars' safety systems. Energy-absorbing rear underrun systems are effective at speeds of up to 70-90km/h for airbag-equipped cars. An English study estimated that rear underrun protective systems would prevent about 35% of fatalities in rear underrun crashes [14].

2. ENERGY ABSORPTION

The absorbed energy per unit volume Ev in a certain strain interval ($\varepsilon_1, \varepsilon_2$) is equal to the area below the stress-strain curve and can be expressed as:

$$E_V = \int_{\varepsilon_1}^{\varepsilon_2} \sigma(\varepsilon) d\varepsilon \quad (1)$$

A comparison between the typical energy absorption of a fully dense elastic solid and the foamed material is given in *Figure 1* in the form of a diagram. Obviously, the foam can absorb much more energy at a given peak stress level than the dense solid (at a given strain level the dense solid naturally absorbs more energy but this situation does not represent a realistic condition). Due to their capability for keeping the peak stress while absorbing kinetic energy, foams are, in general, excellent energy absorbers [15].

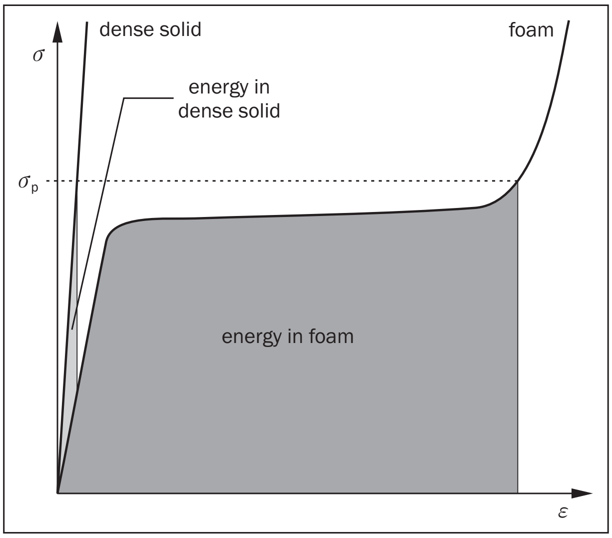

Figure 1 - Comparison: energy absorption by foam and by a dense solid [15]

Here, it is assumed that near-ideal foam absorbs a given energy at minimum stress. In *Figure 2*, showing the compression behaviour of three foams of various densities, these facts are explained in detail. The shaded areas correspond to an equal amount of energy E_V absorbed by the three foams. The right margin of each of the shaded areas marks the compression which is necessary to absorb this amount of energy. In the case of the lowest density, the stress-strain curve has already passed through the regime of constant stress before the energy E_V is absorbed; therefore, the stress reaches high values. On the other hand, the foam of the highest density hardly shows a plateau area with constant stress and it also has the highest maximum stress. In contrast, for a given impact energy E_V, the foam of the medium density is loaded exactly up to the end of the plateau area. Therefore, it shows the lowest peak stress to the full energy absorption. In this way, for each given impact energy, a foam of a specific density can be determined, showing the lowest possible maximum stress during deformation [8].

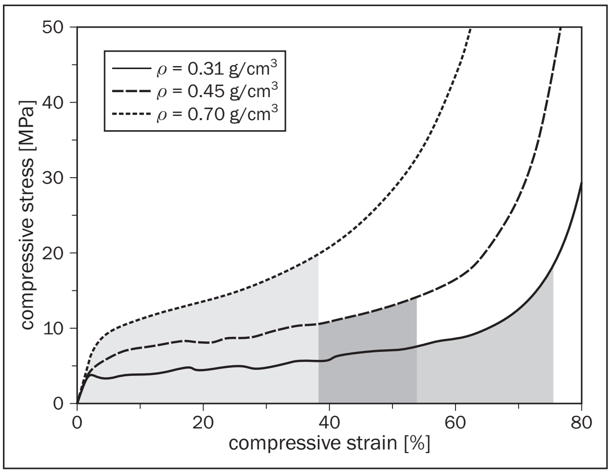

Figure 2 – Compression behaviour of three AlSi12 foams of various densities. The various shaded areas correspond to the same absorbed amount of energy E_V, [8]

3. EXPERIMENTAL PART

Determination of energy absorption was carried out at the Laboratory for Mechanical Properties Testing at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. A universal test machine, with a maximum compressive force of 400kN was used, *Figure 3*. The feed rate was 6mm/min.

