In: Processing and properties of Lightweight Cellular Metals and Structures (TMS Annual Meeting), Seattle, 2002, p.25

REINFORCED ALULIGHT FOR STRUCTURAL USE

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Abstract

Alulight aluminum foam parts prepared by PM-techniques are very promising for lightweight structures because of their excellent stiffness-to-weight ratio. However they structural use is considerably limited by a fact, that they are not able to withstand higher tensile stresses, which provide good conditions for rapid widening of surface cracks in highly porous structure. This essential drawback can be overcome via strengthening of tensile loaded surface of the foamed part with various wires or fibers woven into webs, similarly as it is in a case or reinforced concrete. According to a novel foaming technique, the reinforcements are placed in the foaming mould together with foamable precursor and in a course of foam expansion they are infiltrated with molten cell-wall material. The main advantages of this method are the simplicity and the possibility to reinforce the foamed part selectively and anisotropicly according to the applied load. The required mechanical properties of the structure can thus be achieved at minimum weight and manufacturing costs.

Introduction

Metallic foams are relatively unknown structural materials, however with enormous future potential for applications where lightweight combined with high stiffness (see Fig.1), and acceptable manufacturing costs are of the prime interest. The metallic foams are crushable offering high impact energy absorption capacity at low stresses, they are stable at elevated temperatures, they possess superior fire resistance and do not evolve toxic fumes in a fire, they are also efficient in shielding of electromagnetic waves and in vibration and noise damping [1]. Although the metallic foams appeared already during 2nd world war [2], they have remained almost unknown for designers up to now. Due to the development of new technologies, which enable the manufacturing at reasonable costs [3], this type of material becomes again very attractive and makes a strong impetus for rapid increase of R&D activities in this field.

The metallic foams generally 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 round and closed, although some inevitable cracks or other defects originate in the cell walls due to shrinkage of solidifying cell wall metal and/or due to pressure reduction inside the pores on cooling [4].

Alulight is a net shape aluminum foam made by powder metallurgical (PM) route [5], which comprises 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. 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 precursor in the mould in which the precursor is distributed and then heated (together with the mould) to the melting point of used alloy. The foam fills the mould and follows its shape. After melting and foaming, the mould is rapidly cooled to prevent collapse of the foamed structure. There are almost no constraints concerning complexity of the outer shape and geometry. The possibility to use the simple-form precursor e.g. extruded rods, for foaming of components with various shapes and sizes [6] significantly reduces the production costs usually accompanying the PM manufacturing techniques.

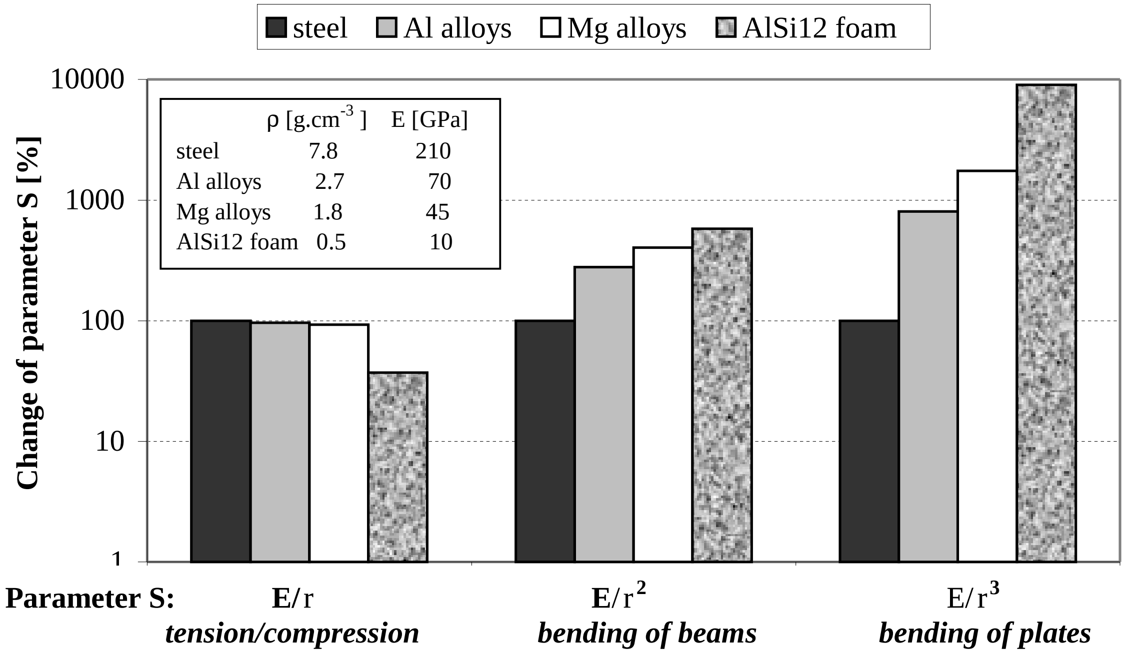


Figure 1: Parameter S defining stiffness-to-weight ratio for various materials and loading conditions (E - elasticity modulus, r - density, 100 % - value for steel).

