Aluminium Foam Fabrication by Powder Metallurgy Route

C. Umashankar, Kaushal Jha and K.N. Mahule
Engineering Design & Development Division

and

T.R.G. Kutty
Radiometallurgy Division

Abstract

Aluminium foams play a key role in providing a cushion for absorption of shock and impact. They have also found increasing applications in a wide range of structural and functional products, due to their exceptional mechanical, thermal, acoustic, electrical and chemical properties and offer great potential for lightweight structures. Aluminium foam structures have densities only fractions of that of a solid structure and have high specific strength and stiffness. They have excellent properties for absorption of impact energy, vibration and sound. In this paper, a process for development of aluminium foam by powder metallurgy route has been discussed. The metal foaming process is based on a procedure where uniform mixing of aluminium powder and foaming agent is done and compacted in a cold isostatic press. The compacted billet is extruded. The extruded billet is heated up to foaming temperature. The heating process leads to partial metal melting with the release of the foaming gas. Aluminium foam having a density of around 0.3 g/cm\(^3\) have been fabricated. The effects of various fabrication parameters like compaction pressure, extrusion ratio, foaming temperature are discussed. The above-mentioned Aluminium foams are characterized in terms of density, microstructure, porosity content. It is necessary to obtain various mechanical properties like yield strength, tensile strength and impact energy for metal foam to understand the behaviour of foam under different conditions.

Keywords: Aluminium Foams, Cellular Microstructure, and Compressive behaviour

Introduction

Metal foam has a lot of promising industrial applications and most important among them is shock mitigation. Among the metal foams, Aluminium foam deserves a special place as it has high specific strength and higher stiffness than other contemporary packaging materials.

The Aluminium foams were not manufactured indigenously in the past. Their cost of procurement is exorbitant. Therefore, development of Aluminium foam by indigenous means has become a necessity. The foam is defined as a uniform dispersion of gas bubbles in a liquid, separated by thin film of liquid making a cell or pore. This morphology when preserved in solid state is known as solid foam or cellular solid. If we consider the structural aspects of metal foam, there are three most common cell structures, namely, open cell structure, closed cell structure and the combination of the above two. Recently, a novel structure has been developed, which is known as lotus-type growth structure consisting of long cylindrical pores aligned in one direction. The open cell structures incorporate interconnected pores, whereas, in closed cell structures, a metallic thin wall surrounds pores.

Solid metallic foams are known for their interesting combinations of physical, mechanical, thermal, electrical and acoustic properties such as high stiffness in conjunction with very low specific weight or high compression strengths combined with good...
energy absorption characteristics. They are a new class of materials, offer potential for lightweight structures, for energy absorption and for thermal management. Aluminium foams are isotropic porous materials with several unusual properties that make them especially suited for engineering applications. Due to their low densities between 0.3 g/cm$^3$ and 0.8 g/cm$^3$ the foams can float in water (in case of closed porosity). They exhibit a reduced conductivity for both heat and electricity. The strength is lower than conventional dense aluminium and declines with decreasing density. Foams are stable at temperatures up to the melting point. The metal foaming process is based on a procedure consisting of a base metal and a foaming agent, which are mixed by milling and pre-compacted by cold isostatic pressing. This is followed by cold/warm extrusion. The extruded piece is then heated up to a foaming temperature. The heating process leads to partial melting as well as the release of the hydrogen gas and consequently leads to the material foaming in the semi-solid state.

**Experimental**

In this process, aluminium powder is weighted and mixed with 2-3.5% TiH$_2$ powder. The powders are milled in a High-Energy Stirred Ball mill at 100 rpm for 6 hours. The milled powder is removed, packed and sealed inside silicon rubber mould. The weighing, mixing and sealing operation is carried-out inside an inert atmosphere enclosure. The tapped density of the powder as calculated analytically, was 76% of theoretical value.