In order to determine the energy absorption capacity of metal foams, a compression test was carried out on a steel tube, a steel tube filled with aluminium foam and on aluminium foam.

Figures 4, 5 and 6 show that the "force – compression" diagram of aluminium foam has the most favourable shape for energy absorption.

Figure 3 – Universal test machine

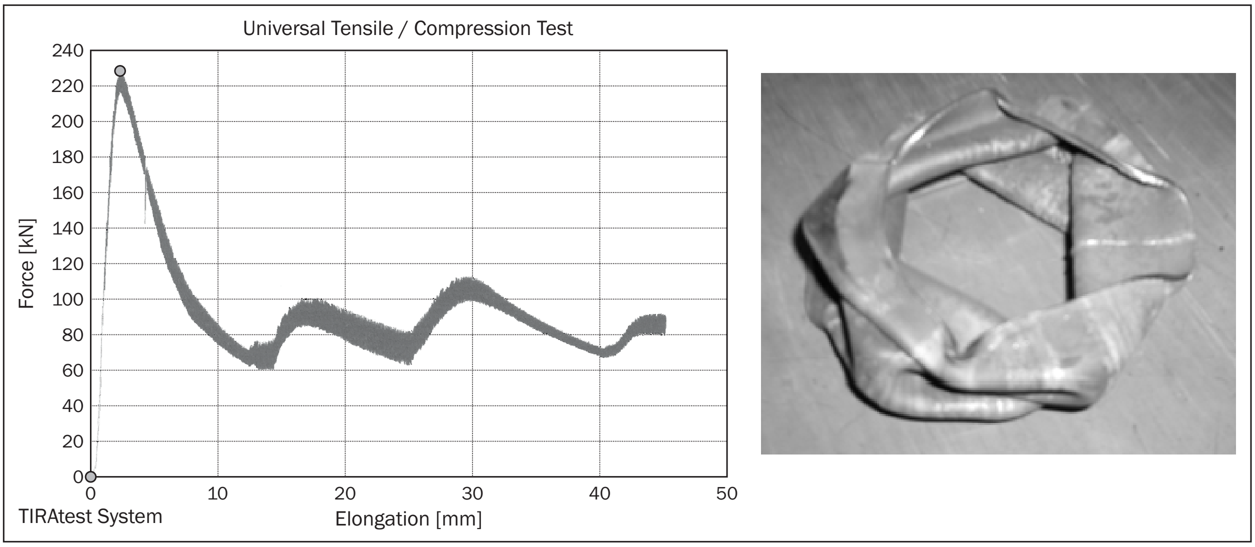

Figure 4 – "Force – elongation (compression)" diagram of a steel tube

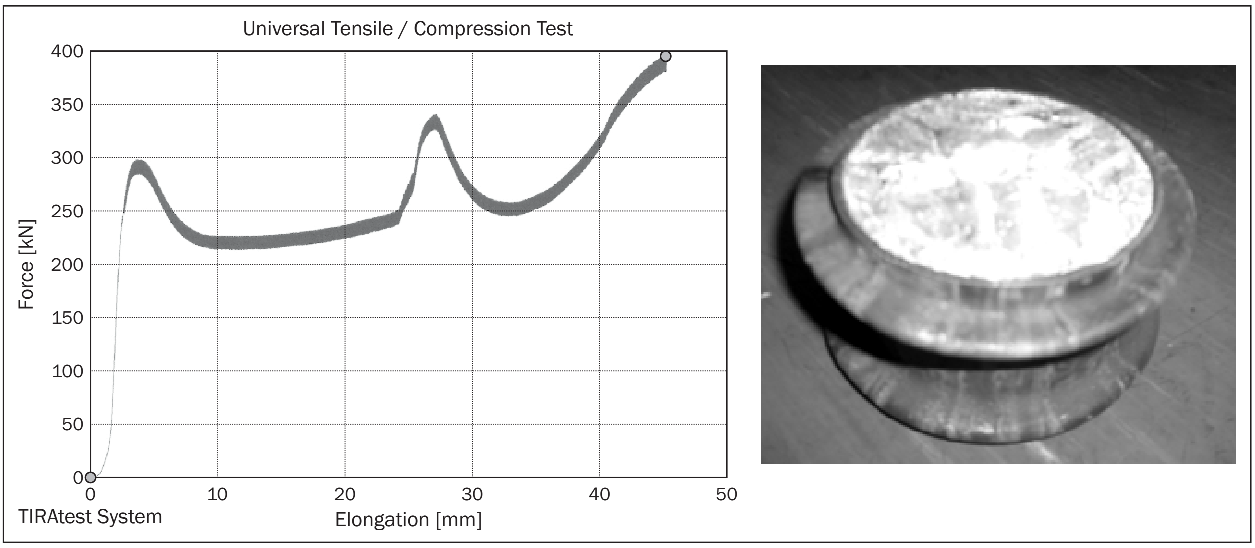

Figure 5 – "Force – elongation (compression)" diagram of a steel tube with aluminium foam

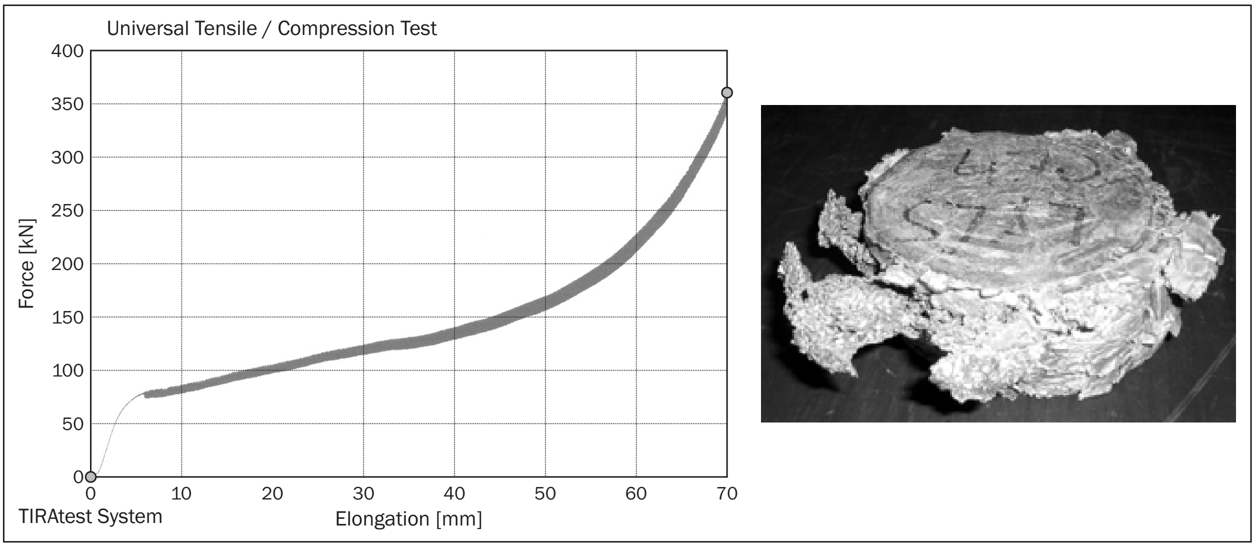

Figure 6 – "Force – elongation (compression)" diagram of aluminium foam

Further research was conducted regarding the influence of the aluminium foam chemical composition and density on the energy absorption.

In this research, two closed-cell aluminium foams were tested:

- Alulight AlSi 10 TiH_2-0.8,
- Alulight AlMgSi 0.6 TiH_2-0.4.

A powder compact foaming technique was used for producing the samples. An electric resistance furnace with a power of 2.5kW was used (located at the Laboratory for Non-metals at the Faculty of Mechanical Engineering and Naval Architecture). *Figure 7* presents the process of producing aluminium foam samples. A given mass of precursors is put into a mould, and then the filled mould is put into the furnace and treated at a temperature of 850°C for a given time required for the foaming process to be completed.

Figure 8 and *Table 1* show various aluminium foam samples.

Figure 9 presents stages in the process of sample testing.

Figure 10 presents aluminium foam samples after testing and *Figure 11* approximated "force – compression" diagrams.

In order to compare the results obtained for different samples, the dependence of absorbed energy for different forces is shown in *Table 2* and *Figure 12*.