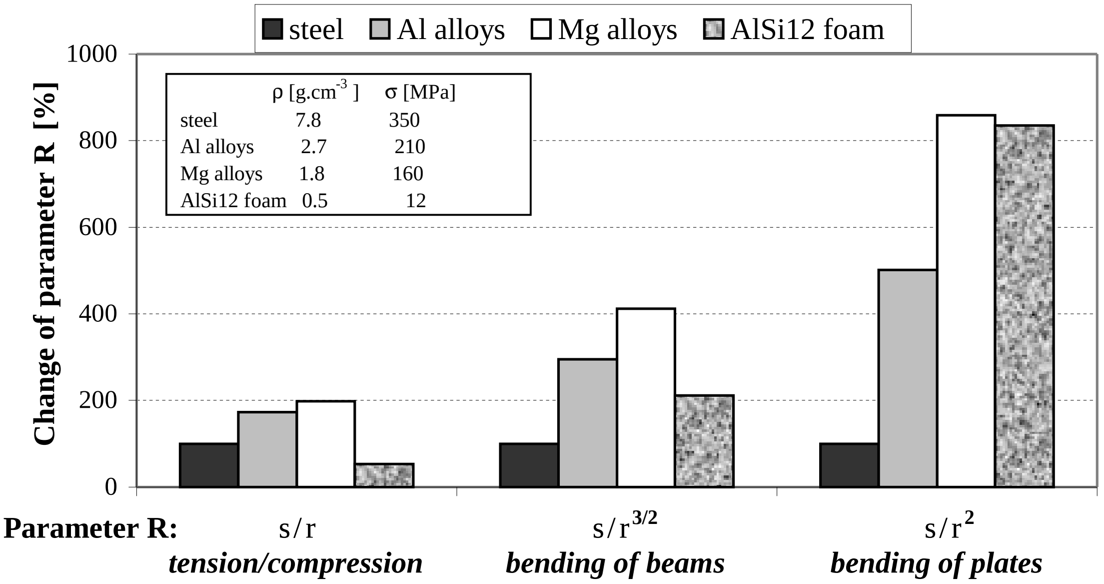
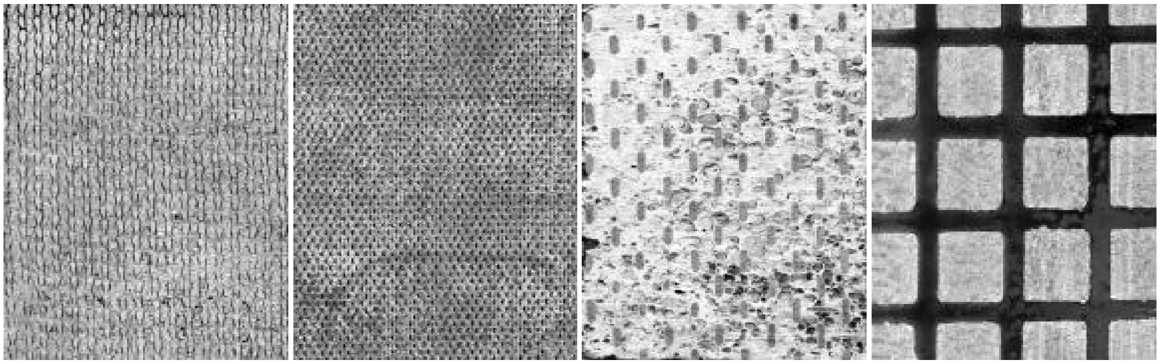


Figure 2: Parameter *R* defining strength-to-weight ratio for various materials and loading conditions (*s* – yield strength, *r* - density, 100 % - value for steel).

Alulight foamed parts are always covered with dense skin, which significantly improves their appearance and the properties (e.g. the bending stiffness). However this skin possesses variable thickness and always contains microcracks or even holes. These inevitable defects can initiate premature fracture of the foam, especially if it is loaded in tension, when the conditions for crack displacement in highly porous structure are favorable. Therefore the tensile strength of foamed parts is often insufficient and exhibits too high dispersion to allow their efficient use as the load bearing structural elements (see Fig.2), though their stiffness to weight ratio is excellent.

The growth of cracks in cell walls can be prohibited by strengthening of the foam with some kind of reinforcing elements, similarly as it is in a case of reinforced concrete (see Fig.3). If the reinforcements have higher elasticity modulus and sufficient yield strength, the tensile stresses are transferred from the foam onto these elements and existing cracks in cell walls become inactive.



net expanded metal woven wire perforated sheet

Figure 3: Aluminum foam AlSi12 reinforced in the surface with stainless steel.

