Reproducibility of aluminium foam properties

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Abstract

The industrial exploitation of a new material is clearly determined by the possibility to reproduce its mechanical and physical properties. The aim of this paper is to discuss the potential of aluminium foams to meet this objective.

1. Introduction

Over the past ten years a range of aluminium cellular materials has been developed for potential applications in lightweight structures which are stiff, strong, absorb crash energy and are cheap to be used by the transport and construction industries. Some of the engineering properties of aluminium foams are superior to those of polymeric foams; they are stiffer by an order of magnitude, they have a higher melting temperature, they possess superior fire resistance and do not evolve toxic fumes in a fire. However, it is widely believed that the acceptable reproducibility of the properties is still questionable. The aim of this paper is to try to explain the reasons for this mistrust in aluminium foams and to make some suggestions how to improve their image.

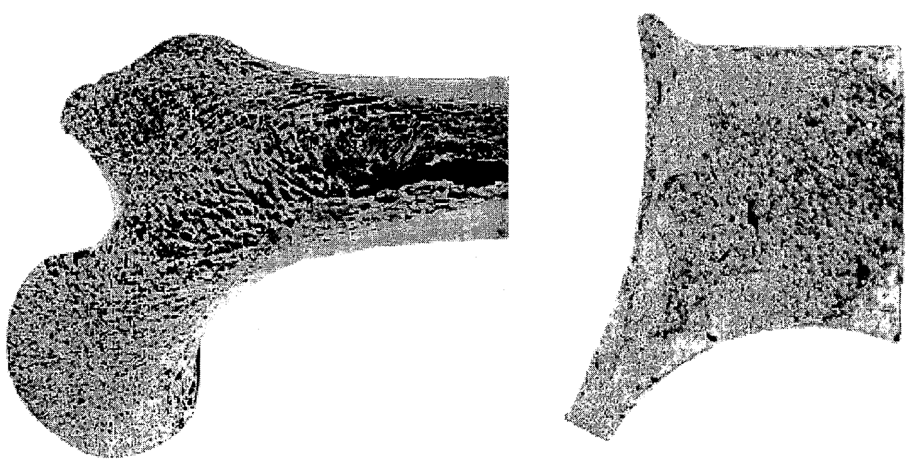
2. Reasons for the low reproducibility of aluminium foam properties

There is no doubt that foam properties strongly depend on the pore structure. Various constitutive laws have been suggested for the characterisation and modelling of this relationship [1]. These laws originally developed for polymeric foams are usually based on the relative density of the foam and therefore assume uniform cellular structure at least at a macroscopical level. However, aluminium 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 in the cell walls, corrugated cells etc. If these features are not taken into account and the properties of the foam are characterised only in relation to apparent density, higher scatter of properties is to be expected. Aluminium foams can be prepared by various processing methods, such as foaming of the melt, investment casting or by powder metallurgical (PM) techniques [2]. Although they are all mostly called "aluminium foams", these materials are not very alike. The manufacturing technique affects the distribution of the cell-wall material in such a way, that the properties of differently manufactured materials are not comparable. The foaming process dictates not only the properties but even the potential applications of the foam. Thus the foams prepared by PM technique (usually containing a dense skin) can be effectively used as net shape components, stiffening cores in castings or in complicated hollow profiles, whereas the foams prepared by "molten metal route" (typically large blocks or panels) can be effectively used as voluminous energy absorbers, cores for sandwiches or for blast protection [3]. The open-celled foams (made by investment casting) are good for heat exchangers, sound absorbers or for electrodes in batteries [3]. 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 aluminium foams manufactured differently are not necessarily strictly competitive materials.

The most promising applications for aluminium foams come from automotive industry. But, realistically, only near-net-shape foams (cast or foamed in a mould) can be effectively applied. These foams have following features:

- They always have a surface skin, which significantly affects the component's properties Although the skin can be removed, nobody will do it, because it is too expensive. Moreover the effect of the skin on the properties is usually very positive.
- They usually have non-uniform pore structure (variable pore size and sometimes also preferred orientation of pores). These effects are inevitable; it is not possible to achieve an identical heating rate for all parts of the complex mould and a uniform temperature distribution by currently used technologies which lead to variable pore size; the preferred orientation of the pores arises from the arrangement of the foamable precursor in a mould or from the flow of the molten foam during casting.

Nevertheless, it should be noted that a uniform structure is not necessary to obtain acceptable and reproducible properties. Natural load bearing structures such as bone (Fig. 1a) or wood are also not uniform and not isotropic, because they have an optimum distribution of the cell-wall material according to the loading requirements. Therefore, the challenge for the manufacturers is not to get the uniform structure, but to achieve the reproducible properties with a predetermined non-uniform structure (Fig. 1b).

