PROCESSING AND APPLICATION OF ALUMINIUM FOAMS

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WHAT IS FOAM ?

Foam is defined as a uniform dispersion of a gaseous phase in a liquid, separated by a thin film of liquid making a cell or pore. This morphology when preserved in solid state is known as solid foam or cellular solid. When we talk about metal foam, it is understood to have uniformly distributed gas pores in solid metal with volume fraction in the range of 40-98%.

NEED OF METALLIC FOAMS

The motivation behind the development of metal foams is due to their unique combination of physical and mechanical properties such as high stiffness, low specific weight, high gas permeability, low thermal conductivity, unusual acoustic properties, high impact absorption capacity and good electrical insulating properties. The potential applications of metal foams have been envisaged to be in the area of automotive industries, light weight construction materials, silencers, flame arrester, heaters, heat exchangers, catalysts, electrochemical applications, military armour vehicles and aircraft industries. Depending upon the requirements, several metals and alloy foams have been developed in the last three decades, e.g., Al, Al-Si, Al-Mg, Cu, Pb, Fe, Steels, Ni_3Al, Zn, Mg and Ti , Al-Cu, MMCs, metallic glasses etc. Though, a large number of new materials have been processed, only Al-foam has shown tremendous development and also in industrial production. However, seeing the unusual multifunctional properties of metallic foams, research in this area has got a thrust in the recent years in all directions encompassing material and process development, understanding the mechanism of foam formation, finding avenues for wide spread applicability and developing predictive models for foaming process. It is now widely accepted that metal foams have potential of becoming a prime structural material for the next generation of automotive and aerospace products, lightweight construction materials and military armour vehicles.

STRUCTURAL ASPECT OF FOAMS

There are three most common cell structures, namely, open cell structure, closed cell structure and combination of the two. The open cell structure incorporates interconnected pores whereas, in closed cell structure pores are surrounded by a metallic thin wall. Recently, a novel structure known as the lotus-type growth structure has been developed. This morphology consists of a long cylindrical pores aligned in one direction is shown in the Fig. 1.

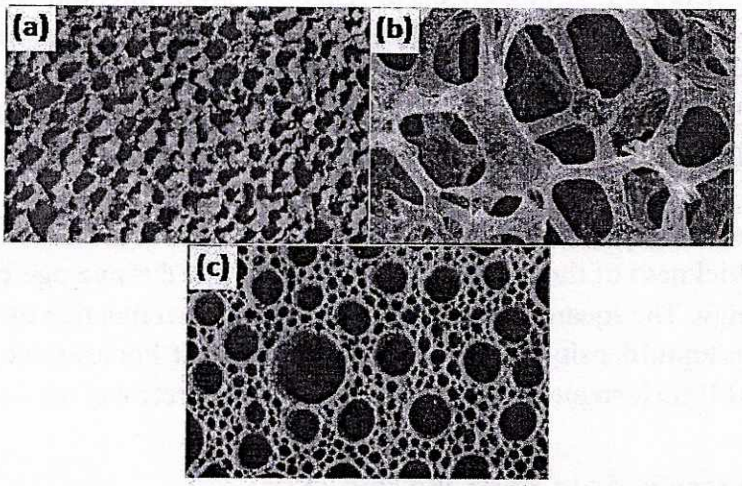

Fig. 1 : Representative structures of (a) closed cell (b) open cell and (c) lotus-type morphologies.

