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Alulight - Aluminum Foam for Lightweight Construction

Frantisek Simancik
Institute of Materials and Machine Mechanics SAS

Walter Rajner
Non Ferrum of America L.P.

Rainhard Laag
Alulight GmbH

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ABSTRACT

The new concept for design and manufacturing of lightweight load-bearing components has been presented. This concept is based on utilization of complex shaped hollow parts (such as hydroformed profiles or castings) which are (partially) filled with aluminum foam prepared by PM techniques. Partial foaming will improve the properties in weakest points of the hollow component which allows to design its overall thickness according to mean and not peak stress, thus saving the overall weight and increasing the property to weight ratio. Utilization of aluminum foam core will increase the capability of component to absorb crash energy in multiple impact directions. The reduction of noise and vibration of initially hollow component is expected as well.

INTRODUCTION

The research in automotive industry always focuses on new concepts that save the fuel consumption and CO_2 emissions, improve the passive safety and suppress the noise and vibration of future vehicles. These targets cannot be simultaneously achieved with recently used concepts; the improvements in safety and comfort lead always to a weight increase. Weight savings in load-bearing components are usually accomplished by a utilization of welded or hydroformed metallic profiles or castings having weight-saving cavities. However, the use of such hollow components is accompanied with high level of disturbing noise and vibration. Although hollow parts are often utilized as absorbers of crash energy, this property is usually effective only in one impact direction. The wall-thickness of these parts (often limited by the technology used) is mostly constant and is determined by most loaded section of the component, which leads to an additional weight in cross sections where it is not necessary.

DESIGN WITH ALUMINUM FOAM

The main aim of this paper is to suggest a new concept for design and manufacture of light-weight structural components based on utilization of complex shaped hollow load-bearing parts (such as hydroformed profiles or castings) filled with aluminum foam.

CHARACTERIZATION OF ALUMINUM FOAM

Metallic foams create a relatively new class of structural materials possessing enormous application potential in lightweight construction because of high stiffness at low apparent density, capability to absorb high amounts of deformation energy at relatively low impact forces and possibility to attenuate noise and vibrations [1]. Several of the engineering properties of metallic foams are superior to those of polymeric foams; they are stiffer by an order of magnitude, they are stable at elevated temperatures, they possess superior fire resistance and do not evolve toxic fumes in a fire. Because of low density and melting temperature the main attention is paid to the foams made of aluminum and its alloys.

Production of aluminum foams

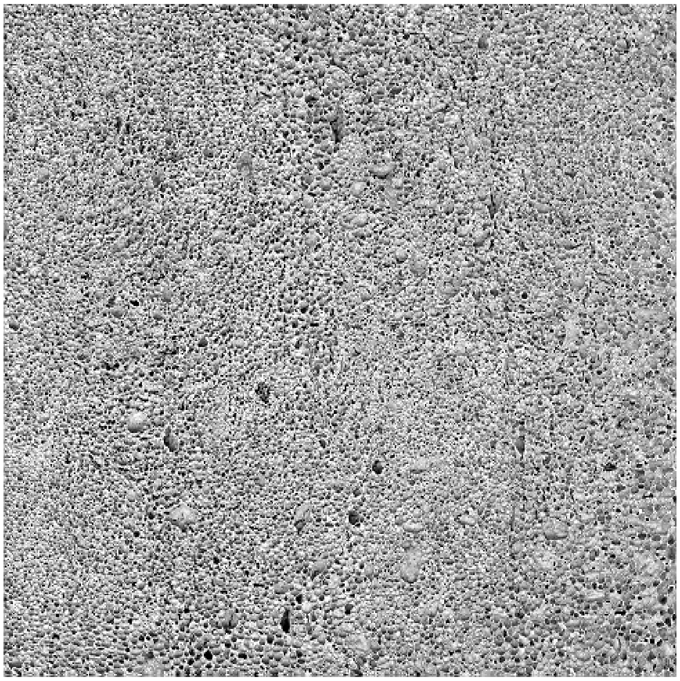
Aluminum foams can be prepared by various processing methods, such as foaming of the melt, investment casting or by powder metallurgical (PM) techniques [2]. The manufacturing technique affects the distribution of the cell-wall material in such a way, that the properties of differently manufactured materials are not comparable. Therefore the foaming process dictates also potential applications. Thus the foams prepared by PM techniques can be effectively used as net shape components, stiffening cores in castings or in complicated hollow profiles, whereas the foams prepared by melt route (typically large blocks or panels) can be used as voluminous energy absorbers, cores for sandwiches or for blast protection [3]. The open-celled foams (made by investment casting) are good for heat exchangers, sound absorbers or for electrodes in batteries [4]. The properties arising from the “typical” foam structure made by one of the foaming techniques, cannot be effectively achieved with the foam prepared by another method. This means that aluminum foams manufactured differently are not necessarily competitive materials.