From *Figure 12* it is obvious that the lower density foams can absorb more energy with a greater relative shortening. Also, one can notice that the Alulight AlMgSi 0.6 TiH_2-0.4 foam (marked with "SJAJ" /Eng. bright) is a material with better energy absorption capacity than the Alulight AlSi 10 TiH_2-0.8 foam (marked with "MAT") at lower densities.

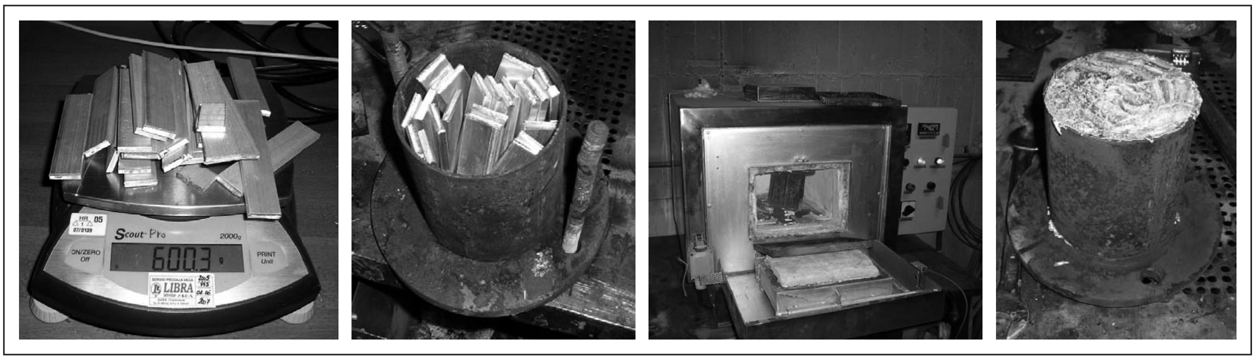

Figure 7 – The process of producing aluminium foam samples

Figure 8 – Aluminium foam samples with different densities and wall materials

Table 1 – Aluminium foam samples with different densities and dimensions

Samples	470 sjaj square	600 sjaj square	600 sjaj annular	470 mat square	470 mat annular
Material	Alulight AlMgSi 0.6 TiH_2 – 0.4			Alulight AlSi 10 TiH_2 – 0.8	
Dimension of samples, mm	76´	76´	f	76´	f
Mass (kg)	0.47	0.6	0.6	0.47	0.47
Density (g/cm^3)	0.81	1.04	1.07	0.81	0.83