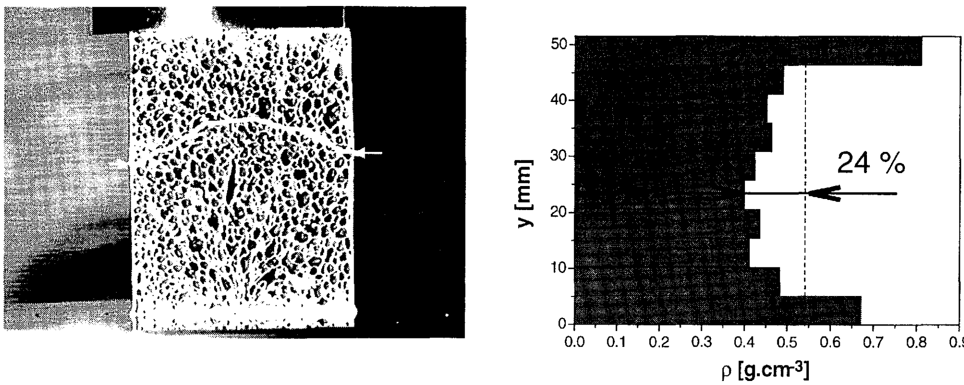


a. **b.**

Fig. 1 Non-uniform (gradient) cellular structures: (a) natural structure of bone; (b) artificial structure of aluminium foam (courtesy of Neuman AluFoam)

Concepts for modelling of property/density relationships will obviously fail in this case. In Fig. 2 we can see an example how different the compression strength of samples with almost equal apparent density, but different distribution of the cell wall material can be. Both samples made of brittle AlSi12-alloy fractured at the first peak stress (compression strength) via a "weakest link" (e.g. layer of pores with the smallest volume fraction of pore walls in a loaded cross section). The peak stress predominantly depends on the amount of load-bearing material in this weakest link and not on the overall apparent density of the sample.

peak stress: **8.5 MPa**



peak stress: **6.9 MPa**

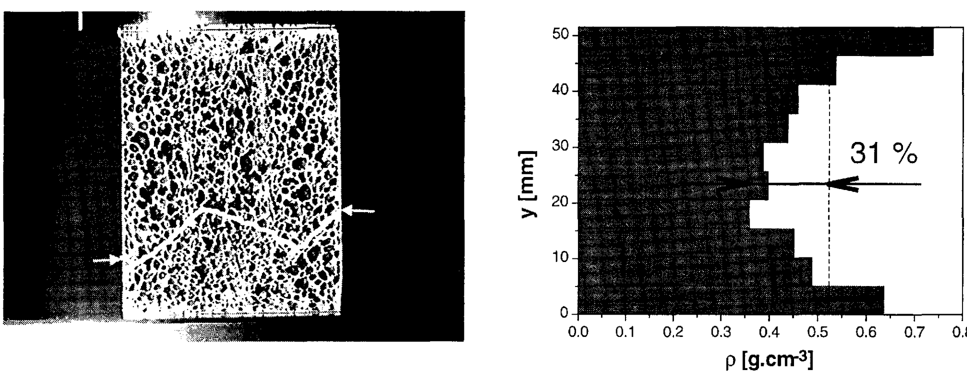


Fig. 2 Effect of the density distribution on the compression strength of AlSi12 - foams. (samples ϕ 40 x 51 mm, apparent density of both samples was 0,527 g cm^{-3})

The probability for the occurrence of a pore layer (weakest link), the apparent density of which is considerably lower than the average apparent density of the sample, increases with increasing sample length. Fig. 3 shows the probability for failure under compression stress for AlSi12-foams with the same apparent diameter and density but different height. It can be seen that the higher samples exhibit better "reproducibility" of the compression strength (coefficient of variation: 19.4 %); the probability for the occurrence of a significantly weaker pore layer in the smaller sample is lower (coefficient of variation: 41.6 %). However, despite higher scatter, the designer can calculate with the compression strength of at least 4 MPa for this density range. Accordingly, the failure of the sample can be predicted by statistical methods using suitable distribution function (e.g. Weibull distribution [4]) at least in a case of brittle foams.

The position of the weakest link depends strongly on the loading direction (different weakest links usually exist for various loading conditions in the same sample). Fig. 4 illustrates the differences in compression strength due to the orientation of pores (anisotropy of the sample). The actual load-bearing cross section of the sample with pores oriented parallel to the loading direction is larger, although apparent cross sections of both samples are equal (equal outer diameter). If this fact is not considered, the measured properties will also exhibit wide dispersion.