PM route for production of aluminum foams

Over the past ten years a range of techniques has been developed for production of aluminum foams with acceptable reproducibility of the properties at reasonable cost to be used also in automotive industry. However, realistically seen, only near-net-shape foam components containing a dense skin (cast or foamed in a mold) can be effectively applied. Manufacturing of such components needs to enhance the foam stability since the liquid foam tends to coarsening and gravitational stratification during holding at foaming temperature. One way to eliminate rapid cell coarsening and foam collapse is to increase the melt viscosity by incorporation of very fine refractory particles into molten aluminum alloy [5]. This can be effectively achieved by using of powdered precursor material always containing a certain amount of oxides on the surface of powder grains. Therefore, the most promising technology enabling nowadays the production of net shape foam components is based on PM process.

Manufacturing of metallic foams from metal powders (typically aluminum and its alloys) and particulate foaming agents (typically TiH_2 and ZrH_2) was patented in 1963 by Allen et al [6]. The metal and foaming agent powders are blended, cold compacted and then extruded at about 400-480°C. The foaming agent thus becomes uniformly distributed and gas-tightly embedded in the metal matrix. The extrusion process is useful in helping to break up the oxide films on the surface of the metal powders, which facilitates consolidation. The product may be considered as a precursor material, itself not far from full density but readily convertible to a foam. This conversion is effected by simply heating the precursor to a temperature at which the alloy is liquid. The foaming agent evolves gas, thus creating a foam which is stabilized by very fine oxide particles uniformly distributed throughout the precursor after extrusion. The final step of the process is a rapid cooling of the obtained structure. If metal hydrides (corn size of about 5 μm) are used as foaming agents a content of less than 0,5% is sufficient in most cases. The optimum grain size of metal powder lies in the range of (60-200) μm. The precursor can be principally prepared from powders made of any casting or wrought aluminum alloy. However the choice of the alloy considerably effects the quality of the foam:

a: casting AlSi12 alloy



b: wrought AlMg1Si0.6 alloy

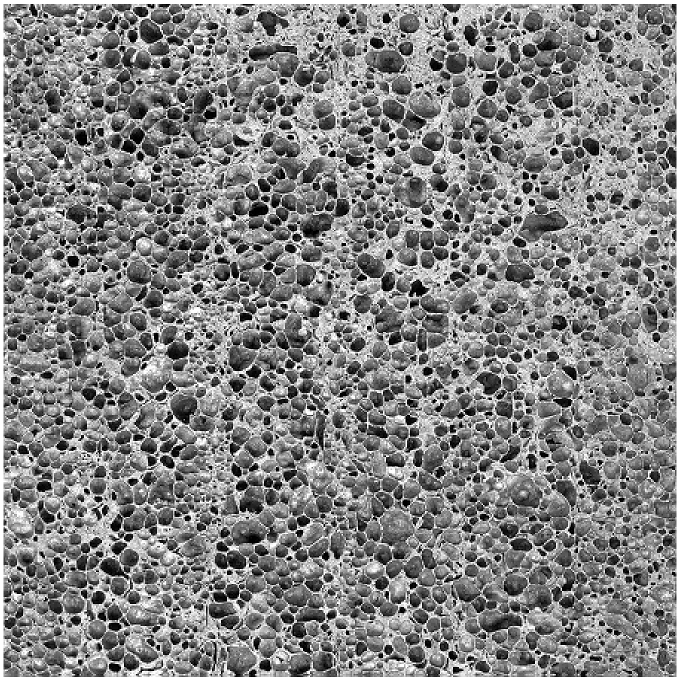


Figure 1: Structure of aluminum foam prepared from different aluminum alloys (density of both samples is about 0,5 g.cm^{-3})

