State-of-the-Art Manufacturing of Metal Foams and Processing—A Review

A. Changdar and S. S. Chakraborty

Abstract Metal foam recently has grabbed a significant amount of interest due to its promising prospects in fulfilling the crisis led by steel and its counterparts. The recent studies indicated commercialization of metal foam which is disrupted mainly because of high cost and lack of design knowledge. Industries had expressed the need of more detailed studies, in order to the amicability of the material to machining, joining and other manufacturing processes. Thus, this article, in brief, clubs all the major processing routes of metal foams along with their limitations. It also discusses how secondary processing methods can contribute in tailoring metal foam for different applications. The article shall help future researchers to bridge the existing gaps which restricts metal foam utility in concerned industries.

Keywords Metal foam · Lightweight structure · Shaping metal foam · Manufacturing metal foam · Processing metal foam

1 Introduction

Metal foams are cellular materials, wherein voids are introduced in a solid base metal, to acquire desired properties. With time, the material emerged as a potential solution for various applications due to its low density coupled with extraordinary mechanical, structural and physical properties [1]. They are porous cellular structure containing air voids within the solid base metal. The material displays high strength-to-weight ratio and potential to absorb shock and noise. The structural reaction of these materials remains same under compressive loads, because the material exhibits plateau stress under such loads. Its potential of acoustic absorption makes it ideal for soundproof construction. The material is also ideal for heat exchangers owing to its substantial surface area and higher cell wall conduction. To have such a unique combination of features within a single conventional material seems non-viable [2, 3]. With time, the material has emerged as a potential solution for various structural and

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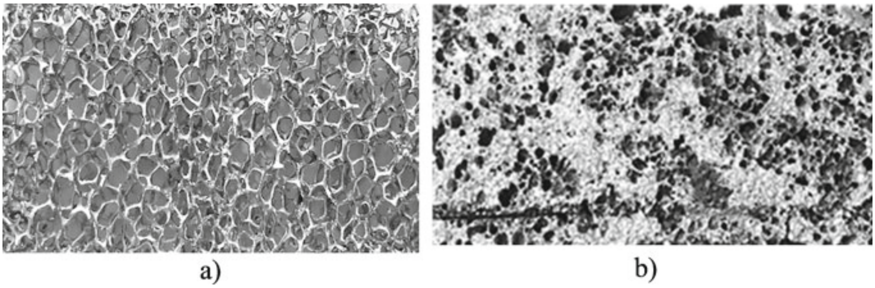

Fig. 1 **a** Open cell metal foam, **b** closed cell metal foam

functional applications. Aluminium-based metal foams out of the rest were exploited the most, and its utilization is expected to rise in near future [4, 5].

The material is classified based on its cellular topology as shown in Fig. 1, and most of its significant properties depend on the same. Foams in which cells are interconnected are known as open cell, whereas when the cells are separated by distinct cell wall, it is known as closed cell [3]. The understanding of the classification is significant as it determines the kind of application, a metal foam is suited for. ASTM standard D2662 quantifies the porosity percentage of closed cell and open cell foams. Closed cell metal foams owing to its lightweight and high stiffness are ideal for structural applications. However, open cell foams due its reticulated structure and larger surface area are mostly applicable in functional areas, like filters and heat exchangers.

Metallic foams exhibit a certain number of unique properties, difficult to obtain using other materials. The structural properties of these materials are of great significance, and its uniqueness lies in the stress–strain response mainly under compression. These materials do not display catastrophic failure, when under deformation. Instead, the material exhibits plateau stress under compressive deformation, because of cell collapse and densification. The reason behind such deformation behaviour is owing to the fact that elastic modulus due to cell collapse obtained during initial loading is less than the actual elastic modulus (E). Apart from this, the deformation characteristics of these materials also depend on the relative density and the ductility of the base metal.

