COMPARISON OF ZINC AND ALUMINIUM FOAM BEHAVIOUR

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The zinc foam was studied in the porosity range of 78–91 %. It was found that to foam zinc it is necessary to overheat significantly the foam above the melting temperature of metal or to use higher amount of foaming agent. Deformation behaviour of zinc foams is comparable to aluminium foams behaviour: compression strength of zinc foams is significantly lower at similar density; foams of equal porosity possess almost identical compression strength. Situation is similar when absorbed deformation energy is considered. Thanks to low foaming temperature, zinc foams can be used for partial stiffening of complex hollow profiles by "in-situ" foaming.

Key words: metallic foams, zinc foams, foaming, compression, bending

POROVNANIE VLASTNOSTÍ PENOVÉHO ZINKU A HLINÍKA

Študovali sme penový zinok v intervale pórovitosti 78–91 %. Ukázalo sa, že na spenenie zinku je potrebné výrazne prehriať penu nad teplotu tavenia kovu alebo použiť väčšie množstvo speňovadla. Deformačné správanie penového zinku je porovnateľné so správaním penového hliníka: pevnosť v tlaku penového zinku je výrazne nižšia pri porovnateľnej hustote. Peny s rovnakou pórovitosťou sa vyznačujú takmer rovnakou pevnosťou v tlaku. Situácia je podobná, ak uvažujeme absorpciu deformačnej energie. Vďaka nízkej teplote speňovania sa penový zinok môže použiť na lokálne spevnenie komplexných dutých profilov priamym speňovaním v profile.

1. Introduction

The natural load bearing materials usually have the cellular structure, which provides a tool for the realization of optimal combination of the mechanical properties and functionality at minimum weight. The discovering of benefits of natural structures gives a chance for new artificial cellular solids. However, the cell wall material has to be chosen very carefully if the structure is expected to carry the loads. Polymers appear to be insufficiently rigid and ceramics are too brittle. Perhaps, metals could be the right choice. Several of the engineering properties of

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metallic foams are superior to those of polymeric ones; 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. Moreover, these materials are fully recyclable without any pollution and waste problems.

Metallic foams possess unique combination of various properties such as high stiffness at low weight, high energy absorption capacity at adjustable stress levels, low thermal conductivity, good electrical conductivity, efficient electromagnetic shielding, sound and vibration damping [1]. Nowadays industrial interests are predominantly focused on aluminium foams due to the low density and low melting temperature of aluminium alloys. One of the attractive industrial applications of this material is in hollow steel profiles made by hydroforming technology (see Fig. 1) where the partial foaming in weakest points of profiles eliminates the peak stresses. This allows the use of cost-efficient hydroforming technology in applications where it was recently not possible because of insufficiently attainable wall-thickness. The removing of peak stresses enables the reduction of the thickness with the overall weight savings, thus increasing the property-to-weight ratio of the component. Partial foaming avoids welding of various stiffeners, which has negative environmental impact and is also cost intensive. Moreover, the use of the foam increases the capability of the component to absorb front and/or side crash energy and suppresses the noise and vibration of an initially hollow structure. The problems still to be solved are too slow foaming rate for high production output, negative impact on the properties of profile material because of relatively high foaming temperature (removing of work hardening, changes on the surface) and potential corrosion problem when aluminium foam is used in combination with steel.

