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COMPARISON OF ZINC AND ALUMINIUM FOAMS IN DEFORMATION AND FRACTURE

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Abstract:

One of the very promising applications of aluminium foams is their utilisation as a filler in a hollow steel profiles to enhance stiffness and increase energy absorption at reduced weight for various components in automotive industry. However, the combination of aluminium and steel can cause a potential corrosion problem. Moreover, the heating of the steel profile to the melting temperature of aluminium during foaming leads to the loss of cold-working strengthening. The utilisation of zinc instead of aluminium for the foaming of steel profiles would certainly minimise these problems. 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 that ones for aluminium foams.

Keywords: *zinc foams, aluminium foams, deformation behaviour, compression strength*

1. Introduction

A powder metallurgical process recently developed at the Institute of Materials and Machine Mechanics, Slovak Academy of Sciences in close co-operation with Austrian companies MEPURA and Illichmann GmbH enables the cost effective production of the aluminium foam parts in various shapes and sizes, e.g. panels, profiles or complex 3D-castings [1]. The foam is usually covered by a dense metallic skin which significantly improves mechanical properties and the appearance of the foamed component. Due to the highly porous structure the permanent deformation of foam starts under loading which is considerably lower than the loading needed for the collapse of the pore-free part. Then the deformation of the foam furthers without significant increase of the applied load until the pore walls crush together, thus consuming a relatively large amount of the deformation energy at nearly constant stress level. This is why metallic foams are recommended for the impact energy absorbers in cars, lifting and conveying systems [2].

One of the very promising applications of metallic foam is partial stiffening of hollow steel components. Partial foaming will improve the properties in the weakest points of the profile which allows to design its overall thickness according to mean and not to peak stress, thus saving the overall weight. Moreover, the use of the foam increases the capability of the component to absorb crash energy and suppresses the noise and vibration of an initially hollow structure.

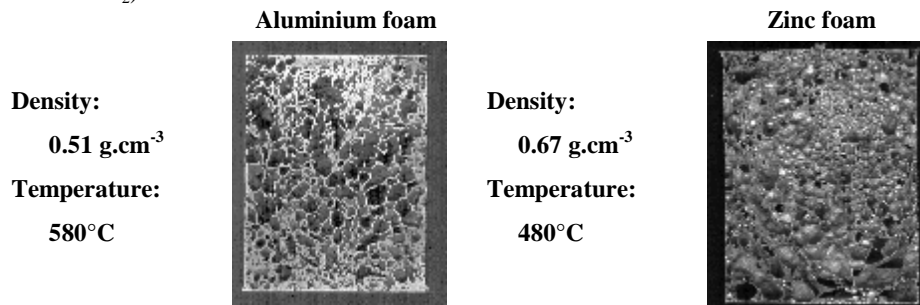
Recently, the aluminium foam has been intensively investigated and seems to be very promising for this purpose. However, the combination of aluminium and steel can cause a

potential corrosion problem. Moreover, the temperature needed for the foaming of aluminium inside a steel profile is relatively high (over 600°C) and can affect the microstructure and properties of steel. Both problems can be minimised if zinc foam instead of aluminium foam is applied for the stiffening of the components made of steel. The main aim of this work was to investigate the possible performance of zinc foam and to compare the experimental results with that ones obtained for aluminium foams. The attention was given to the foaming temperature, compression strength and ability of foam to absorb deformation energy.

2. Experimental

The foam samples were prepared via powder metallurgical route [1] from the metallic powder that was mixed together with a foaming agent (TiH_2) and then continuously hot extruded into a foamable precursor. The precursor expands into the highly porous liquid due to hydrogen released from the foaming agent, during the heating of the precursor above the melting temperature of the metallic matrix. Then the rapid cooling process takes place to freeze the obtained cellular structure. The zinc foams were prepared from plain Zn and ZnCu4Al1-alloy powders. The aluminium foam samples made of AlSi12-casting alloy were used for comparison. All samples were cylindrical with the diameter of 40 mm and length of 51 mm with surface skin (see Fig. 1). The compression tests were carried out using the INSTRON testing machine at a crosshead speed of 0.01 m/min.