Manufacturing of Reinforced Foams

PM process developed for manufacturing of Alulight offers also simple and cost effective possibility for making reinforced foams or “metal foam matrix composites (MFMC)”. According to a novel foaming technique [7], the reinforcements are inserted into the foaming mould together with foamable precursor and properly positioned. In the course of foam expansion the reinforcements are moved to the mould surface, where they are infiltrated with molten cell-wall material. The liquid foam alloy reacts with reinforcements, forming metallurgical bond. The quality of this bond depends on the chemical composition of both materials (foam and reinforcement) and can be controlled by contact time and proper surface treatment of the reinforcement. If appropriate, the mutual reaction can be prohibited by coatings providing diffusion barrier. Fig. 4 shows $Al_{12}Fe_3Si$ interfacial phase formed between reinforcement made of expanded stainless steel and AlSi12 foam. This type of metallurgical bonding provides a certain formability of the foam and results in a significant improvement of the mechanical properties and the thermal stability in comparison with glued or brazed sandwiches. In distinction to typical metal matrix composites, in this case the interfacial layer does not represent “the weakest link”; its properties are usually better than the properties of highly porous and brittle AlSi12 foam matrix.

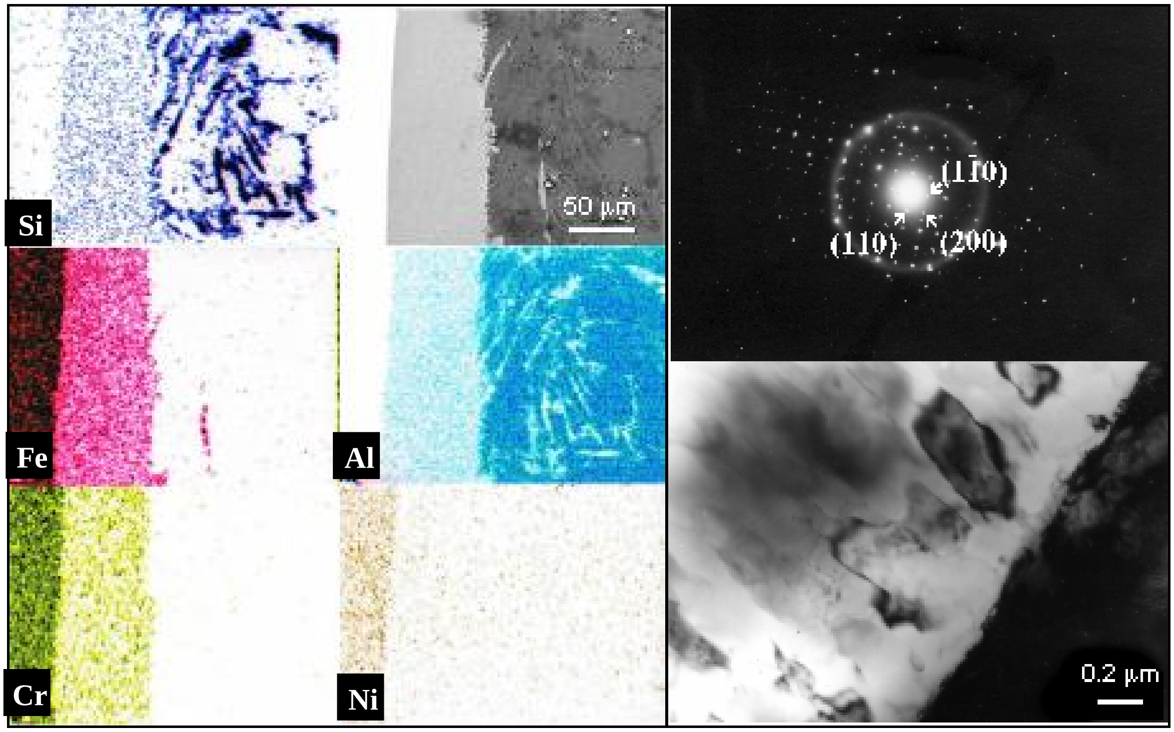


Figure 4: Interfacial reaction zone $Al_{12}Fe_3Si$ formed between stainless steel reinforcement and AlSi12 foam. (element distribution - left; TEM and diffraction pattern - right).

The reinforcements prevent liquid foam from collapsing on cooling and thus they have also an additional stabilizing effect. Moreover the reinforcements increase the thickness of surface skin (Figure 5), simplify joining of foamed parts (welding is possible) and enable limited shaping after foaming process. The foamed components can be reinforced also selectively and anisotropicly according to expected load, thus saving the weight and the reinforcement costs. The shaped foamed parts can be strengthened via the same way. One of the attractions of this process is that these composites are prepared in one technological operation what significantly simplifies the process and reduces manufacturing costs.

