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Process Parameters and Foaming Agents Used in Manufacturing of Aluminium metallic foams: A Review

Sri Ram Vikas K., N. Raghu Ram, Ch. Kishore Reddy, V.V. Sridhara Raju
Department of Mechanical Engg, Prasad V.Potluri Siddhartha Institute of Technology, AP India
[1]sriramvikas@gmail.com,raghu1449@gmail.com,kishorereddymtech@gmail.com, vvsridharraju@yahoo.co.in

Abstract: Porous metals and metallic foams are composite materials in which one phase is gaseous and another phase is solid metal. The mechanical behavior of these materials depends mainly on the mechanical properties of the solid metallic phase, the structural configuration of the solid and the density of the composite ρc, relative to the density of the solid phase ρs. The primary distinction between a porous metal and metallic foam is the relative density, metal gas composites with a relative density (ρc/ρs) above 0.3 are generally considered porous materials, while those with a relative density below 0.3 are generally considered to be metallic foams or honey combs. Another distinction between the two is in the interaction between adjacent voids in the structure. Porous metals and metallic foams can have open cells, with completely interconnected voids, or closed cells, with each void being isolated by a solid film. This review outlines the process parameters and foaming agents used in manufacturing methods of Aluminium metallic foams and discusses benefits and concerns associated with their uses. Many research works have been done on this particular topic and various technologies have been proposed and applied at experimental and field levels.

Key words: porous metals, foaming agent, honey combs.

INTRODUCTION

Metal foam is a cellular solid, like wood, coral bone and bread but with the cells made out of metal. Usually the metal is an aluminium alloy, but it can also be made of other metals like steel, nickel, titanium and gold etc. [1]. They have enormous potential for applications where light weight combined with high stiffness is required [2]. Among cellular materials, aluminium foams are the most commonly produced material which provides a unique combination of properties such as very low density, high energy absorption under static and dynamic compressions, blast amelioration, sound absorption and flame resistance [3].

Because of the strong demand of the transport industry for lower operating costs, higher payloads, improved environmental compatibility, increased passenger safety and comfort, aluminium foams have become more and more important during the last few years [4]. Aluminium foams produced by the powder metallurgy (P/M) route have a high potential for use in weight-sensitive construction parts [5]. The primary driver for the use of aluminum P/M is the unique properties of aluminum coupled with the ability to produce complex net or near net shaped parts which can reduce or eliminate the operational and capital costs associated with intricate machining operations. Many research works are being carried out to produce metallic foams [6].

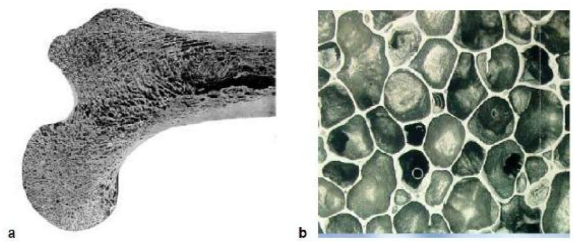


Fig 1: Natural and artificial cellular structures: (a) bone; (b) aluminium foam [2]

This review describes the process parameters and foaming agents used in manufacturing of aluminium metallic foams with respect to engineering field. A small message the authors wants to deliver through this study is that the unique structure with interconnected porosity of Aluminium metallic foams led to create a good perfect uniform energy absorption at deformation material. Aluminum foams have remarkable physical properties and create a lot of application possibilities.Enthusiasm in this field arises because of the unique properties of the material and also due to its perfectly well-defined compression strength and high gas permeability. Aluminum foams predicted to be beneficial in future technology.

Foaming agents and manufacturing process parameters.

Twin-screw Rheomixer with closely intermeshing, self-wiping and co-rotating was used in [10].