Instead of such wide bandwidth of prospective applications, several factors exist, which can challenge the usability and market growth of aluminium metal foams and its sandwich panels (Banhart et al. 2017). A recent survey suggested, the two major reason which restricts the widespread application of these materials are high cost and a lack of design knowledge. The survey also suggested for increase in literature investigating the amicability of the material to machining and joining process [6, 7]. Growth of aviation and automotive industries has been very prominent due to rapid urbanization and globalization of late. These industries mostly rely on metals and alloys for manufacturing components. The recent tendency of these industries to reduce material weight from their value chains has led to the advent of many

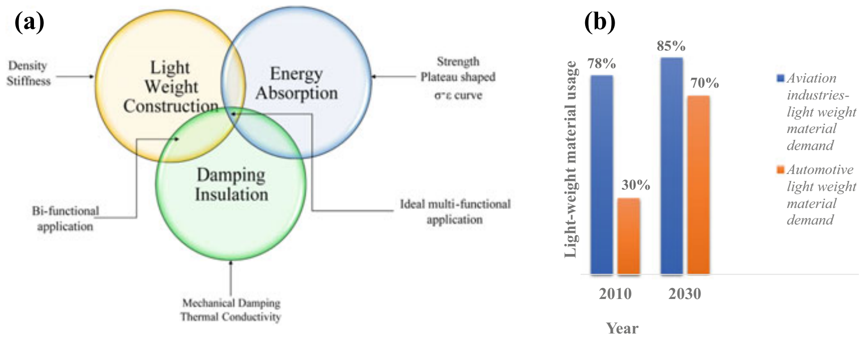

Fig. 2 **a** Multiple applications of metallic foam, **b** survey result on lightweight material usage of aviation and automotive industries

lightweight materials. The current design intent of most industries is biased towards the use of lightweight materials with a wide span of properties. Metal foam, thus stands out to be an ideal material of choice for such industries due its multifunctional capabilities as shown Fig. 2a. Market reports suggest usage of lightweight material share for aviation industries may increase by 10%. However, in automotive industries: a rise up to 70% in 2030 is expected as shown in Fig. 2b. Thus, it is very important to reduce the existing knowledge gap between these materials and industries, in order to scale up its industrial adoption and usability.

Currently, existing processing methods lack the potential to generate parts tailored to industrial requirement. Thus, a more economical way is to process metal foam in bulk in generic shapes like slabs and plates, using available processing methods. Subsequently, the material in their generic form is shaped as desired by introducing a secondary manufacturing process route like forming, welding or cutting. But undergoing conventional manufacturing processes stand out to be challenging for these materials due to their fragility under tensile stresses, and several alternative secondary manufacturing processes like laser or thermal forming of these materials are gaining popularity. Therefore, it can be well-anticipated that a proper process route definition in order to generate practical parts and components out of these materials is of great significance. Currently, several literatures exist enveloping process mechanisms and applications of the material. But a single article confronting all the process routes along with its limitations and describing the possible secondary manufacturing process routes hardly exists.

Henceforth, this article clubs the major processing routes of metal foams along with their limitations. As the properties of metal foam mostly depends on its structure, a reliable fabrication process for continuous production is of prior importance. Unavailability of such a process is the major drawback of the material and thus imposes limitations to its full-fledged industrial adoption [1, 3]. The article also discusses the further processing methods of metal foams, which includes forming, welding and cutting. These processes are quite significant when it comes to tailoring of foam/foam sandwich as per desired application. When a foam core is covered with the sheet of the similar material at top and bottom, it makes a foam sandwich.

2 Processing Methodologies of Metal Foam

Though metal foam's widespread application was realized very recently, the history of metal foam dates back to twentieth century. Since then, the methodologies and materials used for processing of foam underwent many adaptations, as proclaimed in the existing literature. With advancement of technologies and to obtain tailored to application properties, fabrication of metal foams has evolved to next level. Irrespective of ongoing advances, extensive adoption of metal foam is impeded due to inadequacy of production methodologies to process variety of materials in highly effective and economical method [8–10]. The current advancements in processing approaches are quite convincing and certainly show a promise to conquer the existing hindrances in the way of widespread acceptance of metal foam. An exhaustive representation of processing methodologies on porous material is shown in Fig. 3.

