Deformation and Fracture Mechanism of Aluminium Foams

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Abstract: Foamed aluminium is highly porous metallic material with a cellular structure. The samples with densities of 500 - 1000 kg.m^{-3} were prepared from cast and wrought aluminium alloys by powder metallurgical route. Influence of the sample geometry, matrix composition, density distribution, local defects, presence of the surface skin and pore size on the deformation behaviour of foamed samples has been investigated. The deformation behaviour in compression was studied by CCD camera and image analysis software. The stress-strain curves exhibit the deformation plateau, which is mainly affected by the apparent density and geometry of the sample. In the case of a brittle cell-wall material the stress drops at the plateau region were observed. The presence of surface skin leads to higher and more uniform plateau stress. It has been confirmed that the permanent deformation or fracture starts predominantly in the regions with the largest defects and the lowest local density.

Introduction

A powder metallurgical process recently developed at Institute of Materials and Machine Mechanics SAS in close cooperation with Austrian companies MEPURA and Illichmann enables the cost effective production of aluminium foam parts in various shapes e.g. panels, profiles or complex 3D-castings [1]. The foamed parts are usually covered by dense aluminium skin which significantly improves their mechanical properties and metallic appearance. Due to the highly porous structure the permanent deformation of such parts starts at medium stress levels and continues without significant increase of applied load until the pore walls crush together. This is why aluminium foams are recommended for impact energy absorption components for cars, lifting and conveying systems [2]. The energy absorbing ability of aluminium foam can be very well estimated from the stress response to the compression loading [1, 3]. This response is significantly affected by the foam's density, surface skin, pore size and cell-wall alloy [1]. The main aim of this work is to study the influence of these parameters on the deformation behaviour of various aluminium foams under compression loading.

Experimental

Compression tests were carried out using the INSTRON testing machine at a crosshead speed of 0.01 m/min. Foam samples were prepared via powder metallurgical route [1] from cast - AlSi12Mg0.6 and wrought -AlMg1Si0.6 aluminium alloys, respectively. The apparent density calculated from the weight and the volume of samples was in the range of 500 - 1000 kg.m^{-3}. Samples were cylindrical with various dimensions (diameters: 25 and 40 mm, length: 10, 20, 30 and 40 mm) in order to study the effect of foam's geometry. The surface skin of the samples was removed via electric discharge machining. Some measurements were performed also on samples with the surface skin to reveal the effect of the skin on the studied properties.

Results and discussion

The typical stress-strain curve of the aluminium foam can be divided into three parts [3]; in the first part the stress increases with increasing compression strain almost linearly (elastic deflection of the pore walls), then follows a deformation "plateau" 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 load after the cell-walls crushed together.

Cast alloy foams exhibit a significant drop of the stress at the end of the first part of the deformation curve (Figs. 1 and 2). This drop is often defined as an upper (UYS) and lower (LYS) yield strength [3]. However, the structural observation during deformation have revealed, that the initial failures in the structure of the foam (fractures of the pore walls) appear after first peak 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. This shift depends on the size of pores in the fractured layer as can be demonstrated in Tab. I. for the samples with nearly equal density but with a different pore size (see also Fig. 3).

It can be seen in Fig. 2 that the initial failure appears in the region with the lowest local density of the sample. The crack propagates through the whole cross section of the sample (preferentially along the existing failures of the structure) and results in total failure of the foam. The stress level UYS should therefore be defined as ultimate compression strength (UCS) for the foams prepared from the cast aluminium alloys. The initial shift is followed by the densification of the region with fractured pore walls and then the compression stress moderately increases. Subsequently, preferential fractures take place in cell-walls that neighbour with the broken layer, whereas the rest of the sample remains undeformed. This can be seen, e.g. in Figs. 2 and 7. The brittle failure mode of the cell walls results again in the decrease of the stress. This process is repeated practically up to the full densification of the sample. 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 even to the zero value. Therefore the stress-strain curve after first stress drop is not suitable for real interpretation of the deformation behaviour of cast aluminium foams. However, this deformation behaviour is of the great importance when related to the absorption of the deformation energy.