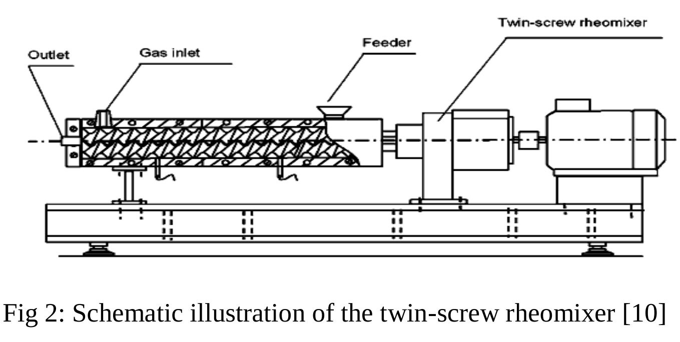


Fig 2: Schematic illustration of the twin-screw rheomixer [10]

Gaseous elements can be mixed in Al melts at a high temperature and decompose into gas bubbles during solidification, but the solubility of gas in Al melts is too low to form Al foams. In order to produce Al foams, a large amount of gas has to be introduced into the Al melt. It is also very important to keep the gas bubbles stable in the melt. The behaviour of gas/Al system is quite similar to immiscible systems, such as Zn–Pb, Ga–Pb and Al–Pb, which have been successfully mixed together using the rheomixer [7–9].

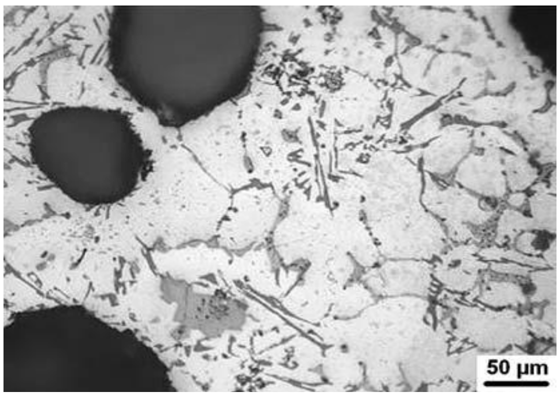


Fig. 3: Optical microstructure of the premixed Al/Al_2O_3 slurry [10]

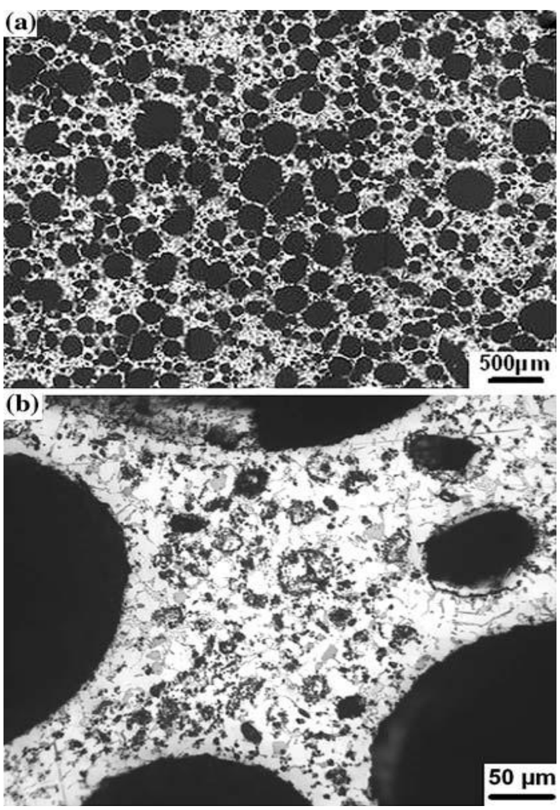


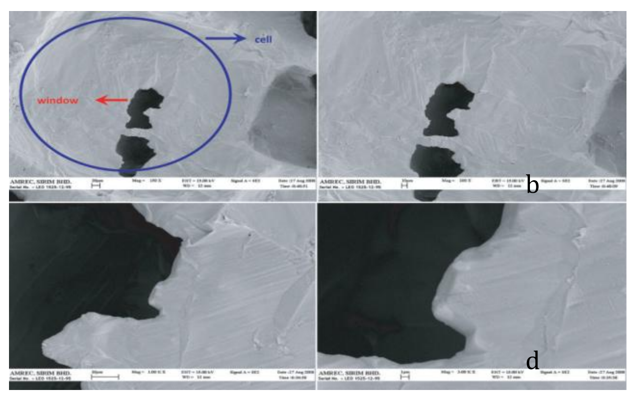
Fig 4: Optical microstructure of Al/Al_2O_3 foams produced using the rheomixer, (a) low magnification (b) high magnification [10]

Submicron Al_2O_3 particles were added to aluminium (A380Al) alloy and N2 gas was passed into semi solid slurry using a twin-screw rheomixer, which offered high shear rate and intensive turbulence. It was found that rheo mixing increased the percentage of porosity than that of premixing. 72% porosity was obtained by Rheomixer. When the melt temperature drops to a semisolid temperature ranging from 575^0C to 585^0C, the sub-micron Al_2O_3 particles are easily engulfed in to the melt by stirring. The temperatures of 575–585^0C correspond to 10% and 20% volume fractions. The concept of rheofoaming has been proven to be feasible to produce high quality Al/Al_2O_3 foams of Al primary particles for the A380 Al alloy, respectively and it can become a potential route for industrial products of high quality metallic foams.

