Structural Property Correlation With Process Parameters In The Manufacture Of Closed-Cell Aluminum Foam

R. Edwin Raj* and B.S.S. Daniel*
*****Metallurgical and Materials Engineering Department, Indian Institute of Technology Roorkee, Roorkee 247667, Uttarakand, India.

ABSTRACT

The aluminum alloy foam with varying structural properties was prepared with melt foaming method using titanium hydride as blowing agent. The influence of process parameters were investigated in correlation with the structural properties of foamed aluminum. It is observed that the amount of titanium hydride and the duration of holding time for foaming have significant influence on the final cell structure over other process parameters. The microstructural analysis reveals the presence of intermetallics inside the cell wall and alumina on the pore surface contributing for the stability during foaming process. The mechanical properties and energy absorption capacity were calculated and analyzed, showing direct dependence with relative density of the foam.

Keywords: aluminum foam, foam structure, mechanical properties.

1. INTRODUCTION

Metallic foams are an important class of engineering material which find useful engineering applications owing to the unique combination of physical, mechanical, thermal and acoustic properties. These attributes offer opportunities to be used for light weight structures, for energy absorption, and for thermal management.

Cellular materials are common in nature, such as wood, cork, sponge, coral, bone, etc [1]. Foams may be defined as a dispersion of gas in solid. Foams are made up of an interconnected network of struts or plates which form the edges and faces of cells. If the gaseous phase in the cell structure is completely enclosed and is not interconnected with other cells, then by that morphology it is called as closed-cell foam. However, if there is interconnection between the cells, then it is called open-cell foam. The relative density, which is defined as the ratio of the density of foam to the solid metal (ρ^*/ρ_s), is generally used to characterize foam structures.

The cell wall materials of foams have to be chosen carefully according to the application. Polymers may be flexible but lack fire resistance capability. Ceramic foams are too brittle to be used for structural applications. Compared with polymeric foams which are widely used, metal foams offer superior properties with elevated temperature capability and fire resistance. These materials are fully recyclable without any pollution or waste problem.

Due to the presence of pores in its structure, metallic foams offer a set of unusual properties compared with bulk structural materials. Metallic foams exhibit engineering applications primarily due to two aspects of the material. Firstly, its high specific strength, if sandwiched between two solid face sheets attracts light weight structural applications [2-4]. Secondly, the energy absorption capability due to large compressive strains at nominally constant stress levels up to densification. In fact aluminum foams can absorb large energy at force levels appropriate for crash and blast protection systems [5-9]. They hold promise for market penetration in various other applications as well, due to the combination of its special features.

2. MELT FOAMING PRINCIPLE

Metallic foams are produced by various methods [10]. One of the methods of foaming molten metal is by introducing gas releasing agent into the melt after appropriating the melt viscosity. Liquid foams are metastable due to continuous drainage and rupture of cell walls. Therefore, foam stability can be interpreted as the delayed rupture of cell walls and subsequent retardation in melt drainage [11].

Pure liquid metal cannot be foamed. A certain amount of solid second phase particles are incorporated to alter the surface tension and viscosity to favor faomability

Corresponding authorpvenkatachalapathi@yahoo.co.in

[12-15]. In bulk liquid metal low viscosity will lead to rapid floating of the bubbles and faster bubble growth making the cell wall thin leading to coalescence. If the viscosity is too high, it would be difficult to disperse the foaming agent in the melt, which is a necessary pre-condition for obtaining uniform cell structure [16-19]. The driving force for bubble growth during foaming is the gas pressure due to the decomposition of TiH_2.

3. EXPERIMENTAL PROCEDURE

About 0.5 kg of 6061 aluminum alloyed with 4 wt.% Cu was taken in a clay-graphite crucible and melted (730°C) in the muffle furnace with a stirring arrangement. Once the temperature has reached, the viscosity of the melt is appropriated for foaming by adding 0.8 to 1.2 wt.% of calcium granules (98.8 % metal basis and -16 mesh powder) while stirring at 750 rpm for 10 to 12 minutes. Subsequently, titanium hydride powder (TiH_2), -325 mesh powder, 99 % metal basis was added and immediately dispersed uniformly throughout the melt by stirring at 1000 rpm for 1 minute. The stirrer is then removed and the melt is held inside the furnace for 80 to 150 s (holding time) during which time the foaming occurs. Finally, the crucible is taken out of the furnace and quenched in water to arrest the foaming process and to solidify the liquid foam. The experimental setup is detailed elsewhere [20].