Fig.1. The foaming temperature and corresponding typical structure and apparent density of aluminium foams (AlSi12-casting alloy with 0.4 w.% TiH_2) and zinc foams (plain Zn with 1 w.% TiH_2).



3. Results and discussion

The structures of foamed aluminium and zinc are shown in Fig.1. The optimum temperature for foaming of aluminium lies just above the liquidus temperature of the used alloy (600-680°C). Significantly lower foaming temperature and thus less influence on the steel structure can be expected if zinc or its alloys are used, because of lower melting temperature of zinc. However the melting temperature of zinc (420°C) is not sufficient for the proper decomposition of TiH_2 which was used as a foaming agent in this case. At lower foaming temperatures the foaming agent only starts to release hydrogen, thus leading to the heterogeneous structure with low density shell around a high density core (Fig. 2). The decomposition of TiH_2 starts at 450°C [3] and continues up to the melting point of titanium. The largest amount of hydrogen is evolved at about 550-600°C at normal (atmospheric) pressure [3]. Therefore foaming temperature should be applied in this range to use the TiH_2 effectively. If the foaming temperature is lower, more TiH_2 has to be used to attain the same

porosity level. Another possibility is a utilisation of other foaming agent, such as MgH_2 with lower starting decomposition temperature (Fig. 2). However, lower decomposition temperature of foaming agent significantly limits the temperature needed for the successful hot extrusion of foamable precursor.

Fig.2. The effect of foaming agent on the typical structure and apparent density of zinc foams (plain Zn with 1 w.% TiH_2 and 1w.% MgH_2).