P.O.Bonaldi et al [11] produced Al metallic foams by powder metallurgy method and found the best conditions for obtaining round pores, with homogeneous size and distribution of aluminium foam by addition of 1.0% TiH_2 as a foaming agent mixed with Al powder for 2 hours and compacted at 450Mpa at temperature of 710^0C for 10 min obtained good expansion, linear and pore size distribution and obtained density of 0.717g/cm^3.

Through pressure assisted high frequency induction heated sintering dissolution process with NaCl as leaching agent; 150-400µm open pores were obtained with foam porosity 0.5-2% and found that most of the Al particles have changed their original shape at compaction of 120Mpa and sintering temperature of 620^0C which lead to strong bonded aluminium particles.

a



c

Fig4: a, b showing cells and windows (a ×150 and b ×200); c, d showing quality of cell wall (c ×1000 and d ×3000)3 Images (SEM) of pressure assisted sintering aluminium foam [12]

By filament winding technology hybrid component which contained aluminium foam cylinder core and the outer layer in epoxy/S2-glass and obtained average density of 0.5g/cm^3.Hybrid components characteristics improved compared to sum of the single components (metal foam cylinder and epoxy/S2- glass

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tube). Hybrid components exerts maximum load slightly superior to the sum of maximum load values obtained for the foam cylinder and composite tube, and for a particular load hybrid component one is constant, and energy absorption during deformation is very high due to constrain effect of the composite tube.[13]

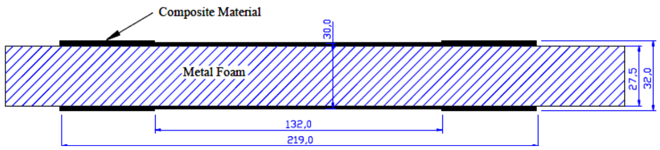

Fig5: Cross section of hybrid metal/composite component: cylindrical core in aluminum foam and outer shell in Epoxy/S2-Glass (dimensions in millimeters). [13]

In [14] Al foams were produced by combined process of hot powder extrusion and molding and obtained densities in the range of 0.2 to 0.3g/cm^3. Stainless steel was used as mold. Compacting pressure is 100Mpa, and the container is heated to 420^{0}C for hot extrusion. The effect of gravity is significant when a large step exists at the connection between mold inlet and the die outlet, and friction is dominant in the cases where the foam is mold in a narrow space. Volume ratios of the foams were examined by filling foams in three different molds with different shapes. The influence of gravity and friction on the molding of the foam was found.

Low cost sintering dissolution process (SDP) for manufacturing open cell Al foam and obtained net shape controlled pore morphology of density 0.15-0.5g/cm^3.SDP is most suitable for manufacturing Al-foams with relative densities between 0.15-0.5 g/cm^3. The relative foam density can be controlled with reasonable accuracy by mixing Al and NaCl powders at specified weight ratio. It is difficult to obtain foam density below 0.15 g/cm^3 by SDP [15]. The foam has a homogeneous structure with open pores and pore size in the range of 300- 1000µm. Sintering temperatures lower than 640^{0}C resulted in poor or no bonding between Al particles. Sintering time shorter than 120 min were not efficient to ensure good bonding and longer than 360 min may lead to oxidation of the Al matrix. The optimum sintering temperature and time was found that is 680^{0}C at 10 min.