Density [kg.m^{-3}]	f [mm]	e_p [%]	l_p [mm]
508	5.94	3.68	1.88
513	4.66	1.65	0.84
514	3.03	1.51	0.77
514	2.25	1.15	0.59

Table I *The shift of the crosshead l_p after the first maximum on the stress/strain curve as a function of apparent diameter of pores for cast-AlSi12Mg0.6 foam (see Fig. 3).*

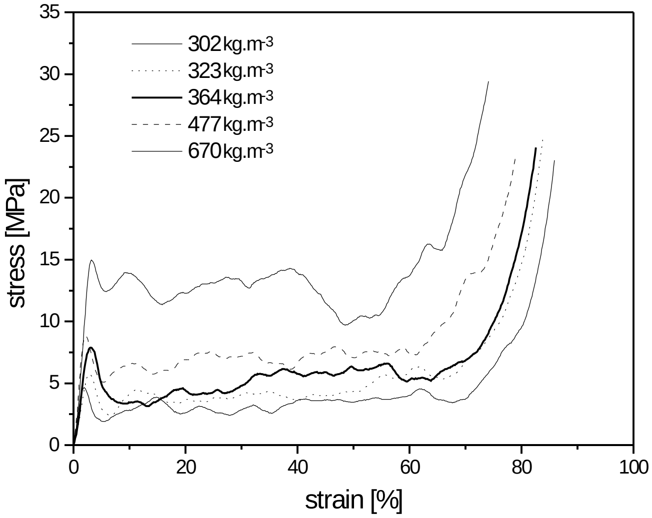
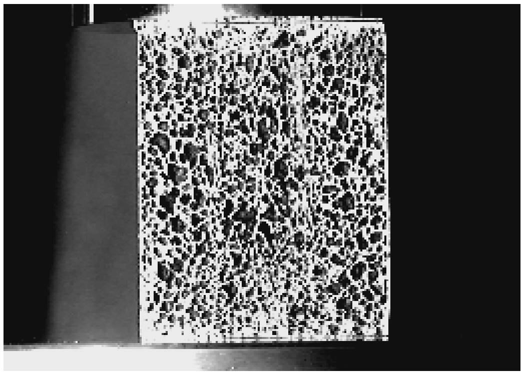
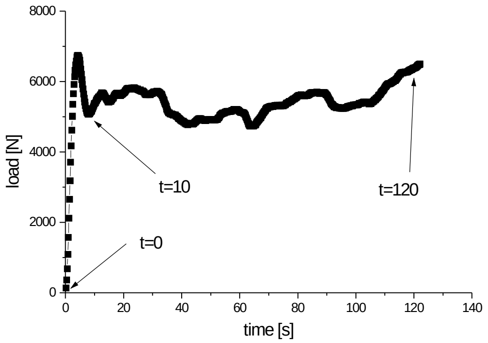


Fig. 1 *Deformation curves of cast-AlSi12Mg0.6 aluminium foams with different densities (cylindrical samples f 20 mm x 20 mm without surface skin).*

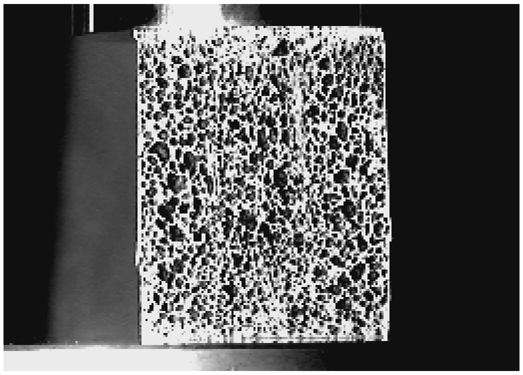
The value of the first peak on the stress/strain curve, i.e. UCS, unambiguously grows with increasing apparent density of the foam (larger portion of pore walls in a cross section of the foamed sample) as can be seen in Fig. 1. This dependence is non linear and can be fitted by power law function [1]. Fig. 3 reveals that if the samples possess almost equal apparent density, UCS increases with decreasing pore size. It is predominantly due to the lower probability of the appearance of large local defect in the structure, if this is formed by small pores (apparent density is only an average value). However the effect of the apparent density is substantially more important than the effect of the pore size, particularly when the porosity in the sample is homogeneous.

