International Conference "ADVANCED METALLIC MATERIALS"
5 – 7 November, 2003, Smolenice, Slovakia

REINFORCED ALUMINIUM FOAMS

Jaroslav Kováčik, František Simančík, Jaroslav Jerz, Peter Tobolka

Institute of Materials and Machine Mechanics, Slovak Academy of Sciences, Bratislava, Slovakia

Abstract – The concept for the design and manufacturing of reinforced aluminium foams will be presented. The reinforcing of the foam eliminates the problem of premature catastrophic failure due to excessive tensile stresses. This enables the use of aluminium foam as load bearing part in various structural applications without need to cover it with bulk materials. Significant weight reduction is thus expected. Excellent stiffness-to-weight ratio of the foam combined with unique crash absorption capability and strength of reinforcements provide enormous potential for application of reinforced foams in lightweight load bearing structural parts, especially in transport industry. In the paper the proper use of reinforced foam is suggested and the potential benefits are discussed.

Keywords: aluminium, foam, composites, lightweight

1. INTRODUCTION

The cellular structure frequently used in various natural load-bearing solids (wood, bone) provides very good tool for highest stiffness and buckling resistance at minimum weight [1]. This knowledge leads to the development of artificial cellular materials for applications where lightweight plays a primarily role. Aluminium is potentially interesting candidate for cell-wall material, because of its low density, good ductility, fair corrosion and heat resistance, moderate melting temperature, environmental compatibility and easy recycling [2].

In spite of a long time since the first patents concerning manufacturing of aluminium foams appeared [3-4], the material has not been put into the large commercial production up to now. This discouraging result can be attributed to inadequate design of applications, low reproducibility of the properties, missing of testing procedures and calculation approaches, absence of concepts for secondary treatment, as well as to complicated and relatively expensive preparation technology. [5].

However, the main obstacle for use of metallic foams in structural applications is their insufficient ability to resist excessive tensile stresses in critically exposed surfaces of components. Due to this drawback the properties of the foam cannot be fully exploited and the application of foam is thus relatively expensive. The reinforcing of the foam by insertion of simple metallic elements (e.g. wires woven into meshes) in tensile loaded surfaces can effectively solve this problem [6]. The main aim of this paper is to suggest a way for proper use of reinforcements in aluminium foam structure, to discuss achieved benefits and suggest potential applications.

2. STRUCTURAL USE OF ALUMINIUM FOAM

Typical use of aluminium foam in structural parts is usually in various cores, e.g. in hollow profiles, in sandwiches or in aluminium castings [7]. In all these cases the foam is use as a filler or space holder and its main role is to increase inertial moments of initially hollow cross section. Foam filled bulk parts possess thus increased stiffness and exhibit higher resistance to buckling. However, this alone is not sufficient for successful application of foam, because increasing of shell thickness can easily enhance the stiffness of hollow profile, as well, sometimes even more effectively.

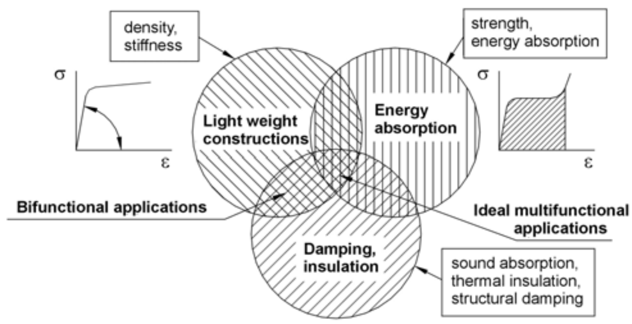
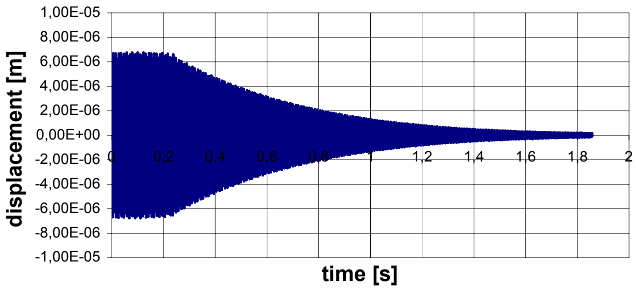