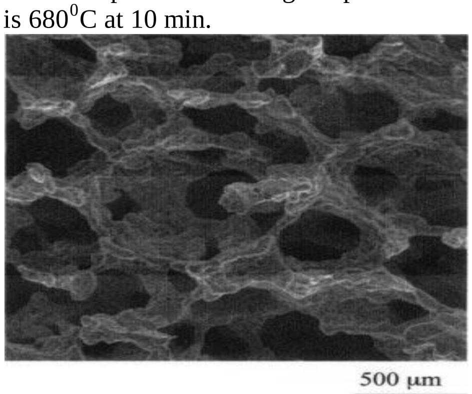

Fig 6: SEM micrograph of typical Al foam manufactured by SDP [15].

stabilized aluminium foams by using particles of rice husk ash (RHA) particles to aluminium, titanium hydride powder, improved pore structure By addition of 1 wt% RHA has resulted maximum expansion of composite foams (393 vol. %) compared with pure Al foams and beyond this amount resulted decreased expansion. Compressive strength and energy absorption was increased. This resulted in increasing viscosity of Al melt [16].

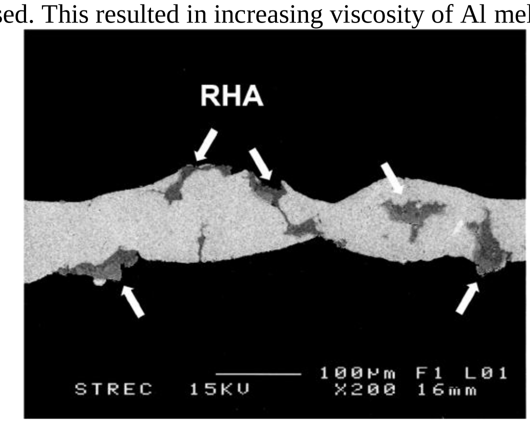

Fig 7: Rice husk ash particles embedded in a cell wall [16].

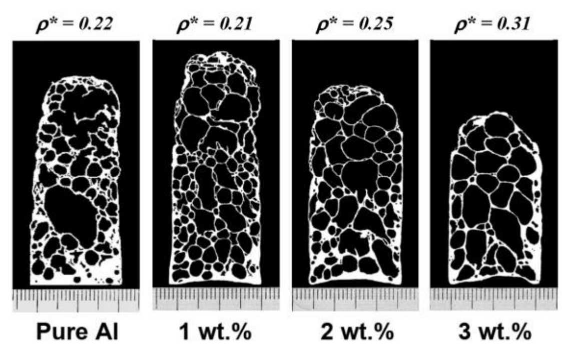

Fig 8: Expansion and pore structure at maximum expansion of Al foams added with rice husk ash at various contents [16].

N.Michailidis et al [17] produced Al foam by using crystalline raw sugar cane, as a novel leachable pattern by dissolution and powder sintering process and obtained 40-70% porosities. Optimum pressures and sintering temperatures were 250-300Mpa and 680-750^{0}C, in low vacuum furnace (P=0.01Mpa).

Holding time was 3hrs. Heat applied to specimens was 20^{0}C/min. It was observed that at high compaction pressures (600Mpa) cracks were introduced, sometimes led to complete collapse of the foam network.

40-70% of sugarcane particles were varied. It was stated that higher contents of raw sugar particles lead to an absence of continuous network of Al. It was stated that compact consisting of 65vol % raw sugar and 35% Al powder showed a behavior similar to that of pure cane particles which are harder than the Al powder, and also raw cane sugar particles did not affect the green density of the compacts and is strongly affected by compaction pressure and raw cane sugar/Al ratio in the compact. It was found that the density of the green product increased almost linearly with increasing compaction pressure of raw cane sugar/Al ratio. Sliding of particles under high compacting pressure increased friction among Al and raw cane sugar particles that caused local fracture of the oxide film. Optimum compaction pressure was stated to be 250-300Mpa. At this pressure it exhibited the highest quality of original shapes and had satisfactory strength. It was observed that at lower compaction pressures, metallic contacts between Al powder was likely to be created. Severe spalling of Al powder was observed when the space holder material was removed from the water bath during dissolution stage. At higher compaction pressures the samples often crack, sometimes leading to complete fracture. It was observed that below 600^0C resulted in insufficient bonding and required prolonged period for establishing bonding between the Al powders.

Fig 9: Cracking and fracture of green products leading to severe spalling of Al powders at the leaching stage, due to high compaction pressures (~600 MPa)[17].

