# Metallic foams – ultra light materials for structural applications

## ABSTRACT

Metallic foams are relatively unknown structural materials, however with enormous future potential for applications where lightweight combined with high stiffness and acceptable manufacturing costs are of prime interest. The performance of metallic foams, in particular those made of aluminium, in various prototypes, such as foamed panels, sandwiches, complex 3-D-parts, foamed hollow profiles as well as castings with foamed cores, has been discussed with respect to the expected and achieved goals. The important contributions of aluminium foam to the improvement of the product's properties are highlighted and most promising utilisation is suggested.

## INTRODUCTION

The evolution of a mankind is going hand in hand with the request for new constructional and tooling materials. Until recently, the principal evolutionary forces were those relating to improved performance and functionality. Although the polymers, ceramics or composites have been already employed in various industrial applications the demand for stronger, stiffer and lighter material is still growing. However, the production, disposal and use of materials in products have the environmental impacts throughout the whole product life cycle, and this fact cannot be longer ignored.

The strong and stiff materials can be found also in the nature but they usually do not induce any recycling and pollution problems. The difference between natural and artificial structural materials was very well characterised by Ashby [1]:" When modern man builds large load-bearing structures, he uses dense solids: steel, concrete, glass. When Nature does the same, she generally uses cellular materials: wood, bone, coral." Really, natural materials are strong enough to withstand loads in bones of running elephant or to carry the weight of 100 m high redwood tree. Cellular structure in these cases provides the tool for the realisation of optimal combination of properties, e.g. highest stiffness at minimum weight (Fig.1).

A man within living memory tried to imitate the nature. The development of new structural materials is therefore more often oriented to the creation of artificial cellular solids similar to natural structures. Polymer and ceramic foams are widely used for isolations, filters, or in packaging. However they cannot be used for constructional purposes, due to insufficient rigidity (low elasticity modulus of polymers), or brittleness of ceramics. Mentioned obstacles lead to extensive development of metallic foams based on lightweight metals, especially aluminium and its alloys.

Although the first metallic foams appeared already during 2nd world war, they have remained almost unknown for designers up to now. Due to the development of new technologies, which enable the manufacturing at reasonable costs [2], this type of material becomes again very attractive and makes a strong impetus for rapid increase of R&D activities in this field. The main reason for these activities lies in unusual combination of the properties offering by the foam, in particular high stiffness at low density, high impact energy absorption capacity at low stresses, and the good damping properties. 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.