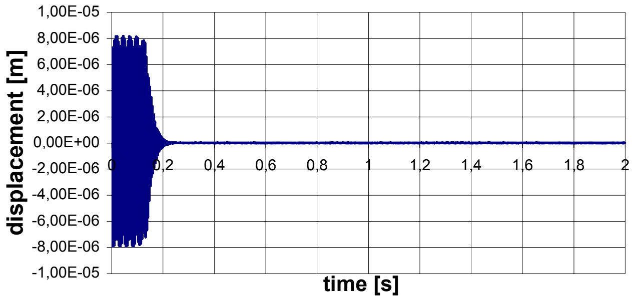
Fig. 1. The benefits achieved by use of aluminium foams. [8]

The application of aluminium foams is valuable only if more properties of foam are utilised simultaneously – the foam must be exploited for multiple functions (Fig.1). Improved capability to absorb crash energy for deformation at moderate stresses or vibration and noise damping are typical benefits, which additionally accompany high specific stiffness of aluminium foam. However, it should be noted, that the good vibration or noise damping in profile filled with aluminium foam is predominantly caused by sliding contact surfaces between the foam and profile. The vibration energy is thus converted to heat by friction. If the foam adheres to profile without sliding possibility, the damping capability is significantly reduced (Fig.2). On the other hand, the good bonding is required to achieve radical improvement of stiffness. Therefore the use of foam for stiffening and damping simultaneously is rather speculative.

hollow profile



profile with foam insert without adhesive



profile with foam insert fastened with epoxy adhesive

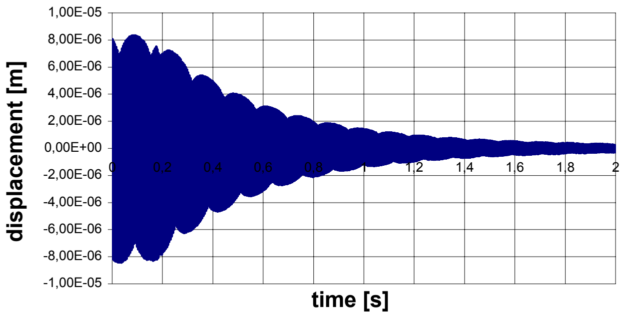
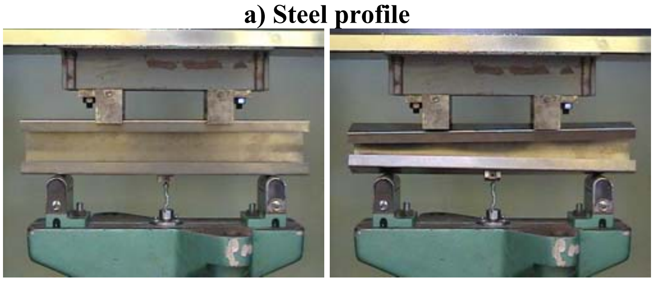


Fig. 2. Vibration attenuation of foam filled hollow profile

a) Steel profile



b) AlSi12 foam filled steel profile

Fig. 3. Bending of hollow (a) and foam filled (b) steel profile

As the main potential of aluminium foam is in lightweight construction, let us consider this case. Fig. 3a illustrates the 4-point bending of lightweight profile made of 1 mm thick steel sheet. Corresponding load-deflection diagram is given in Fig. 4. As can be seen, the profile is not stiff enough and starts to buckle at relatively low load.

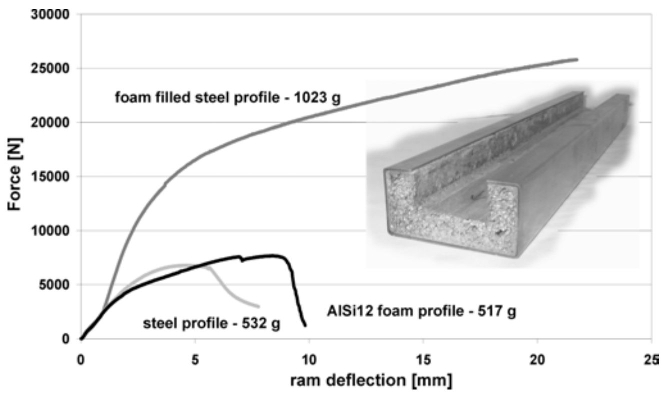


Fig. 4. Comparison of steel, aluminium foam and aluminium foam filled steel profile response to 4-point bending