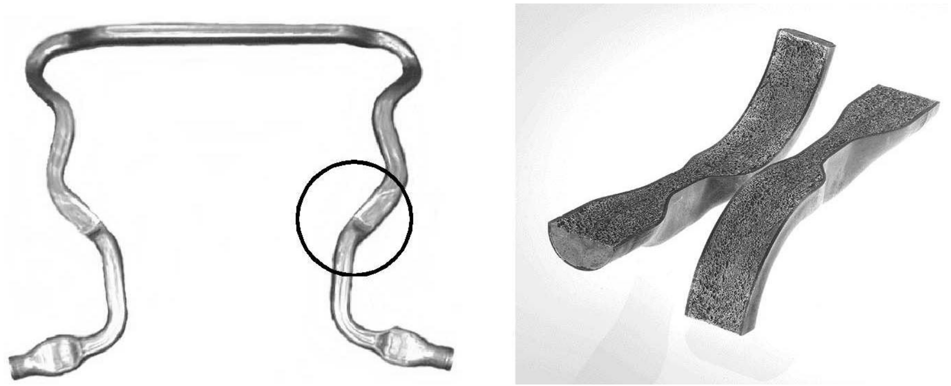

Fig. 1. Example of hydroformed profile (left) filled in weakest section (circle) with aluminium foam (right) in order to increase the insufficient stiffness and energy absorption capacity.

These problems could be significantly minimised when zinc or its alloys are used instead of aluminium because of lower melting temperature of zinc and its compatibility with steel regarding the corrosion resistance. This possibility was studied in this work. The foaming temperature, compression strength and energy absorption capacity of foamed zinc were investigated and the experimental results were compared with results obtained for aluminium foams.

2. Manufacturing of zinc foams

The zinc foams investigated in this study were prepared by PM route similarly as aluminium foams [2], however in this case plain Zn or ZnAl4Cu1-alloy powders were mixed with a foaming agent (TiH_2 or MgH), precompacted into billets by cold isostatic pressing and then hot extruded into a foamable precursor. The precursor was placed in the foaming mould and heated above the melting temperature of the alloy. On heating hydrogen is released from the foaming agent and the liquid matrix expands filling the die cavity. Then the rapid cooling freezes the obtained highly porous cellular structure [1]. The aluminium foam samples based on AlSi12 alloy were also made by the same route for comparison.

3. Structure of zinc foam

The temperature required for the foaming has to be slightly above the liquidus temperature of the used alloy. While for aluminium and its alloys it is in the range of 600–680 ℃, in the case of zinc foams it is in the range of 390–460 ℃. It is known that the structure of the foam significantly depends on the viscosity and surface tension of the melt, on the pressure within and outside the pores and on the atmosphere in the mould [3]. The melting point of zinc (420 ℃) is relatively low for the sufficient decomposition of usually used foaming agents such as TiH_2 or ZrH_2(Fig. 2b). For example, the decomposition of TiH_2 starts at 400 ℃ and continues up to the melting point of titanium. The largest amount of hydrogen is evolved at about 550–660 ℃ at normal (atmospheric) pressure. This is very suitable for the foaming of aluminium (Fig. 2a), however if zinc is foamed at this temperature the foam collapses due to the significant reduction of melt viscosity and also due to rapid oxidation of surface of liquid foam. When ZrH_2 is used, the proper foaming temperature and amount of used foaming agent is similar or even higher than in the case of TiH_2. Another possibility is an exploitation of foaming agents with lower decomposition temperature, such as MgH (decomposition starts at about 280 ℃). However, if this compound is used the resulting porosity is lower than in a case of TiH_2 and the obtained structures are very heterogeneous with excessively large pores (Fig. 2d). Moreover, lower decomposition temperature of MgH significantly limits the temperature needed for successful hot extrusion of the foamable precursor.