Different process parameters such as the amount of TiH_2, holding time, amount of calcium and the duration of stirring after calcium additions are varied to access different foam properties. The foamed specimen is removed from the clay-graphite crucible and vertically sectioned into two halves and then horizontal sections are made. The average cell diameters are calculated at different places on the foaming direction and also in the radial direction using the formula L=1.5/N, where N is the number of cells per unit length. The cell diameter varies in the foaming direction due to gravity induced drainage and on the radial direction due to differential cooling rate encountered during solidification. The cell shape anisotropy-ratio is also calculated as R= L1/L2, where L1 is the largest principal dimension and L2 is the smallest principal dimension [1]. Microstructural analysis is carried out to investigate the distribution of the in-situ formed intermetallic and oxide particles in the aluminum cell wall matrix. Metallographic samples are prepared by the standard procedure and examined by Scanning Electron Microscope (SEM; Quanta 200 FEG, FEI Company) fitted with Energy Dispersive X-ray Spectroscopy (EDS; Genesis 2000, EDAX) for elemental analysis. Particle/phase identification is done by correlating the EDS results with powder X-ray diffraction (XRD; D8 Advance, Bruker AXS) using Cu Kα radiation.

The compression test specimens are cut approximately into regular square prism having height twice that of the width. The specimen dimensions are recorded and weighed accurately to estimate relative density taking the base metal density as 2.721 g/cm^3. The compression tests were carried in the material testing machine (H25KS/05, Hounsfield) with computer interface for data acquisition and control. Tests are conducted at a strain rate of 1×10^{-3} s^{-1} while taking care to reduce friction between the specimen and the plunger. The stress is calculated by dividing the load by the cross-section area and the nominal strain, ε, calculated on the basis of the initial specimen height and the cross-head movement of the plunger. The stress values are plotted against engineering strain. The plateau stress, σ_{pl}, is taken as the average stress between 5 % and 30 % strain during compression. The energy absorption per unit volume, W, is the area under the stress-strain curve up to densification. The densification strain, ε_d, is determined where the slope of the stress-strain curve increases steeply, accommodating more stress for small increment in strain. The determination of mechanical properties and energy absorption capacity of foam from the compression stress-strain curve is schematically shown in Fig.1.

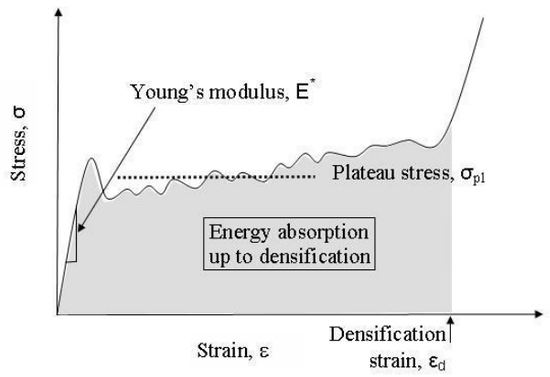

Fig 1. Schematic representation of mechanical property and energy absorption capacity determination from the stress-strain plot.

4. RESULTS AND DISCUSSION

4.1 Macrostructural Analysis

The precise control of structure is rather difficult due to the stochastic nature of foam development. However, it is required to develop certain control of structural properties with process characteristics to reproduce the required morphology and properties of the foam. In the

manufacturing of aluminum foam, calcium is added to modify the melt properties by increase of viscosity. The influence of the variation of calcium amount from 0.8 wt.% to 1.2 wt.% is not significant in the final cell structure.

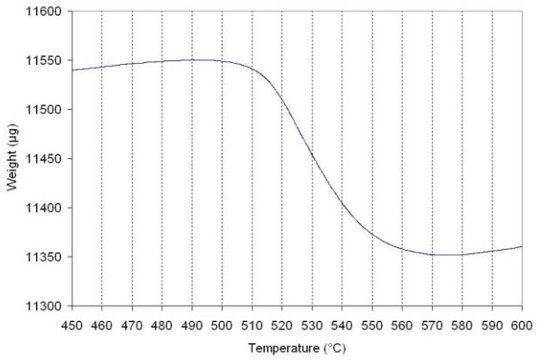

Fig 2. TGA analysis done in argon atmosphere at a heating rate of 10 °C/min showing weight loss of TiH_2.