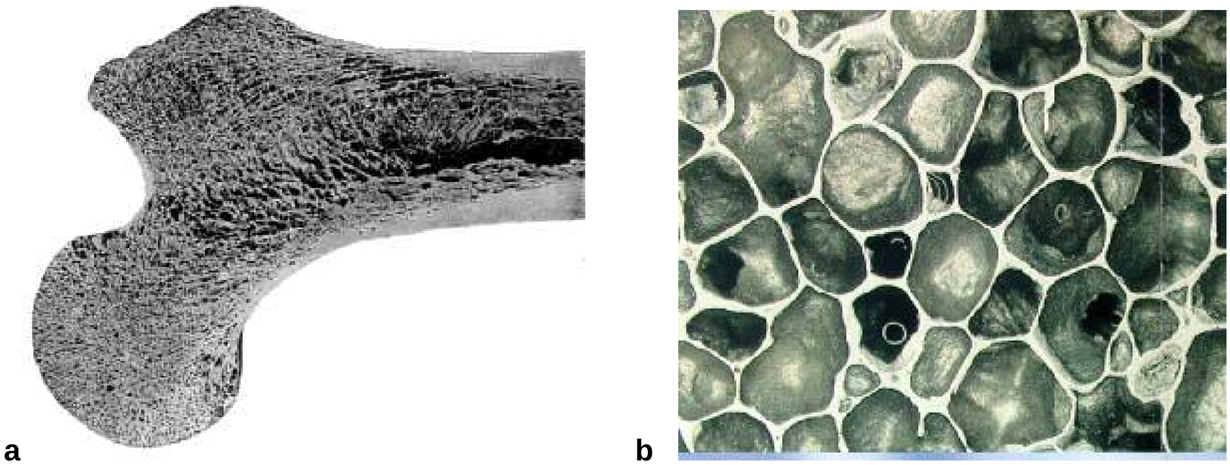

**Fig.1. Natural and artificial cellular structures: (a) bone; (b) aluminium foam**

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## MANUFACTURING OF METALLIC FOAMS

Metallic foams arise by nucleation and subsequent growth of gas pores in a liquid or semi-liquid metal. The distribution of pores is therefore pretty random. The pores are initially closed although some cracks or openings can be found in the cell walls after solidification and cooling. These are the main features of this kind of cellular solids. Metallic foams can be principally prepared by direct foaming of the melt or by powder metallurgical (PM) techniques

Molten metal is foamed by blowing a gas in the liquid alloy [3] or by admixing of foaming agents, which decompose at elevated temperature evolving a pore forming gas [4, 5]. Metallic hydrides releasing hydrogen, or carbonates releasing $CO_2$ are most frequently used as foaming agents. The presence of gas in the molten metal requires considerably higher viscosity, that is achieved by additional alloying, e.g. with B, Na, Ca or by addition of insoluble ceramic particles (SiC, $Al_2O_3$) [6]. Though the process of direct foaming of the molten metal is economically most efficient, the forming of the foam structure can be controlled only with difficulties and the achievement of more complex shapes is not possible. As the molten foam cannot be cast yet, this fabricating method is limited to the production of large foam blocks that can be machined to simple shape components. The surface of the component is "open" revealing the cellular structure of the material. Aluminium foam fabricated in this way exhibits closed pore structure with the total porosity in the range ~ 80-95 % [6] and is being used mostly combined with other metallic materials for damping and insulating purposes, as a core in glued or brazed sandwiches or as absorbers in blast or crash protection.

Alternative technique (GASAR-process [7]) is based on the saturation of the molten metal in an autoclave at a controlled hydrogen pressure until the eutectic concentration is achieved. The controlled cooling results in the formation of eutectics consisting of oriented hydrogen pores and of the solidified alloy. The size, orientation and morphology of pores can be affected by pressure, cooling rate and orientation during directed solidification. Size of the pores is in the range from micrometers to several millimetres and the porosity is in the range 5-75 %. The possibility of the preparation of oriented porous structures belongs to the main advantages of this method. High costs and dangerous technique can be outlined among the main disadvantages of the process. It is possible to produce metallic foams based on Ni, Cu, bronzes, Mg, Al, Co, Cr, etc.

**PM techniques** comprise foaming of the precursor prepared by compacting of powdered metal or alloy, whereas the pore forming gas is developed during melting of this precursor from admixed foaming agent [8]. The powder must be thoroughly compacted in order to seal the particles of foaming agent. This avoids the premature release of the gas at heating. The formation of the pores starts during the melting of the metal matrix. If the precursor is inserted in a suitable mould before foaming, the foam follows its shape. Subsequent rapid solidification produces final shaped component with a continuous surface skin and a cellular internal structure. PM foams can be prepared with gradiently variable pore size and also with preferred orientation of pores. The possibility to use the simple-form precursor e.g. extruded rods or ribbons for foaming of components with various shapes and sizes [9] lowers the high production costs, which represented the main disadvantage of PM process.

An alternative method is gas foaming (mostly using Ar), which is pressurised into a metal can filled by powder of the same metal as the can. The can is then sealed by welding and compacted by hot isostatic pressing. Subsequent heating causes expansion of enclosed gas, which creates pores in the mould [10]. This method allows production of sandwiches with foamed core and originally was developed for manufacturing of aircraft wings. However, the porosity of foamed core is highly limited (max. 40%) and the method is too expensive for practical use.