- Casting aluminum alloys (AlSi8, AlSi10, AlSi12) are suitable for the production of more complicated foamed components because of lower viscosity, low surface tension, better resistance to oxidation of the molten metal and the resulting good fluidity. These properties make also possible the preparation of foams with lower density and lower average size of pores. Pore walls as well as the surface skin of the foam are relatively thin (see Fig. 1a). Pore shapes are considerably irregular (nonspherical), often mutually interconnected and possessing a large number of cracks. Due to the cracks, the porous structure is partially or fully open and allows the penetration of gas or liquid. Practical advantage of casting aluminum alloys is the lower melting temperature, i.e. lower foaming temperature and thus longer mold and equipment endurance limit and shorter foaming stroke too. The main disadvantage of aluminum casting alloys is their low plasticity resulting in more difficult compacting of the precursor and the high sensitivity of the foam to fracture under loading in tension.
- Wrought aluminum alloys (Al, AlMg, AlMgSi, AlCuMg) are suitable for the production of foamed components with a higher plasticity. Pores are more spherical and mostly closed. The average pore size

is principally higher than in the case of casting alloys and the pore walls and the surface skin are thicker (see Fig. 1b). The resultant apparent density is comparable with foams made of casting alloys. The main advantage of these foams is their higher plasticity that allows, to a certain degree, also the subsequent forming. When the age hardenable alloys is used, the strength of the foam can be further improved by an appropriate thermal treatment, however with simultaneous reduction of the foam's plasticity. Because of poor corrosion properties, the use of Al alloys containing Cu and Zn is not recommended.

The precursor can be foamed into various products like panels, profiles or complex parts using the novel foaming techniques which are usually "tailored" to the part to be foamed. The main benefit of the powder metallurgical method recently developed at Institute of Materials and Machine Mechanics of the Slovak Academy of Sciences, Bratislava, for the Austrian company MEPURA, is the possibility to use the simple-form precursor e.g. extruded rods or ribbons for foaming of components with different shapes and sizes. This possibility lowers the high production costs that represented the main disadvantage of the PM process for the production of metallic foams. Aluminum foam produced in this way has a tradename ALULIGHT (trademark of Mepura GmbH). Three principally different foaming techniques are available at present:

1. **Foaming in the mold** in which the precursor is distributed and then heated together with the mold in a furnace up to the melting point of used aluminum alloy. After melting and foaming, the mold is rapidly cooled to prevent collapse of the foamed structure. This technique needs special thin walled molds withstanding temperature changes and is restricted to the production of rather simple shapes and small sizes. Larger parts such as foamed panels are foamed in special setup that provides simultaneous molding, heating and cooling. Sandwich panels with foamed cores can also be produced via foaming of PM-precursor between metal sheets (aluminum or steel). The liquid foam adheres to the solid sheets in the course of expansion, forming a diffusion bond. This type of bonding provides a certain formability of the sandwich and results in a significant improvement of the mechanical properties and the thermal stability in comparison with glued or brazed sandwiches. One of attractions of the process is that the sandwiches are prepared in one technological operation what significantly reduces manufacturing costs. Also shaped sheets can be used as a cover.
2. **Casting of liquid foam** [7] is based on low pressure casting process. The liquid foam is formed from the PM-precursor outside the mold in a special container and then it is injected in a controlled manner into the desired cavity. Metallic molds, hollow profiles or even sand molds can be used as a cavity, thus allowing cost effective large and small scale production and prototyping. Complex 3D-shaped foams can be produced in this way with a wall thickness from 3 mm.
3. **Foaming in hollow profiles** does not require a mold. The foam is prepared from the PM-precursor directly in a hollow thin-walled profile and remains inside the profile in order to improve its mechanical properties. The profile can be filled with a foamed material also continuously in computer controlled way. Sometimes the profiles are filled only partially in weakest sections.