The standard solution of this problem is to fill the profile with aluminium foam. This situation is also illustrated in Fig. 3b and Fig. 4. In this case the foam was inserted into the profile and fastened with epoxy adhesive to achieve good bonding. The effect of foam is clearly visible in significantly increased stiffness and buckling load. From this point of view the application of foam is superior and can be warmly recommended. However, the use of foam insert brings also some less optimistic effects; it almost doubles the weight of original part, and of course it considerably increases the costs (cost of foam insert are added to cost of original profile). In order to minimize the weight, outer shell structure (e.g. thickness of the steel sheet) can be reduced. This can lead to better “property-to-weight” performance than it was in a case of originally hollow profile, however still at significantly higher costs. Moreover, adhesive is used, which also brings some weight, costs and uncertainties concerning quality of bonding. Of course, there is a possibility to foam hollow profile “in situ” without need to use adhesives [7]. However, also this method has essential drawbacks, i.e. negative impact on the steel properties due to high foaming temperature, potential danger of contact corrosion between aluminium and steel and again questionable bonding quality [9]. All these effects significantly affect the technical and economical viability of “foam insert” solution and this is why it cannot find a large industrial acceptance.

Therefore in order to reduce the weight, improve properties and keep the cost at reasonable level, it is just necessary to replace the original part. Unfortunately, the use of plain aluminium foam itself is not possible, because it is not able to withstand excessive tensile stresses. The corresponding situation is demonstrated in Fig. 5 showing the bending of aluminium foam beam with the similar outer geometry and weight as in a case of original steel profile. The foam beam exhibits much better resistance against buckling, however only up to certain load level at which it failures catastrophically.

AlSi12 foam profile

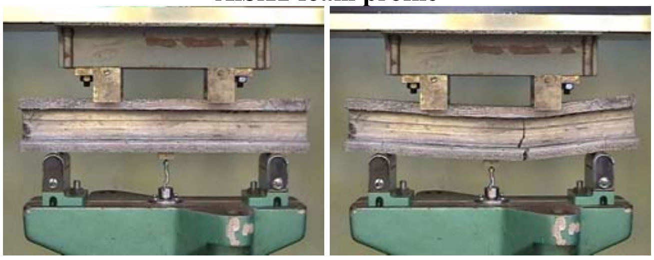


Fig. 5. Bending of AlSi12 foam beam of the similar weight and outer geometry as original steel profile

The load at which the foamed beam breaks is comparable with the maximum buckling load attained for original steel profile (see Fig.4). It means that notable improvement has not been achieved; just quite the opposite, the tendency towards sudden failure disqualifies the foam for structural use.

The foam's sensitivity to tensile stresses is difficult to control. Because of principally larger structures (foam cannot be tiny) considerably high strains are attained in the surface skin, already at relatively low bending deflection. In a case of tensile strain, favourable conditions are provided for opening of existing small cracks in the cell walls. These cracks are inevitable; they arise on foam cooling from foaming temperature, in order to balance the pressure difference between atmosphere and initially closed cells (Fig.6.). These defects can uncontrollable initiate premature fracture of the foam even at relatively low tensile stresses.

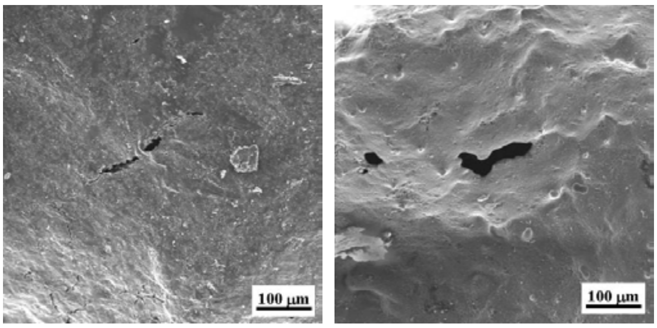


Fig. 6. Defects and cracks present in aluminium foam cell walls (left– casting AlSi12, right– wrought AlMg1Si0,6 alloy)

The opening and 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. 7). 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.