Experimental

Preparation of specimens for testing

Alulight panels with variable porosity based on AlSi12- and AlMg1Si0.6-alloys were reinforced at one or both surfaces with expanded metal made of stainless steel. The mesh size of expanded metal was 6 x 3 mm and its square weight 3.4 kgm^{-2}. The specimens for bending tests, performed in this investigation, were cut from the reinforced panel in two directions; with longitudinal and transversal orientation of expanded metal along the length of the specimen (see Fig. 5). It is obvious, that the load-bearing cross section is higher in longitudinal orientation and therefore better properties can be expected in this direction at the same overall weight of the specimen.

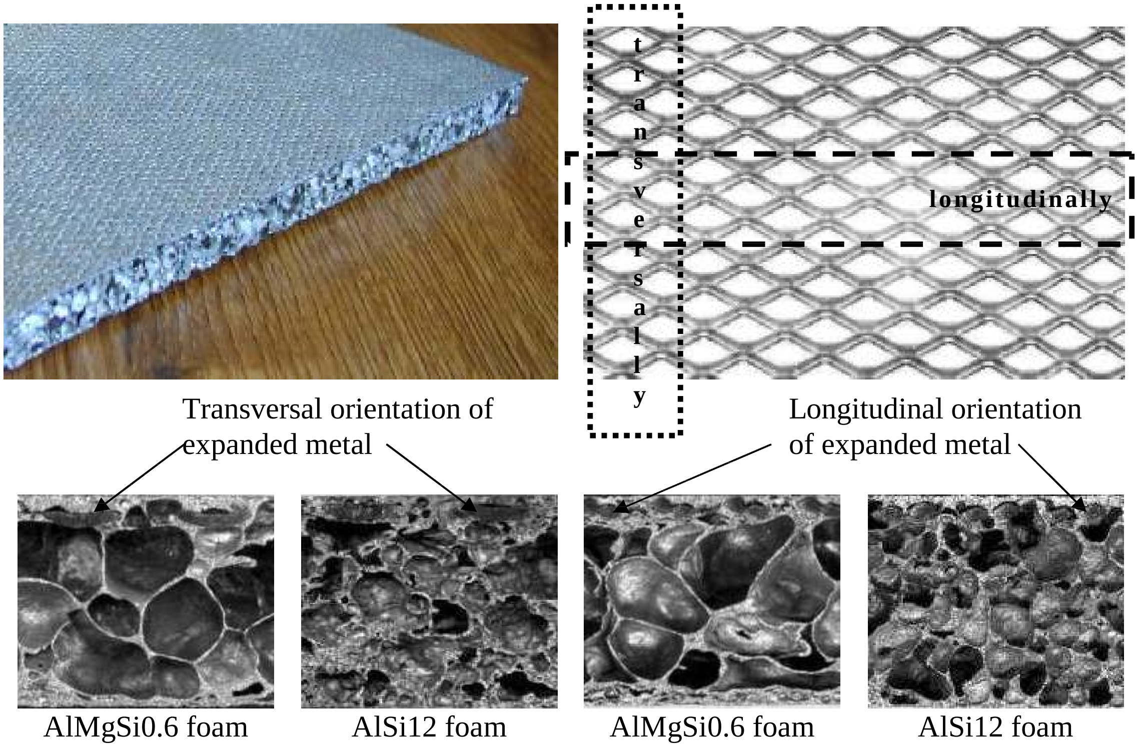


Figure 5: Typical cross sections of testing specimens (10 x 12 mm) cut from aluminum foam panel (top left) reinforced in upper surface with expanded metal sheet (top right).

Bending test

4-point bending tests were performed on beams cut from reinforced panels. The size of specimens was 10 x 12 x 100 mm (thickness x width x length). The 4-point bending tests was used, as it is more suitable for materials with a heterogeneous structure due to the more convenient distribution of the bending moment during application of the bending loads. The reinforcements were located either in tensile- or compression-loaded foam surface. The beams made of plain foam were also tested for comparison. The deformation of selected specimens was recorded on CCD camera, to observe the initiation of the cracks in the porous structure. The bending stiffness *B* was calculated from the slope of the load-deflection curve recorded during four-point-bending test according to:

$$B = EJ = \frac{1}{48}\frac{Fc}{y_e}(3l^2 - 4c^2) \tag{1}$$

where *E[MPa]* refers to the elasticity modulus of the material and *J [mm^4]* is the cross sectional moment of inertia, *F[N]* is the load causing the deflection y_ε *[mm]*, *l* and *c* refer to the span between the supports and to the distance between the bending force and the supports, respectively (*l=70* and *c=20 mm* in this study). In order to obtain a linear part of the load-deflection curve the short unloading was applied at the strain of *e » 0.1.* The deflection was measured in the center of the specimen by electronic extensometer; ram speed was kept constant at 2 mm/min. The bending stress *s* was calculated according to:

$$s = 6\,Fc / bh^2 \tag{2}$$

where *b* refers to the width and *h* to the thickness of the test sample.

