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Technical Report

Influence of cell wall microstructure on the energy absorption capability of aluminium foam

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ABSTRACT

The microstructure of aluminium foam produced by decomposing TiH_2 in the stabilized melt can be modified by heat treatment to improve the mechanical properties of the cell wall. Different microstructures were developed through solutionizing and quenching followed by thermal ageing treatment. Uniaxial compression tests were performed on foam specimens to understand as to how the microstructure of the cell wall influences the energy absorption capability of the foam. It is found that the solutionized sample has the best energy absorption capability (29.3 MPa) when compared to the as-foamed (13.2 MPa) and aged samples (15.9 MPa). The crack progression studies carried through interrupted compression tests confirm the detrimental influence of the cast dendritic structure and the lamellar Al_2Cu precipitate formed during aging. The results suggest that the extent of thermal aging in aluminium foam depends on the precipitation behaviour in the aluminium matrix.

1. Introduction

New technology development requires stringent design criteria which can only be met by the development of new materials with improved properties. In highly competitive market segment, safety standards have gone up considerably forcing designs which can absorb impact energy and improve passenger safety. Aluminium foam is a class of material that offers a unique combination of properties, for instance, high specific strength, good stiffness, excellent energy absorption and sound absorption capability [1–3]. All these properties make aluminium foam a potential candidate for use in sandwich cores, mechanical damping, vibration control and acoustic absorption applications [4]. The mechanical property of closed-cell aluminium foam depends on the relative density and to a lesser extent on cell size and shape. Baumeister et al., Raj and Daniel, and Mondal et al. [5–7] investigated the dependency of the mechanical properties on the density of the foam and suggest the linear relationship whereas Cao et al. [8] suggest that medium cell size foam significantly increase strength upto 112%. Mu et al. [9] suggested that at the time of deformation of foam sample, deformation force is influenced by cell shape and homogeneity of the structure.

The cell wall consists of several phases, including intermetallic and oxide phases dispersed in aluminium matrix. Moreover, the cell wall microstructure can be modified by heat treatment techniques, which in turn will alter the mechanical properties of the cell wall. It is of interest to know as to how the property modification of the cell wall materials will influence the mechanical property of the aluminium foam as a whole, and more specifically, in the case of energy absorption during compressive loading.

There is limited literature available on the influence of heat treatment on the cell wall microstructure and mechanical properties of closed cell aluminium foam. Much of the reported work pertains to foams processed by powder metallurgy route. Such foams were solutionized above 500 °C and aged at about 165 °C for varying durations followed by quasi-static compression testing. It has been reported that energy absorption has improved from 25% to 75% for thermally aged samples over the as-foamed condition [10–12]. Furthermore, Lehmhus and Banhart [13] have made the distinction between samples aged after solution treatment and those that are heat treated without the solutionizing step and reported that the samples that were only aged demonstrate more ductility and perform better for energy absorption application. In our previous work it has been found that there is a significant improvement in energy absorption capacity with peak aging is due to finer precipitation of second phase particles instead of thick dendrite structure [14].

In the present work, an attempt is made to understand the strengthening mechanism of aluminium foam during the process of thermal ageing. The effect of heat treatment combined with microstructural modification of cell wall on the energy absorption capability were examined. TEM (transmission electron microscope) studies were carried out on solutionized and aged samples to characterise the intermetallic precipitates. The study of the morphology and distribution of intermetalic phases in the cell wall

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material will enable us to understand the strengthening mechanism of the cell wall material and to optimise the structure for energy absorption application.

2. Experimental procedure

Closed-cell aluminium foam was produced by decomposing TiH_2 in a stabilized melt. The processing details are detailed elsewhere [15]. Samples of $10 \times 10 \times 20\ mm^3$ were prepared using the slow speed diamond cutter and polished down to 1200 grit size SiC paper. Sample used for optical micrography, SEM (scanning electron microscope) and microhardness were prepared according to ASTM: E3-11. The density and microstructure of the samples were carefully recorded. Sample for the following heat treatment schedule was carried out in a tubular furnace: (i) solution heat treatment of the as-foamed sample for 1 h at 550 °C followed by quenching in water; (ii) aging treatment at three different temperatures (100, 150 and 180 °C) for four different durations (20, 40, 60 and 120 min). The heat treated samples were then tested under uniaxial compression.