The reinforcements must be located in the surface areas where highest tensile stresses are expected, if possible also with preferred orientation according to loading direction [6]. It is not necessary to reinforce compression-loaded locations. These features allow the use of reinforcements very effectively, saving weight and costs. The performance of foam beam reinforced with expanded metal made of stainless steel is given in Fig. 8. Again, similar outer geometry and weight as in Fig. 3a was used for illustration.

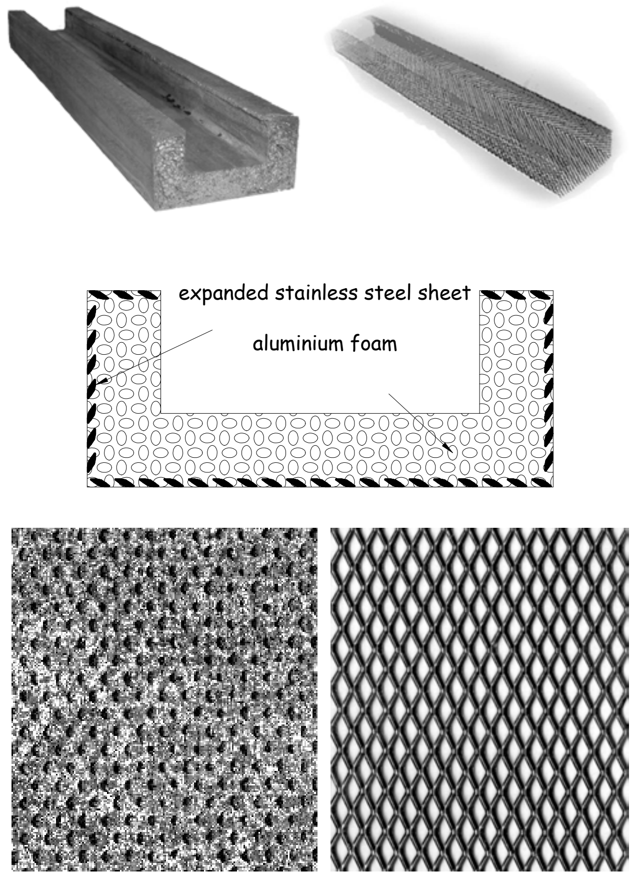


Fig. 7. Surface skin of aluminium foam reinforced with expanded stainless steel sheet (M1:1)

reinforced AlSi12 foam profile

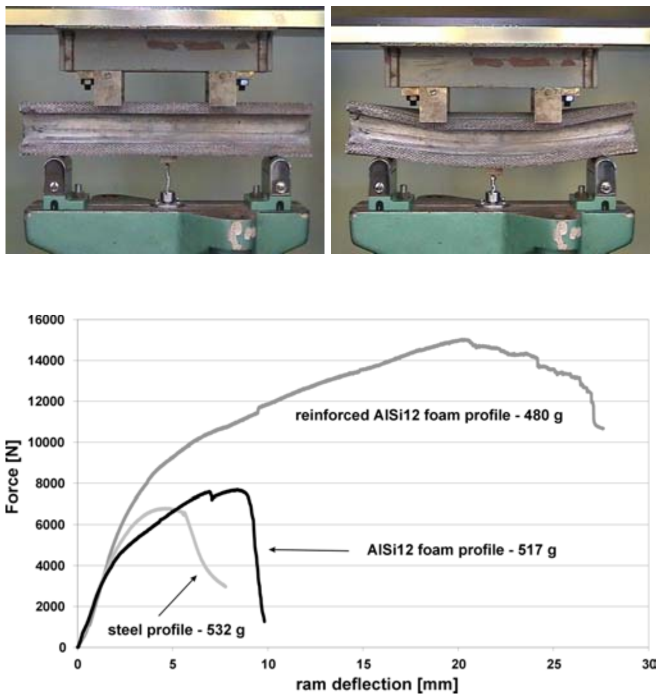


Fig. 8. Bending of reinforced foam beam in comparison with plain foam beam and hollow steel profile, all of similar outer geometry and weight.