DESCRIPTION OF DIFFERENT STAGES OF FOAM

The detailed description of the foam can be related with the birth, life and death. This can be said with an instance that the foaming process creates gas-liquid mixture (birth stage), peruse a life of gradual evolution (life stage) and then finally collapses as thin film ruptures spontaneously (death stage). In other words, the complete foaming process is concerned with (1) foam inception or genesis where blowing agent decomposes (2) the evolution and growth of spherical pores (3) further foaming leads to thinning of cell wall and thus, change of pore shape from spherical to polygonal and (4) pore coalescence due to surface tension and gravitational pull. This means the eventful life of foams comprises birth, life and death. Our aim is to avoid the death or collapse of foam during the processing. The main convict for the death of foam is the instability of cell walls under the pressure differences due to surface tension of liquid or gravity. The death or collapse of foam occurs at the peak of third and start of the fourth step. All three stages of its existence can be utilised for studying the eventful life of the foam. In this there is always some role for drainage, which is the transport of the liquid through the foam, driven by pressure differences of gravity. In normal gravity it quickly reduces wet foam to dry one, with less than a percent of liquid. In disordered foam, the gas in each cell has a different pressure and so the gas diffuses through thin films, which constitute the cell walls. In this way the foam structure changes and coarsens as cells are continually eliminated. This process, which is quite slow, is punctuated by sudden topological changes. They also play a key role in the deformation and flow of the foam under stress. The basic properties that determine the key parameters regarding the effects of drainage and coarsening upon each other are surface tension and liquid viscosity. Non-linear effects in surface tension and surface effects in viscosity may be important but the elementary model can describe structure, coarsening and drainage. Faster time scales should be confronted, as quasi- static models do not apply. As a result, wet foams remain largely unexplored, because the natural starting point is wet foam in equilibrium, and drainage prevents us from making such a system in normal gravity. Only very close to the underlying foam wet, i.e. with a liquid fraction of more than say 15% (slightly less than half of the volume in equilibrium). There is an approximate thumb rule that whenever the foam is in contact with the underlying liquid in equilibrium the thickness of the foam layer $= lo^2/d$, where, d = average bubble diameter, lo = capillarity length. The squared capillarity length is the usual function of $\sigma/\rho g$, where σ is surface tension, ρ is liquid density and g is gravitational constant. For example, both lo and d are often of the order of 1 mm for aqueous foams, in which case the wet foam consists of only a single layer of bubbles.

BLOWING AGENTS FOR ALUMINIUM FOAMS

Usually for aluminium foams the blowing agents used are titanium hydride (TiH_2) and zirconium Hydride (ZrH_2). But in most cases TiH_2 is used for the foaming of aluminium. The role of foaming agent is that it entrapped in the metal matrix after densification builds up an internal gas pressure upon heating of the compacts and leads to foam formation. Titanium hydride has been chosen to be the best blowing agent for aluminium alloys because strong hydrogen release takes place between 400°C to 600°C which coincides well with the melting point of aluminium (660°C). Titanium hydride has been characterised by the thermal analysis to characterise their decomposition temperature and to derive their suitability for foaming.

PROCESSING ROUTE OF METAL FOAMS

The basic aim of foam processing is to incorporate large size and uniformly distributed gas pores in the metallic materials. This can be accomplished by several routes, which are summarised in Fig. 2. The figure indicates the possibility of producing metallic foams in two materials states: liquid metal and powdered metal. The external gas source signifies that the melt is foamed with the help of injection of gases such as air, nitrogen or argon directly into the melt. However, utmost precaution in the gas flow rate, bubble formation frequency and solidification rate is necessary to effect uniform distribution of pores. The gas source from a blowing/foaming agent implies their incorporation in a high viscosity melt to effect foaming or mixing a blowing agent with metal powder followed by compaction, sintering and foaming. In these processes high temperature exposure of foaming agent leads to gas formation, which, in turn, results in expansion of liquid/semi-liquid metal. There are some other processing routes such as gas entrapment,