The optimal thermal aging condition was identified by carrying out microstructural analysis and hardness measurement on foam specimens. Microhardness testing was carried out on cell wall nodes using a Leitz-Wetzlar Vickers microhardness tester with a load of 5 g (49.03 mN) and loading time of 10 s. At least six hardness readings were noted and the average taken to eliminate experimental anomaly. Quasi-static compression test was carried on the as-foamed, solutionized and aged samples using a universal testing machine (H25KS/05, Hounsfield, England) with computer interface for data acquisition and control. Compression samples were tested according to ASTM: E9-09 standard. Tests were conducted at a constant strain rate of $1 \times 10^{-3}\ s^{-1}$. The specimen was aligned such that the load applied was parallel to the foaming direction. The yield strength, plateau stress and densification strain are estimated from the stress–strain curve. The yield stress, σ_y, is the upper limit of the elastic region beyond which the cells undergo irreversible deformation. The plateau stress, σ_{pl}, was calculated as the average stress value between 5% and 30% engineering strain. The energy absorption capability of the as-foamed and heat treated samples were evaluated in the quasi-static compression test. The energy absorption per unit volume, W, is taken as the area under the stress–strain curve up to densification as given by

$$W = \int_0^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon \quad (1)$$

where ε_d is the densification strain wherein all the cell walls have collapsed and flattened out. During compression, the foam samples usually fail by successive layer-by-layer collapse of the cell starting at the end contacting the moving cross-head. Interrupted compression tests were carried out to examine the stages of failure at different regions of the specimen. In certain experiments, the compression tests were stopping after 30% strain to study the failure mode and fracture characteristics.

3. Results

The micrographs of aluminium foam in as-foamed condition, on solutionizing treatment and after aging are shown in Fig. 1. In the as-foamed condition, the microstructure consists of coarse dendritic structure with fairly thick interconnected inter-dendritic phase (Fig. 1a). The inter-dendritic region consists of Al_2Cu as identified by the energy dispersive spectroscopy (EDS) analysis. After solutionizing, the solute phases in the inter-dendritic region dissolve and reprecipitate as a discontinuous phase with reduced thickness (Fig. 1b). Fig. 1c shows the microstructure after ageing. As compared to the solutionized sample, the microstructure of the aged sample shows fine intermetallic precipitates evenly distributed throughout. The backscatted electron image (Fig. 1d) of the aged sample shows Al_2Cu and Al_3Ti precipitates as identified by the EDS analysis.

Microhardness values of as-foamed sample, after solutionizing and after ageing at different temperatures is given in Table 1. The aging behaviour is shown in the microhardness values of the thermally treated samples shown in Fig. 2. The hardness value of sample after solutionizing is slightly lower as compared to the as-foamed samples. The samples showed typical response to ageing treatment at 100, 150 and 180 °C with the hardness values of peak-aged samples being greater than both the as-foamed and solutionized conditions. The sample aged at 150 °C for 40 min after solutionizing treatment has the maximum hardness value. The foam samples in the peak aged condition were selected for compression test and their behaviour was compared with the as-foamed and solutionized samples.

During the quasi-static compression test, the collapse of the foam cells is observed to progress layer-by-layer from one end until full densification occurs. The compressive stress-strain curves were obtained by plotting the applied load divided by the original specimen cross-sectional area to obtain the applied nominal stress against percentage compressive strain. Compression curves of samples in as-foamed, solutionized and peak aged condition are plotted in Fig. 3. The values of yield stress, plateau stress and energy absorption of the respective samples are shown in Table 1. The values of plateau stress and energy absorption for as-foamed and peak-aged samples are similar, whereas, that of solutionized condition was significantly higher.

SEM micrograph of fractured samples from interrupted compression test taken from as-foamed, solutionized and aged condition are shown in Fig. 4. Backscattered electron image of fracture sample in the as-foamed condition (Fig. 4a) show that the crack has initiated from cell walls and is propagating through the brittle inter-dendritic region. The embedded Al_3Ti intermetallic phases also act as crack initiation site. From Fig. 4b it is clear that the crack propagation characteristic of solutionized sample appears quite different from as-foamed sample. It can be seen that the inter-dendritic region is rather discontinuous, which means that there is no easy path for crack propagation. However, the undissolved Al_3Ti acts as crack initiation site. Fig. 4c shows the fracture micrograph of aged sample, from where it is clear that inter-dendritic region is absent, however, large precipitates formed during aging allow easy path for crack propagation.

Fig. 5 shows bright field TEM micrograph of solutionized and aged sample confirming the presence of Al_2Cu precipitates. The size of the intra-granular Al_2Cu precipitates after solutioning and subsequent quenching is found to be as low as 75 nm in length (Fig. 5a). On the contrary, the aged sample exhibit coarser intergranular Al_2Cu precipitates of average size 420 nm (Fig. 5b), the precipitate growth is due to coarsening. Examination of the TEM micrographs have shown the interactions of dislocation with Al_2Cu precipitates in the aluminium matrix. The precipitates hinder the dislocation movement resulting in enhancement of the yield point. As compared to solutionized sample, the volume fraction of precipitates in aged condition increases and contribute to strengthening of the cell walls. On the other hand, it is also noted that the coarsening of intermetallic precipitates causes the cell wall to become brittle in nature and leads to the lowering of energy absorption capability of the foam.

4. Discussion

Energy absorption capability of foams depends on the area under the stress-strain curve. Therefore to increase the energy