2.1 Liquid-State Foaming Methods

In liquid-state processing, porosity is introduced in a liquid or semi-solid metal matrix. Currently, this method is widely used for commercial production owing to its higher foaming rate and capabilities to produce greater volume of porous material.

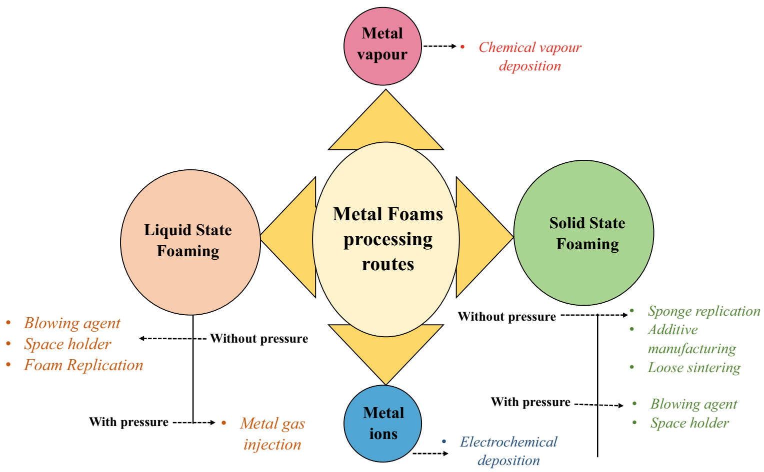

Fig. 3 Processing routes of metal foams

Liquid-state foaming being a traditional method has been studied a lot and detailed understanding of the process can be found in adequate literature. The liquid-state foaming is usually classified as, direct and indirect foaming [10–12] (Tianjian 2002).

Direct foaming methods
The method is achieved by direct introduction of either, a gas (air, nitrogen or argon) or any secondary substance (TiH_2, ZrH_2, MgH_2, $CaCO_3$, etc.) in to the melt pool. Introducing of secondary substance in molten metal matrix is also known as foaming by phase decomposition. The process is achieved by heating the secondary substance in the melt above its decomposition temperature as to evolve gas. In both cases, gas bubbles are formed on the surface of the melt, which are captured and cooled to create voids. CYMAT, a Canada-based company, and HYDRO ALUMINIUM in Norway use direct gas injection method; whereas, Shinko-wire, a Japan-based company, uses phase decomposition method for manufacturing of closed cell aluminium foam. Aluminium foams of Shinko-wire are popularly known as ALPORAS. Both methods are capable of processing close cell aluminium foam with a relative density ranging from 0.04 to 0.4 and cell size varying between 0.5 and 15 mm. The process can be advantageous, as it is capable of producing large volumes of foam along with reduced densities consistently. Foams resulting from these methods are thus probably less expensive compared to other porous materials. The ultimate necessity for cutting off the foam is a disadvantage of this sort of processing technique as it leads to opening of the cells. Additionally, due to the addition of silicon carbide, aluminium oxide or magnesium oxide particles in the melt for enhancing the viscosity lead to the brittleness of the gas injected foam. Reinforcement of ceramic particles within cell wall is one of the complications which is not desired. In order to avoid the effects of additives into melts, foaming of pure metallic melts with gases was suggested. The foaming process is usually established at temperatures near to melting point, as to maintain a uniform viscosity. This is sometimes carried out by bubbling gas through a melt that can be chilled down at a continuous casting process. Further, a foam like structure is formed, by capturing the bubbles in the solidifying molten metal liquid. To circumvent the disadvantages mentioned, foam processing went biased towards indirect foaming in which molten metal is not directly foamed rather they are processed by investment casting [11, 13–15].