The foamed parts prepared by PM-techniques are always covered by dense aluminum skin, which significantly improves the mechanical properties (e.g. bending stiffness, etc.) and metallic appearance of the foam. Such foams can be considered as a "special aluminum profile" with more or less isotropic properties, what is its the main advantage in competition with common aluminum profiles, such as tubes. Moreover there are almost no constraints considering complexity of the outer shape and geometry of foamed components.

The foams have usually non-uniform pore structure - variable pore size and sometimes also preferred orientation of pores). These effects are inevitable; it is not possible to achieve an equal heating rate for all parts of the complex mold and uniform temperature distribution by recently used technologies which leads to variable pore size. A preferred orientation of the pores arises from the arrangement of the foamable precursor in a mold or from the flow of the molten foam during casting [3]. Nevertheless, it should be noted that a uniform structure is not necessary to obtain acceptable and reproducible properties. Natural load bearing structures such as bone or wood are also not uniform and not isotropic, because they have an optimum distribution of the cell-wall material according to the loading requirements. Accordingly the challenge for the foam producer is to obtain a structure similar to bone-like one as it can be seen in Fig. 2.

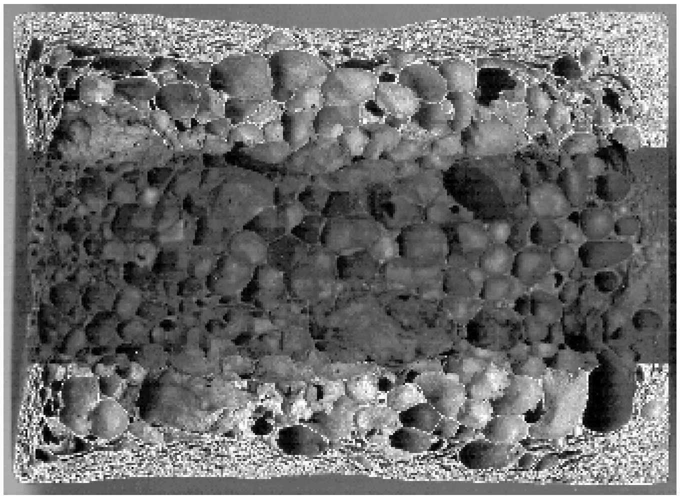


Figure 2: Gradient structure of AlSi12-alloy foam

Typical properties of aluminum foams

The foaming process principally does not affect the properties of the cell-wall material. However, it leads to a unique spatial distribution of aluminum which results in significantly different properties of foamed component in comparison with a bulk part. It is obvious that the properties of aluminum foam significantly depend on its porosity, so that a desired profile of properties can be tailored by changing the foam density (see Fig. 3). This is one of the attractive aspects of this remarkable material.

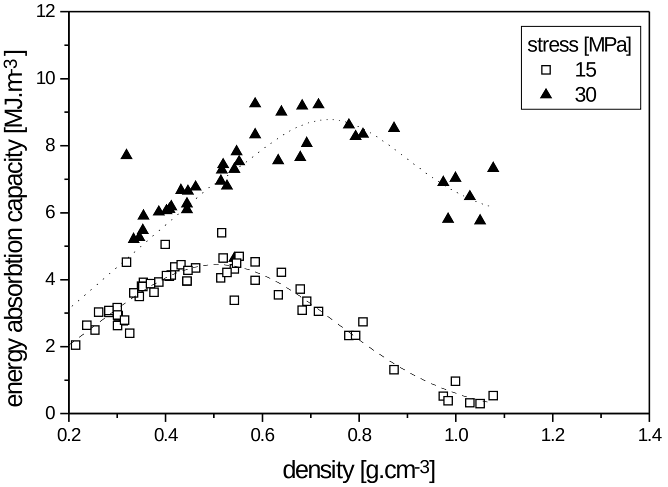


Figure 3: The optimization of the density range for maximum energy absorption capacity for different stress levels. (static compression test, AlMg0.6Si0.3 alloy, cylindrical samples ϕ20 mm without surface skin)