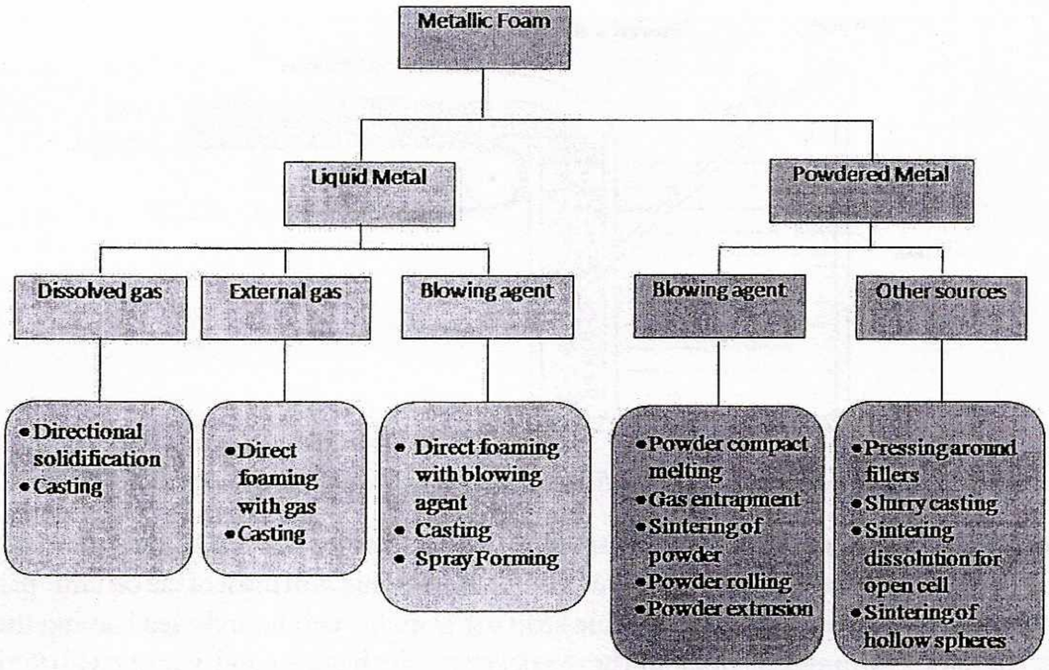

Fig. 2 : A processing tree for metallic foams

hollow sphere sintering, slurry or slip casting, sintering dissolution technique and by using powder around filler materials. All these techniques give variable performance of the foamed materials in terms of pore size and size distribution, density and mechanical properties.

Liquid state processing

The liquid state foaming involves three different gas sources: external gas source, gases generated by some foaming agent and dissolved gases.

External gas source

The principle behind this process is blowing of liquid metal by gases and to ascertain uniform distribution of large size gas pores in the liquid metal. This is accomplished by creating very fine gas bubbles in the melt via especially designed rotating impellers as shown in Fig. 3. However, the stability of foamed structure is an important factor.

The movement of gas bubbles in the liquid becomes relatively easy when the liquid melt viscosity is very low, and the bubbles segregate and coalesce together giving rise to large pores. Keeping this in view melt viscosity is enhanced by incorporating some second phase ceramic particles e.g. SiC, Al_2O_3 or MgO. As the incorporation of ceramic particles in the liquid metal depends on several factors, the first step in this kind of processing is to make metal matrix composite followed

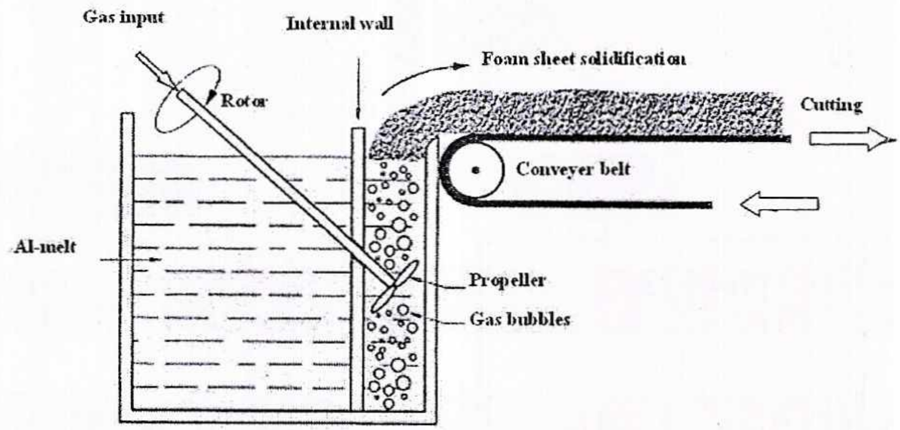

Fig. 3 : A schematic showing direct foaming of liquid melt by gas injection

by gas injection. The stabilization of foamed structure obtained via this route is derived from the presence of particles in the cell wall. Due to high contact angles of most of the ceramic particles with Al melt, there are chances of particle strip off from the cell boundaries leaving the wall weak. Therefore, the imperative should be to select particles having good wetting with the liquid metal so that the particles are not stripped off the cell wall. A very low contact angle also does not give stabilization effect. The volume fraction of the particles may range from 10-20% with a mean particle size of 5-10 μm. However, the size and fraction of particles for a good foaming has been empirically established as shown in Fig. 4. On the one hand, particles smaller than 1 μm are difficult to mix, and on the other hand particles more than 20μm leads to severe particle settling. A low volume fraction does not stabilize the foam, whereas, a high fraction of particles