As can be seen in Fig.8 significant improvement of stiffness, strength and resistance to buckling was achieved without any weight increase. Additionally, the problem of catastrophic failure was removed as well; the reinforced foam beam failed in buckling and did not break. The increase of energy, which is needed for ultimate deformation, is also remarkable. This characteristic can be successfully used in design of load bearing structural parts, which will be simultaneously able to absorb high amounts of crash energy. Note, that these parts are predominantly aimed to carry the load; excellent ability to absorb impact energy is only their additional feature.

When energy-absorbing parts are designed, control of the force causing deformation is of primary importance. The maximum force acting on the structure must be strictly kept under required level; overloading can cause irreparable damages. The use of reinforced foam is very suitable for this purpose, because the required level of deformation can be relatively easy tailored by proper selection and placement of reinforcements. This possibility is demonstrated in Fig. 9 again on the foam beam similar to previous ones. In this case the beam was reinforced only locally in bottom part, allowing upper part to deform in compression at moderate loads. After densification of upper foam part the beam deforms in bending, finally achieving the same bending strength as it was in a case of fully reinforced beam.

Fig.10 shows that the energy absorption capability of locally reinforced foam beam is superior in comparison with previous beam types within entire loading range. This behaviour is really unique.

AlSi12 foam profile reinforced locally (bottom)

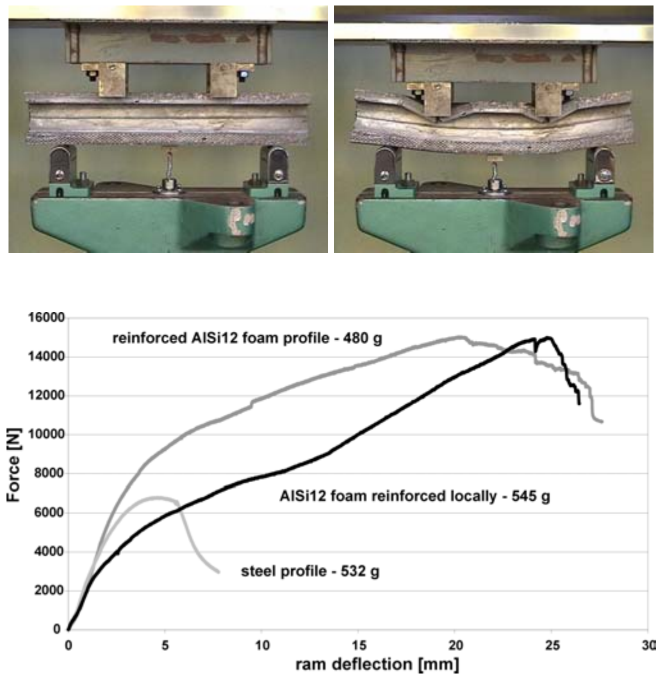


Fig. 9. Deformation of locally reinforced foam beam in comparison with fully reinforced foam beam and hollow steel profile, all of similar outer geometry and weight.

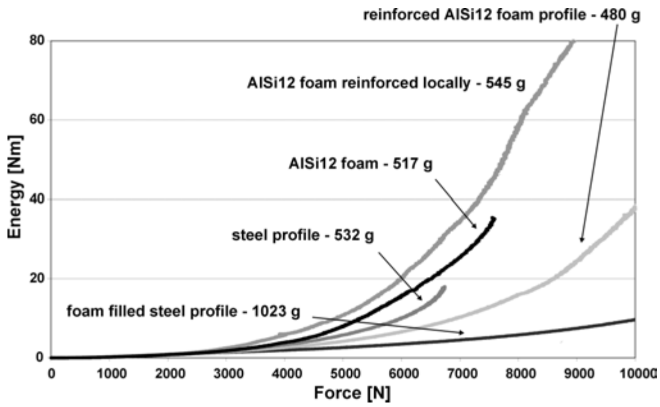


Fig. 10. Energy needed for deformation of various beams in 4-point bending as a function of peak load

Another important characteristic of lightweight structural profiles is their resistance to buckling when submitted to axial loading. The critical load at which profile of length l, modulus of elasticity E, and second moment of area I, will buckle is given by Euler's formula [1]

$$F_{crit} = \frac{n^2 \pi^2 EI}{l^2},$$

where factor n describes the degree of constraint at the ends of the column. Second moment of area can be simply related to the thickness of the profile $I \propto t^4$. Therefore the critical load is significantly low when $t << l$. It implies that buckling occurs easily for long and thin profiles. This situation is demonstrated in Fig. 11 and 12, where the resistance to buckling of reinforced aluminium is compared with the performance of hollow steel profile and plain foam of about the same weight.