Relatively new process is foaming using reactive sintering [11]. The pores are created in the compacted powder mixture by gas resulting from a chemical reaction among elements at sintering temperatures.

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 metallic foams manufactured differently are not necessarily competitive materials. The most promising technique for the manufacturing of net shape foamed parts is based on PM-process [8, 9]. There are almost no constraints considering complexity of the outer shape and geometry. Three principally different foaming techniques are available at present:

- Foaming in the mould in which the precursor is distributed and then heated together with the mould in a furnace up to the melting point of used alloy. After melting and foaming, the mould is rapidly cooled to prevent collapse of the foamed structure. This technique needs special thin walled moulds 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 set-up that provides simultaneous moulding, heating and cooling
- Casting of liquid foam [12] is based on low pressure casting process. The liquid foam is formed from the PM-precursor outside the mould in a special container and then it is injected in a controlled manner into the desired cavity. Metallic moulds, hollow profiles or even sand moulds 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.
- Foaming in hollow profiles does not require a mould. 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.

PM foams are always covered by dense skin, which significantly improves the mechanical properties (e.g. bending stiffness, etc.). However the natural skin of foams has variable thickness and sometimes contains small holes or even cracks. These inevitable defects can initiate premature fracture of the foam, especially when they appear on the tensile loaded surface of foamed part. Reinforcing of tensile loaded surface skin with metallic or ceramic wires woven into grids with various mesh size can solve this problem very efficiently. According to a novel foaming technique developed recently [13], the reinforcements are placed in the foaming mould together with foamable precursor and the foam expansion moves them to the mould surface where they are infiltrated with molten cell-wall material. The main advantages of this method are its simplicity, lower manufacturing costs and the possibility to reinforce the foamed part selectively and anisotropicly according to the applied load.

Sandwich panels with foamed cores can also be produced via foaming of PM-precursor between metal sheets (aluminium 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 the attractions of this 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. The skin and the properties of the foam can be alternatively enhanced by casting of bulk-metal shell onto the foam [14] or by filling hollow metallic part with the foam [15].

## PROPERTIES OF METALLIC FOAMS

Metallic foam is a highly porous cellular material were pores represent 65 - 90 % of the total volume. The foaming process principally does not affect the properties of the cell-wall material. However, it leads to a unique spatial distribution of metal, which results in significantly different properties of foamed component in comparison with a bulk part. The cellular structure generates thus the properties, which cannot be obtained by conventional treatments. It is obvious that the properties of metallic foam significantly depend on its porosity, so that a desired profile of properties can be tailored by changing the foam density. Anisotropic or gradient pore structure allows the distribution of load bearing material in most convenient way according to loading conditions (simulating optimum bone-like structure), without need to increase the overall weight or volume of the component. Foam is crushable enabling to convert kinetic (crash) energy into heat at adjustable stresses. These are some of the attractive features of this remarkable material.

Moreover, the metallic foam

- is fire resistant, non inflammable and does not evolve toxic fumes in a fire
- is fully recyclable and thus environmentally friendly
- has high capability to absorb crash energy
- has low thermal conductivity and magnetic permeability
- is efficient in sound and vibration damping or electromagnetic shielding.

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$^{-3}$ for foams made of aluminium and its alloys. Some of the properties of metallic 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 [16, 17]:

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

where $K$ and $\rho$ are property and apparent density of the foam, $K_S$ and $\rho_S$ 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, metallic 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 [18].

In fact, most of the individual foam properties can be achieved also with another materials, sometimes even more effectively. However, metallic 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 [9]).