The size and distribution of pores in a metallic matrix is random. The exact definition of the foam structure is very difficult. Therefore, the properties of foamed component are usually evaluated according to its apparent density. A typical porosity level of PM-foams lies in a range of 70-90 % of the total volume which gives the apparent densities in a range of 0.3-0.9 $g.cm^{-3}$. Some of the properties of aluminum foam, such as modulus of elasticity, plastic collapse stress, thermal and electrical conductivity, etc., can be estimated from the apparent density of foamed component according to the scaling relation of the type [8]:

$$\frac{K}{K_S} = z\left(\frac{r}{r_S}\right)^t$$

where K and r are property and density of the foam, K_S and r_S are property and density of the cell-wall solid, and z and t are constants which depends on the structure and considered property. On the other hand, some of the properties, such as thermal expansion, specific heat etc., do not depend on the porosity and are the same as for a bulk material.

It should be noted, that scaling relations, originally developed for polymeric foams, assume uniform cellular structure at least at a macroscopic level. However, aluminum foams are dramatically different from polymeric foams: polymeric foams generally have a regular microstructure, whereas metallic foams are highly disordered with a wide dispersion of cell size and cell shape. Moreover, many imperfections exist in a cell structure, such as cracks or holes, corrugations etc. If these features are not taken into account and the properties of the foam are characterized only in relation to apparent density, a higher scatter of properties can be expected. Accordingly, the properties of the foam should be predicted by statistical methods using suitable distribution function [3].

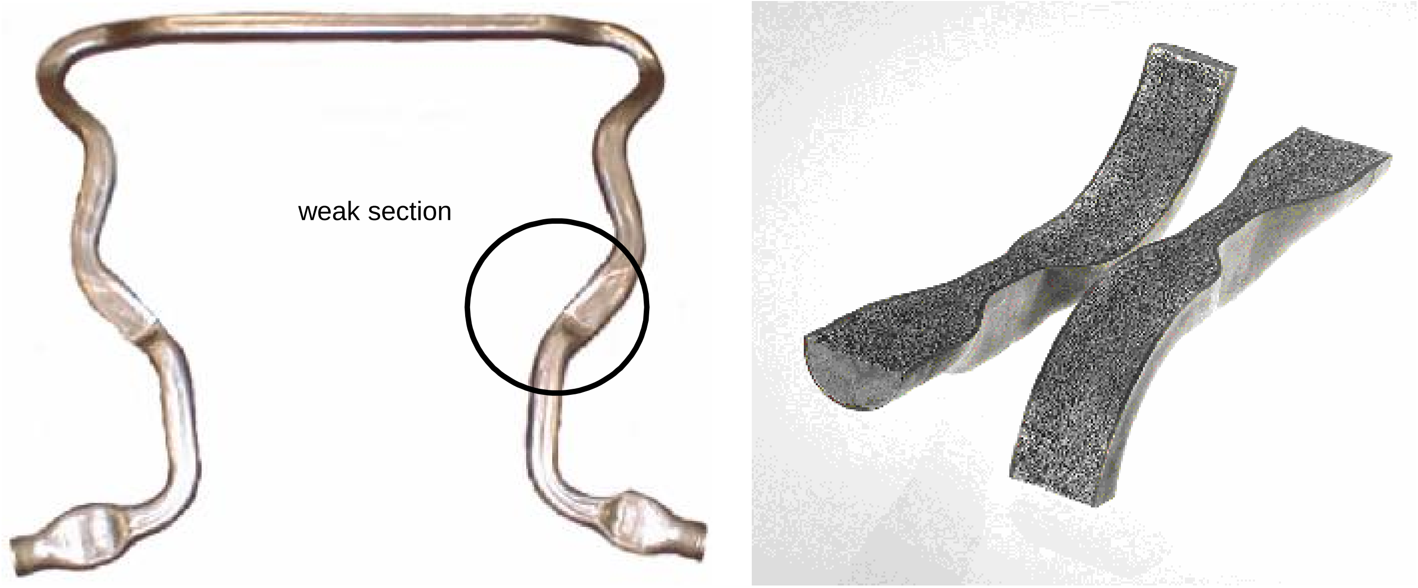
In fact, most of the individual aluminum foam properties can be achieved also with another materials, sometimes even more effectively. However, aluminum foam can offer a unique combination of several (apparently contradictory) properties that cannot be achieved by one conventional material at the same time (e.g. ultra-low density, high stiffness and capability to absorb crash energy, low thermal conductivity and magnetic permeability, acceptable electric conductivity, efficiency in sound and vibration damping or electromagnetic shielding [4]).