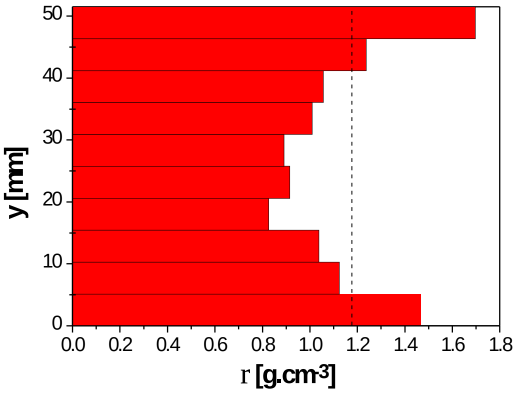




compression test

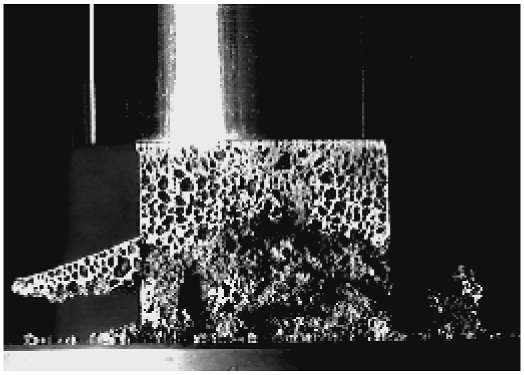
t = 0 s





t=10 s

density distribution



t=120 s

***Fig. 2** The effect of the density distribution on the failure mode of cast- AlSi12Mg0.6 aluminium foam with a surface skin (half-cylindrical sample, f 40 mm x 51 mm density 680 kg.m^{-3}).*

The effect of the surface skin is demonstrated in Fig. 4. The compression strength of the sample with the surface skin is nearly three times higher than the strength of the sample without the surface skin at almost equal apparent density. The presence of the surface skin with nearly constant thickness results in a more constant and homogeneous plateau stress. It can be concluded that it is the surface skin that controls the deformation of the aluminium foam. The substantial influence of the surface skin on sample properties overlaps the effects of other parameters such as apparent density or pore size.

Effect of the sample's geometry on the stress-strain behaviour is visible in Fig. 5. With increasing length (height) of the foamed samples UCS decreases and the length of the deformation plateau increases. The decrease of the strength was due to the higher probability of the presence of large local defect in longer samples. The longer plateau can be attributed to the partial disintegration of longer samples (significant stress drops in Fig. 5). If the sample disintegrates the load is applied only on a part of the initial cross section, which leads to the lower calculated stress and also to longer plateau in the stress-strain curve.

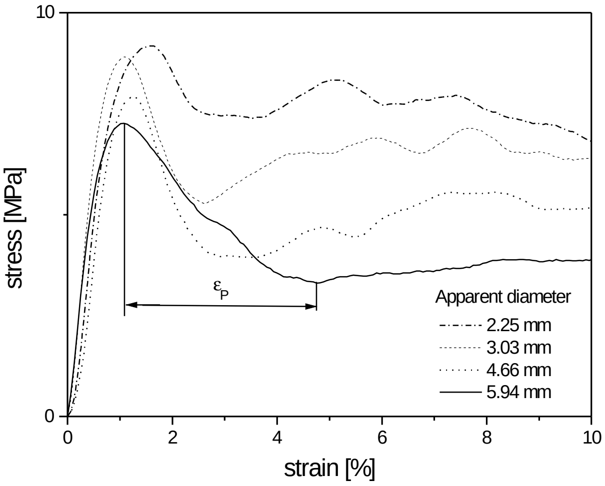


Fig.3 *The effect of pore size on the compression strength at a constant density 510 kg.m^{-3}.*

Deformation behaviour of the foams made of wrought aluminium alloys principally differs from the behaviour of cast aluminium foams (Fig. 6). This is due to substantially higher plasticity of the wrought alloy, that results in the bending of the cell- walls and not in their fracture. The deformed structure does not exhibit extensive cell-wall failures. Therefore the stress drops on the stress/strain curve have been observed only rarely. The curves are smoother without sudden changes (Figs. 6 and 7). Like in the foams prepared from cast alloys, the initial plastic deformation starts in regions with the lower local density. Further compression leads to the local densification of the deformed layer and to the smooth increase of plateau stress. Then the yielding continues again in the regions with locally lowest density at slightly higher stress. This results to the continuous growing of the plateau stress (typical plateau with a constant stress does not practically exist) and to the homogenisation of the density distribution. At the end of the deformation plateau, practically all pores are plastically deformed, not only those neighbouring the initially deformed layer, as it was in the case of cast aluminium foams (Fig. 7).

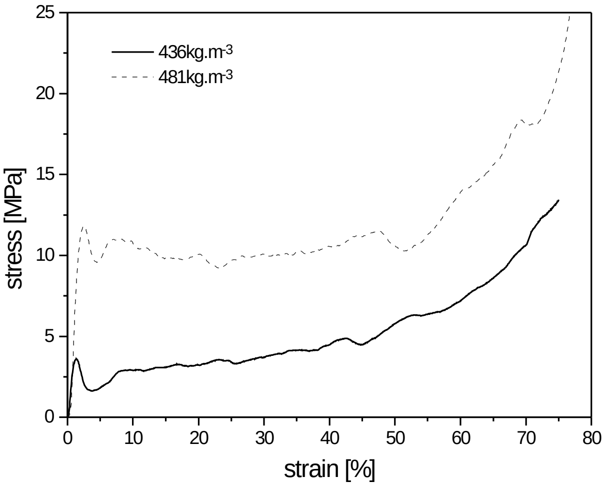


Fig. 4 *Deformation curves of cast AlSi12Mg0.6 foams: cylindrical samples with (440 kg.m^{-3}, f 35 mm x 51 mm) and without surface skin (480 kg.m^{-3}, f 40 mm x 51 mm).*