## POTENTIAL STRUCTURAL APPLICATIONS

The recent theoretical works and prototyping studies revealed following potential for structures made of metallic foams:

**Lightweight load bearing panels** (flat or shaped - see Fig. 2) can be used as dividers (doors, floors), in various technological equipment (display stands, tables), portable containers, furniture, in railway wagons, trams and ships, or as various cover panels for interior or facades. The panels made of metallic- in particular of aluminium foam are considered for these applications due to high values of parameters $E/\rho^3$ and $\sigma_c/\rho^2$ ($E$ - elasticity modulus, $\rho$ - apparent density, $\sigma_c$ – collapse stress), which characterise the performance of the material in bending with respect to minimum weight [1]. The competing materials are sandwiches with honeycomb core, ribbed or waffle panels and magnesium die-castings, but their price is usually considerably higher. In distinction to foamed panels the honeycomb sandwiches can be used only at ambient temperatures because of low thermal stability of used adhesives. The isotropy of foamed panels is valuable when the load is applied multiaxially or when the panels are to be shaped. Using of diffusion-bonded coversheets or reinforcing meshes on the tensile loaded surface can overcome the high sensitivity to tensile stresses without significant increase of the weight (Fig. 2).

The foamed panels can be machined as easily as wood, using conventional techniques like sawing, drilling, turning, etc. They can be nailed, screwed, bolted or joint using connection elements built in the foamed structure. The panels can also be soldered at temperatures below the melting point of base alloy. It should be noted that the very thin surface skin is removed by machining revealing the inner pore structure. The sealing of surface imperfections by appropriate coating is usual precondition for external use.

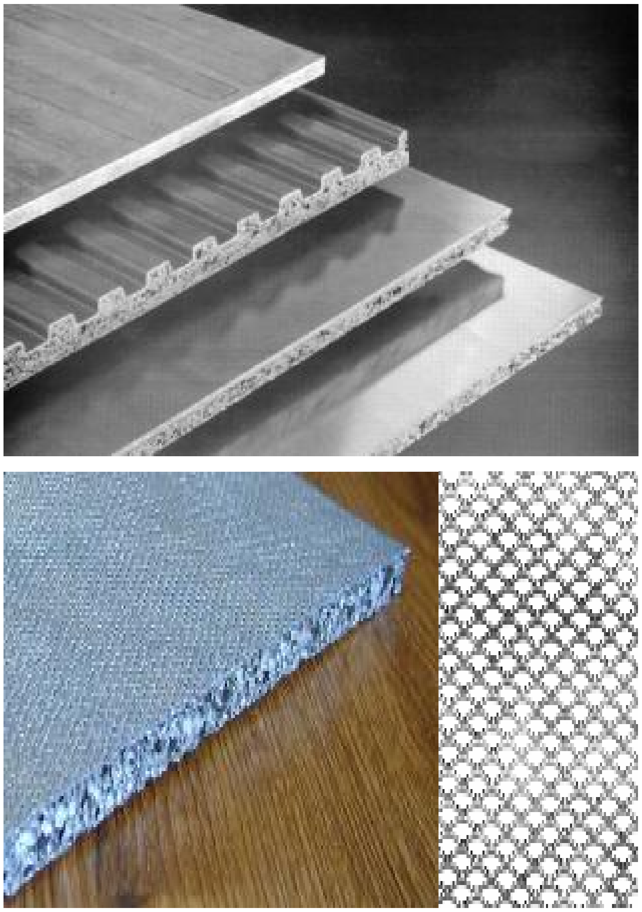

**Fig. 2. Foamed panels and sandwiches (up); panel reinforced (down left) with steel mesh (down right)**

Beside excellent mechanical properties the foamed panels possess low thermal conductivity and capacity, high resistance to humidity and UV-radiation and they are also good in noise attenuation and electromagnetic shielding. The unique surface structure of foamed panels attracts a considerable interest of architects and furniture designers (Fig. 3). Finally, the foamed panels are ecologically harmless and fully recyclable.

