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Experimental validation of micromechanical models for brittle aluminium alloy foam

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ABSTRACT

Micromechanical models used to predict mechanical and fracture properties of brittle metallic foams are validated experimentally for closed-cell aluminium foam (AlSi12Mg0.6) prepared by powder metallurgy route. Compression, tensile, tensile on notched specimens and fracture toughness tests were carried on, and the results are presented together with micromechanical models from literature. Moreover, the Digital Image Correlation technique was applied to identify the failure mechanisms of aluminium foams. Finally, the Theory of Critical Distances was employed to predict the fracture load of notched specimens. The novelty of the study is that the inherent stresses and critical distances were obtained by employing micromechanical analysis.

1. Introduction

Metallic foams, especially those made from aluminium and its alloys are widely used in a number of critical applications. Excellent stiffness-to-weight ratio, low density, good shear and fracture strength, the damping capacity, higher natural flexural vibration frequency and sound-absorbing capacity makes metallic foams ideal for lightweight structures, sandwich cores, isolation, mechanical damping devices, vibration control, acoustic absorption, biocompatible inserts, electrical screening, heat exchangers and filters [1,2]. The capacity of metal foams to undergo large strains in compression (up to 70%) at almost constant stress allows significant energy absorption without generating damaging peak stresses, making them ideal for energy – absorption devices.

This extensive applicability of aluminium foams are direct consequence of their cellular structure and properties. The properties of metallic foams depend directly on those of the solid material from they are made and their relative density; but they are influenced also by its cell topology (open/closed cell), cell size and cell shape [2–10]. It has been found that the structural non-homogeneity affects the overall material properties [6,7]. The metallic foam behavior in compression is extensively studied [6–10].

Different aspects regarding the fracture of metallic foam were investigated since 2000 [11–21]. Some of these studies presented the failure mechanisms of metallic foams [11–15], others the foam behavior in tensile [16], or the fracture toughness of metallic foams [17–22]. However, fewer studies were focused on the effect of notches and crack like defects on load caring capacity of metallic foams [23–26]. The Digital Image Correlation technique was successfully used to investigate the failure mechanisms in cellular materials [27,28].

Micromechanical models are often used to predict elastic, mechanic and fracture properties of cellular structures, [1–3,29]. In this study, brittle metallic foam is experimentally investigated, in order to validate the micromechanical models.

2. Micromechanical models for metallic foams

Micromechanical models allow the prediction of mechanical properties for cellular materials based on the properties of solid material from the cell edges (density of solid material ρ_s, Young' modulus E_s, yield stress σ_{ys}, and so on), density of cellular material ρ^* and some cellular structure characteristics length or diameter of cells l and cell wall thickness t. For example, the compressive strength of a closed cell foam is a combination cell face stretching and cell edge bending, Ashby et al. [2]:

$$\frac{\sigma_c^*}{\sigma_{ys}} = C_0\left[C_1\left(\frac{\rho^*}{\rho_s}\right)^{3/2} + C_1'\left(\frac{\rho^*}{\rho_s}\right)\right], \quad (1)$$

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Nomenclature

a	crack length of SENB specimen
B	thickness of SENB specimen
C_0, C_1, C_1', C_2, C_3, C_3', C_3''	proportionality constants
D	hole diameter of notched specimens
E_s	Young's modulus of solid material
H_c	height of semi cylindrical specimens for compression test
K_{IC}^*	fracture toughness of foam
K_{ss}^*	steady state fracture toughness
l	cell diameter
L_0	critical distance
R	radius of notched specimens
R_c	radius of semi cylindrical specimens for compression test
t	cell wall thickness
v	loading speed
W	width of notched specimens
ρ^*	foam density
ρ_s	density of solid material
ϕ	radius of tensile specimens
σ_1	maximum principal stress
σ_0^*	inherent stress
σ_c^*	compressive strength of foam
σ_{eff}	effective stress
σ_{max}^*	maximum net section stress in notched specimens
σ_t^*	tensile strength of foam
σ_{ys}	yield stress of the solid material
ω	geometric parameter

where σ_{ys} represents the yield stress of the solid material from cell edges, ρ^*/ρ_s is the relative density of the foam, $C_0 = 0.1–1.0$, $C_1 = 0.5$ and $C_1' = 0.3$ for close cell metallic foams, Ashby et al. [2].