Indirect foaming methods
In case of indirect foaming methods, molten metal is not directly foamed. One of the known processing is investment casting using a polymer foam. Polymer foam like polyurethane is employed initially. Polymer foam needs to be converted into an open cell type with reticulation therapy in case it is closed cell type primarily. Further, the polymer foam is filled with adequate substances like easy plaster, mullite or phenolic resin in the form of slurry. The plastic foam is later removed by thermal treatment once the plastic foam has been properly cured and is cast into the consequent open voids to replicate cellular arrangement of the primary polymer foam. After eliminating the mould material, metallic foam is obtained that is a precise replica of the initial polymer foam. ERG company as already described previously manufactured

metallic foams using this method known as DUOCEL. Advantages of this process include fabrication of complex shaped foam structures by preforming the polymer foam. The sense of controlled manufacturing is predominant in this method as the pore morphology and density of the metallic foam is determined by polymer foam precursor. Other than aluminium, this process is also capable of producing foams of copper and magnesium which certainly make this process more reliable compared to direct foaming process. Indirect foaming can also be established, by casting molten metal around hollow spheres of low density, and the same can also be done using organic and inorganic granules. The vice versa of the aforementioned method is also possible, wherein the granules are either washed away using proper treatment after casting or are allowed to remain within the cast as to form syntactic foam. This process is also capable of processing diversified materials like aluminium, magnesium, zinc, lead and tin. Mould as desired can be designed as to obtain functional shaped metal foam and porosity up to 98%. Osprey process is another method of liquid-state processing also known as spray forming. This process allows processing of different distinct metals and alloys. Metallic melt is atomized, and a spray of fast flying little metal droplets is made. The resulting droplets are collected to create a dense deposit on a substrate. The process results in formation of dense deposit in generic shapes like billet and sheet. The materials usually exhibit low oxide content with better grain size [11, 13]. Some of the examples of metal foams produced by various liquid-state processes are illustrated in Fig. 4.

Fraunhofer processing method developed at Fraunhofer Institute, Germany, follows powder metallurgical route for development of metal foam. The processing technique involves heating of foaming agent and metal powder mixture at a temperature exceeding melting temperature of the base metal, hence, it can be categorized under liquid-state foaming. The manufacturing process starts with the mixing of metal dyes: basic metallic powder or metallic powder mixes using a blowing agent, and the mixture is compacted to produce a compact, semi-finished item. In principle, the compaction could be carried out by any method that makes sure that the blowing agent is inserted into the metallic matrix with no previously occurring porosities. Selection of the compaction technique (hot uniaxial or isostatic compression, pole extrusion or powder rolling) is dependent upon the necessary form of the precursor substance. The production of this precursor needs to be performed very carefully since any remaining porosity or other flaws will cause bad results in additional processing. The precursor is further heated to temperatures comparable to melting point of the base metal as a result blowing agent start decomposing. The released gas as a result starts expanding the precursor material which consequently results in formation of metallic foam. The foaming agent depends on the sintering and melting temperature of matrix material. For example, TiH_2 and ZrH_2 are used to foam Al and Zn, respectively, $MgCO_3$ and $SrCO_3$ can be used for foaming steels, $BaCO_3$ for copper, and $PbCO_3 \cdot Pb\ (OH)_2$ and MgH_2 for Pb. The decomposition speed, heating rate and also the firmness of cell wall construction ascertain the final density of the foam generated. This method occasionally also includes heating of the compacted metal powder mixture with additives as to activate exothermic reaction to melt the mix. Overall, the process is very flexible and versatile and can foam a wide range of

Fig. 4 Examples of metallic foams processed by liquid-state processes

materials in near net shape. Proper selection of blowing agent and process parameters allows foaming several metals like aluminium, aluminium base alloys, tin, zinc and brass. On more judicious selection of parameters materials like, lead and gold can also be foamed. Aluminium foams processed using the method are termed as "Foaminal" and "Alulight". More detailed understanding of liquid-state processing is described in several literatures with its current applications and state-of-the-art innovations [8, 9] (Banhart 2013).