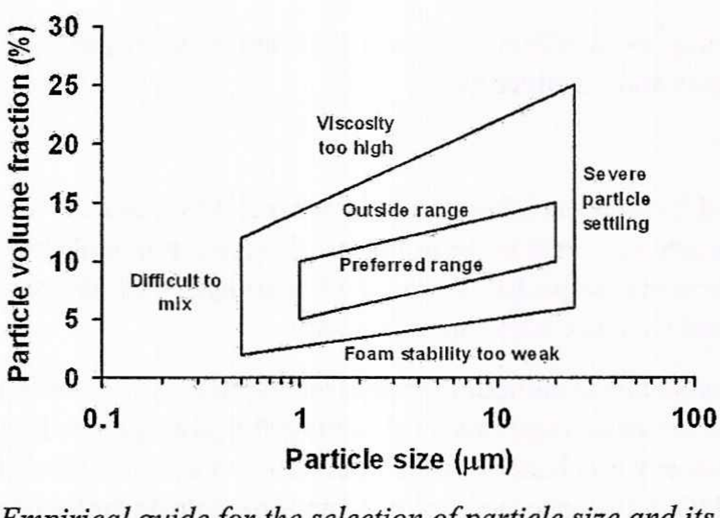

Fig. 4 : Empirical guide for the selection of particle size and its content for foaming MMC melt

culminates into high viscosity leading to a difficulty in gas injection. This technique has been extensively used for foaming Al and its alloys and porosities in the range of 80-95% with 3-25 mm cell size have been realized. The process is very effective in producing large size foams continuously; however, the presence of ceramic particle leads to difficulty in machining due to high hardness and brittle behavior of foams. To avoid these disadvantages, it is suggested that foaming should be carried out in a melt, without second phase particles, very close to its liquidus temperature with an arrangement to continuously cool the liquid metal during bubbling. This helps in keeping the viscosity of the melt at low level.

Blowing agent as gas source

Direct foaming

As an alternative to the direct foaming of melt by external gas source, a blowing agent can be added to a viscous melt which decomposes on heating and releases gas leading to foaming process. In this processing route also, the enhancement of melt viscosity is a prime requirement, which can be accomplished by the incorporation of calcium, ceramic reinforcements, aluminium dross, metallic viscosity-enhancing additives and manganese dioxide etc. A schematic of the process is shown in Fig. 5. For example, Ca addition to Al melt forms oxides and intermetallics (CaO,

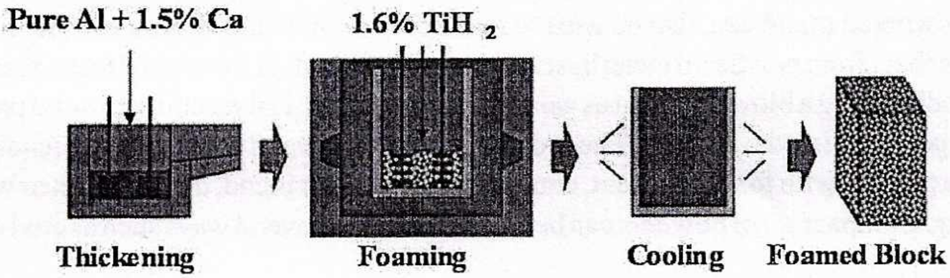

Fig. 5 : Processing steps involved in liquid melt foaming with a blowing agent.

$CaAl_2O_4$ and Al_4Ca), which increases the viscosity by thickening the melt. To achieve high viscosity of the melt (6-7x10^{-3} Pa.s), a continuous stirring for up to 8-12 min is required for calcium content of 1.8 wt%. The process is carried out by melting Al in a crucible followed by addition of about 1.5-3.0 wt% Ca. Subsequently, the melt is stirred and a blowing agent (namely, 1.6 wt% TiH_2 for Al) is added. The blowing agent releases hydrogen gas under the influence of hot viscous liquid, leading to gradual foaming of the melt. A careful control of the process parameters such as temperature uniformity of the melt, viscosity and distribution of TiH_2 particles give rise to homogeneous foam structure. The foaming is generally carried out at 680-720°C. Instead of TiH_2, ZrH_2 (0.5-0.6 wt%) can also be used for the production of Al foam with a temperature preferably between 670-700°C. In some cases, it becomes difficult to mix blowing agent in the liquid metal as it decomposes very fast at the liquidus temperature. To avoid such as situation, a low melting point precursor e.g., Al-Si, Al-Cu or Al-Mg, with eutectic composition is prepared with dispersion of blowing agent without decomposition and subsequently added in the high temperature melting liquid in the second stage. The second foaming step, therefore, becomes easy to control the foam structure.