However, the amount of titanium hydride addition and the duration of holding time after dispersing into the melt have significant influence on the structural properties of aluminum foam. From the thermogravimetric analysis (TGA) curve (Fig. 2), it can be noted that the weight loss occurs between 510°C and 570°C signifying the decomposition temperature range. The driving force for the bubble growth is the gas pressure caused by the decomposition of TiH_2 which has to overcome by the hydrostatic pressure of the melt.

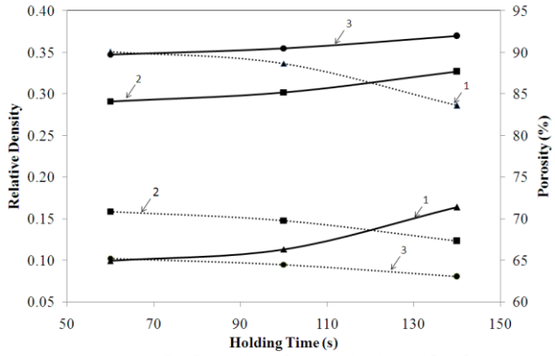

Fig 3. Graph showing the variation of relative density and porosity of foam with holding time and the amount of TiH_2 ((1) 0.5 wt.% TiH_2, (2) 1.0 wt.% TiH_2 and (3) 1.5 wt.% TiH_2, dotted line for relative density and thick lines for porosity).

The amount of TiH_2 addition significantly affects the density of foam, thereby the porosity. It can be observed from the Fig. 3, with increase in the amount of TiH_2 the relative density decreases and consequently the porosity increases. There is a significant jump in relative density/porosity values when TiH_2 is varied from 0.5 wt.% to 1.0 wt.% which is also reported in literature [21].

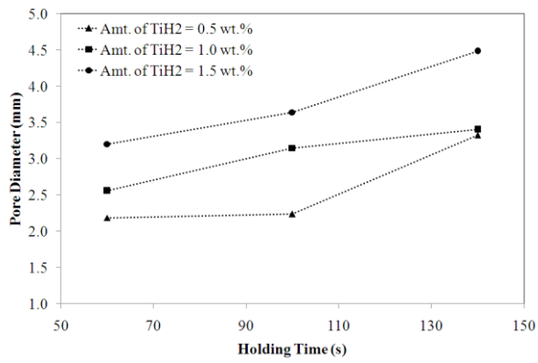

Fig 4. Variation of average pore diameter of foam with holding time and the amount of TiH_2.

The average pore diameter of the foam shows monotonous increase with the addition of TiH_2 (Fig. 4) and also with the increase in holding time [22]. In the macrograph shown in Fig. 5, the holding time is varied as 60s, 100s, and 140s, while other parameter are held constant (TiH_2 = 1.0 wt.%, Ca=1.0 wt.%, stirring time for Ca =10 minutes). The increase in holding time results in increase of the average pore diameter as 2.24mm, 3.20mm and 3.64mm respectively. Similar variation in cell macrostructure is observed with different percentage addition of TiH_2 (Fig. 4). It is reported elsewhere [20] that for the same relative density different pore size can be obtained. It is observed that, uniform regular cell structures are obtained with addition of 1.0 wt.% TiH_2 and 100s holding time.

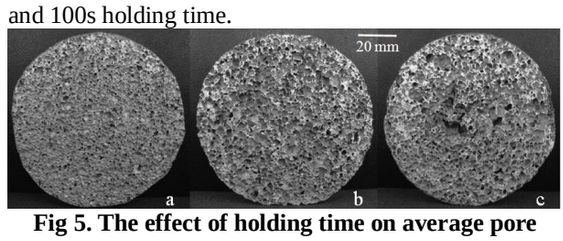

Fig 5. The effect of holding time on average pore

diameter of the foam at (a) 60s, (b) 100s and (c) 140s when other parameters such as TiH_2 = 1.0 wt.%, Ca=1.0 wt.%, stirring time for Ca =10 minutes are constant.

4.2 Microstructural Analysis

The term foam stability in aqueous foams is related to the absence of cell wall rupture and to a limitation of drainage. Whereas in metallic foams the term stability is a misnomer as cellular structure is constantly changing in the time scale of the foaming process. Cell rupture is a

sporadic and spontaneous process and drainage is a continuous process influenced by local pressure difference in the cell wall and gravity. So, metal foam stability can be understood as a slowing down of the cell wall rupture and drainage process.