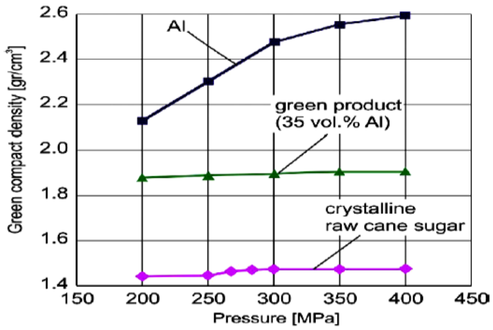

Fig 10: Compaction pressure versus density of green product for pure Al, pure raw cane sugar and 65 raw cane sugar and 35 vol. % Al compacts. The mean size of the Al-powder and raw cane sugar particles is 0.26 mm and 0.7 mm respectively [17].

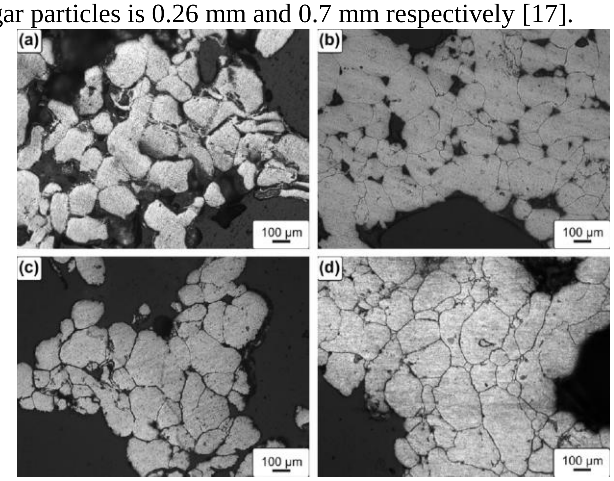

Fig 11: Typical microstructure of the cell walls of produced Al-foams (a) without sintering (green product), (b) sintered at 600^0C, (c) sintered at 680^0C and (d) sintered at 750^0C with a magnification of 100× [17].

Al foam by EFF (Extrusion free form fabrication) rapid prototyping process obtained 50-60% porosity. The fabrication cost of components can also be reduced further if this can be achieved directly from CAD designs. The Al foam samples were processed by blending metal powder (nominally 87% Al, 6.5% Mg, 6.5 % Sn by weight).They showed 18-20% shrinking of the component. An EFF technique was employed to fabricate metallic foams with controlled pore size and orientation. Compression tests conducted at lower strain rates (10^{-3}s-1 to 4s-1). Compression tests results indicated that EFF Al foams were stronger than Al foams processed by alternative methods. Strain rate strengthening was observed and is attributed to plastic flow of the EFF foam [18].

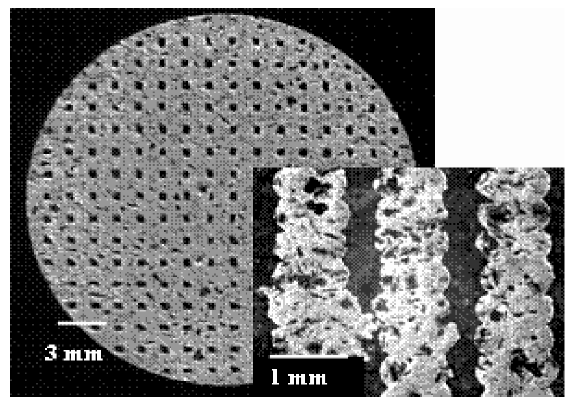

Fig 10: Cross section through the Al foam showing the 0/90 degree layup possible and the available porosity [18].

A.Yavuz et al [19] investigated the effect of the dissolving agent morphology on the production of the Al foams by SDP (sintering and dissolution process). The effect of two different foaming agents (NaCl and Na_2CO_3) was studied. It was found that tabular shaped Na_2CO_3 resulted in much faster and vigorous dissolution rate than the NaCl. It was found that NaCl and Na_2CO_3 together improved the dissolution step in SDP process. The usage of Na_2CO_3 was better alternative to increase the interconnectivity of the pores. The two important problems will occur, firstly when Na_2CO_3 was used alone in the sample a mixing problem will encounter due to the long tabular shape of Na_2CO_3 because Al and Na_2CO_3 are very different. Secondly, after dissolution process loss in sample weight will be observed. The optimized dissolution yield occur when two salt types used together with equal weight, the shape and dissolution problems can also optimized when compared to using Na_2CO_3 alone. Long tabular shape Na_2CO_3 usage alone in production of metallic foams by SDP process is not useful. Such a production approach results in problems during mixing, pressing and dissolution stage. It was observed that, Na_2CO_3 with NaCl in certain amounts solved novel problems in SDP process, improved the dissolution yields and speed up the process.