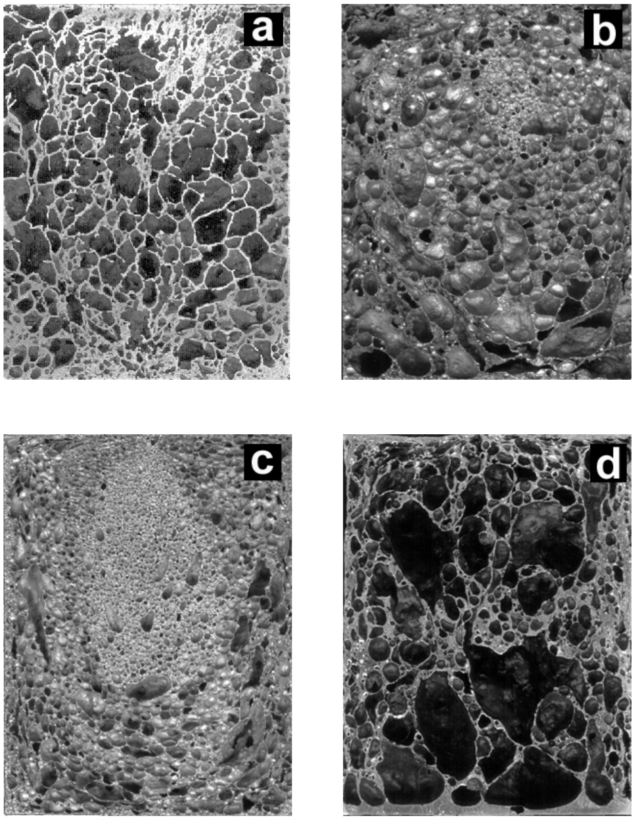

Fig. 2. The foaming temperature and corresponding typical structure and apparent density of a – aluminium foam (AlSi12 + 0.4 wt.% TiH_2), foaming temperature 620 ℃, density 0.51 $g \cdot cm^{-3}$, b – zinc foam (plain Zn + 1 wt.% TiH_2), foaming temperature 430 ℃, density 0.87 $g \cdot cm^{-3}$, c – zinc foam (plain Zn + 1 wt.% TiH_2) foaming temperature 450 ℃, density 0.67 $g \cdot cm^{-3}$, d – zinc foam (plain Zn + 1 wt.% MgH) foaming temperature 430 ℃, density 1.25 $g \cdot cm^{-3}$ (sample size ϕ 40 × 51 mm).

Nevertheless, the experiments have confirmed that, if TiH_2 is used as a foaming agent, it is possible to prepare foam samples from aluminium as well as from zinc alloys. For the successful foaming of Zn-alloys it was necessary to use more TiH_2 and the matrix had to be heated further over its melting point (Fig. 2c). The apparent density calculated from the weight and the volume of the samples was in the range of (0.6–1.7) $g \cdot cm^{-3}$ for zinc and (0.4–0.8) $g \cdot cm^{-3}$ for AlSi12-foams, respectively. The lowest apparent density that has been attained at a relatively uniform pore structure was 0.6 $g \cdot cm^{-3}$ for zinc (1 wt.% TiH_2, foaming temperature 450 ℃) and 0.4 $g \cdot cm^{-3}$ for AlSi12 alloy (0.4 wt.% TiH_2, foaming temperature 610 ℃). In the

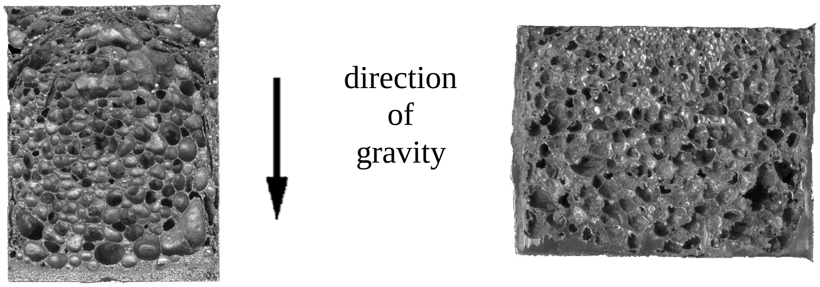

Fig. 3. The effect of the drainage on the typical structure of zinc foams (left plain Zn, right ZnAl44Cu1-casting alloy, all with 1 wt.% TiH_2).

terms of porosity it was 92 % for zinc and 85 % for AlSi12 alloy. The much higher porosity achieved with zinc was due to the significant overheating of the matrix above its melting temperature, which simultaneously lowers the viscosity of zinc.