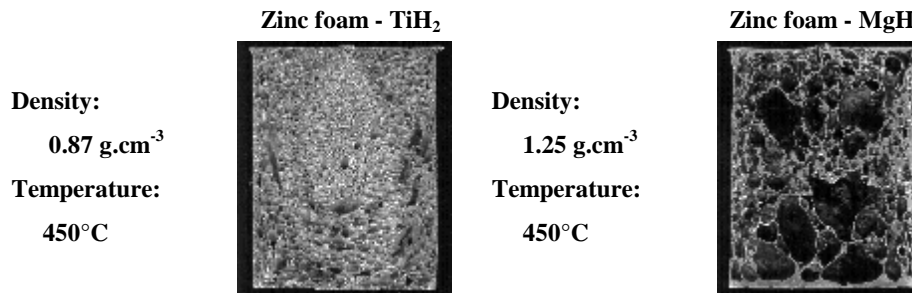
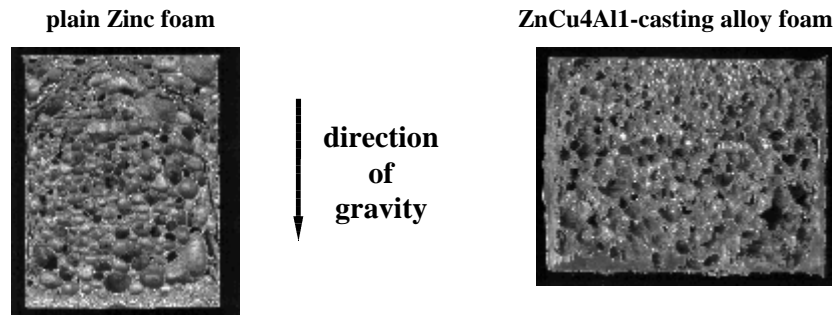
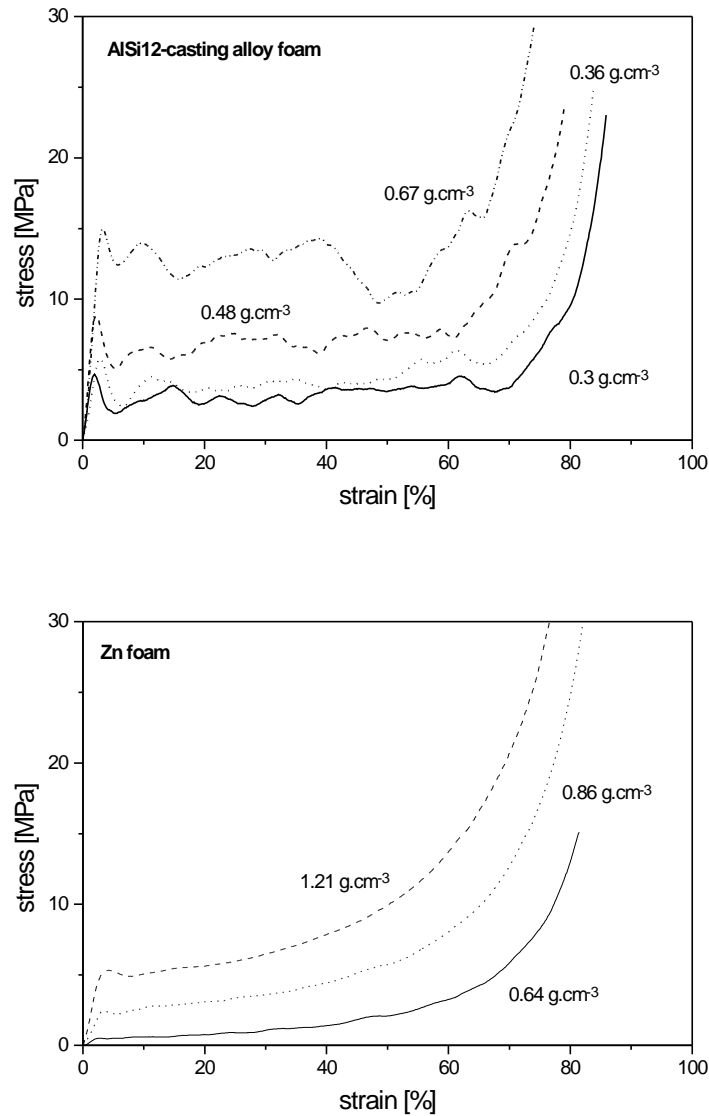


Fig.3. The effect of the drainage on the typical structure of zinc foams (plain Zn and ZnCu4Al1-casting alloy with 1 w.% TiH_2).



The experiments have shown that, if the TiH_2 is used as a foaming agent, it is possible to prepare foam samples from both aluminium, as well as 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. The apparent density calculated from the weight and the volume of the samples was in the range of 0.6 - 1.7 g.cm⁻³ for zinc and 0.4 - 0.8 g.cm⁻³ for AlSi12-foams, respectively. The lowest apparent density which has been attained at a relatively uniform pore structure was 0.6 g.cm⁻³ for zinc (1 w.% TiH_2 , foaming temperature 480°C) and 0.4 g.cm⁻³ for AlSi12 alloy (0.4 w.% TiH_2 , foaming temperature 610°C). In the 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 [3]. 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 significant and sometimes does not allow to produce acceptable foam samples from such alloys (providing TiH_2 is used as a foaming agent).

Fig.4. The compression stress-strain curves of AlSi12- and Zn-foams at various apparent densities.



The typical stress-strain curve of metallic foam consists of three parts [4]; in the first part the stress increases almost proportionally 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 [5]) for the zinc foams similarly as for aluminium foams unambiguously grows with increasing apparent density of the foam (see Fig. 4). The structural observations during the deformation of AlSi12-foams have revealed [5], that the initial failures in the structure of the foam

(fractures 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. Contrary to the AlSi12-foams the Zn-foams do not exhibit a significant drop of the stress, when the compression strength is reached. Similar behaviour has been observed if more 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 without sudden failure of the whole pore layer (weakest link) and without subsequent shift of the upper part of the test sample. It means, that the Zn-foams behave like ductile Al or AlMg1Si0.6 foams where the deformation of the sample is caused predominantly by bending (not cracking) of the pore walls. However, if more brittle alloy (such as ZnCu4Al1-casting alloy) is used, the deformation behaviour changes dramatically (Fig. 5) and the character of the stress-strain curve is very similar to that one for AlSi12-foams. Sudden failures of the pore walls accompanied by the drop of the stress result in the "bumpy" character of the stress-strain curve. If a large portions of disintegrated foam move diagonally the loading of the sample substantially decreases sometimes even to the zero value.