Conclusions

The deformation and failure mode of various aluminium foams under compression loading has been studied. It was shown that there are two basic deformation mechanisms that depend on the type of used aluminium alloy: Cast aluminium alloys exhibit brittle failure of the cell-walls already at low strain. Failure of the cell-walls leads to the multiple stress drops and thus to the uneven stress/strain curve in plateau region. The magnitude of the first stress drop depends on the average pore size. Cell-walls of wrought aluminium foams yield which results in smooth stress-strain curve in plateau region.

Deformation behaviour of aluminium foams is mainly affected by the local inhomogeneities in the structure. The first cracks and serious deformations of the structure can be found in the regions with lowest local densities and highest concentration of the defects. The further densification of cast aluminium foams takes place in damaged neighbouring layers while the rest of the sample remains almost undeformed. Densification of ductile foams is more homogeneous and leads to the continuous increase of the plateau stress.

The presence of surface skin on foamed samples leads to much higher and more uniform plateau stress. The substantial influence of the surface skin on the stress/strain behaviour diminishes the effects of other parameters such as apparent density or pore size.

It has been confirmed that the plateau stress increases with increasing apparent density of the sample. This dependence is non linear and can be fitted by power law function.

It was further shown that the sample geometry has an effect on stress/strain behaviour especially in a case of cast aluminium foams; the plateau stress decreases and plateau length increases with increasing sample height due to the effect of partial disintegration of the sample and changes in the compressed volume.

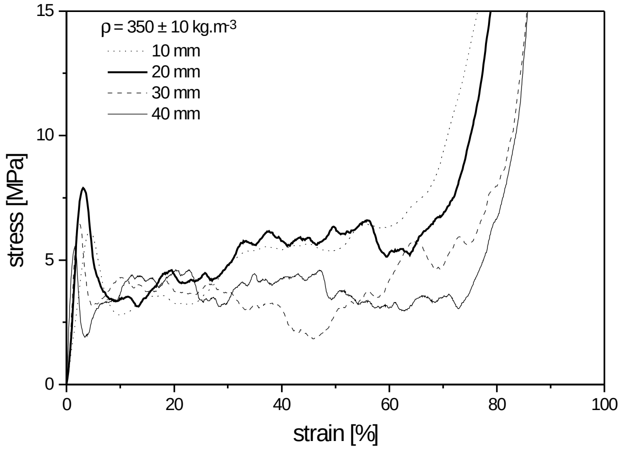


Fig. 5 *Deformation curves of cast AlSi12Mg0.6 foams without surface skin at constant density in dependence of the sample height (cylindrical samples f 25 mm x height of the sample).*

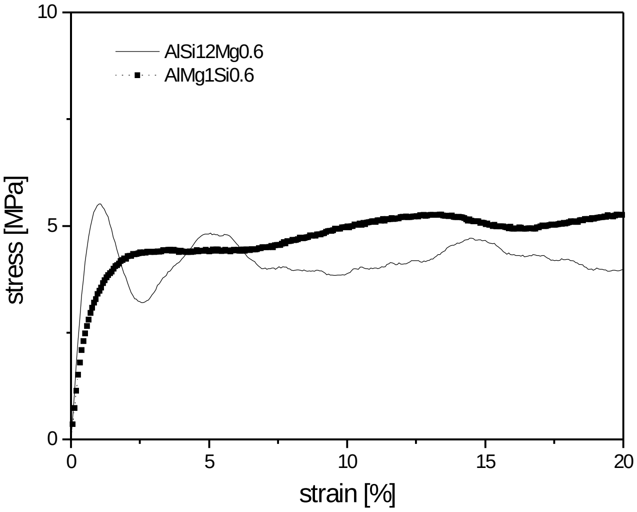
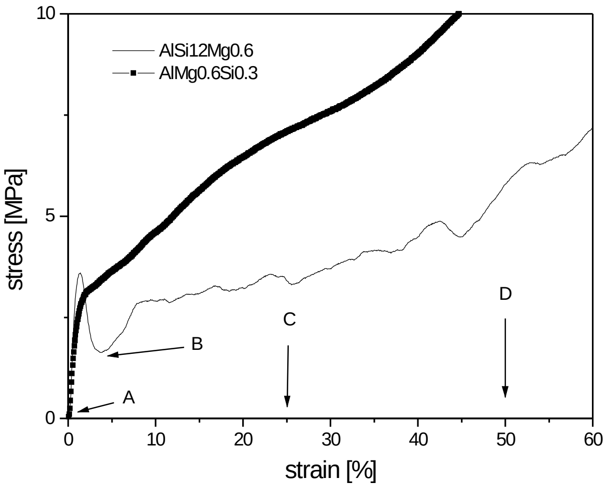