**Deformation elements** made of metallic foams can be utilised for protection of car passengers or sensitive devices against sudden crash. They do this by converting the impact energy into plastic deformation keeping the peak force on the protected object below the level, which causes damage. The thin cell walls in metallic foam start to buckle (ductile alloys) and fracture (brittle alloys) at relatively low stresses,

**Fig. 3. Attractive design of aluminium foams made by PM-route**

which remain almost constant until substantial densification of the foam 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 utilised for plastic deformation or for cracking, i.e. this energy cannot be released in rebound.

In comparison with other impact energy absorbers metallic foam enables to adjust the energy absorption capacity according to limiting stress level by simple altering of density. If the density is too low the foam crushes before energy is sufficiently absorbed. If the density is too high: stress exceeds critical value at low absorbed energy (Fig. 4).

The competing absorbers are components made of various hollow profiles. Although they are often better than foam absorbers, their absorbing performance is usually good only in one impact direction. The foam absorbers are superior when the impact is expected in multiple directions. Aluminium foam based deformation elements are under intensive development and testing in automotive industry [19].

Filling of originally empty cavities with metallic foam improves the mechanical properties (resistance against buckling, torsion, transversal compression), enhances ability to absorb crash energy, protects the cavity from dirt and moisture contamination and reduces the noise and vibration [14]. Contemporary tested applications in the automotive industry include various suspension parts, motor carrier, body frame stiffeners, etc.

The utilisation of metallic foam for **stiffening of welded components** enables cost effective stiffening of existing components for small series application submitted to increased loading (e.g. heavier engines, off-road condition etc.). In this case the foamed part is inserted into the component before welding without significant changes in a common technological process. (see Fig. 5)

In modern vehicle design the expensive welded structures consisting of many components can be replaced by hydroformed profiles (see Fig. 6). 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

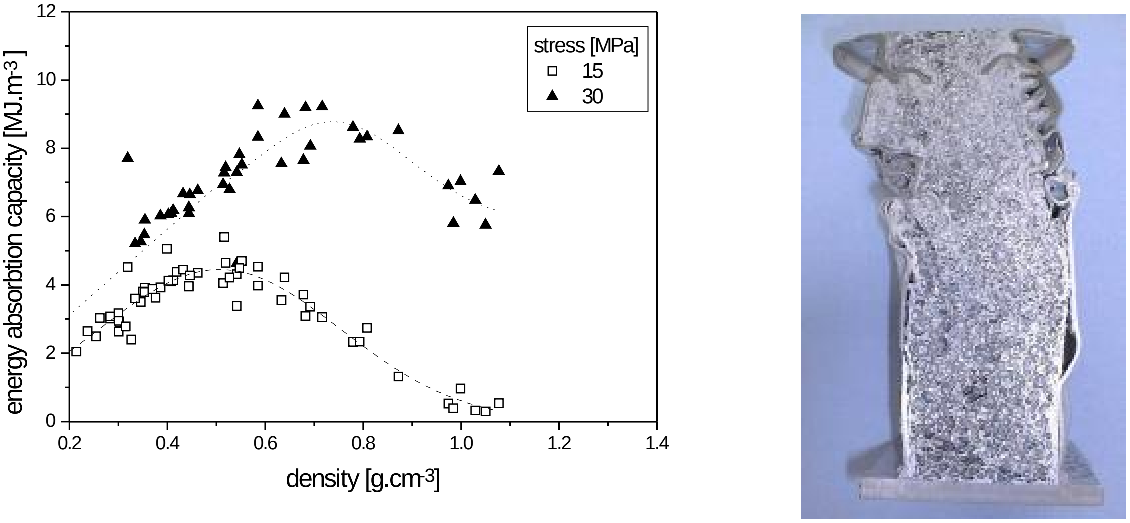

**Fig. 4. The foam density giving maximum energy absorption depends on allowed stress level (left). The foamed motor carrier after frontal impact (right)**

**Fig. 5. Suspension and car body part reinforced with aluminium foam inserts**

forces and sometimes even excludes the possibility to use this technology.

