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Influence of heat treatments on the microstructure and mechanical behaviour of open cell AlSi7Mg0.3 foams on different lengthscales

Paul Schüler [a], Robert Frank [a], David Uebel [a], Sebastian F. Fischer [b], Andreas Bührig-Polaczek [b], Claudia Fleck [a, *]

[a] Materials Engineering, Technische Universität Berlin, Straße des 17. Juni 135 - Sekr. EB13, 10623 Berlin, Germany
[b] Foundry-Institute, RWTH Aachen University, Intzestraße 5, 52072 Aachen, Germany

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ABSTRACT

This paper reports about the influence of different heat treatments such as solution annealing (W) and solution annealing plus ageing (T6, T7) on the microstructure of AlSi7Mg0.3 open cell foams and their effect on the mechanical properties. The mechanical properties and the local failure mechanisms of individual struts and foam specimens have been evaluated by micro-hardness measurements and micro-tensile testing of struts as well as *in-situ* compression tests on foam samples, combined with scanning and transmission electron microscopic evaluation of the microstructure. Contrary to published results for the bulk material, we only found a weak influence of the heat treatments on the struts' and foams' mechanical properties. We assume that this is mainly due to the inhomogeneous microstructure of the struts with coarse plate-shaped Si phases, leading to a subordinate effect of the precipitates formed during the heat treatments. The morphology of the coarse Si and intermetallic phases is only slightly influenced by the heat treatments, but profoundly determines the deformation, cracking and failure behaviour of the struts and thus of the entire foam.

1. Introduction

Open cell metal foams, also referred to as 'metal sponges' [1], have a porous structure permeable for fluids making these materials interesting for different functional applications as e.g. catalysers, heat exchangers or batteries. Under compression they deform at a nearly constant load over a wide strain range of up to 50–80% depending on the relative density. This deformability correlates with a very efficient and, because of their random structure, almost isotropic energy absorption making these materials also suitable as impact protection devices that necessitate high and effective crash energy absorption [2–4].

The mechanical properties of metal foams can be estimated by different scaling laws, which have been derived from analytical modelling or from empirical fits [3]. These laws describe the ratio of a certain foam property (P^*) to the bulk property (P_s) as power-law functions of the relative density, that is the density of the foam ρ^* related to density of the bulk material ρ_s. For example, the plateau stress (σ_{pl}^*) of open cell metal foams (with $\rho^*/\rho_s \leq 30\%$) has been described according to the Gibson–Ashby model by the following equation:

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} = C \cdot \left(\frac{\rho^*}{\rho_s}\right)^{3/2} \quad (1)$$

with σ_{ys} being the yield strength of the strut material and C a structure-dependent constant, which spans values between 0.25 and 0.35 for most open cell metal foams [2,5].

The specific energy absorption of metal foams is connected with the plateau stress and can therefore be enhanced by altering the foam topology (mesostructure), increasing the relative density or improving the strength of the strut material. While the former two factors cannot or must not always be changed freely, the improvement of the strut properties by an appropriate heat treatment is another promising approach. Only few studies on the effects of heat treatments on the mechanical properties of foams are found in the literature [6–12], in particular for open cell aluminium foams. However, due to differences in the fabrication method, composition and metallurgical state of the struts or cell walls as

* Corresponding author.
E-mail addresses: paul.schueler@tu-berlin.de (P. Schüler), robert.frank@mailbox.tu-berlin.de (R. Frank), uebel@mailbox.tu-berlin.de (D. Uebel), sebastianfischer1001@gmail.com (S.F. Fischer), sekretariat@gi.rwth-aachen.de (A. Bührig-Polaczek), claudia.fleck@tu-berlin.de (C. Fleck).

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well as the fact that different heat treatment parameters were used, the results are partly inconsistent and only comparable to a limited extent. Specifically, no data regarding heat treatment of foams made from the alloy AlSi7Mg(0.3) have been published so far.

We therefore investigated the influence of different heat treatments, solution annealing (W) and subsequent ageing (T6, T7), on the mechanical behaviour of AlSi7Mg0.3 open cell foams in comparison to the as-cast (F) state. We focused on the correlation between microstructural changes related to the heat treatment, and the mechanical properties and the failure behaviour of individual struts, and on the effects on the foams' macroscopic mechanical deformation behaviour. The influence of the heat treatments on the microstructure was investigated by light, scanning and transmission electron microscopy to characterise possible precipitation states. The mechanical properties of individual struts were characterised by hardness measurements and micro-tensile testing, based on a method provided by Zhou et al. [13], and the foams' compressive mechanical behaviour was investigated by *in-situ* compression testing. Strains both on the level of the struts and of the foams were determined by digital image correlation. The mechanical testing was further combined with metallographic and fractographic investigations, which give insights into the local failure mechanisms.