Properties of Reinforced Foams

Fig. 6 shows the bending behavior of AlSi12-foams with and without reinforcement. The porosity of the foams was approximately the same. The reinforcement was placed either in the top or in the bottom of the bending specimen. The expanded metal sheet increases the bending stiffness of the foam almost twice, though the weight due to the reinforcement increases only about 30%. The most efficient use of reinforcement is in bottom part of the specimens, i.e. in tensile loaded surface. In this case the sample does not break during the whole loading cycle. Foam shearing can be observed at higher deformation (Fig. 7a) in parts above the reinforcement. If the reinforcement is placed on top (compression loaded surface), the sample fractures with sudden failure (Fig. 7b) at significantly lower stress, which is comparable with the fracture stress of the foam without reinforcement.

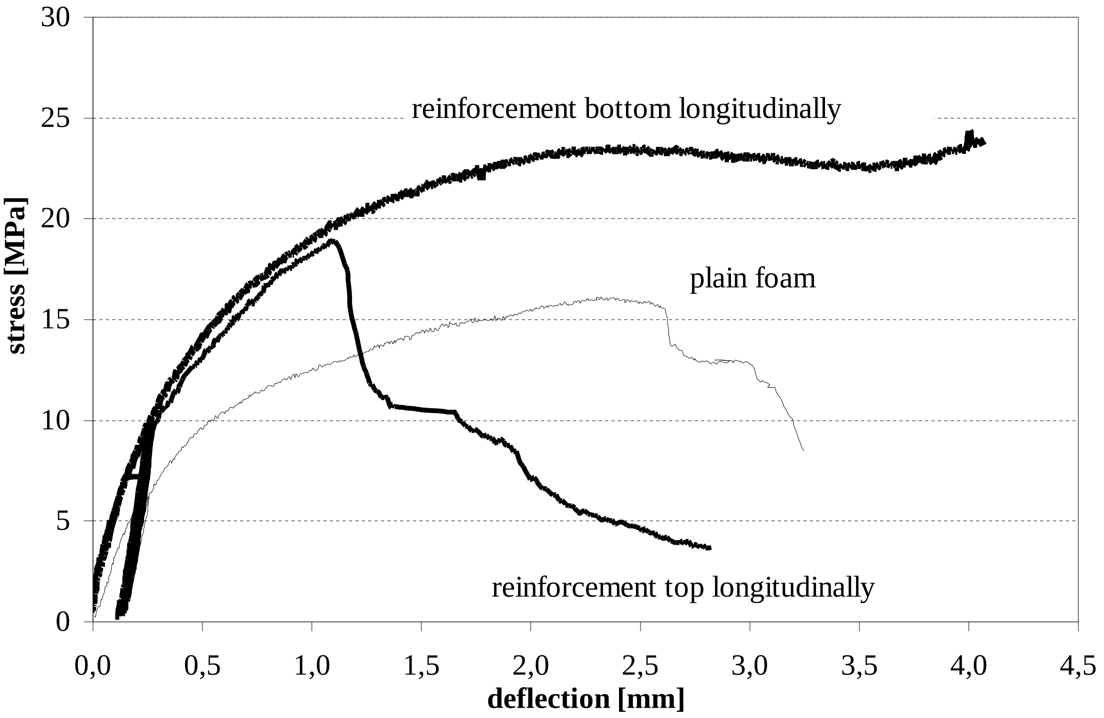
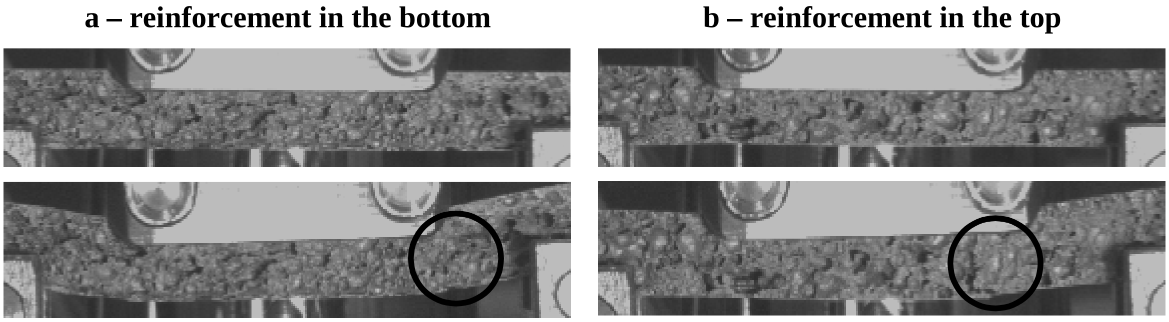


Figure 6: Effect of the reinforcement on bending behavior of foamed beams based on AlSi12 alloy at the same porosity of the foam - 81%.



shearing of the foam

fracture initiated in the tensile loaded surface

Figure 7: Failure mode of reinforced AlSi12 foams with different position of reinforcing expanded metal (porosity of the foam - 81%).