**Partial foaming** of hollow profiles improves the properties in weakest points of the profile (see Fig. 6) and allows designing its overall thickness according to mean and not peak stress, thus saving the overall weight and increasing the property-to-weight ratio of the component. This allows also the use of cost efficient hydroformed parts in applications where it is recently not possible because of insufficiently attainable wall-thickness. Finally, it avoids a cost intensive welding of internal stiffeners. The obstacles are too slow foaming for high production output, potential impact of "in situ" foaming on the properties of profile material and potential corrosion problem when steel hollow profile in combination with aluminium foam is used.

In aluminium castings internal configurations (stiffeners, ribs completely closed cavities) can be accomplished with permanent aluminium foam core (see Fig. 7). Also relatively small cross-sections can be filled up with foamed core thus saving an additional weight. Due to the supplementary stiffening effect of the foam and the possibility to preheat it, significant reduction of the shell thickness can be attained while the mechanical properties remain unchanged or they are even improved. Aluminium foam core will enable application of high volume production casting techniques (squeeze casting, HPDC, thixocasting), so far not accessible with sand cores [14]. Finally, the use of permanent cores instead of sand will reduce intensive labour cost and negative impact on environment.

Systematic investigation of various techniques for casting of shaped components and evaluation of possible contributions are the main preconditions for the introduction of this application into practice. The main obstacles are relatively high density of foam, high costs and possible infiltration of the foam core during casting. Development of technological methods aimed in the reduction of weight and costs of shaped metallic foams suitable for encasing by casting is under intensive research at present.

## CONCLUSION

Metallic foams are structures having a unique distribution of metal into cells filled with gas, which offers an unusual combination of various properties that cannot be achieved with bulk conventional