Dissolved gas sources

In general, gases are dissolved in liquid metal depending upon the temperature and externally applied pressure for example, H_2 in Al, Fe and Cu, N_2 in Fe, and O_2 in Ag and Cu. Such metals with absorbed gases in liquid state eventually undergo an eutectic reaction, to a two-phase system (gas + liquid), as the temperature is lowered. A coordinated effort to entrap the gas during solidification leads to porous structure. It is generally carried out by directionally solidifying the gas saturated liquid with a controlled cooling, proper external pressure (usually of the order of gas partial pressure at a particular temperature) and solidification velocity. The process parameters have to be chosen such that the gas bubbles do not float on the surface of the melt but remain near the solidification zone and get entrapped in the solid.

Powdered metal processing

In the above section, foaming of metallic materials in liquid state has been discussed. However, solid powdered metal can also be used to make cellular metallic structures. The formation of metallic foam from powdered metal has been extensively studied. Powdered metal foamed mainly prepared by using a blowing agent as gas source where chemical reactions or solid parts are used to give pores during the process. The process comprises several steps such as blending of metal or alloy powder with foaming agent, compaction of powder blend, deformation or working and foaming. Compaction of powders can be accomplished in several ways such as cold compaction

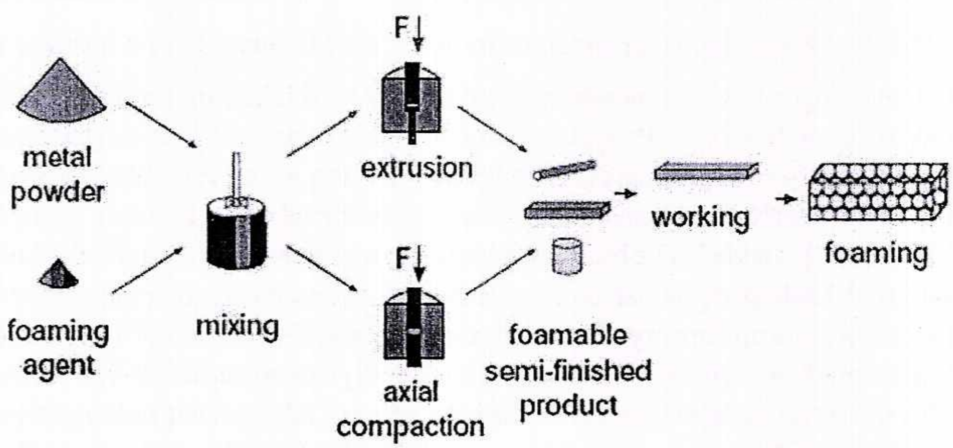

Fig. 6 : Schematic diagram of powdered metal processing route for Al-foam

followed by sintering, hot pressing, and powder rolling and powder extrusion. The fundamental aim of all such processing up to foaming step is to form a highly dense foamable precursor with uniform distribution of embedded blowing agent and without any notable residual open porosity. The foamable precursor is subsequently heated to just below the melting point of the matrix material to effect foaming process. A schematic diagram of the process is shown in Fig. 6. As the temperature is increased, the blowing agent decomposes releasing gas, which in turn leads to expansion of the highly soft matrix metal. The selection of foaming agent depends upon the sintering and melting temperature of the matrix material. The decomposition rate, heating rate and the stability of cell wall structure determines the final density of foam produced. To delay the decomposition of foaming agent some heat treatments are given to it so that decomposition and melting takes place simultaneously. This way a uniform foam structure can be developed. The heating rate of the sample during foaming plays an important role in determining the size and distribution of pores. A relatively high heating rate leads to smaller pore size with increased pore number density, whereas, a slow heating results in larger size pore and the final foam density is higher. This work has been carried out on Al-6.5Si (wt%) alloy with TiH_2 as foaming agent. The present authors have also tried the same composition by powder rolling technique. The foam structures obtained from these experiments are shown in Fig. 7.