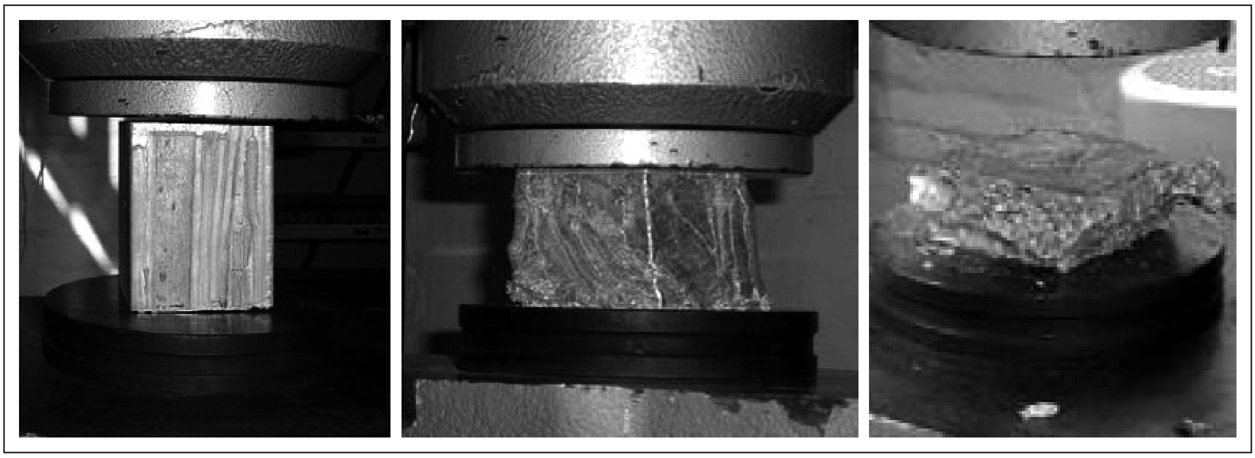

Figure 9 – Sample testing

Figure 10 – Samples of aluminium foam after testing

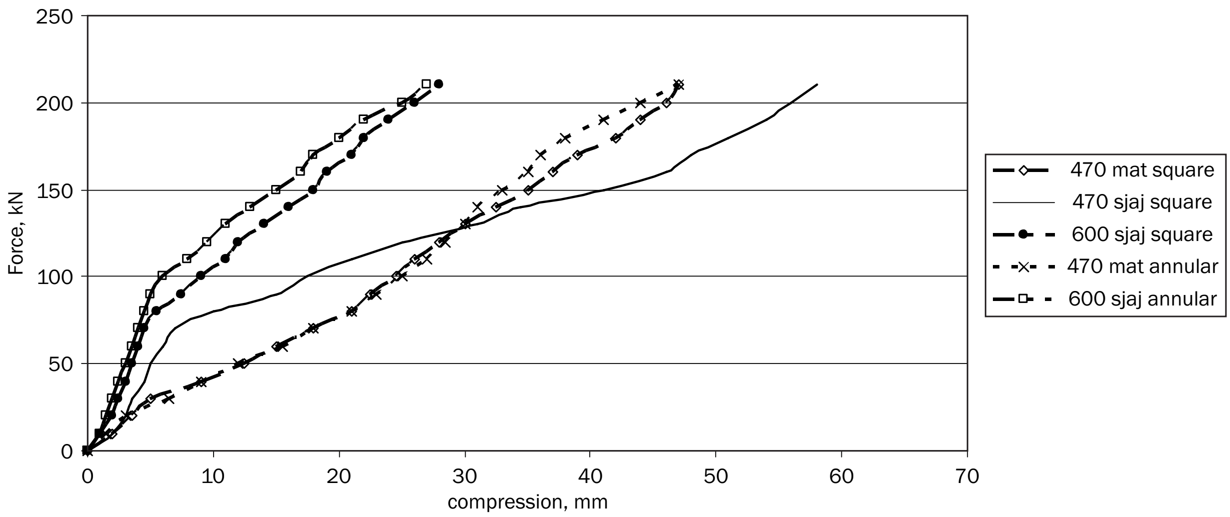

Figure 11 – "Force – compression" diagram of samples

Table 2 – Absorbed energy for different forces (E_{100} for 100kN, E_{150} for 150kN and E_{200} for 200kN)

Samples	Energy absorption, J		
	E_{100}	E_{150}	E_{200}
470 mat square	1,190	2,584	4,508
470 sjaj square	1,150	4,081	6,659
600 sjaj square	545	1,680	3,101
470 mat annular	1,284	2,285	4,251
600 sjaj annular	320	1,456	3,236

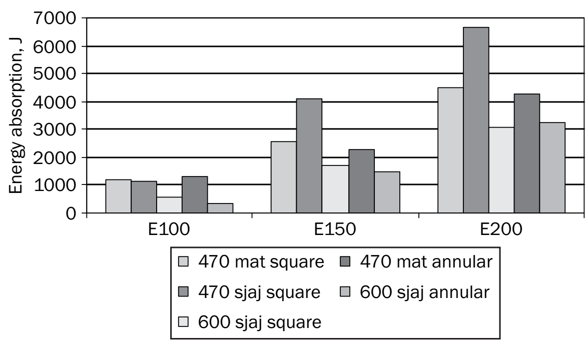

Figure 12 – Absorbed energy for different forces

4. ALUMINIUM FOAMS AND TRAFFIC AND TRANSPORT TECHNOLOGIES

The concept underlying the consideration of the application of aluminium foams in the design of the transport means is based on the unique combination of their properties. These are low density (0.3-1.0g/cm^3), capability of impact energy absorption and insulation properties [6, 7]. This combination in its essence is interesting to designers because it meets the today's often contradictory requirements. These are primarily the requirements to reduce the mass, i.e. to save energy, requirements for efficiency and safety of the means. By moderating the chemical composition of the matrix material, the density and structure of aluminium foam pores, as well as the possibilities provided by the composite structure, an entire spectrum of possible applications opens up (*Table 3*).