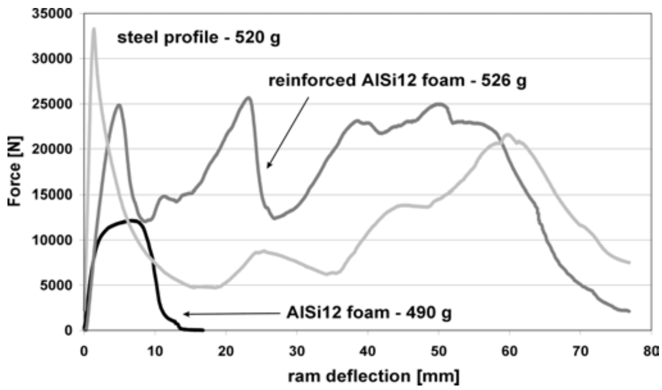


Fig. 11. Performance of steel, aluminium foam and reinforced aluminium foam long profiles under axial loading

The response of these profiles to axial loading was considerably different. The highest load was attained for steel profile because of highest compression strength and elasticity modulus of bulk steel. Correspondingly the lowest peak load was measured for plain foam.

After first maximum the steel profile starts to fold. Due to insufficient stiffness of cross section the initial U-shape is opening, which is accompanied with significantly reduced load at subsequent folding. On the other hand the profile made from plain foam breaks apart in weakest pore layer [6] after achieving first peak stress and its performance is over in short time without notable compression of the foam. No folding or distortion of initial shape of cross section was observed in this case. The deformation of reinforced foam comprises combination of axial compression of the foam and folding of reinforcing expanded metal. The opening of cracks at the foam surface and sudden breakage of the profile was prevented by the reinforcement. In other words, due to the reinforcements, the profile was allowed to deform in compression, what is the best deformation mode for foam. Thanks to foam the cross section of the profile is stiff enough and no distortion of U-shape or buckling of profile was observed. This leads to almost the same load at each subsequent folding of reinforcements, what is the main advantage if compared with hollow steel profile, especially for energy absorption purposes.

It can be concluded, that also in the case of buckling, the reinforced foam is superior concerning relation of mechanical properties to weight.