However, lowering of the viscosity of molten matrix negatively affects the stability of liquid foam providing better conditions for gravitational drainage. The intensive drainage results in the density gradient along vertical axis of the sample (Fig. 3). If the matrix alloy is used with lower melting temperature or viscosity (such as ZnCu4Al1-casting alloy), the effect of the drainage becomes more pronounced and sometimes does not allow producing acceptable foam samples from such alloys (providing TiH_2 is used as a foaming agent).

The investigations have shown that it is possible to prepare zinc foam with apparent density comparable to aluminium foam (note that pure zinc possesses three times higher density than aluminium). The significantly higher final porosity was attained in the case of Zn foams due to lower amount of stabilising oxides and thus lower viscosity of the melt. However, due to the lower viscosity the drainage appears to be a serious problem, especially when the metal with higher density such as Zn is used for foaming of higher parts. On the other side, the drainage effect can be effectively used for the manufacturing of gradient porosity or for enhancing the skin of some parts of the foamed component. The challenge for the producers is not to manufacture the parts with homogeneous structure (though often requested by scientists not able to model non-perfect foam), but to prepare the parts with reproducible properties and optimum (though inhomogeneous) distribution of material [4] according to expected loading conditions.

4. Compression behaviour of zinc foam

The typical stress-strain curve of metallic foam consists of three parts [5]; in the first part the stress increases almost linearly with increasing strain, then a deformation "plateau" follows at nearly constant compression stress (pore walls yield or fracture, whereas the deformation does not require an increase of the load) and finally there is a part of rapidly increasing stress after the cell-walls crushed together.

The value of the compression strength (first maximum on the stress-strain curve [6]) for the zinc foams similarly as for aluminium foams unambiguously grows with increasing apparent density of the foam [5]. The structural observations during deformation of AlSi12-foams have revealed [6] that the initial failures in the structure of the foam (fracture/plastic deformation of the pore walls) appear after the first maximum in the stress-strain curve. The stress drop that follows is related to the shift of the upper part of the sample due to the failure of the walls in one layer of pores (weakest link). The value of this drop is a function of pore size at given density, however it depends also on foam heterogeneity [6]. This was observed also for zinc foams: highly heterogeneous ZnAl4Cu1 foams exhibit at constant porosity significantly larger stress drop than pure Zn foams with more homogeneous structure (Fig. 4).

Contrary to the AlSi12-foams the Zn-foams exhibit rather smooth stress-strain curve after the compression strength is reached (Fig. 5). Similar behaviour was observed if ductile aluminium matrix (such as Al 99.96 or AlMg1Si0.6-alloy) was used instead of brittle AlSi12-alloy. In this case the pore walls plastically bend in overall sample, but preferably at the weakest link. It means that the Zn-foams behave like ductile Al or AlMg1Si0.6 foams where deformation of the sample is caused predominantly by bending (not cracking) of the pore walls. However, if

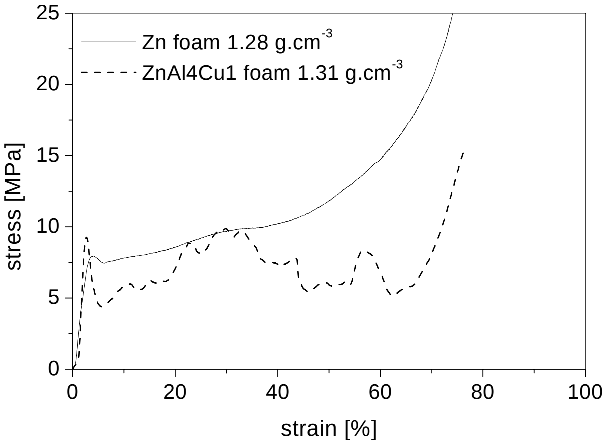

Fig. 4. Comparison of the stress-strain curves of zinc foams made of plain zinc and ZnAl4Cu1 alloy.