Weight reduction of vehicles of any traffic mode is the primary requirement faced by the designer profession since it affects directly the fuel consumption, payload transport as well as the vehicle performance. *Table 4* shows the savings expressed in $/kg in different transport systems.

The capability of aluminium foams to absorb impact energy is their property that caused the greatest interest in the designer-construction circles.

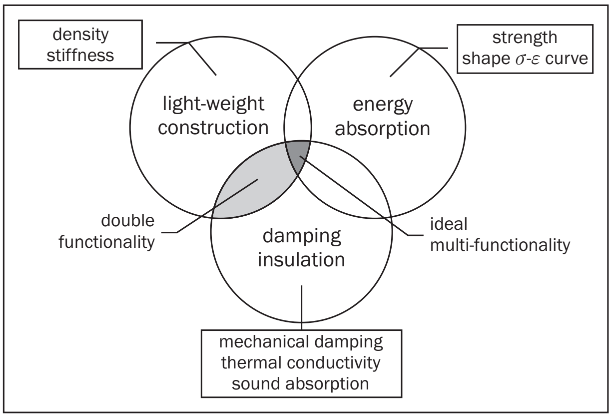

Figure 13 – Range of application of metal foams in automotive industry. The boxes contain the relevant property of the foam which makes it useful for one of the three fields of application presented in the circles [7]

Collisions or impacts are complex physical and mechanical phenomena that occur within a very short time interval. The study of collision mechanics is based on the Law of preservation of kinetic energy and the amount of movement. The difference in the amount of kinetic energy before and after the collision is proportional to the work necessary for deformation and fracturing of vehicle parts and the developed thermal energy due to friction [5].

During the impact process (compression), a sudden change of direction and vehicle velocity result in impact-contact forces whose destructive action threatens the lives of traffic participants and causes permanent damage to vehicles. The injuries of the passengers result as consequence of their inertial movement in the vehicle cabin or by impact of vehicle parts. The vehicle damages result from the deformation action of the impact forces.

Regarding its structure, a vehicle is a heterogeneous mechanical assembly which consists of a shell that houses a large number of components of various geometrical forms made of the materials of very divergent plastic/elastic characteristics [5, 16].

The origin of the impact forces is located in several points of the external vehicle surface. Since they depend on the impact area, mechanical properties of material, velocity, etc., during their propagation, i.e. progression of impact through the vehicle structure, they show a very complex flow. On their impact path and in impact time they change the direction and value, and thus impulsively deform various components, of various positions [5].

Table 3 – Possibilities of aluminium foam applications in the construction of transport means

	Application potentials for aluminium foam
Weight reduction	Casting core element Floating body element Constructions with high stiffness at low weight
Energy absorber	Crash absorber for mobile and stationary transportation means Safety pads for lifting and conveying systems Protective covers Blast mitigation
Acoustic, electromagnetic and fire insulation	Casingscover plates Filling material Absorption under different conditions (high temperatures, moisture, powder, vibrations etc.) Heat resistant, non-flammable constructions

Table 4 – Useful weight savings in transport systems [18]

Transport system	U(US $/kg)	High requirements and utility requirements
Family car (based on fuel savings)	05-1.5	CAFÉ limit or secondary weight savings
Truck (based on payload)	5-10	Value of payload
Civil aircraft (based on payload)	100-500	Power/weight ratio guarantee limit
Military aircraft (performance, payload)	500-2,000	Power/weight ratio guarantee limit
Space vehicle (based on payload)	1,000-10,000	Value of payload
Bicycle (based on perceived performance)	1-1,000	Tour de France standard

In principle, the dimension and the form of the deformation are the result of a complex relation of the impact force value, plasticity of material and impact area. The more solid and the harder the component material, the higher the impact forces and the shorter the impact time and the impact path. Then the acceleration/deceleration will be higher and the inertial forces will increase. The opposite is true in case of softer materials.

The components of today's vehicles are made of different metals, polymers and composite materials. The composite materials are of later date and in themselves represent a big unknown regarding the behaviour under different circumstances and loads in exploitation [16].

