Modelling of the aluminium foam properties according to percolation theory

J. Kováčik and F Simančík
Institute of Materials and Machine Mechanics, Slovak Academy of Sciences,
Račianska 75, 838 12 Bratislava, Slovakia

Abstract
The industrial exploitation of aluminium foams is determined by the possibility to measure, predict and reproduce their mechanical and physical properties. These properties are significantly affected by the relative density of the foam. Using the percolation theory and scaling ideas the model for the description of aluminium foams properties was proposed.

1 Theoretical
The relationship between relative density and selected property of aluminium foam can be modelled using percolation theory and scaling ideas [1]. In this case the foam is considered as an "infinite" aluminium cluster with a complicated structure defined by the randomly distributed gas pores in the metallic matrix. The presence of such cluster is essential for the existence of the foam. If the cluster does not exist (a connectivity threshold) the foam disintegrates and its effective properties are zero. According to percolation theory the effective property near connectivity threshold behaves as a power-law function of a relative density

$$\frac{K}{K_0} = z.\left(\frac{\rho}{\rho_0}\right)^t$$

where K and ρ are the effective property and density of the foam, while K_0 and ρ_0 are the corresponding properties of the cell wall material. The constant z ought to be 1 because for $\rho = \rho_0$ the effective property $K = K_0$. Constant t is often called the critical exponent, and can be theoretically predicted for various physical properties [2]. The scope of this work is to investigate the validity of the percolation theory for the modelling of the mechanical and physical properties of aluminium foams.

2 Experimental
The fractal dimension for the pores of an aluminium foam sample was found to be 1.897 ± 0.011. This is in good agreement with the two-dimensional theoretical value 1.896. It indicates that the examined foam structure can be considered as a self-similar. Experimental measurements of electrical (σ) and thermal (λ) conductivity [1,3], modulus of elasticity (E) [1], and compression strength (σ_{CS}) of aluminium foams prepared from various aluminium alloys by powder metallurgical route have revealed, that the property - porosity relationship can be successfully characterised using the power-law function (see Table I and Figs. 1 - 5). The characteristic exponents obtained from the experimental measurements for electrical and thermal conductivity, and modulus of elasticity are slightly lower than the critical exponents theoretically predicted by the percolation theory. This is due to the finite size of aluminium foam samples in comparison with theoretical infinite cluster and to some extent due to the existence of surface skin. The reduction of characteristic exponent observed for thermal conductivity at increasing temperature has been probably influenced by increasing heat transfer through the gas and radiation through the cell walls (see Table I). The values

J. Banhart, M.F. Ashby, N.A. Fleck: *Metal Foams and Porous Metal Structures.* © MIT Verlag (1999)

determined for the samples with higher densities exhibit some deviation from the optimised power law due to non-uniform structure caused by uncompleted foaming in some sections of these samples. The characteristic exponents obtained for compression strength measured on foam samples without surface skin agree fairy well with the theoretical prediction [4]. It should be noted that the first peak stress (compression strength) depends strongly on the inhomogeneities in the foam structure. The foam failures via a weakest link (e.g. layer of pores with the smallest volume fraction of pore walls) which density is usually lower than the average apparent density of the sample [5]. It must be further noted, that the data for compression strength of aluminium foams showed statistical fluctuations due to variations in the pore sizes, pore shapes and orientations (see Figs. 3 - 5).