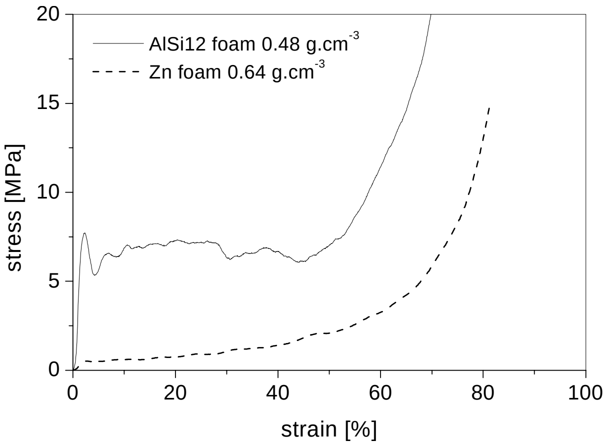

Fig. 5. Comparison of the stress-strain curves of aluminium and zinc foams at similar apparent density.

more brittle alloy (such as ZnAl4Cu1-casting alloy) is used, the nature of the stress-strain curve is very similar to that one for AlSi12-foams (Fig. 4): sudden failures of the pore walls accompanied by the stress drop result in the "bumpy" character of the stress-strain curve. If a large portions of disintegrated foam move diagonally (kinking of the sample) the loading of the sample substantially decreases sometimes even to the zero value.

The compression strength of pure zinc foam (0.5 MPa) is much lower than the corresponding strengths of brittle AlSi12-foam (7.5 MPa), ductile AlMg1Si0.6-foam (5.1 MPa) even also of very ductile Al 99.96 foam (3 MPa) at the similar apparent density (see Table 1). This is due to the much higher porosity (92 %) of zinc foam, resulting in less load-bearing fraction in comparison with aluminium foams

Table 1. Comparison of the compression strength for brittle and ductile aluminium and zinc foams

Matrix alloy	Density [$\mathrm{g\cdot cm^{-3}}$]	Porosity [–]	Compression strength [MPa]
AlSi12	0.5	82	8
AlMg1Si0.6	0.5	82	5
Al 99.96	0.6	78	3
Zn	0.6	92	0.5
Zn	1.2	83	7
ZnAl4Cu1	1.3	81	9

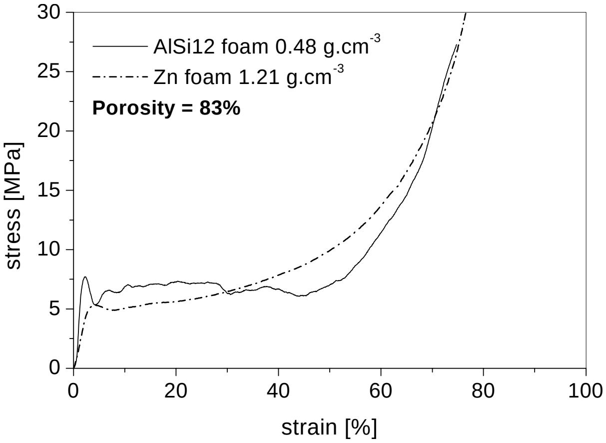

Fig. 6. Comparison of the stress-strain curves of aluminium and zinc foams at constant porosity.

(82 %). However, if the porosity is similar, the compression strengths of foams are comparable (Fig. 6). Of course, in this case the overall weight of zinc foam part is about three times higher than the corresponding part made of aluminium foam.