The compression strength of zinc foam (0.5 MPa) is much lower than the corresponding strengths of brittle AlSi12-foam (7.5 MPa), AlMg1Si0.6-foam (5.1 MPa) even for more ductile Al 99.96 foam (3 MPa) at the similar apparent density (see Fig. 6). This is due to much higher porosity level of zinc foam (91%) in comparison with aluminium foams (83%) at the same apparent density.

The relation obtained between compression strength of the foam and its porosity can be derived from the percolation theory [6, 7] as follows:

$$S_{CS} = S_{CS0} \cdot \left(\frac{r}{r_0} \right)^f,$$

where S_{CS} is the compression strength and r is the apparent density of the foam, while S_{CS0} is the compression strength and r_0 is the apparent density of the solid material. The characteristic exponent f is about 2.0 for aluminium foams and the same value can be expected also for the zinc foams. It means, that zinc foam with 91% porosity would have a comparable compression strength with AlSi12 foam having 83% porosity if the compression strength of zinc is 3,5 times higher than the compression strength of AlSi12-alloy. However this is not true in reality. Compression strength of zinc is comparable (even slightly lower) than that one of AlSi12. Therefore, nearly the same values of the compression strength have been obtained for the foams with similar porosity (see Fig. 7). However, in this case the samples made of zinc foam are almost three times heavier than the corresponding aluminium foams, because of higher density of zinc in comparison with Al-alloy. This indicates that the aluminium foam in hollow profiles cannot be replaced with zinc foam without significant reduction of the property to weight ratio. The same stiffness as with zinc foam can be achieved with aluminium foam at much lower weight.

Fig.5. The comparison of the stress-strain curves of metallic foams made of brittle and ductile alloys.

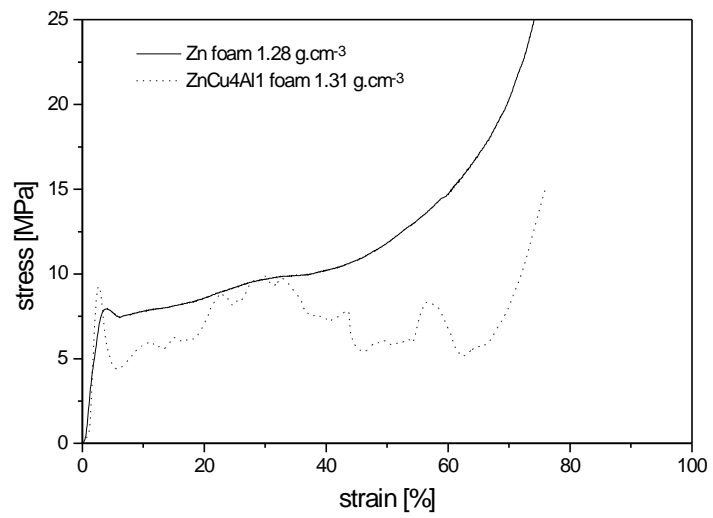
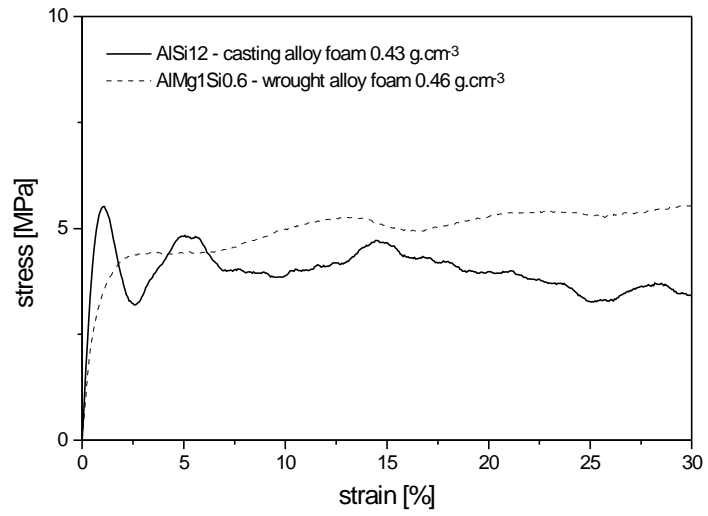