FOAMED HOLLOW PROFILES

The hollow load-bearing components are usually made of steel or aluminum in vehicle design. Without replacing the material (changing the elasticity modulus) their bending (torsion) stiffness-to-weight ratio can be maximized only by increasing moment of inertia of the most loaded cross-section. This can be achieved by reduction of wall thickness with either simultaneous implementation of internal stiffeners (ribs) or enlarging of the cross section (volume increase). Other approaches leads always to the weight increase of the component. However there is a lot of technical limitations and disadvantages concerning the above mentioned possibilities:

- Welded structures or hydroformed profiles are manufactured from metallic sheets or tubes with a constant thickness (there is only a little flexibility to vary the thickness according to the loading requirements). The thickness is determined by the most loaded section, which leads to an additional weight in the sections where it is not necessary. Moreover the thickness is often limited by available pressing forces or by the technology (e.g. hydroforming can be only used for a limited thickness range)
- Internal stiffeners (ribs) are possible only if welded hollow components are concerned. However, this approach considerably increases the manufacturing costs, it is time-consuming and has a negative impact on environment (welding).

In modern vehicle design the expensive welded structures consisting of many components can be replaced by hydroformed profiles (see Fig. 4). In mass production this will lead to significant reduction of costs and manufacturing time. Starting material for such profile is usually tube with a constant thickness. However, the component has a variable thickness after forming that is often insufficient in the most loaded sections. Therefore, the starting thickness of the tube has to be chosen according to these sections, resulting in a weight increase in sections where it is not necessary. Moreover, increasing of the starting thickness requires higher pressing forces and sometimes even excludes the possibility to use this technology. According to the proposed concept the stiffness of hydroformed profile can be enhanced using aluminum foam. Partial foaming will improve the properties in weakest sections (see Fig. 4) of the profile, which allows to design its overall thickness according to a mean and not a peak stress. This approach increases the property-to-weight ratio of the component. The effect of (partial) foaming on bending properties of hollow components is illustrated with the results of three-point-bending tests on foamed steel tubes (Table 1 and Fig. 5).



a

b

Figure 4: Motor carrier made by hydroforming (a) filled in weakest sections with aluminum foam made by PM-process (b)

Table 1: Bending properties of steel tubes partially foamed with AlSi12 alloy (density 0.65 g.cm^{-3}).
(three-point-bending, cross head speed of 10 mm/min, span between supports of 300 mm)

sample: steel tube ϕ40 - 400 mm wall thickness 0.7 or 1.5 mm	weight [g]	bending force at collapse [N]	deflection (y) at 1500 N [mm]	bending force at y = 9 mm [N]	absorbed energy at y = 9 mm [MJ]
empty tube 0.7 mm	272	1460	2.61	1240	11.2
tube partially foamed *	304	2670	0.93	2725	21.1
tube fully foamed	541	5250	0.51	5428	39.9
empty tube 1.5 mm	557	3642	0.28	3919	32.8