The relation obtained between compression strength of foam and its porosity can be derived in power-law form similar to the percolation theory [7] as follows:

$$\sigma_{\mathrm{CS}} = \sigma_{\mathrm{CS0}} \cdot \left(\frac{\rho}{\rho_0}\right)^{T_{\mathrm{f}}}, \tag{1}$$

where σ_{CS} is the compression strength and ρ is the apparent density of the foam, while σ_{CS0} is the compression strength and ρ_0 is the apparent density of the solid material. The experimentally obtained characteristic exponent T_{f} is about 2.0 for aluminium foams [8] and the same value can be expected also for zinc foams.

Equation (1) implies that the compression strength of both foams is comparable at the same porosity, if also the strengths of cell wall materials are comparable. In order to obtain the same compression strength for the same weight of the foamed part, the strength of Zn-alloy must be approx. 3.5 times higher than the compression strength of compared aluminium alloy. Realistically, it is not possible. This indicates that the aluminium foam cannot be replaced with zinc foam without significant reduction of the property to weight ratio.

On the other hand, low values of compression strength (also plateau stress) are promising for passenger protection in cars during collisions (Fig. 7). To protect hip area of occupants, it is required the crash energy absorber with compression

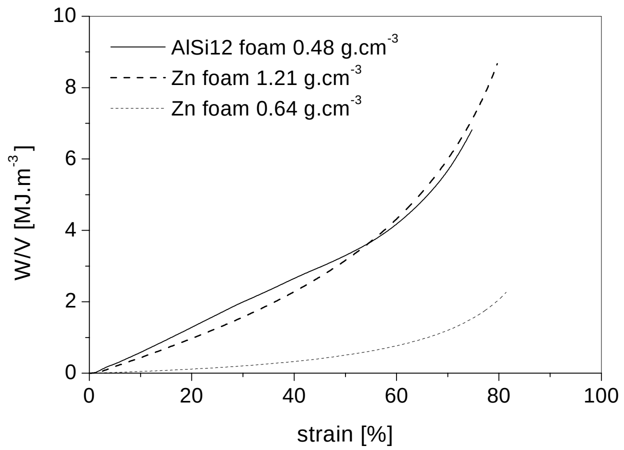

Fig. 7. Absorbed energy per unit volume for zinc foams with the same density and porosity as AlSi12 aluminium foam.

strength about 0.5 MPa and for thorax area about 0.1 to 0.15 MPa [9]. Low dense aluminium foams prepared by melt route process can be used for this purpose, but unfortunately, these foams cannot be manufactured as net shape parts. This drawback can be overcome by using of PM zinc foams that can be easily formed by foam injection technique [10, 11, 12]. Use of zinc foams can also avoid the problems connected with recycling of crash absorbers made of polymers that are nowadays widely used in cars.

5. Bending properties of steel profiles foamed with zinc

As mentioned previously, one of the potential industrial applications of metallic foams is to improve stiffness and strength of hollow profiles. There are two possible ways to do this. The first one is to insert the foam stiffener into the profile. The stiffener does not fill the hollow space entirely because of necessary tolerances and usually has to be fastened expandable adhesives. This approach is usually used for steel or aluminium profiles of simple shape or profile consisting of various parts welded together (Fig. 8). The experiments showed [13] that the filling of the whole profile length with foam is disadvantageous because of the excessive weight increase of the component. The property-to-weight ratio can be improved if the profile is stiffened only partially in weakest section. In this application the aluminium foam dominates always over the zinc one, because of considerably better properties at comparable weight.

The alternative way is to fill the profile by partial foaming "in situ". Also complex shaped hydroformed profile can be applied. In this case the profile is filled

Fig. 8. Complex welded part with AlSi12 aluminium foam insert.