Liquid-state forming with progression of time has evolved a lot and even gained capabilities of processing near net shape products. Aluminium foams are the most commercialized product of these processes. However, processing foams of other materials using these processes hardly crossed the prototype stage. Even processing aluminium foams with virtue of these processes faces many challenges, and aluminium melt being less viscous needs to be stabilized using various additives as to ensure porosity. Additives like BaO_3, SiO_2, SiC, Ca and Al_2O_3 along with some other materials are added in the melt to manipulate the surface tension and decrease the viscosity to obtain desired morphology of the foam. Though powder metallurgical replication process by Fraunhofer exhibits a prominent promise but high production cost and limited commercialization has certainly been the barrier to its extensive growth. Owing to fact that metal foam still lacks widespread commercialization, development of more reliable processing techniques is still a research issue of many organizations. Certainly, just the development of processes at laboratory scale is not going to solve the issue. Certain surveys clearly illustrate conquering the psychological constraints will also play a key role in extensive acceptance of these material [14, 15].

2.2 Solid-State Foaming Processes

Potential crisis of liquid-state foaming has led to the inception of solid-state foaming techniques. Solid-state processing involves introducing porosity into a solid metal using advanced techniques like additive manufacturing and vapour deposition method. Though solid-state processing is new but it is quite flexible when it comes to foaming of wide range of metals which apparently is challenging using liquid-state processing. With solid-state processing, control over manipulating pore size and relative density of metal foam is easier to achieve, assuring better quality of products in terms of functionalities. As mentioned by Atwater et al. [13], solid-state foaming can be defined as those processes which create metal foams in such a way that the processing temperature remains within the melting temperature of the base metal. The processing of metal foam using this process is done either by introducing a blowing agent directly into the blended solid metal or by integrating metal powder around a pre-processed temporary template having voids. Metal powder is either compacted, sintered or electro-deposited on the templates. The porosity developed as a result of first method is known as intrinsic porosity, whereas the latter is known as extrinsic porosity [13] (Banhart and Seelinger 2006).

The extrinsic porosity methods are quite similar to the liquid-state foaming techniques but the operating temperatures are below the melting point of the matrix metal. Loose powder sintering is a kind of solid-state processing and is done by using a sacrificial template mostly with few exceptions. Most commonly used sacrificial template method includes scaffold technique and space holder technique. Both of these processes can again be subdivided depending on the processing conditions. In scaffold technique, metal powder is introduced in porous polymer foam by adopting methods like coating, deposition or by mixing the metal with an expandable precursor also known as in situ foaming (Banhart and Seelinger 2006).

Grumman et al. [16] in their work have exhibited how metal coating can be used for creating foam out of Ni–Ti shape memory alloy. Metal powder mixed with suitable binders was used for coating a polymer foam with pre-defined pore sizes followed by sintering. Once the required strength is achieved, binders and the polymer foam were removed thermally. Yang et al. [17] also adopted the same method for processing foam out of Tantalum (Ta) particles by coating polyurethane foam with Ta powder and PVA binder mix. Prior to sintering Ta at 1950 °C, the polymer and binders were eliminated at a temperature of about 300 °C. The process is very adaptable in terms of materials but decreasing pore size can be a challenge as smaller pores restricts flow of metal in and out of the sacrificial pattern. Deposition of metal powders on the sacrificial foam is usually done using two routes, one of which is chemical vapour deposition (CVD) and is currently used commercially. International Nickel Company (Inco) currently a subsidiary of Brazilian mining company, Vale, developed Ni foam INCOFOAM using CVD at large scale. The process utilizes Ni carbonyl ($Ni(CO)_4$), which is heated under vacuum to modest temperature, where it decomposes and provides Ni vapour to coat the substrate. The porosity can be controlled with a single template geometry by varying the deposition amount, ranging from 74 to 98% and being comprised of pores from 450 to 3200 micron [13]. The other method of deposition is electroplating but sacrificial foam being non-conductive electro-less plating is used for deposition. Electro-less plating has been successfully utilized for Ni material and few literatures report Cu too. There is always a chance of oxidation while removing the precursor material using deposition method. Hence, the process of removal should be done under vacuum or else a suitable heating range should be adopted as to avoid formation of gaseous bye products. Excessive gas products can result fracturing of metallic shells. In case of in situ foaming, blending of polymer and metallic phase is done before foaming. This process is established by mixing polyurethane precursors with metal powders and letting the mixture to react to form bubbles or additional heat is provided to instigate the reaction [13]. Gauthier et al. [18] and Xie and Evans [19] used this process to foam Ni and Cu, respectively. This process has also been used for processing Ti and Fe foams with nearly 90% porosity. Again, this process too faces the challenges in terms scaffold removal, and many studies have elaborated the proper hierarchy to be followed as to remove the precursor material properly. The intricacies involved make the process very challenging for mass production or batch production. To maintain a suitable production rate, multiple parts should be produced at the same time using this process [13].