The sealed mould is cold isostatically compacted to a pressure of 2500-3000 bar for 1 min. The density obtained is nearly 96% of theoretical density. For, better and uniform mixing and to achieve a density as close as to theoretical density, the isostatically compacted billet is extruded in an extrusion machine with an extrusion ratio of 1:16. The extruded billet was sealed and stored in an inert atmosphere to prevent oxidation. The billets are cut into 100 mm long pieces, which are to be heated in an induction furnace. The furnace was pre-heated to 740°C before starting the foaming operation. The extruded pieces are kept inside a one end closed quartz tube having an inside diameter of 35 mm. The quartz tube is inserted inside the furnace. The furnace temperature drops due to the quartz tube insertion. The furnace is allowed to stabilize to 740°C. The foaming starts immediately once the temperature of billet reaches 740°C. The foam expands and takes the shape of quartz tube. Once the foam touches the wall of the quartz tube, it is immediately withdrawn from the furnace. The quartz tube is cooled immediately to get good quality foam.

The foaming was tried at different temperatures and the best foaming temperature obtained is 740°C. The holding time also has been varied. It was found at lower holding time of < 60sec the density was higher and if holding is > 120sec the drainage of the melt occurs resulting an increase in density. Hence, the optimum holding time established was 60 to 120s.

To conclude, the best foaming parameters in this study are as given below:

- Compaction pressure 2500-3000 bar
- Extrusion 200-250°C
- Extrusion ratio 1:16
- Foaming temperature 740°C
- Holding time 60 to 120 s
- Cooling water quenching

**Characterisation**

The powder route is the best method to obtain good quality foam with relative densities as low as 10%. The microstructures of Aluminium foam obtained using powder route are shown in the figures below. The density of the foam obtained using powder process was found to be in the range of 0.2 to 0.3 g/cc depending upon the fabrication parameters. From the figures, it is evident that pores are uniformly distributed and their size varies from 2 to 5 mm. The shape of the pores was irregular in most cases. Typical cell structures showing the pore shape and size distribution are shown in Fig.1.
The exact cell wall thickness measurements were carried out using SEM. Some typical SEM pictures are given in Fig. 2.

The Figure shows a low magnification image depicting the pore distribution and the cell walls in the aluminium matrix. It was observed that the cell wall thickness was not uniform and found to vary between 200-500 μm.

**Density measurement**

The overall density of a porous material is determined by Archimedes’ principle. The density of the foam obtained using powder metallurgy route was found to be in the range of 0.2 to 0.9 g/cc depending upon the fabrication parameters.

**X-ray radiography**

The defects in the cellular metals can be detected by simple X-ray radiography techniques. X-ray radiography as shown in Fig. 3 reveals some of the very large pores, but it is impossible to resolve most of the small pores. The radiography also revealed the absence cracks and the uniform distribution of pores in the Al matrix.

**Compression Test results**

Ideal energy absorbers have a long flat stress–strain (or load-deflection) curve like those of Figs.4a & b. The absorber collapses plastically at a constant nominal stress, called the plateau stress, $\sigma_{pl}$, up to a limiting nominal strain, $\varepsilon_D$. Energy absorbers for packaging and protection are chosen such that, the plateau stress is just below which shall cause damage to the packaged object. The best choice is then the one, which has the longest plateau, and therefore absorbs most energy before reaching $\varepsilon_D$. The area under the curve, roughly $\sigma_{pl}\varepsilon_D$, measures the energy the foam can absorb, per unit initial volume, up to the end of the plateau. Foams which have a stress–strain curve like that shown in Fig. 4 perform well in this $\sigma_{pl}$ function [1-6].

The characteristics of aluminium foam are best described by the material from which it is made, its relative density, $r/r_s$ (the foam density, $r$, divided by that of the solid material of the cell wall, $r_s$) and stating the pores/cell being closed or open. The foam properties are influenced by structure, particularly by anisotropy and defects. The structure of foam is like those of soap films: polyhedral cells with thin cell faces bordered by thicker cell edges (plateau...
The features are governed by surface energy, as they are in soap films[10-11].