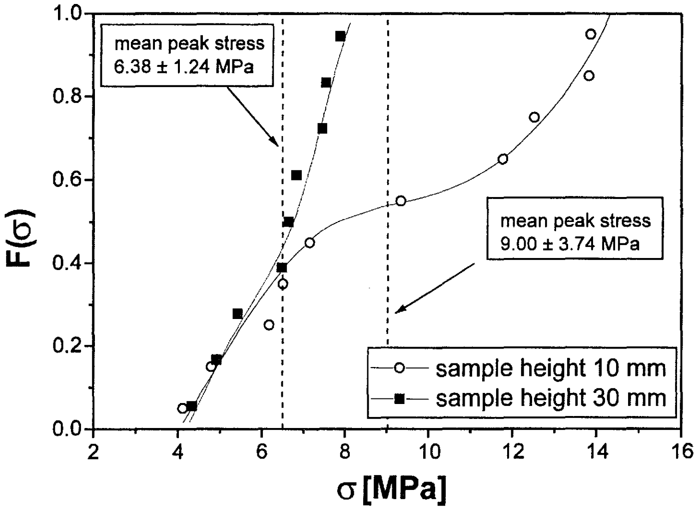


Fig. 3 Probability for failure under compression for AlSi12-foams with different heights. (samples ϕ 20 x 10 (30) mm, apparent density of all samples: 0.4 ± 0.1 g cm^{-3})

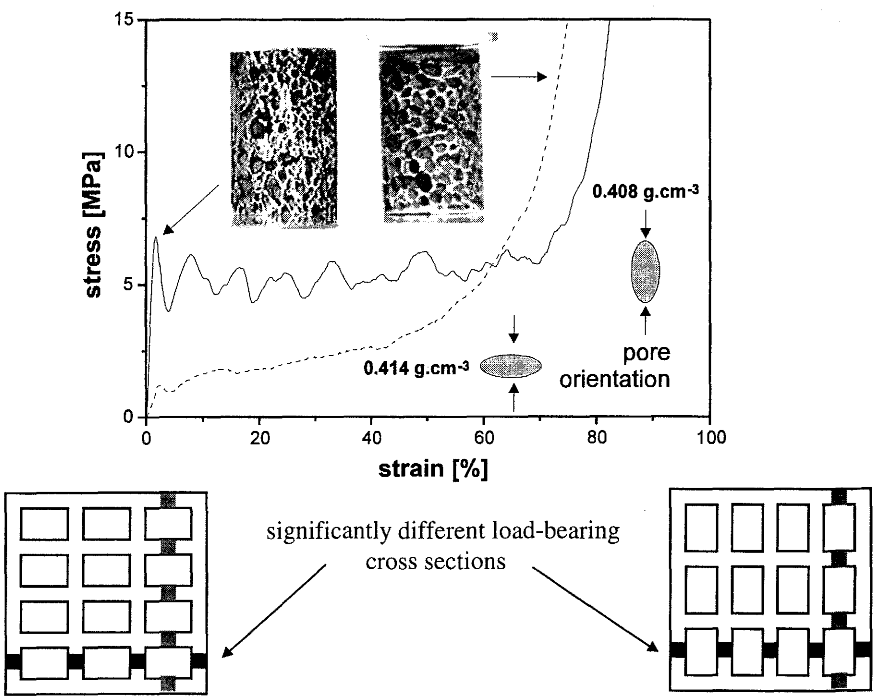


Fig. 4 Effect of pore orientation on the compression strength of AlSi12 - foams (samples ϕ 20 x 30 mm; density difference: 1.5 %; peak stress difference: 79 %)

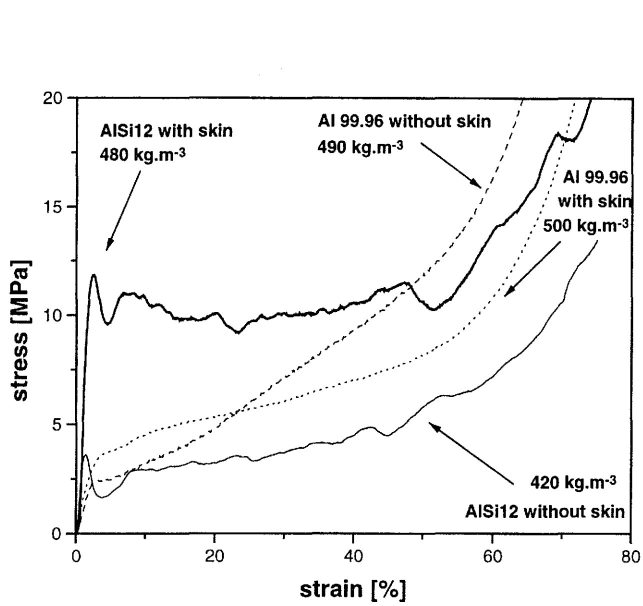


Fig. 5 Effect of the surface skin and matrix alloy on the deformation behaviour of AlSi12- and Al99.96-foams under uniaxial compression (samples ϕ 20 x 30 mm)