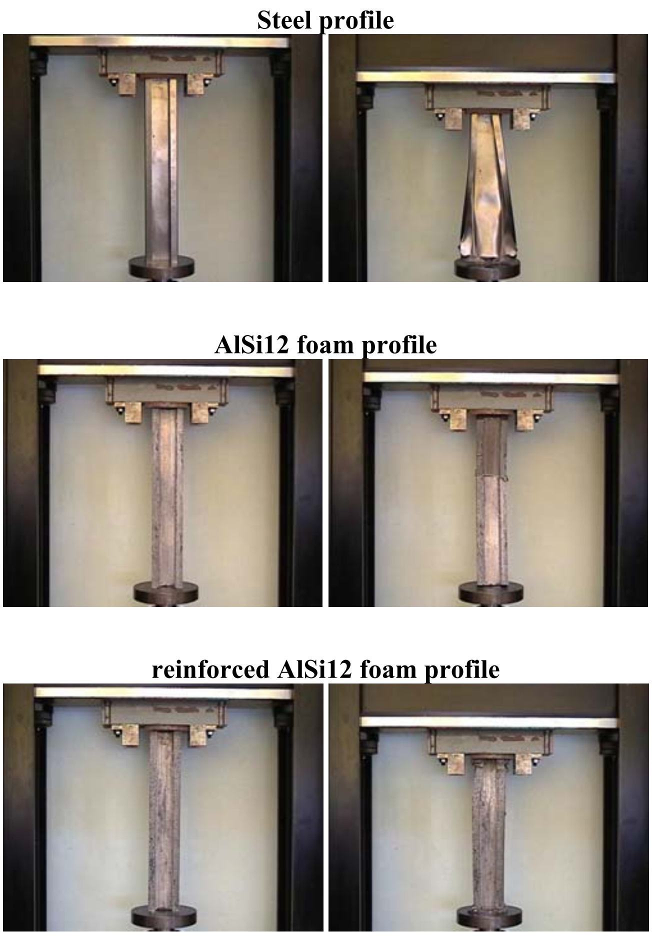


Fig. 12. Response of various lightweight profiles to axial loading (outer geometry of U- profile: 35x70x400 mm, similar weight)

3. MANUFACTURING OF REINFORCED FOAMS

Powder compact foaming technique for aluminium foam manufacturing, at first patented in USA [4], comprises foaming of the precursor prepared by compacting of powdered metal with foaming agent (e.g., TiH_2 powder) by cold isostatic pressing followed by hot extrusion. The obtained precursor of various shapes (rods, wires, open profiles) possesses gas tightly sealed particles of foaming agent within metallic matrix. The pore forming hydrogen is evolved during melting of metallic matrix from admixed foaming agent. If the precursor is inserted in a suitable mould before foaming, foam follows the shape of mould cavity. Subsequent rapid solidification of the foam enables to obtain solid foam with dense surface skin and cellular inner structure.

Similar technology can be used also for manufacturing of reinforced aluminium foams [6]. They can be prepared either by foaming in the mould or by injection of foam into the mould (Fig. 13).

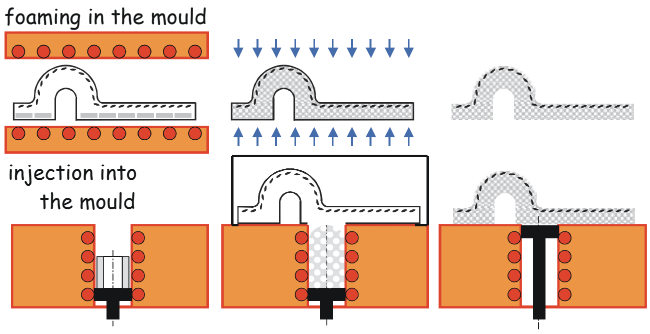


Fig. 13. Manufacturing methods of reinforced aluminium foam

When foamed in the mould, reinforcement, such as expanded stainless steel sheet or other mesh, net or woven textile made from metal or ceramic wires, etc., are placed in the foaming mould together with foamable precursor. The foam infiltrates the reinforcement during foaming or flows around it. After cooling the foam adheres to the solid reinforcement and creates mechanical or optionally diffusion bonds.

Situation is similar when foam is injected into the mould: here the reinforcement is placed in the mould and liquid foam is cast on it. The applied pressure allows foam to infiltrate the reinforcement properly. It is often necessary to preheat the mould and/or reinforcement before foam injection to improve infiltration and bonding between foam and reinforcement.

Both methods allow the use of various types of reinforcements (ceramic, metal, or both simultaneously [10]). The general requirements on the reinforcing material are following:

- sufficient flexibility to be easily formed into 3D shapes (optional)
- proper geometry to be fully infiltrated with liquid foam and to establish good mechanical bond
- higher melting point than that of foam metal to avoid melting during foam expansion
- non-reactivity with liquid foam metal to prevent creation of inevitable phases at the interface
- chemical compatibility with foam to avoid potential corrosion problem
- physical compatibility (similar CTE) to avoid detrimental internal stresses

The reinforcements are inserted into the mould before foaming and in comparison with manufacturing of plain foams no additional working step is necessary. This makes the manufacturing of such foam matrix composites extremely cost effective. Because the reinforcements prevent foam from collapsing, lower foam densities are attainable. Improved stability of liquid foam due to the reinforcements reduces also the number of rejected scrap parts. These effects generally lower total manufacturing cost and to some extent (very often fully) balance cost increase due to the price of reinforcements.

The reinforcements increase the thickness of surface skin [6], which additionally improves mechanical properties of the foam, especially bending stiffness, and enables limited shaping after foaming process. The surface treatment or encasing of reinforced foams is also easier.