* partial foaming 100 mm in the mid of tube

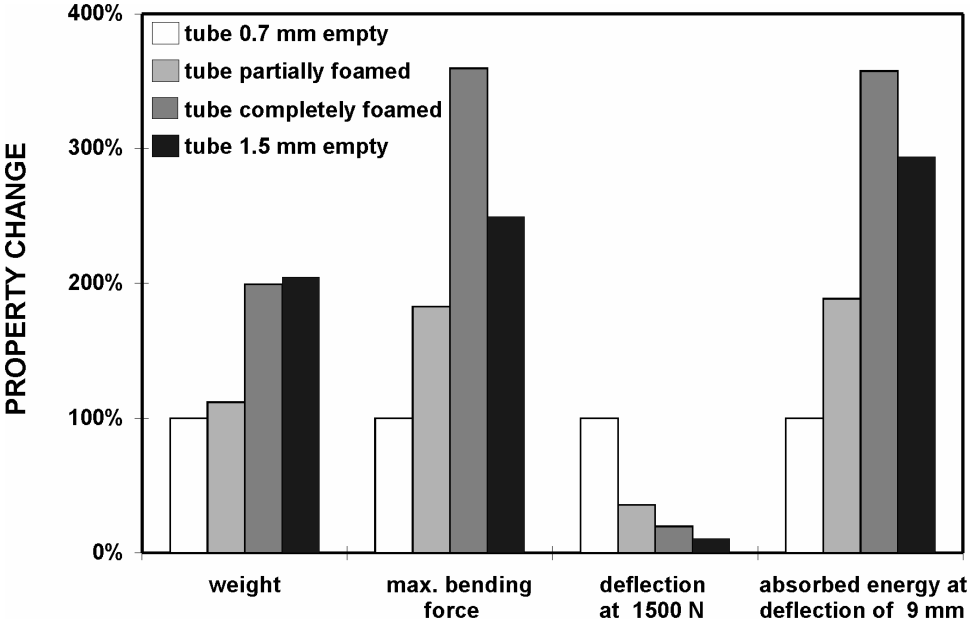


Figure 5: Effect of partial filling with foam on bending properties of steel tubes (see also Table 1)

Figure 6: B-column (a) and suspension part (b) reinforced with aluminum foam insert.

Aluminum foam can also be utilized for stiffening of welded components. In this case the foamed part is inserted into the component before welding without significant changes in common technological process (Fig. 6). It enables cost effective stiffening of existing components for small series application submitted to increased loading (e.g. heavier engines, off-road conditions etc.).

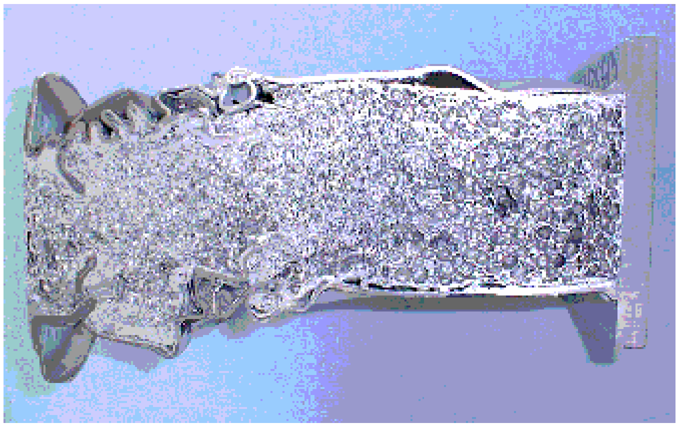


Figure 7: The motor carrier filled with aluminum foam after frontal impact (from the left side).

Many of today's vehicles incorporate deformable energy absorbing elements within the vehicle structure in order to increase passive safety during impacts. These elements represent the crushable zones and have to manage the collision energy for the rigid passenger cell protection, reducing also the deceleration during the impact [9]. Fig. 7 shows that aluminum foam seems to be very efficient also in this application. It can be seen in Fig. 5 that the energy absorption ability of partially foamed steel tube is almost twice higher than that one of the hollow tube of approximately same weight at the same deflection.

Beside stiffening and increasing energy absorbing capabilities the reduction of noise and vibrations is also expected (see Fig. 8). Because of relatively low loss factor, aluminum foam cannot provide good damping characteristics if the vibrations are transmitted directly from the vibrating profile into the foam core [10]. However, this is only in a case of a very good (usually metallurgical) bonding between foam and shell. Without this bonding good damping has been observed. The main reason for this behavior is a friction arising between profile and foam surface which results in a heat dissipation of vibrational energy.