Fig.6. The comparison of the stress-strain curves of AlSi12- and Zn-foams at similar apparent density.

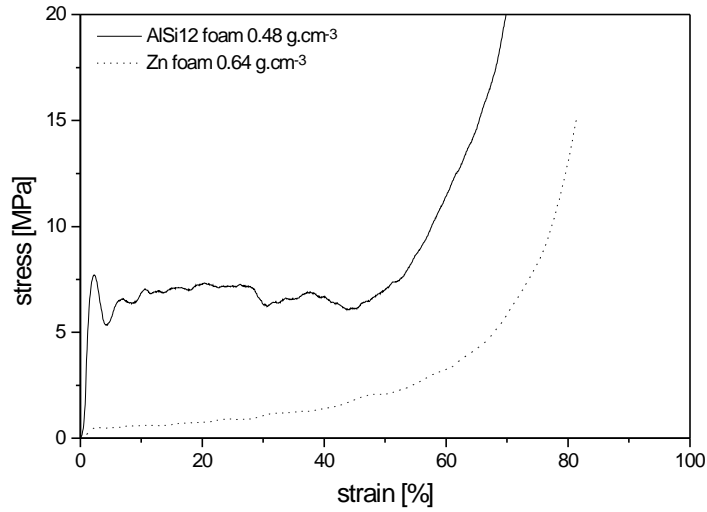


Fig.7. The comparison of the stress-strain curves of AlSi12- and Zn-foams at similar porosity.

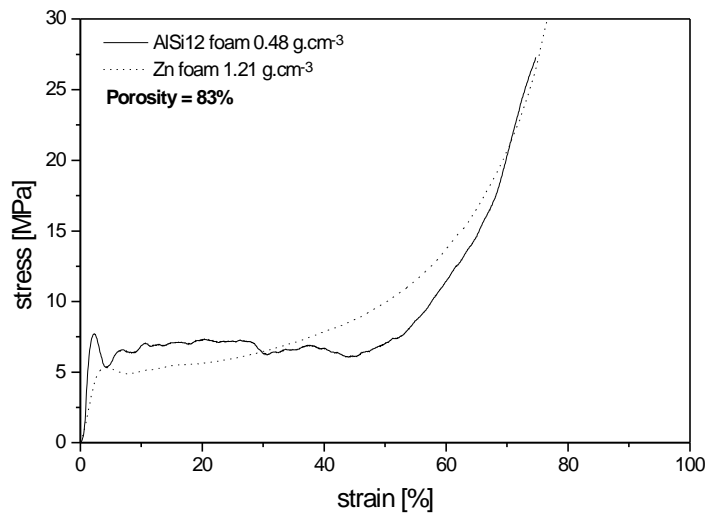


Fig.8. The variation of the energy absorption W per unit volume of zinc foams of various apparent densities