Furthermore the presence of reinforcements simplifies joining of aluminium foams or fixing them to other structural components (Fig.14). Also mutual welding is possible similarly as in a case of steel reinforced concrete panels.

Fig. 14. Examples of joining possibilities of reinforced aluminium foams

Of course, this technology brings also some difficulties, which should be taken into account already at the design of structural component to avoid future problems:

- potential corrosion in the case of chemical incompatibility between the foam and reinforcement
- relatively high internal stresses caused by mismatch between coefficients of thermal expansion of foam and reinforcing element (these can even lead to the geometry distortion of final part)
- more complicated recycling

4. CONCLUSIONS

The capability of reinforced aluminium foams to be applied as lightweight structural element for load bearing purposes was investigated. The reinforced foam-, plain foam- and hollow steel profiles of similar weight were tested in bending and axial loading. It has been shown, that the reinforced foam is superior concerning all relevant characteristics (bending strength, stiffness, resistance to buckling and energy absorption).

The main role of reinforcements is to overtake the tensile stresses, which usually cause the sudden failure of the foam. Mechanical properties of reinforced aluminium foams are not a simple superposition of the single component properties; synergetic effects arising from the interactions between foam and reinforcements were observed. The possibility to reinforce the foamed part selectively and anisotropicly according to the expected load allows significant improvement of the strength, plasticity, energy absorption capacity and damage tolerance without significant weight or cost increase. The reinforcements prevent liquid foam from collapsing, increase the thickness of surface skin, simplify joining of foamed parts and enable limited shaping after foaming process.

Therefore, the reinforced aluminium foams are very good candidates for novel 3D-shaped frameless shell structures where excellent performance (stiffness, strength, passive safety) is expected at minimum weight.

5. ACKNOWLEDGEMENTS

The financial support of Alulight Int. GmbH., Ranshofen, Austria and technical assistance of Roman Uhrík and Katarína Müllerová are greatly appreciated.

REFERENCES

[1] Gibson L.J., Ashby M.F.: “Cellular Solids”, Oxford, Pergamon Press, 1988

[2] Ashby M.F., Evans A., Fleck N.A., Gibson L.J., Hutchinson J.W., Wadley H.N.G.: “Metal Foams - A design guide” Butterworth-Heinemann, 2000

[3] Sosnik A., US Patent 2434775, 1948

[4] Allen B.C., US Patent 3087 807, 1963

[5] Simančík F., “Reproducibility of aluminium foam properties”, In: “Cellular Metals and Metal Foaming Technology”, Ed. by J. Banhart, M.F. Ashby, N.A. Fleck, MIT- Verlag, Bremen, 2001, p. 235

[6] Simančík F., Rajner W., Laag R.: “Reinforced Alulight for structural use”, In: Processing and properties of Lightweight Cellular Metals and Structures (TMS Annual Meeting), Seattle, February 17 – 21, 2002, p. 25

[7] Simančík F., Rajner W., Laag R.: “Alulight - Aluminum foam for lightweight construction”, SAE Technical Paper Series 2000-01-0337, Warrendale: SAE, Inc., 2000, p. 31

[8] Banhart J.: “Aluminum foams: On the Road to Real Applications”, MRS Bulletin, April 2003, Volume 28, No. 4, 2003, p. 290

[9] Kováčik J., Simančík F.: “Use of zinc foam for filling of hollow steel profiles”, In: “Cellular Metals and Metal Foaming Technology”, Ed. by J. Banhart, M.F. Ashby, N.A. Fleck, MIT- Verlag, Bremen, 2001, p. 355

[10] Jerz J., Simančík F., Bortel M., Kubo S., Kováčik J.: “New design of lightweight armour sheets”, In: “Proc. Int. Conf. Cellular Metals and Metal Foaming Technology”, Eds: J. Banhart, N. Fleck, MIT-Publishing, Berlin, 2003

Authors: Jaroslav Kováčik, František Simančík, Jaroslav Jerz, Peter Tobolka

Institute of Materials and Machine Mechanics
Slovak Academy of Sciences
Račianska 75,
831 02 Bratislava, Slovakia
phone: +421 2 49268275
fax number: +421 2 44253301
e-mail: ummsjk@savba.sk