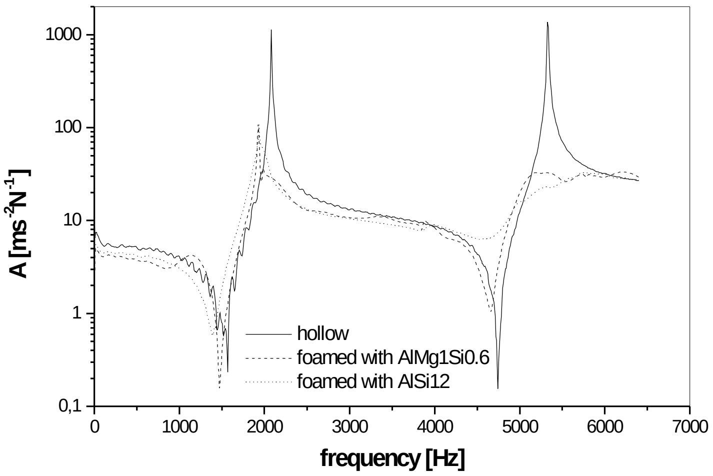


Figure 8: Frequency spectra of reciprocal mass for hollow profile and profile foamed with various types of aluminum foams (steel tube ϕ 22/18 x 245 mm density of the foam 0.7 g.cm^{-3}).

FOAM CORES IN CASTINGS

Thickness of cast components is also limited in a relative narrow range, depending on casting technique. Hollow components are usually cast around sand cores, which have to be removed from the part after solidification (high labor costs and environmental impact). If sand cores are used low output techniques (e.g. gravity casting) can only be applied. Moreover, only simple shape cavities can be designed and each cavity needs an opening for sand removal.

According to the suggested concept, the complex shaped aluminum foam part can be used as permanent cores in a casting, thus replacing the hollows used before for the weight reduction. The weight increase can be eliminated by reduction of the shell-wall thickness while the mechanical properties remain unchanged or are improved. The main goal is the possibility to accomplish completely closed lightweight sections in the casting and to create internal configurations (ribs) not feasible with sand cores. The relatively small cross-sections can be also filled up with foamed core (space holder). This approach saves an additional weight. The very important reason is avoiding of the sand cores because of their cost intensive removal from the casting and ecologically harmful sand reclamation.

The thickness of the skin on the foam surface allows to pour a liquid metal around the foam core without danger of infiltration. Sound castings can be produced if the core is properly preheated. The preheating of cores prevents excessive heat flow from the melt into the core, thus enabling considerable reduction of the shell thickness in comparison with usual sand core, which cannot be preheated. This is a very important, since it is desirable to offset the weight of the foam core through a reduction of the shell thickness [11].

The foam-cored castings are expected to be effectively applied as highly loaded structural components, such as subframes, cross-members, control arms etc. Systematic investigation of different techniques for casting of shaped components and evaluation of possible contributions are the main preconditions for the introduction of this application into practice. Development of technological methods for the preparation of shaped components suitable for this purpose is under intensive research at the moment. The aim of the investigation is the reduction of weight and costs of shaped aluminum foams via optimization of the manufacturing process [12].

CONCLUSION

The main aim of the paper was to present a new concept for design and manufacture of light-weight load-bearing structures. This concept is based on utilization of aluminum foam made by PM-process for stiffening of hollow welded or hydroformed profiles or aluminum castings.

Hollow profiles can be only partially filled with a foam, thus improving the properties in weakest sections of the profile. This enables to design its overall thickness according to mean and not peak stress. It will lead to the reduction of overall weight and to an increase of property-to-weight ratio. This will also allow the use of hydroformed components in applications where it is recently not possible. Finally it will avoid a cost intensive welding of internal stiffeners.

Internal configurations can be accomplished in aluminum castings with permanent foam core. Due to the supplementary stiffening effect of the foam and the possibility to preheat it, significant reduction of the shell thickness can be obtained. Aluminum foam core enables application of high volume production casting techniques (squeeze casting, HPDC, thixocasting), so far not accessible with sand cores.

The proposed technological approach allows the distribution of load-bearing material in most convenient way according to loading conditions, without need to increase the overall weight or volume of the part. This effect can be further enhanced applying foams with gradient and anisotropic distribution of the cell-wall material, thus simulating optimum bone-like structure.

Utilization of aluminum foam core increases the capability of component to absorb crash energy in multiple impact directions.

The reduction of noise and vibration of initially hollow component can be expected as well.

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CONTACT

Frantisek Simancik
Institute of Materials & Machine Mechanics SAS
Racianska 75, SK-838 12 Bratislava, Slovak Republic
e-mail: ummssima@savba.sk
www.savba.sk/sav/inst/umms.

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