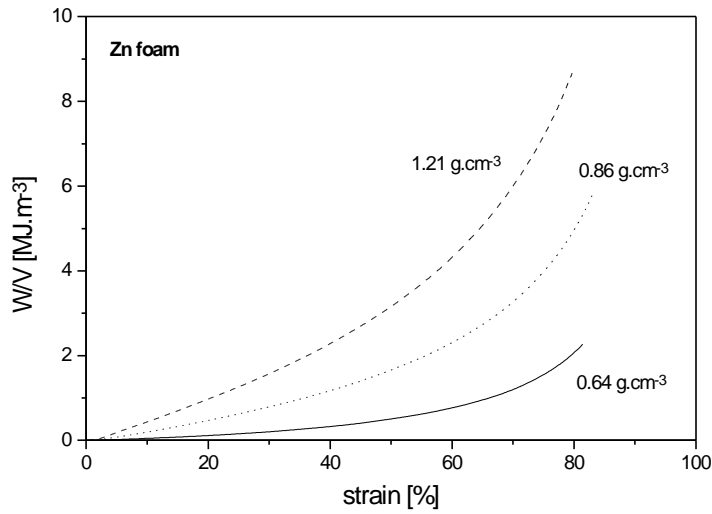
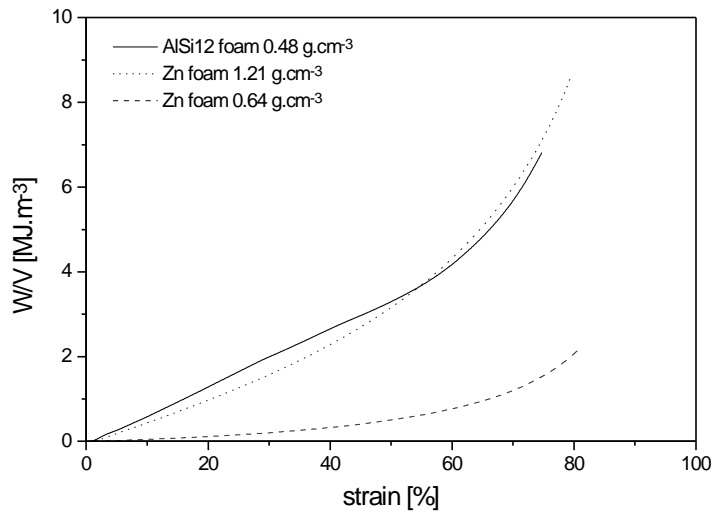


Fig.9. The comparison of the energy absorption W per unit volume of Zn- and AlSi12-foams at similar porosity and apparent density.



If the capability to absorb the deformation energy is considered the situation is similar. It has been shown in Fig. 8 that the energy absorbed until determined level of deformation is attained significantly increases with the increasing apparent density of the foam. The performance of zinc foam in the absorption of the deformation energy is comparable with the performance of aluminium foam of the same porosity. If the same weight of samples is

considered the aluminium foam is evidently superior (Fig. 9).

Therefore also here the zinc foam cannot replace the aluminium foams without weight increase. However, in some applications (e.g. head and knee protection zones in a car etc.), very low impact forces are required. These forces are derived from the stress level in the plateau region, which should be in the range of 0.15 - 0.5 MPa. This level is too low for available aluminium foams although highly porous zinc foams can be successfully applied.

4. Conclusions

The possibility to replace the aluminium foams with zinc foams for the stiffening of hollow steel profiles was investigated. The attention was given to the foaming temperature, compression strength and ability of zinc foam to absorb deformation energy.

It has been shown that it is possible to prepare zinc foams with the apparent densities in the range of 0.6 - 1.7 g.cm⁻³ and corresponding porosity in a range of 76 - 91%. The foaming of the zinc or its alloys requires higher overheating above the melting temperature than it is in the case of aluminium foams, and also needs higher amount of foaming agent, providing TiH₂ is used for this purpose.

The deformation behaviour of zinc foams is comparable with that one of aluminium foams; brittle alloys tend to fracturing 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 almost the same compression strength. The situation is similar if the capability to absorb the deformation energy is considered.

It can be concluded that the aluminium foam in hollow profiles cannot be replaced with zinc foam without significant reduction of the property to weight ratio. The use of zinc foams can be plausible in crash energy absorbers where lower impact forces are required.

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