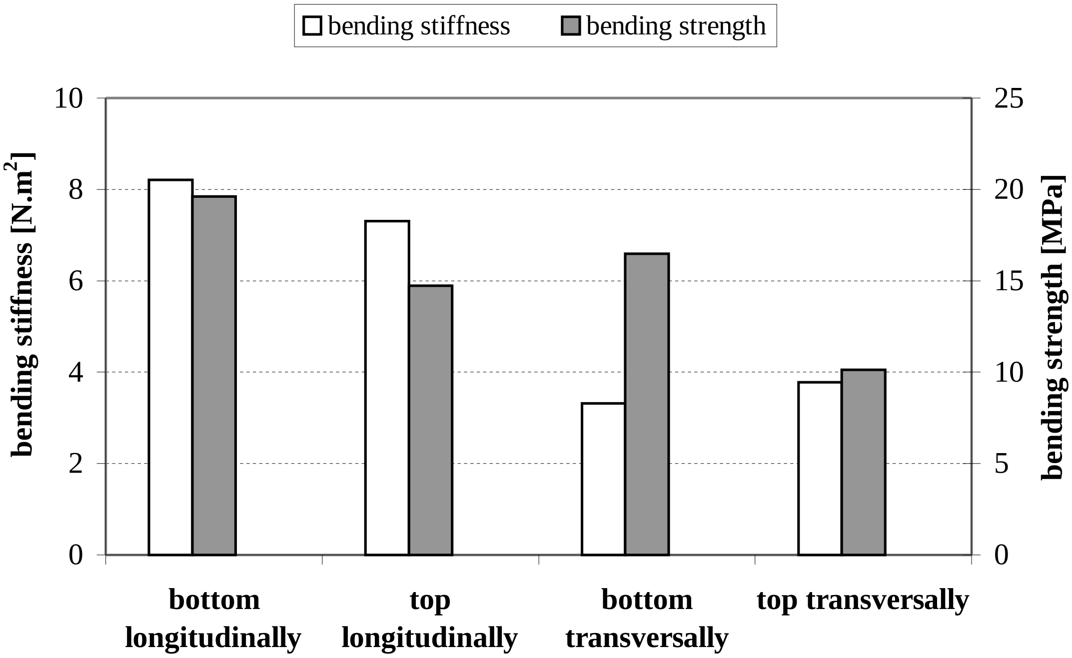


Figure 8: Effect of the orientation and position of reinforcing expanded metal on the properties of foamed beams based on AlSi12 alloy at the same porosity of the foam - 75%.

Fig. 8 shows the effect of the position and orientation of expanded metal on the performance of reinforced beams based on brittle AlSi12 foams. Although the weight of all beams was almost the same, their properties were found considerably different. The bending strength of reinforced beams is always higher when the reinforcements are placed in the bottom of the specimen (in tensile loaded surface). The expanded metal is stronger in longitudinal direction because of larger load-bearing cross-section (see also Fig. 5). This leads to higher bending strength of reinforced samples in all cases.

Also the bending stiffness of the reinforced specimens depends on the orientation of the expanded sheet; is always higher in longitudinal direction. However, the bending stiffness, contrary to bending strength is not affected by the position of the reinforcement; it is almost the same for top- or bottom placements.