In space holder method, metal powder is blended with space holding materials like hollow polymer spheres, ceramic particles, grains of polymer, metals or salts which is removed later to create pores. The physical properties of the space holding material like shape and size along with its volume fraction in the mixture determine the properties of the resultant foam. The mixture is compacted in room temperature or at higher temperature if the material is heat resistant, for better compaction and to initialize the sintering process. The space holder material is either kept as a secondary phase in the final structure to create Syntactic foam, or else it is removed using vaporization or dissolution methods. Dissolution methods are common when the used space holding material is capable of dissolving in an appropriate solvent. NaCl is one such material which can be dissolved and removed. The method is convenient with open cell structure as it is easier for solvent material to flow through it. Vaporization method follows removal of space holder material thermally. The added advantage of the process is removal of the template material and porous metal sintering is combined in one step [13]. Freeze casting method is another template-based foaming method recently applied to metal foam processing. The method involves formation of a slurry of fine nanoscale particles of selected metal using a binder and dispersant in water or other liquid that is appropriate, for example camphene. The mix goes through freeze casted and then dried for a certain time period (24–48 h), and the binder is burned out subsequently. The particles are either sintered or reduced under hydrogen after removal of binder. The process is in its early stages has been applied on diverse range of materials like tungsten, copper, nickel, titanium and iron. Porosity up to 75% can be achieved and foam morphologies can be controlled by selection of proper process parameters. Another method is to sinter hollow metal spheres together to form porous structures. The metallic spheres are either obtained by electro-deposition or chemical deposition of an individual metal onto polymer spheres that are eliminated in a next step, or from coating polymer spheres (e.g., of polystyrene) using a binder/metal powder and then sintering the alloy to acquire a dense metallic shell while the polystyrene is eliminated. There are many other processes to obtain the hollow metallic spheres and can be found in the existing literature. The obtained hollow spheres are subsequently joined together by sintering into desired open cell or closed cell configuration. Titanium, nickel and Inconel foams have been processed using this method. More recent template-based methods include deposition of metal films around bubbles such as dynamic hydrogen bubble template (DHBT). The process is gaining increased attention for processing of battery electrodes and catalysis owing to higher surface area of processed foams. The field is very new and a few available literature [13, 15] should be referred for in-depth understanding of the process. Figure 5 illustrates few of the foams developed by solid-state foaming methods.

Intrinsic porosity methods include gas entrapment technique, wherein, adequate metal powders are compressed in a dense precursor material while a gas is entrapped within it. The precursor material is then heated which leads to expansion of the metal due to the internal pressure created by the entrapped gas which leads to formation of pores. The process is popularly known as Kearns process after the name of Michael Kearns who was the inventor and was first to apply the same at Boeing the US-based aerospace company. Boeing implemented it by filling titanium powder into a