APPLICATION OF ALUMINIUM FOAMS

There are many possible applications for metallic foams ranging from automotive industry, aerospace, light weight construction, sound and heat insulation to energy absorption applications. The use of foams can satisfy the demand for light-weight parts of several branches of industry. Compared to synthetic materials (plastics, PUR-foams), which are also light weight, Al-foams have special advantages; like good heat resistance, a higher strength, the incombustibility and the possibility for an easy recycling. The environmental concerns and the social pressures forced

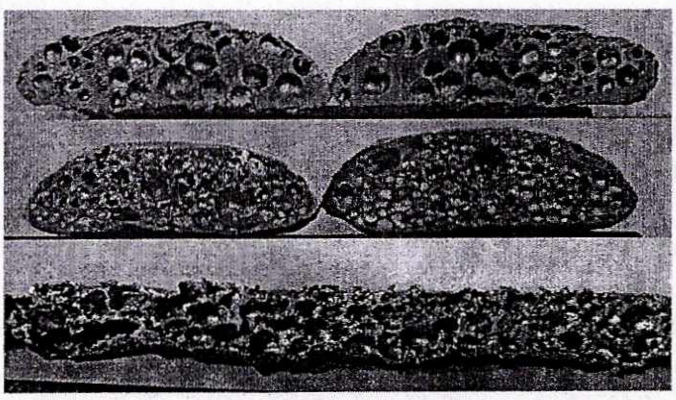

Fig. 7 : Aluminium foams developed at NML (Jamshedpur, India) by PM route (a) slow heating rate (b) high heating rate and (c) by powder rolling technique at high heating rate

the automotive manufactures to go towards the weight reduction in vehicles. Another requirement is the improvement in passenger safety of cars, which is mainly influenced by the choice of materials and the car design. Three main applications of metallic foams can become important in a car energy absorption, lightweight construction and insulation. In the area of energy absorption, the crash absorption against side and frontal impact may be considered. The good relation between weight and stiffness supports the use of foams for large area light-weight automobile body sheets and structural parts that are used in areas of the cars with increased requirements on stability (e.g., trunk lids, engine hoods and sliding roofs). The sound absorbing properties make foams useful for a sound insulating covering of the engine compartments of cars. In the aerospace application Al-foam sheets or sandwich panels could replace the expensive honeycomb structures. Building and construction applications are good possibilities for the use of Al-foams mainly because of their good fire penetration resistance and thermal insulation properties. In the area of household and furniture industry it can be used for lamps, tables or household articles and accessories.

FUTURE PROSPECTS AND CHALLENGES

The strength and weight saving by using Al foams are currently believed to be insufficient for critical areas of applications. Therefore, recently, tremendous efforts are directed towards steel foam developments which, in principle, can have several potential advantages over aluminium foams such as increased strength and specific stiffness, lower raw material cost, higher melting temperature and compatibility with steel structures. Initial developments in the processing of steel foams have already been done by conventional powder metallurgical routes, and also by space holding techniques. However, for the commercial production of steel foams, one has to go a long way as the high operating temperature and the low viscosity of liquid steels are the major challenges to overcome. The amorphous foams are seen to have promising prospects in applications such as sporting goods and cellular telephone housings due to their high strength, high elastic strain and high wear and corrosion resistance. Despite the current developments and future possibilities in processing and applications of metallic foams, there are several limitations, which has to be considered and addressed so as to open new avenues for the metallic foams. The first and the foremost hindrance in the wide applicability of metallic foams is the cost of production. The second concern is the variability in the materials and the large scatter in measured properties. And also, reliable test methods have to be invented to fully exploit the potential of these cellular materials. World-wide efforts are being made to model mechanical behaviour of metallic foams and researchers are, to some extent, successful in predicting the same. However, theoretical and numerical models related to the processing of metal foams are not available, which could be useful in predicting the effect of process parameters. The developmental process could be made faster by making process models, otherwise 'trial and error" would be the only way. The lack of process models is due to the fact that the mechanism of foaming process is still not fully understood. All these aspects of metallic foam development have restricted the industries only in niche areas, whereas, prior to undertaking wide spread commercial production these challenges have to be overcome. Further, large structures of metallic foams can be built only by joining bare foams or sandwich structures. However, currently, joining metal foams is a big challenge as the foam structure is difficult to keep the foam morphology intact at the joints.

CONCLUDING REMARKS

Though, the foam has high potential for various applications but there uses are limited mainly due to its cost and lack of uniformities in properties. But it is expected that the price of foams will decrease in the coming years as the volume production increases. Recent technological advances in the field of metallic foams have led to the development of a wide range of processing techniques for the open as well as closed cell morphologies. The processing route has to be decided on the basis of the cost of production, materials properties and the intended applications of the final product. Foams of new classes of materials such as high temperature melting materials, superalloys, steels, bulk metallic glasses etc are seeing tremendous application opportunities in the near future.