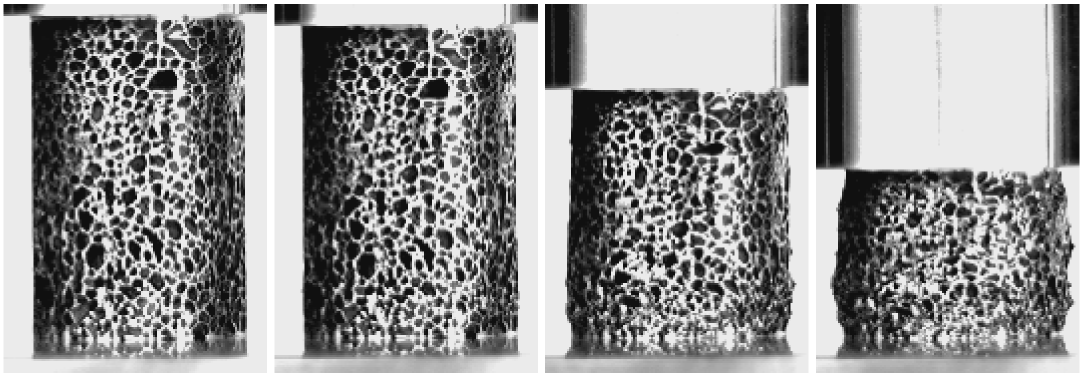
Fig. 6 *Detail of transition between elastic part and deformation plateau of half-cylindrical foamed samples f 40 mm x 51 mm with surface skin prepared from cast AlSi12Mg0.6 alloy (density 420 kg.m^{-3}) and wrought AlMg1Si0.6 alloy (density 460 kg.m^{-3}).*

References

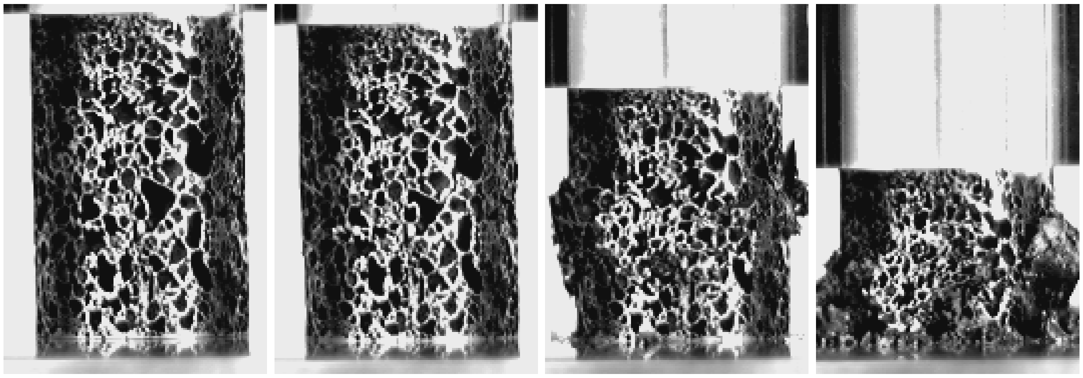
[1] SIMANČÍK, F. *et al.*: Technical report ŠO 95/5305/035, Bratislava, IMMS SAS 1997
[2] Alulight™, Mepura GmbH., Ranshofen, Austria, 1995 - 1997
[3] THORNTON, P.H. and MAGEE, C.L.: Met. Trans. **6A**, 1975, p. 1253



A : t =0 s **B: LYS** **C:** e = **25%** **D:** e = **50%**



a. AlMg0.6Si0.3 (density 540 kg.m^{-3})



b. AlSi12Mg0.6 (density 440 kg.m^{-3})

***Fig.** 7 The deformation curve and the changes in the structure of cylindrical samples f 35 mm x 51 mm without the surface skin. (a: plastic deformation of a wrought alloy, b: brittle deformation of a casting alloy)*