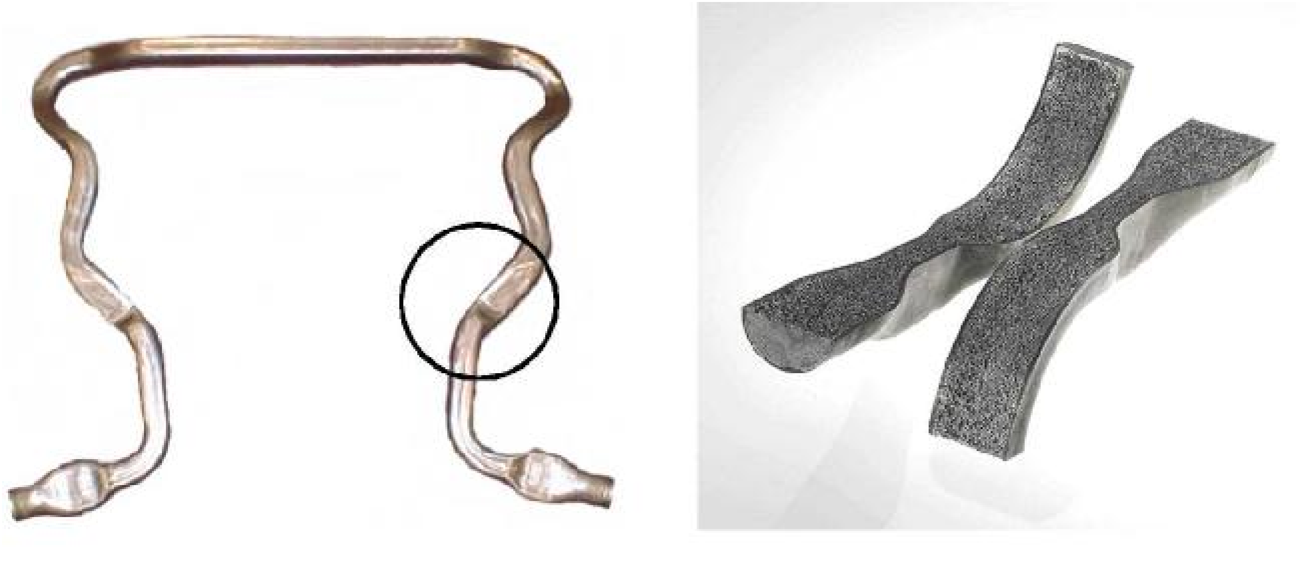

**Fig. 6. The motor carrier reinforced in the critical cross section with aluminium foam**

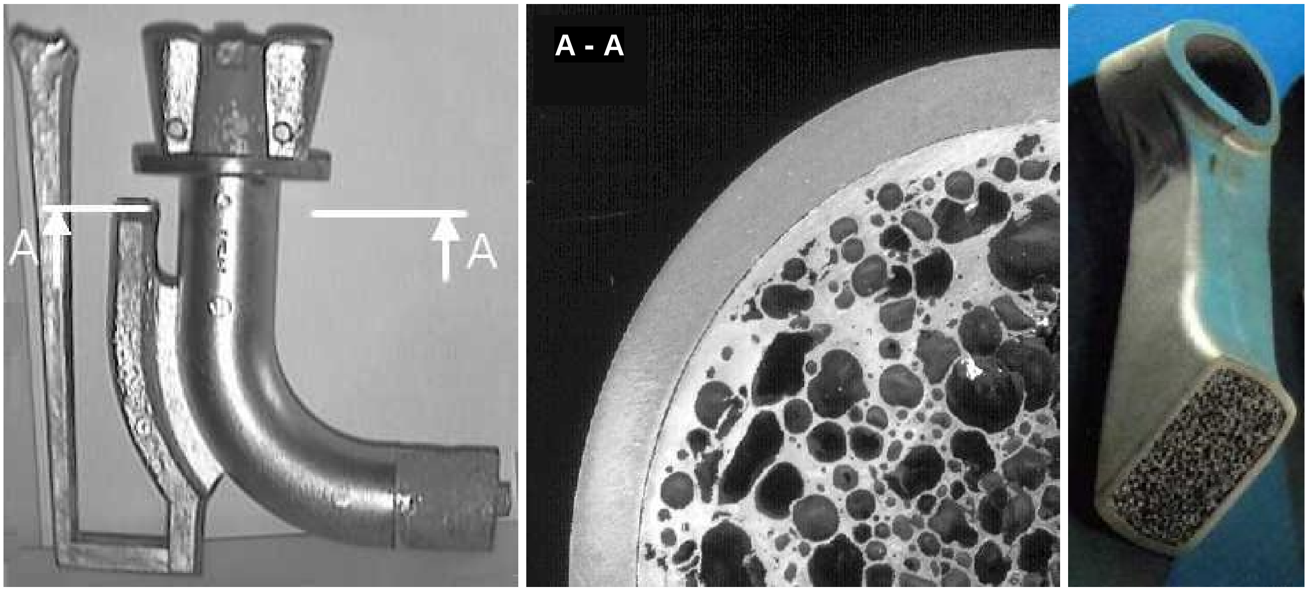

**Fig. 7. Examples of foam cored aluminium castings**

materials. The most promising practical applications are now expected in the light panels loaded in bending, in local stiffening of hollow steel or aluminium profiles, in weight saving cores for aluminium castings, and for safety parts for impact energy absorption. The typical fields of interest are transport industry (ships, railway wagons, trams, buses - light dividers, doors, floors, etc.) and building industry (cover panels of walls, facades and furniture).

It should be noted that in spite of a long time since the first patents concerning manufacturing of metallic foams appeared, this material has not been put into the large commercial production yet. The main reasons are low reproducibility of the cellular structure as well as complicated and relatively expensive preparation technology. At present metallic foams are inadequately characterised, and the process understanding and control are incomplete, resulting in variable properties. But even present generation of metallic foams suggests alluring potential, and process control and characterisation are improving rapidly.

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