The response of the vehicle structure to the impact is in fact a simultaneous response of all its individual components. However, in practice, in detailed analyses, based on the consideration of individual responses, it is very difficult to define their individual behaviour during the impact, which includes also the share in the total response [17].

How to frame the relation of force transmission and/or deformation within the limits of the force value experienced or survived by the passenger in their cabin is therefore the main issue in all the studies of the vehicle impact behaviour [16, 17, 20]. The use of materials of high energy absorption capacity in the manufacture of target components in the vehicle structure seems as one of the solutions that might help significantly.

According to rough statistical data, in case of passenger cars, the most frequent impacts occur with the vehicle front part, about 67%, followed by lateral ones with about 22%. The components of these areas, externally or internally, are in fact the target areas of the possible aluminium foam application [19].

No less important are the possible applications in the construction of other transport means exposed to impact such as protective fences on roads, posts, then also important applications for the manufacture of tanks for the transport of various types of dangerous goods (explosives, radioactive substances, etc.).

Noise reduction in traffic is also an important issue. The requirements that are often present in the manufacturing of sound insulations are the resistance to heat and independence of elements that absorb sound. With current technology the aluminium foams do not feature the best sound damping due to predominantly closed porosities, but they are heat resistant and they are self-supporting. Further modelling of porosity and composition represent the path to the development of excellent material for sound insulation [7].

The concept which considers the use of aluminium foams in the construction of traffic means is in principle equal for all the traffic modes.

It is most similar in aircraft and automotive sector. In aircraft applications, the replacement of expensive honeycomb structures by foamed aluminium sheets or metal foam sandwich panels could result in better performance at reduced costs.

Modern passenger ships can be entirely built from aluminium extrusions, aluminium sheets and aluminium honeycomb structures. Large panels of aluminium foam with aluminium cores already express the potential to design the important elements of these structures.

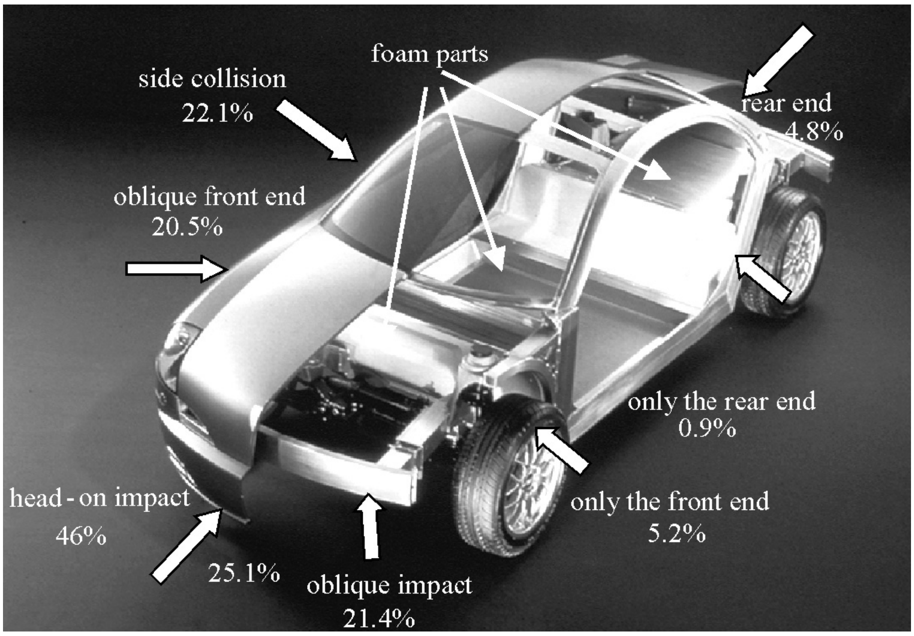

Figure 14 - Karmann car prototype with parts made of aluminium foam (courtesy of: IFAM, Bremen, Germany) along with collision types and associated in-vehicle injury cost

The application of metal foams in railway equipment follows conceptually the same rules as for automotive industry concerning the three main application fields. Impact energy absorption is an issue especially for light railway sets and trams which operate in urban areas where collisions with cars are more frequent. The advantages of foamed lightweight elements are the same as for cars, the main difference being that structures for railway wagons are much larger.