The tensile strength could be obtained from the compressive strength [2]:

$$\frac{\sigma_t^*}{\sigma_c^*} = C_2, \tag{2}$$

with $C_2 = 1.1–1.4$.

The fracture toughness of foams could be expressed in the form:

$$\frac{K_{IC}^*}{\sigma_{ys}\sqrt{\pi l}} = C_3\left(\frac{\rho^*}{\rho_s}\right)^{3/2}, \tag{3}$$

where constant $C_3 = 0.65$ and l is the cell structure dimension.

Sugimura et al. [22] determined the fracture toughness of a closed cell aluminium alloy foam, manufactured by gas – releasing particle decomposition in the melt, using single edge notched specimens loaded in four point bending. They expressed the steady state fracture toughness in the form:

$$K_{ss}^* = \omega\sqrt{E_s\sigma_{ys}l}\left(\frac{\rho^*}{\rho_s}\right)^{3/2}, \tag{4}$$

where E_s is the Young's modulus of the solid material and ω is a geometric parameter. It was observed that crack growth occurs along cell wall faces in a similar mechanism to plastic tearing of thin sheets.

A similar equation was proposed by Olurin et al. [13]:

$$K_{ss}^* = C_3'C_3''\sqrt{E_s\sigma_{ys}l}\left(\frac{\rho^*}{\rho_s}\right)^{1.75}. \tag{5}$$

It should be noticed that for ductile metallic foams the fracture toughness is expressed in terms of J-integral, like J_{ss} [13] or J_{Ic} [22,24], and will not be addressed in this paper.

However, all these micromechanical models should be calibrated and validated experimentally, prior to be used in engineering design.

3. Investigated metallic foams

The investigated aluminium alloy foams AlSi12Mg0.6 were produced using powder metallurgical (PM) route, by the Slovak Academy of Science from Bratislava, using 0.4 wt.% of titanium hydride as foaming agent (Alulight foams in older literature). The chemical composition is: Al with 12 wt.% Si and 0.6 wt.% Mg having variable porosity, pore size and thickness of surface skin. The density of the investigated foams was between 340 and 1100 kg/m^3 (see Fig. 1).

A quantitative evaluation of the aluminium foam structure was performed by digitizing the microstructure and a quantitative assessment was done using Image Pro Plus (Media Cybernetics Inc., USA) software, [14]. After this analysis for the foam with 400 kg/m^3 density the obtained average pore size was 1 mm. It was also observed that the pores are not spherical at all with maximum aspect ratio (length of minor to major equivalent ellipse) between 0.5 and 0.7 and with preferred orientations at 0°, 45° and 90° with respect to vertical axis of the structure. Using this quantitative evaluation of the microstructure a relationship between density and cell size l was found as follows $l = 400/\rho^*$.

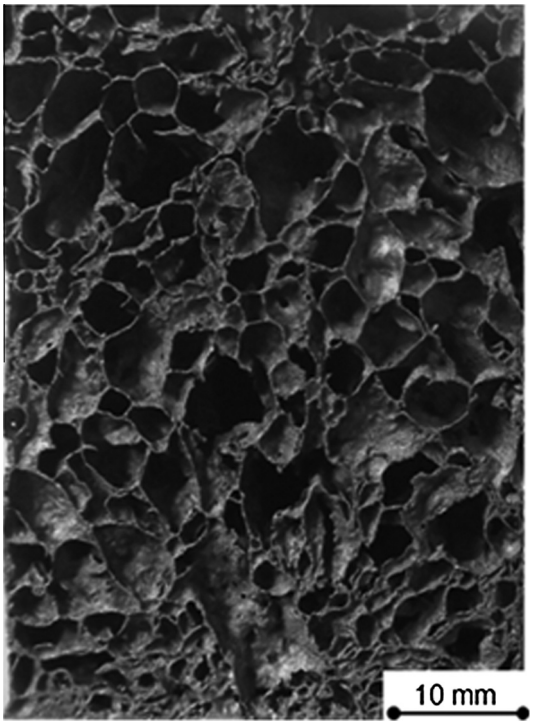

Fig. 1. Cellular structure of AlSi12Mg0.6 foam.