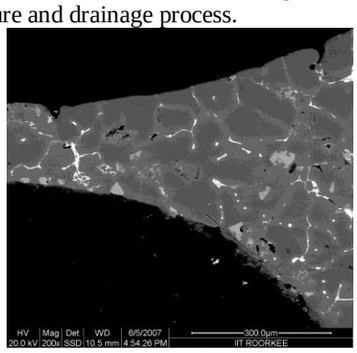

Fig 6. Micrograph showing thickness variation in cell edge and cell face.

The important task is in identifying the parameters which improve foam stability. Experimental evidence points out that second phase solid particle additions improve stability by altering viscosity [15,17]. The solid particles wet by the molten metal lead to flatter curvatures around the plateau borders which reduces the suction of metal from the cell wall into the cell edge. Particle addition to liquid aluminum alloy can significantly decrease the apparent surface tension of the liquid-metal dispersion [23]. Additionally, one cannot discount the nano alumina skin layer which forms on the cell walls [23,24].

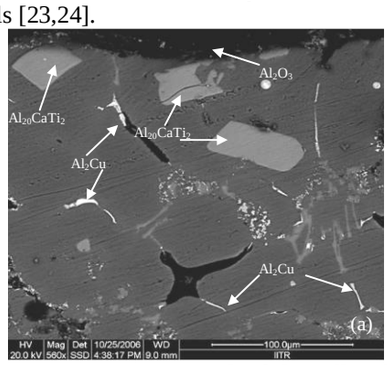

Fig 7. SEM micrograph of the cell wall microstructure of foam showing intermetallic particles.

The oxygen, titanium, calcium, iron and aluminum elemental mapping of the microstructure was also done. A general observation shows that the intermetallic particles are confined to the foam structure and completely absent in the drained metal below. This can be accounted by the pick up of particle by the rising gas bubbles. It is found that aluminum oxide is only confined to the surface of the pores and the intermetallic particles are present within the cell wall matrix. An enlargement of the cell wall section is shown in Fig. 6, where the concentration of the metal at the cell edge is more relative to the cell face. There is also a uniform distribution of intermetallic particles throughout the matrix. The EDS analysis of the in-situ particle dispersion formed is done and is shown in Fig. 7. Al_2Cu lamella is present as fine lamella whereas $Al_{20}CaTi_2$ is present as blocky precipitates within the cell wall.

4.3 Mechanical and Energy Absorption Property Analysis

Fig. 8 shows the typical compression stress-strain plot of aluminum foam and the sequential photograph at different strains during the compression test. As detailed in section 3 and schematically represented in Fig. 1, the mechanical properties are evaluated. Twenty one set of experiments are conducted at different process conditions and the average obtained by the compression test of five specimens for each set is used for analysis.

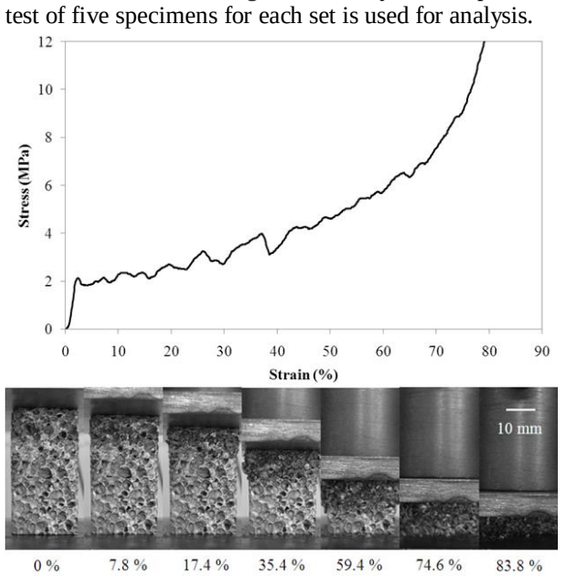

Fig 8. Stress-strain curve along with the macrograph of a specimen (relative density 0.1063) at different strains during the compression test.