In space technology, the aluminium foam is intended for the manufacture of impact elements of space vehicle landing pads, as reinforcement for load bearing structures in satellites, etc. Their purpose is to replace the materials which cause problems in adverse environmental conditions in space (temperature changes, vacuum, etc.) [7].

The aluminium foams are available today on the market in substantial share. According to the estimates the demand will increasingly grow, with the highest increment precisely in the transport sector.

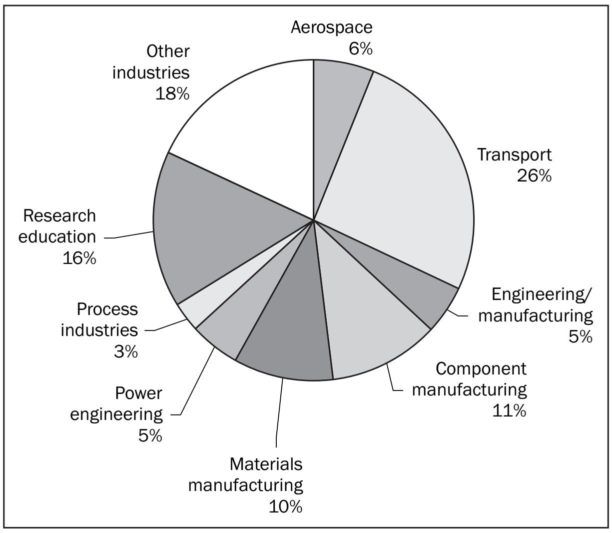

Figure 15 - Planned sector requirements for aluminium foam applications [19]

Consequently, the application of aluminium foams in the construction of transportation means in the first place the improvement of the energy-ecological and safety aspects and in combination with other series of the desired properties also the improvement of the traffic means efficiency, which eventually means also the improvement of the traffic and transport technology efficiency.

CONCLUSION

A static compression test was used to determine that aluminium foams exhibit good properties at the impact energy absorption. The performed static compression test showed that none of the samples had a pronounced strain phase at constant pressure. It was determined that lower density foams can absorb more energy with greater relative shortening. At lower densities, the Alulight AlMgSi 0.6 TiH_2-0.4 foam can absorb more energy with greater relative shortening than the Alulight AlSi 10 TiH_2-0.8 foam of the same density.

Further research and development of aluminium foams will enable better insight into their energy absorbing characteristics and the range of possible applications in the construction of transportation means. It is evident for the moment that there is high potential in this direction. The application of such materials would improve the efficiency of technology of traffic means, including the technology of traffic and transport.

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SAŽETAK

ALUMINIJSKE PJENE U IZGRADNJI PROMETNIH SREDSTAVA

Zahtjevi za smanjenjem težine i poboljšanjem performansi pri konstrukciji prometnih sredstava često su kontradiktorni zahtjevima za povećanjem sigurnosti. Jedan od mogućih načina udovoljavanja ovim zahtjevima je primjena metalnih pjena. Zahvaljujući celularnoj strukturi aluminijske pjene uz nisku težinu, sposobnost prigušenja zvuka i vibracija, pokazuju i izvanredne sposobnosti absorpcije energije udara. Njihova primjena u izradi udarno osjetljivih elemenata mobilnih ili stacionarnih prometnih sredstava znatno bi doprinijela smanjenju posljedica udara ili sudara.

Težište ovog rada je poboljšanje karakteristika apsorpcije energije aluminijskih pjena sa osvrtom na značenje njihove primjene za tehnologiju prometa i transporta.

U radu je analiziran utjecaj kemijskog sastava i gustoće na tlačno ponašanje aluminijske pjene. Uzorci aluminijske pjene proizvedeni su iz predkursora Alulight. Sposobnost uzoraka da apsorbiraju mehaničku energiju ocijenjeno je prema rezultatima tlačnih testova. Testovi su provedeni univerzalnim ispitnim strojem. Rezultati testa su pokazali da aluminijske pjene pokazuju dobru apsorpciju energije, a sposobnost apsorpcije se smanjuje s gustoćom pjene. Pjena Alulight AlMgSi 0.6 TiH_2 - 0.4 može apsorbirati više energije nego pjena Alulight AlSi 10 TiH_2 – 0.8.

KLJUČNE RIJEČI

aluminijska pjena, apsorpcija energije, otpornost na udar, sudari

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