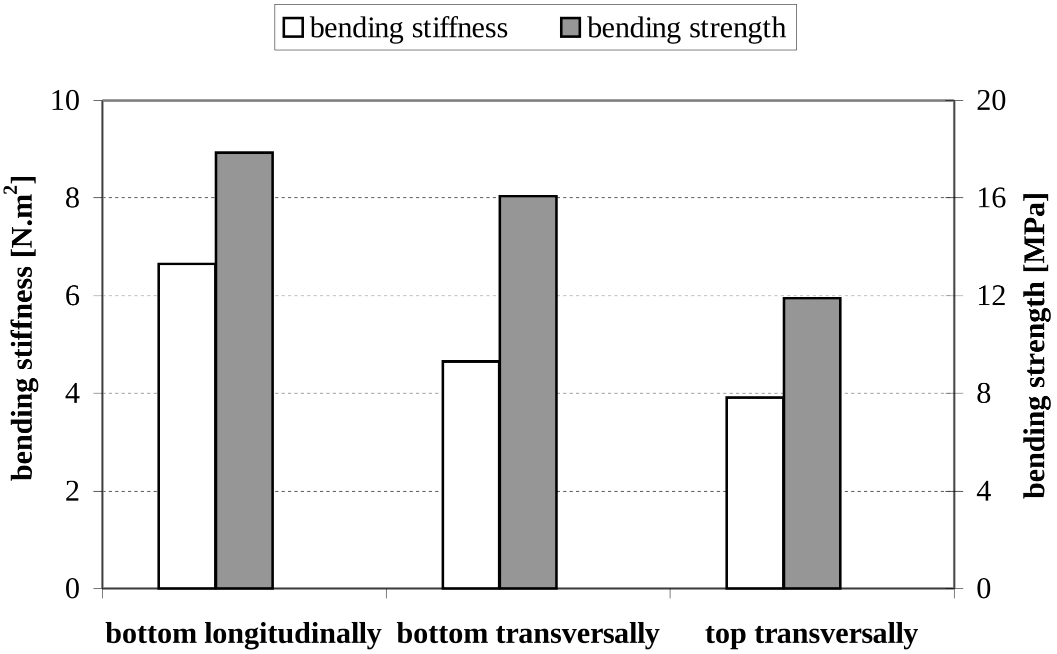
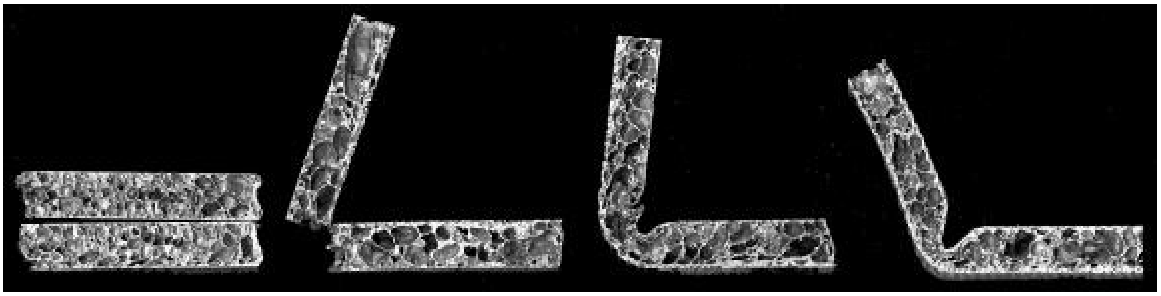


Figure 9: Effect of the orientation and position of reinforcing expanded metal on the properties of foamed beams based on AlMg1Si0.6 alloy at the same porosity of the foam - 76%.

Similar behavior was observed also for the reinforced beams based on ductile AlMg1Si0.6 alloy (Fig. 9). However, in this case the plastic bending without visible fracture was observed also for specimens with reinforcing elements placed in compression-loaded surface. At similar porosity the bending strength of reinforced AlSi12-foam is slightly better than that of AlMg1Si0.6-one, however this difference is not significant (compare also Fig. 8 and 9).

The effect of the position of reinforcement on fracture toughness is clearly visible in Fig.10, which shows the final deformation of the foamed beams after impact test. While almost no impact energy is absorbed with plain foam, the reinforced foams are able to convert whole impact energy into the deformation. The remaining capability to absorb further energy can be estimated from the bending angle; it can be seen in Fig. 10, that the most efficient use of the reinforcement is again in the tensile loaded surface.



no reinforcement

reinforced compression loaded surface

reinforced tensile loaded surface

reinforced both-surfaces

Figure 10: Deformation of beams based on AlMg1Si0.6 foam (15x15x120mm, porosity 85%) after impact test (max energy 15 J) as a function of the position of the reinforcements.

Fig. 11 illustrates the changes of bending properties for various use of aluminum in beams of the same weight. As can be seen the beam made of plain foam possesses considerably higher stiffness than bulk Al-sheet. However, no benefits were observed for bending strength, and the resistance to fracture was even worse. Therefore, for practical use of aluminum foams in structural applications, it will be necessary to reinforce at least the tensile loaded surface of the foam. Similar effect can be obtained if the coversheet is applied [8], however the use of the reinforcements is more efficient, because of their lower weight, which enables to increase the thickness of the foam. The reinforcements have also additional stabilizing effect - they prevent liquid foam from collapsing thus allowing higher final porosity of the foam.