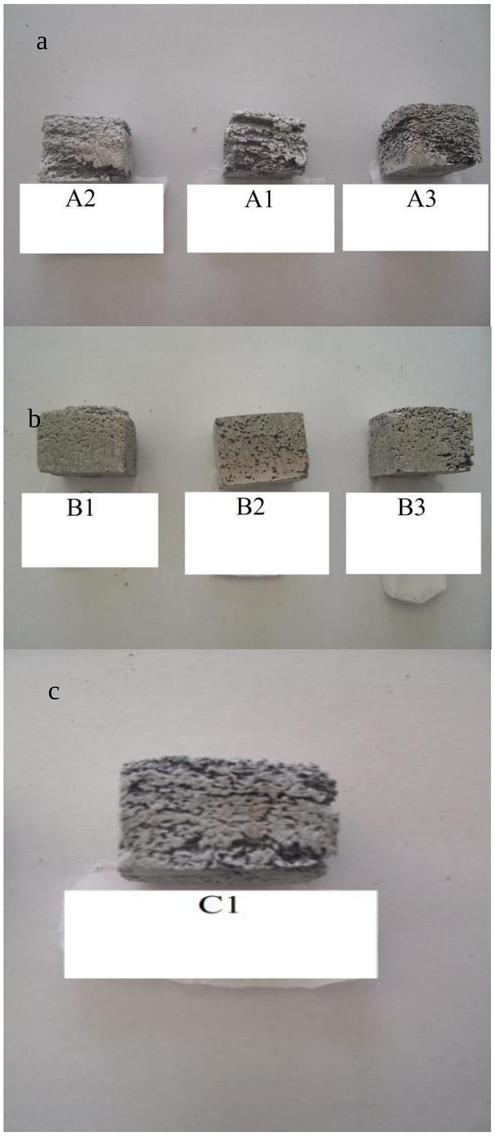

Fig 11: (a) State of Na_2CO_3 containing samples after dissolution step. (b) State of NaCl containing samples after dissolution step. (c) State of Na_2CO_3+NaCl containing samples after dissolution step [19].

J.Banhart et al [20] produced light weight Al foam sandwich structures consisting of Al foam cores and Al face sheets bonded by adhesives by powder metallurgical route of density ranging between 0.60-0.65g/cm^3. The possible application of light weight structures based on Al foams for the hull and super structure of ships was evaluated. Characterized the corrosion behavior of light weight Al foam samples in salt water. It was concluded that the fastening forces were influenced by the thickness of the face sheets and the adhesive used, obtained good results with high strength epoxy resin adhesive. Best results were obtained for glued inserts and the through bolts, where forces up to 20000N could be applied.

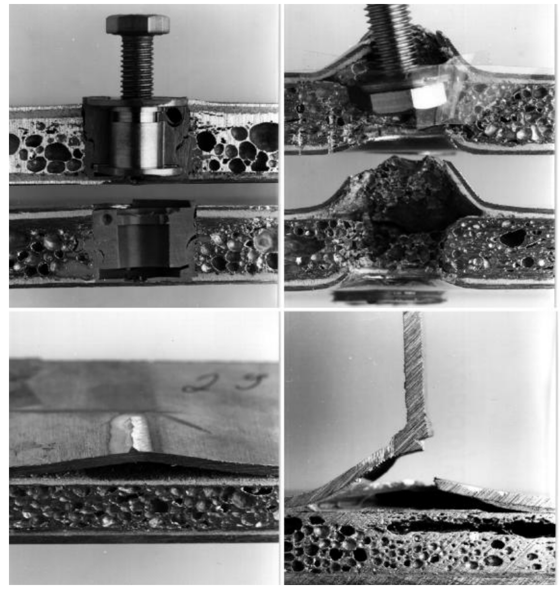

Figure 12: Aluminium foam samples with various fastening elements after testing. Upper part: face sheets 0.8 mm, PU-base adhesive in both cases, left: glued insert M6; right: through bolt, M8; lower part: face sheets 2 mm and welded iron angle in both case. [20]

In [21] By melt-based route using ZrH_2 as a foaming agent CCAF (Closed cell Aluminium foams) were manufactured, obtained porosity of 65%-68% and found uniform pore structure by addition of 1% ZrH_2 and 2.5% ca. Pure Al were melted in a crucible at 1123K and1.5% to3% pure calcium was added as a thickening agent. After reaching the critical viscosity value the foaming agent ranging 0.6% to1.4% mass fraction is added to melt.