Table I The obtained fitting parameters for the dependence of normalised physical and mechanical properties on the relative density for various types of aluminium foam.

	z	t	$t_{predicted}$	χ^2
σ/σ_0 (mix.) [1]	0.999 ± 0.009	1.55 ± 0.02	2.0	$7.31 \cdot 10^{-5}$
σ/σ_0 (Al 99.7) [1]	0.979 ± 0.025	1.75 ± 0.06	2.0	$6.54 \cdot 10^{-4}$
λ/λ_0 (mix., 20°C) [3]	1.000 ± 0.006	1.60 ± 0.03	2.0	$2.97 \cdot 10^{-5}$
λ/λ_0 (mix., 100°C) [3]	1.000 ± 0.008	1.55 ± 0.03	2.0	$5.66 \cdot 10^{-5}$
λ/λ_0 (mix., 300°C) [3]	1.000 ± 0.010	1.48 ± 0.04	2.0	$9.10 \cdot 10^{-5}$
λ/λ_0 (mix., 400°C) [3]	1.000 ± 0.005	1.51 ± 0.03	2.0	$4.00 \cdot 10^{-5}$
E/E_0 (Al 99.7) [1]	1.000 ± 0.004	1.64 ± 0.01	2.1	$1.88 \cdot 10^{-4}$
E/E_0 (Al 99.7) [1]	0.974 ± 0.025	1.66 ± 0.07	2.1	$6.68 \cdot 10^{-4}$
σ_{CS}/σ_{CS0} (AlSi12)	0.953 ± 0.013	2.00 ± 0.04	2.1	$3.85 \cdot 10^{-4}$
σ_{CS}/σ_{CS0} (AlMg1Si0.6)	0.999 ± 0.013	1.97 ± 0.03	2.1	$1.63 \cdot 10^{-4}$
σ_{CS}/σ_{CS0} (Al 99.96)	0.998 ± 0.036	1.96 ± 0.11	2.1	$1.27 \cdot 10^{-3}$

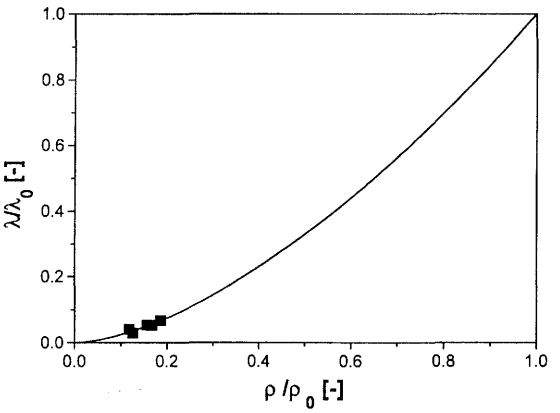

Fig. 1: The power law dependence of normalised thermal conductivity on the relative density for aluminium foam at 20 °C - experimental t = 1.60, predicted t = 2.0 [2] (cylindrical samples with surface skin, $\lambda_0 = 232$ $Wm^{-1}K^{-1}$, $\rho_0 = 2700$ $kg.m^{-3}$) [3].

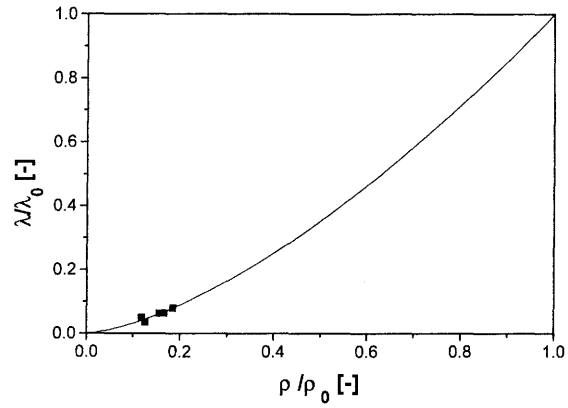

Fig. 2: The power law dependence of normalised thermal conductivity on the relative density for aluminium foam at 400 °C - experimental t = 1.51, predicted t = 2.0 [2] (cylindrical samples with surface skin, $\lambda_0 = 239$ $Wm^{-1}K^{-1}$, $\rho_0 = 2700$ $kg.m^{-3}$) [3].