2. Experimental

2.1. Metal foam specimens

The open cell metal foams were fabricated by investment casting from the pre-grain refined, unmodified aluminium alloy A356 (Anticorodal® 70, ALLOYS Rheinfelden GmbH & Co. KG, Rheinfelden, Germany) - for more detailed information see refs. [14,15]. The cast models were based on polyurethane (PUR) foams with a pore density of 10 pores per inch (ppi). The average chemical composition of the foam samples is within the standardised range for the alloy as determined by emission spectroscopy (5 measurements) (Table 1).

The average cell size of the samples was determined to be 6.25 mm and 4.75 mm for the longest and smallest cell axis, respectively [17], and the relative densities were between 1.56 % and 2.13 %.

2.2. Heat treatments

After fabrication some of the as-cast (F) foam specimens were heat treated with parameters chosen according to recommendations of the alloy producer for the bulk alloy [18]. The solution annealing (W) was performed by heating the samples up to 520 °C within about 50 min, holding them at this temperature for 8 h and then quenching them in water of 20 °C. For the T6 strengthening the solution annealed foam specimens were immediately aged after the annealing procedure in a preheated oven at a temperature of 160 °C for 6 h and then cooled down in the oven to 100 °C, at which temperature diffusion processes became more and more insignificant, within about 65 min. For the T7 heat treatment, a higher ageing temperature of 240 °C was used, also for 6 h in the preheated oven. The samples were then cooled down to 100 °C within about 80 min. The cooling to room temperature took a few more hours for both the T6 and the T7 heat treatments.

2.3. Microscopic investigations

Light microscopic investigations were performed with a Leica DMRM light microscope and a MicroCam 1.3 camera (Leica Microsysteme Vertrieb GmbH, Wetzlar, Germany). The polished sections were prepared from small blocks (ca. $15 \times 15 \times 15$ mm^3) of the foam material. These were embedded in an epoxy resin (EpoFix™, Struers GmbH, Willich, Germany), ground on SiC-paper in several steps down to an abrasive particle size of 10 μm, that is a grain size of 2500, and polished with diamond suspensions with 6 μm, 3 μm and finally 1 μm grain size. All steps took place under constant water irrigation. Selected sections were etched according to Barker's method to obtain information about the grain size.

Higher resolution microscopic investigations and energy-dispersive X-ray spectroscopy (EDX) were performed with a Hitachi S-2700 (Hitachi Ltd., Tokyo, Japan) scanning electron microscope (SEM) on fracture surfaces and polished sections. The latter needed to be coated with a thin, about 20 nm thick, gold layer prior to the microscopic observations.

Transmission electron microscopic (TEM) and selected area diffraction (SAD) investigations of the as-cast and the age-hardened states were performed at the Central Electron Microscopy Unit of TU Berlin with a Tecnai G^2 20 S-TWIN (FEI, Hillsboro, Oregon, USA) operated at 200 kV. The microscope is equipped with a LaB_6-cathode and a Gatan MS794 P CCD camera system (1024 × 1024 pixels) for image acquisition. For the preparation of the TEM specimens, slices of extracted strut samples (see chapter 2.5) were embedded into a titanium specimen holder using a compound of TiN and Gatan G1 epoxy. The hardening of the compound was performed at 130 °C (below the age hardening temperatures of the T6 and T7 states) for 15 min. Both sides of the sample holder were then ground and dimple-ground with diamond paste down to 1 μm grain size until thin enough for ion beam etching with argon ions under steady rotation of the sample and an incident angle of 8°, starting at 4 kV acceleration voltage and 23 μA, and proceeding with stepwise reduction to 1.5 kV and 10 μA, until a hole developed in the centre of the specimen, ensuring electron beam transmittance in the volume near the hole.

2.4. Microhardness measurements

The hardness (HV 0.02) of the α-Al phase in the different heat treatment conditions was measured from Vickers indentations (MHT-4, Anton Paar GmbH, Ostfildern, Germany) on polished strut cross-sections with a test mass of 20 g and 10 s duration of force application.

2.5. Micro-tensile testing of isolated struts

The mechanical behaviour of individual struts was investigated by *in-situ* micro-tensile tests of isolated struts.

Extraction of struts. The struts were carefully extracted with a precision cuticle nipper from about 5 mm thick foam slices. These slices were cut with the precision saw Accutom-50 equipped with

Table 1
Chemical composition of the A356 metal foams and reference values according to DIN EN 1706 [16] (in weight percent).

Element	Al	Si	Fe	Cu	Mn	Mg	Zn	Ti	Others
measured	92.73	6.66	0.105	0.003	<0.001	0.347	<0.002	0.125	<0.027
reference	rest	6.5–7.5	0.19	0.05	0.10	0.25–0.45	0.07	0.25	0.1