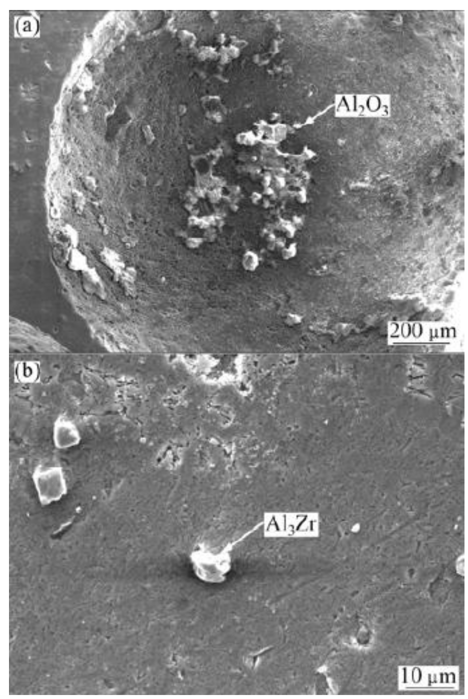

Fig 13: SEM images of CCAF [21].

Spherical carbamide as a space holder aluminum foams were produced by via powder metallurgy route, foam samples with 40–85 vol.% porosity were obtained. Under 330 MPa compacting pressure, sintering temperature and time of 640^{0}C and 2 h, respectively. By adding 1 wt.% Sn and Mg to aluminum powder increased strength of the sintered foams [22].

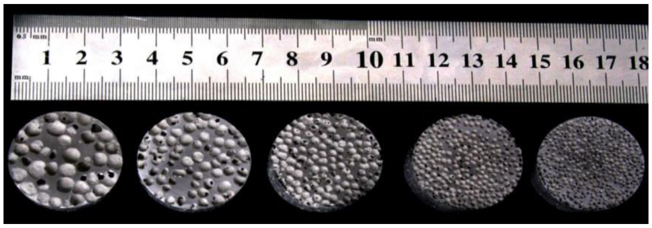

Fig 14: Aluminum foam specimen with different cell size produced by different size of spherical carbamide [22].

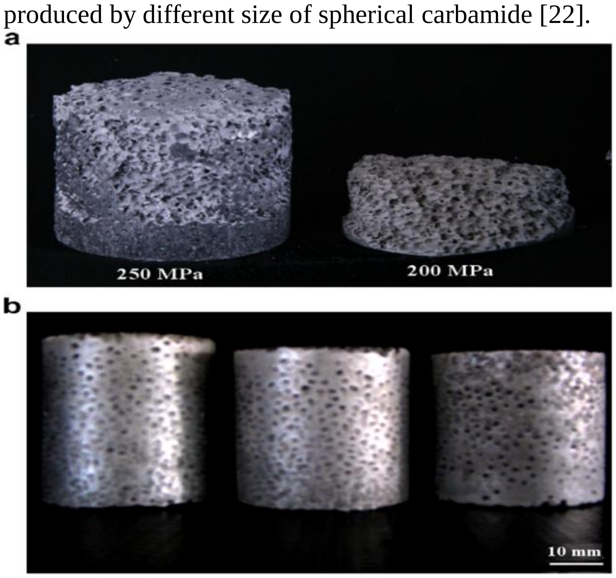

Fig 15: (a) Typical imperfect samples, due to insufficient compacting pressure, and (b) proper samples produced under sufficient pressure [22].

Conclusions:

According to literature 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.
- Metallic foams are structures having a unique distribution of metal into cells filled with gas, which offers an unusual combination of various properties that cannot be achieved with bulk conventional materials.
- Properties of aluminium foams are mainly influenced by apparent density of the foam, and also depend on the shape, size and uniformity of the pore distribution inside the matrix.
- Powder metallurgical route is the best method for producing good quality foams with relative densities as low as 10%.
- Even though different manufacturing techniques of aluminum metallic foams were discussed and many patents filed on this, but commercial production was not in full-fledged scale, the main reasons behind lagging is the difficulty of manufacturability in mass scale and complications in characterization and low cost of production.

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