Near net shape foams usually possess a dense surface skin, which also affects the reproducibility of foam properties (Fig. 5). The compression strength of the samples with the surface skin is significantly higher than the strength of the samples without it, although the apparent density is almost equal. Moreover, the presence of the surface skin results in a more constant and homogeneous plateau stress. This is due to the smaller difference between strongest and weakest pore layer in the samples containing skin (skin has usually uniform thickness). The difference is clearly visible from the densification behaviour of ductile Al99.96 - foam. The sample without skin exhibits a lower stress than the sample with skin at the beginning of the plateau (collapse of the weakest pore layer), while after densification the opposite is true (collapse of the strongest pore layer).

It can be seen in Fig. 6 that the apparent modulus of elasticity obtained in 4-point bending of foamed panels [5] with comparable densities, decreases with increasing thickness of the samples. Although there is no significant difference between Young's moduli of both matrix alloys, the wrought aluminium foams exhibit slightly higher apparent modulus of elasticity than the cast aluminium foams with the same apparent density. The reason for this behaviour is also a non-uniform distribution of the cell-wall material along the thickness; a higher portion of the material is collected near the surface and creates the dense skin, which is usually thicker in a case of AlMg1Si0.6-foams. The contribution of the skin to the actual moment of inertia of the cross section increases when the sample becomes thinner. Therefore a thinner sample will exhibit a higher apparent modulus of elasticity than a thicker one with equal apparent density. This implies that the use of an apparent modulus of elasticity in the case of samples with a surface skin (above all for samples with little thickness, e.g. panels) is not reasonable.

It would be more correct to consider the aluminium foam with a surface skin as a component with defined geometry ("special aluminium profile") and not as a material (the material is aluminium in this case). The properties of aluminium foam should be related to the geometry of the sample (perhaps to its volume or surface) and not only to the relative density of the part.

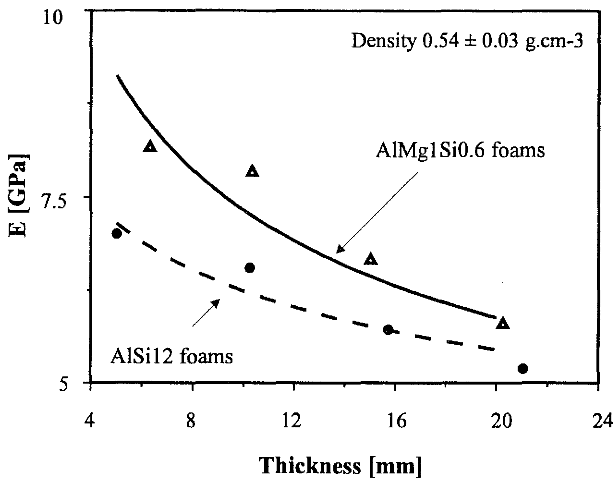


Fig. 6 Effect of the thickness *h*, matrix alloy and density on the apparent modulus of elasticity of the foamed aluminium panels (4-point-bending test [5], samples *h x 50 x 400 mm*)

3. Conclusions

It has been shown that aluminium foams of similar relative density can exhibit a wide dispersion of properties due to various effects such as gradient of density distribution, surface skin, preferred pore orientation, etc. These effects result from the foaming process and significantly depend on the geometry of foamed part.

Aluminium foam usually collapses or fails via a weakest pore layer, the relative density of which is lower than the overall apparent density of the foam. The position of this weakest link depends strongly on the loading direction. The existence of such a link can be predicted by statistical methods. The high scatter of properties due to the existence of a weakest pore layer can to some extent be reduced by the surface skin on the foamed sample and also by the use of a more ductile cell-wall material.

It should be mentioned that the relatively high dispersion of aluminium foam properties is often caused by the use of samples manufactured in small series, which do not allow to keep foaming parameters constant. Foaming technology should be tailored for each component according to the required pore structure. This is possible only if the foamed parts are produced in larger series under stable manufacturing conditions. In this case a reasonable reproducibility of the required foam properties can be expected.

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