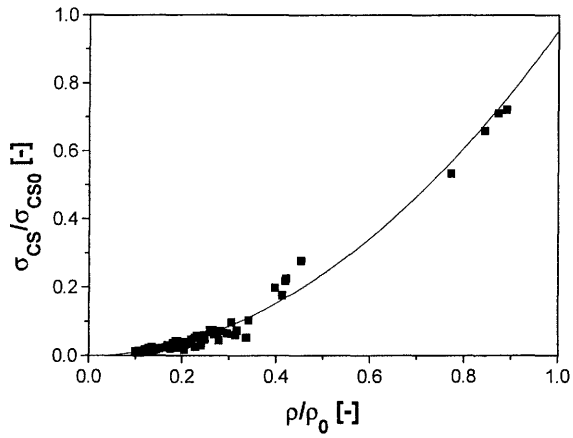

Fig. 3: The power law dependence of normalised compression strength on the relative density for AlSi12 foam - experimental t = 2.00, predicted t = 2.1 [4] (cylindrical samples without skin, $\sigma_{CS0} = 320$ MPa, $\rho_0 = 2700$ $kg.m^{-3}$).

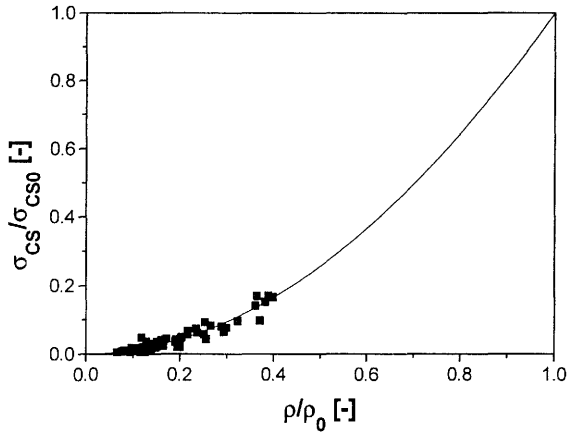

Fig. 4: The power law dependence of normalised compression strength on the relative density for AlMg1Si0.6 foam - experimental t = 1.97, predicted t = 2.1 [4] (cylindrical samples without skin, σ_{CS0} = 110 MPa, ρ_0 = 2700 kg.m^{-3}).

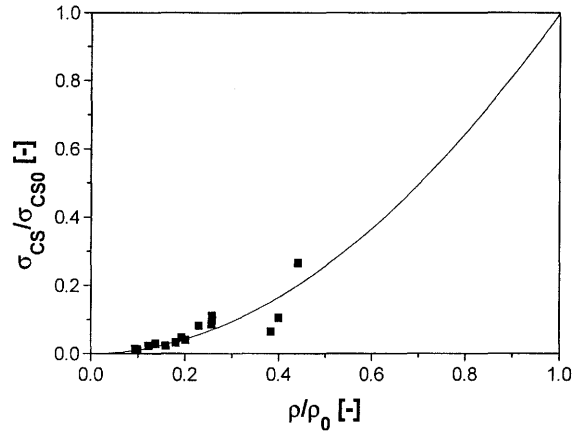

Fig. 5: The power law dependence of normalised compression strength on the relative density for Al 99.96 foam - experimental t = 1.96, predicted t = 2.1 [4] (cylindrical samples without skin, σ_{CS0} = 70 MPa, ρ_0 = 2700 kg.m^{-3}).

References

[1] J. Kováčik, F. Simančík, Scripta Mater. 39, 239 (1998)
[2] D. Stauffer, A. Aharony, *Introduction to Percolation Theory*, 2nd edition, Taylor & Francis, London, (1992).
[3] J. Kováčik *et al.*, Proc. Int. Conf. : The Effect of Non-Standard External Factors on Physical Properties of Solids, Military Academy Liptovský Mikuláš (1996), p. 57
[4] J. Kováčik, Acta Mater. 46, 5413 (1998)
[5] F. Simančík, J. Kováčik, N. Mináriková, Proc. Int. Conf. : 1998 PM Word Congress, Granada, (1998), p. 245