The mechanical properties of aluminum foam depends mainly on their relative density [25,26]. The plateau stress increases with relative density as shown in Fig. 9. It can also be observed from Fig. 10 that for the same relative density the pore diameter increases with plateau stress [20]. The increase in plateau stress for the given relative density is attributed to the cell wall thickness. Fig. 11 shows the monotonic dependence of

the Young's modulus with relative density. Similar

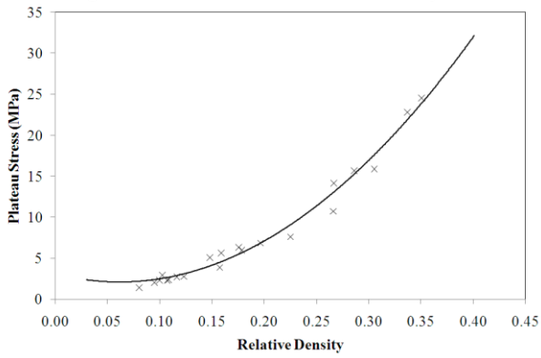

Fig 9. Graph showing plateau stress increasing with relative density of foam.

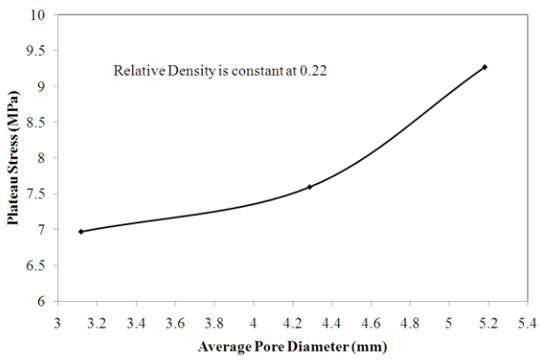

Fig 10. Increase in plateau stress is shown with average pore diameter for the same relative density [20].

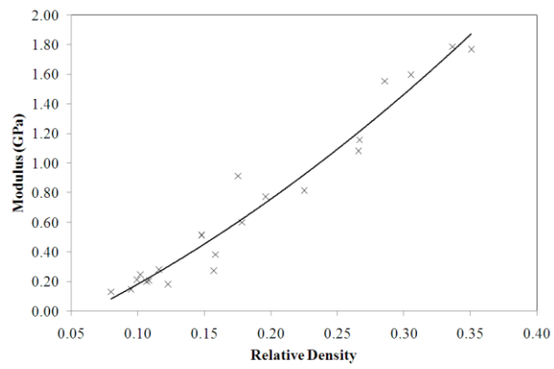

Fig 11. Young's modulus with relative density graph showing direct dependence.

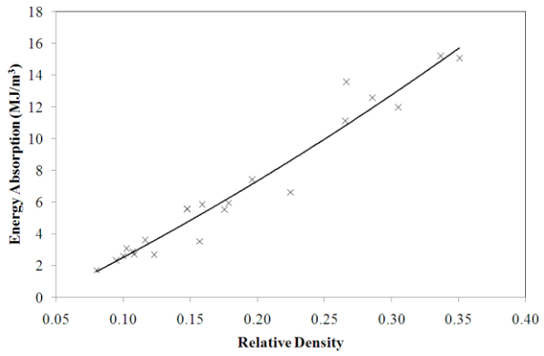

Fig 12. Energy absorption showing direct dependence relative density.

behavior like that of plateau stress, is observed for the Young's modulus of the foam and is shown in Fig. 11. The energy absorption capacity per unit volume (W) is given by

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

Where, σ is the instantaneous stress at strain, ε and ε_d is the densification strain. The energy absorption is also found to have direct correlation with the foam density (Fig. 12). However, the plateau stress defines the stress level at which the energy absorption occurs when the material is used for the energy absorption applications. Large compressive strains at nominally constant stress levels is required to absorb large energy at force levels appropriate for crash and blast protection system [5-9,27]. The results reported in this paper represent comparatively the force levels appropriate for these applications. Experiments are being carried out at higher strain rates commensurate with automobile crash and the results will be reported shortly.

5. CONCLUSION

The control of structural properties and the process parameters influencing the foamed aluminum structure were investigated. It is observed that the two process parameters (1) the amount of TiH_2 and (2) the holding time has significantly influence on the final cell structure. Lower relative density or higher pore diameter can be attained by increasing the amount of TiH_2 or holding time. Optimum aluminum foam structures is obtained at 1.0 wt.% TiH_2 and 100s holding time. The mechanical properties and energy absorption capacity increases with the relative density.

6. REFERENCES

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