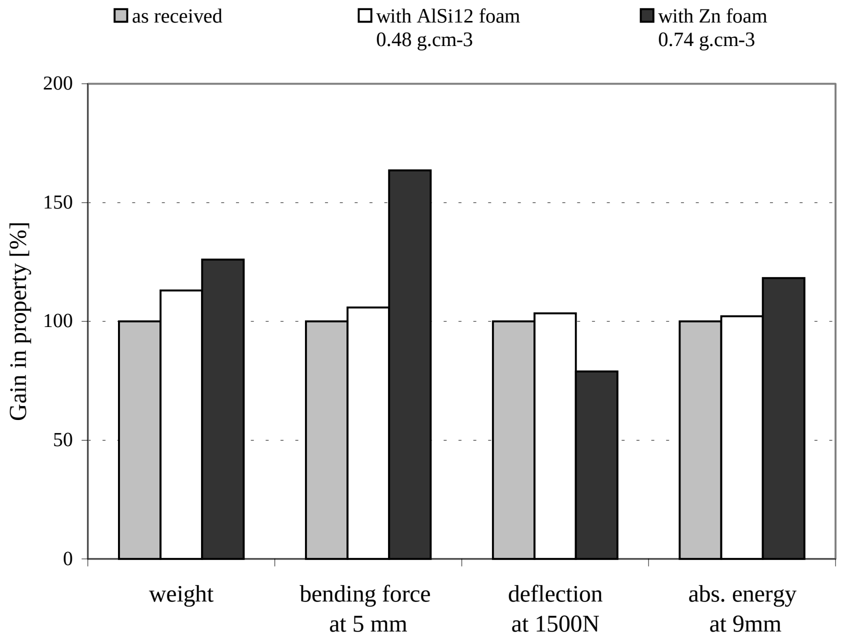

Fig. 9. Gain in the properties for steel tubes ø 38.5/37 × 400 mm partially foamed in the middle with metallic foams (foam length 100 mm, 3 point bending test, $l = 300$ mm, roller diameter 30 mm). Thermal treatment for steel profile: none for as-received, 800 °C for filling with AlSi12 foam, 500 °C for filling with Zn foam.

in weakest sections entirely without gaps between foam and outer shell. Even metallurgical bonding can be realised and therefore no additional fasteners are needed. However, in situ foaming requires heating of profile above the melting temperature of foamed metal. In a case of aluminium foams it is usually above 700 ℃. This temperature leads to significant changes in structure of profile material (increase of grain size, change of grain shape and removing of cold working) with dramatic consequences on the mechanical properties – the properties of the profile are sometimes worse than before foaming [13]. Zinc and its alloys have significantly lower foaming temperature (below 500 ℃) and thus less influence on the steel structure. Therefore, partial filling with zinc foam can be more appropriate leading to better mechanical properties of foamed profile (Fig. 9). Also aluminium profile can be foamed with Zn-foams, especially if the injection foaming technique is applied.

6. Conclusion

It can be concluded that it is possible to prepare zinc foams with the apparent densities in the range of (0.6–1.5) $g \cdot cm^{-3}$ and corresponding porosity in the range of 78–91 %. The foaming of the zinc or its alloys requires either higher overheating above the melting temperature than it is in the case of aluminium foams, or needs higher amount of foaming agent, providing TiH_2 is used for this purpose. The deformation behaviour of zinc foams is comparable with that one of aluminium foams; brittle alloys tend to fracture of the pore walls, while more ductile alloys predominantly deform by bending of pore walls. The compression strength of zinc foams is significantly lower than that of aluminium foams at similar apparent density. The zinc and aluminium foams of equal porosity possess nearly the same compression strength. The situation is similar if the capability to absorb the deformation energy is considered.

Zinc foams can be potentially applied:

1. As crash energy absorbers for passenger protection, where low compression strength is needed. The zinc foams can be easily formed into net shape complex 3-D parts and involve no recycling problems in distinction to polymers.

2. For partial stiffening of complex 3D hollow profiles, especially those made by hydroforming. Because the zinc is usually used for corrosion protection of steel, no corrosion problems are expected. Low foaming temperature does not involve significant changes in the material of the profile and also allows shortening of foaming stroke. Also aluminium profiles can be foamed in situ with Zn-foam.

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