Compression testing is carried out using an Instron machine. The samples used for compression testing are of 35mm in diameter, and length varying from 35 mm to 70mm. In short, we used sample with L/D ratio varying from 1 to 2. Fig. 5 Shows some of the samples with relative densities in the range of 0.2-0.3 gm/cc on which the compression tests were carried out. The tests were carried out with a cross head speed of 60mm/min.

Results and discussion

Aluminium foams are isotropic porous materials with several unusually properties that make them especially suited for some applications. They are incombustible, non-toxic and 100% recyclable. Due to their cellular structure, foams behave differently in testing when compared to conventional metal. The test that gives meaningful results is the compression test. A typical compressive stress-strain diagram for cellular materials consists of three parts:

In foams irreversible (plastic) deformations can occur at low stresses.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Description</th>
<th>Dimensions (mm)</th>
<th>Density g/cc</th>
<th>Relative density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al + 2-3.5% TiH₂</td>
<td>D=35L=70</td>
<td>0.29</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>Al + 2-3.5% TiH₂</td>
<td>D=35L=52</td>
<td>0.27</td>
<td>0.10</td>
</tr>
<tr>
<td>3</td>
<td>Al +20%Mg + 2-3.5% TiH₂</td>
<td>D=35L=46</td>
<td>0.23</td>
<td>0.08</td>
</tr>
<tr>
<td>4</td>
<td>Al + 2-3.5% TiH₂</td>
<td>D=35L=35</td>
<td>0.37</td>
<td>0.13</td>
</tr>
</tbody>
</table>
b) The plateau is caused by a homogeneous plastic deformation.
c) The steep increase is caused by the collapse of the cells. The opposing cell walls begin to touch each other.

The properties of the foam are influenced by the following factors:
a) The properties of the solid of which the foam is made.
b) The topology (connectivity) and shape of the cells.
c) The relative density $\bar{n}/\bar{n}$ of the foam.

In most foam production technologies the properties can be varied over a wide range by controlling the production parameters. It shows a linear increase of stress at the beginning of deformation and a plateau regime of nearly constant stress in the middle, followed by a steep increase in flow stress at the end.

Aluminium foams made by Powder metallurgy route, the length of the plateau increases with decreasing density as show in Fig. 7. The energy absorption of Aluminium foam is 0.15kJ. The compressive strength as observed is 1-3 MPa at a densification strain of 70 to 90%. As, observed during compression testing the Young’s modulus of foams increase with increasing density. Therefore, one can fabricate the foams having different plateau stress and Young’s modulus.

Acknowledgements

I thank Shri H.S.Kamath, Ex-Director, NFG, Shri R.P. Singh, Director NFG and Head Atomic Fuels Division, Shri M.M.Hussain, Head Mechanical Working Section, AFD and Shri Arun Singh, of Mechanical Working Section, AFD, Dr. G.P.Kothiyal, Head Glass and Advanced Ceramics Division, Dr. S.Ramanathan, Head Advanced Ceramic Section, Shri M.R. Gonal, of Advanced ceramic Section for their continued help and support in the fabrication of aluminium foams. I would like to thank, Dr. K.B.Khan, Head Process control and NUMAC Section, Radio metallurgy, and all staff members of NFG for their cordial help and support.

Fig. 7: Stress-Strain curves for different relative densities.

I thank Shri R.K.Mittal, for helping me in fabricating and commissioning induction power source setup and control system. I also, thank Staff members of ED&DD for helping me in carrying out the experiments and laying out the facility at M/s BARC, Mumbai.

References
1. M.F. Ashby, A. Evans et al., Metal foams-a design guide
5. John Banhart, Department of Materials Science, Hahn-Meitner-Institute Berlin, Germany Discusses on the Metal foams-from fundamental research to applications.
8. A.R.Kennedy, Advanced Materials Research Group, Report Manufacturing Engineering and Management University of Nottingham, NG7 2RD, UK