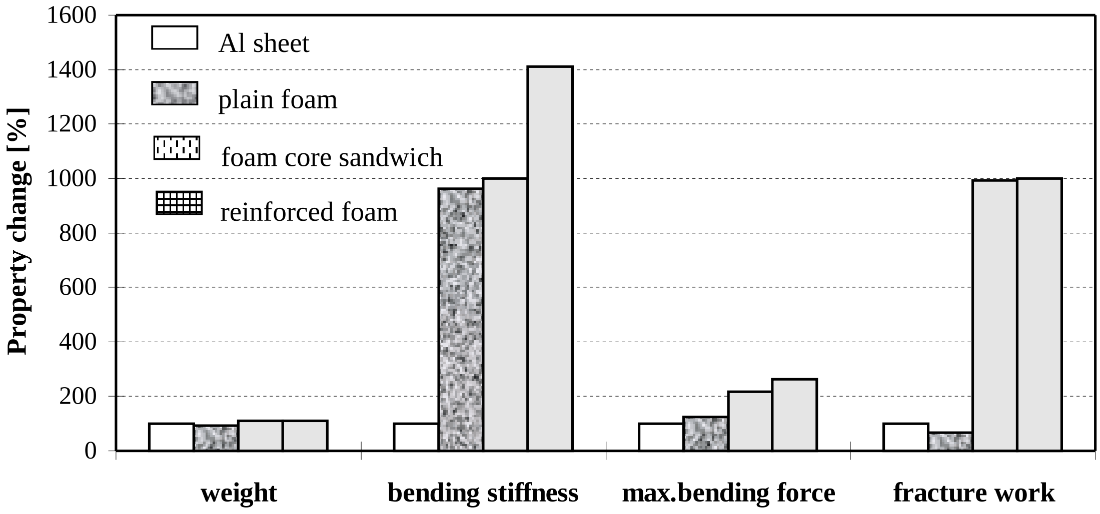


Figure 11: Properties of reinforced aluminum foam AlSi12 (thickness 15 mm, porosity 85%) in comparison with: Al-sheet (thickness 3 mm), AlSi12-foam (thickness 15 mm, porosity 80%) and AlSi12-foam sandwich (foam thickness 11 mm, porosity 80%, Al-coversheet 1 mm at one side).

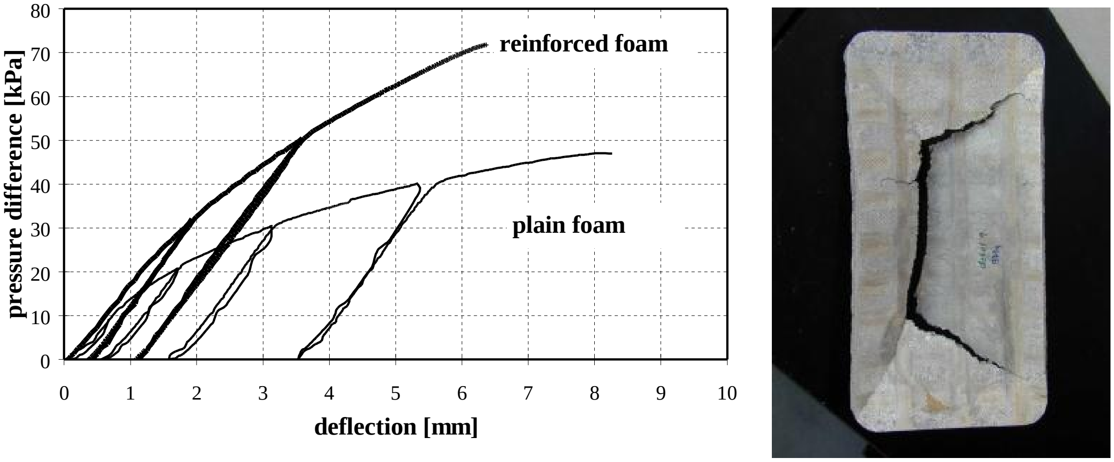


Figure 12: Bending of foamed panels under surface loading (right- broken plain foam panel).

The benefit of reinforcements was confirmed also in bending of foamed panels (565x285x15 mm) [9]. In this case the panels were loaded at the whole surface by pressure difference between two chambers separated with the specimen. The reinforced AlSi12-foam panels withstand the pressure difference of 70 kPa while plain foams suddenly breaks at pressure of approx. 40- 45 kPa (Fig. 12). With increasing load the permanent deformation occurs due to yielding or fracture of weakest cell walls. The reinforcements allowed the cyclic loading of the panel with amplitude of 50 kPa. After first loading the stiffness and permanent deformation of panel remained nearly unchanged during whole experiments (up to 1500 cycles).

Conclusions

The stresses, which usually cause the yielding or even fracture of surface skin of aluminum foams, can be overtaken by reinforcements implemented into the foam surface, preferably on the tensile loaded side of the foam. In this way the significant improvement of the strength, plasticity, energy absorption capacity and damage tolerance of foamed part can be achieved with only slight weight increase (ca. 20-30%). The possibility to reinforce the foamed part selectively and anisotropicly according to the expected load enables to obtain maximum property-to-weight ratio. The reinforcements can be effectively used also for improving of bending stiffness when the thickness of the foam is limited.

The reinforcements increase the thickness of surface skin, simplify joining of foamed parts (make welding possible) and enable limited shaping after foaming process.

Easy manufacturing allowing reasonable production costs can make the reinforced foams very attractive for transport industry, especially for lightweight stiff body structures of future cars, busses, trains, ships, airplanes, etc.

Of course, the use of reinforcements is accompanied also with some difficulties, which should be solved in a future. More complicated recycling, the residual internal stresses in the structure and lower resistance to electrolytic corrosion are some of them.

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