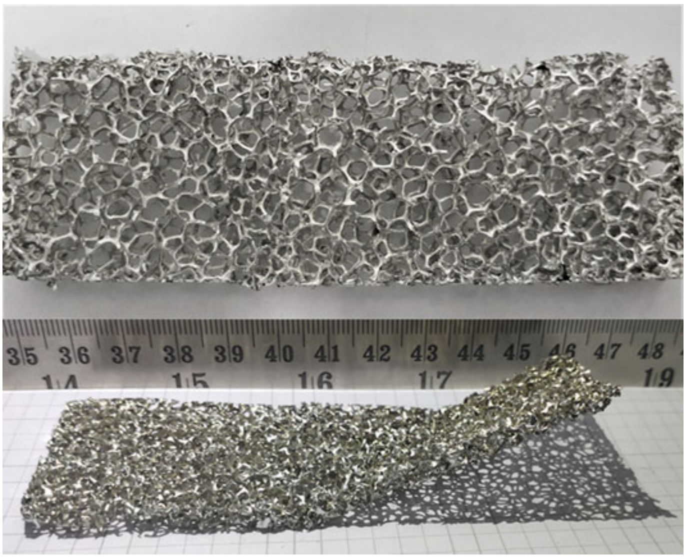

Fig. 5 **a** Examples of metallic foams processed by solid-state processes

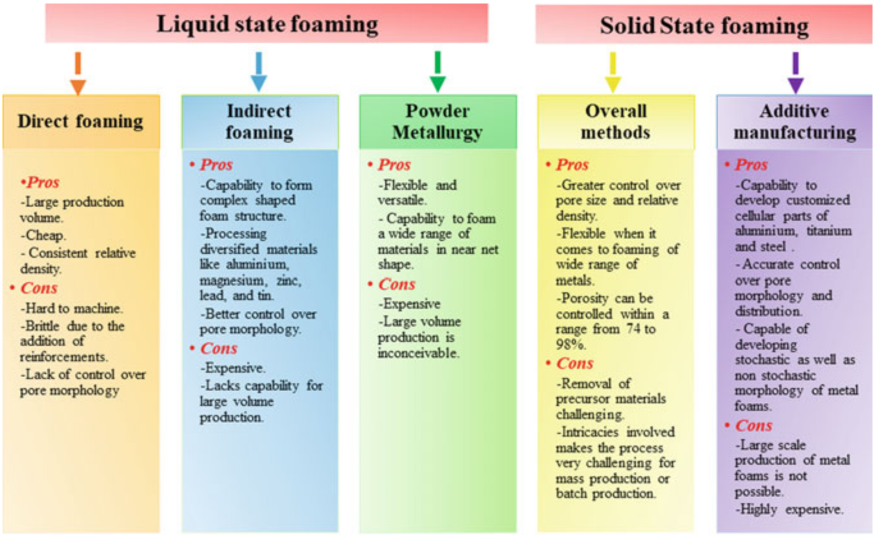

Fig. 6 Diagrammatic representation of pros and cons of various metal foam processing methods

metal can that was outgassed after evacuation. The can was again introduced with pressurized inert gas (Argon) at about 3–5 ATM and then sealed. The structure was densified by applying hot isostatic pressing at a temperature of 950 °C and 1000 ATM for 4 h. The argon gas was entrapped during the compaction and forms uniformly dispersed pores when the compacted material is finally annealed at a temperature of 1240 °C for 65 h. The process is even capable of processing near net shape products and has been widely used for processing commercially pure titanium and its alloys. The other method of intrinsic porosity formation is very new and still have a long way to go. In this process, pores are created in the powder materials unlike other methods, where pores are created in between the powder particles. It is achieved by mixing of metal powders thoroughly with oxides and then subsequent reduction of those oxides leads to formation of steam which starts expanding. The process is very new but many processing routes are being suggested for commercialization of this process and can be found in dedicated literature [12, 13, 15]. Figure 6 schematically illustrates the pros and cons of various foaming methods in processing metal foams.

2.3 Additive Manufacturing

Additive manufacturing technique offers a unique podium for generating, near net shape porous structures, for biomedical and aerospace applications. According to the ASTM standard F2792, it is defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive

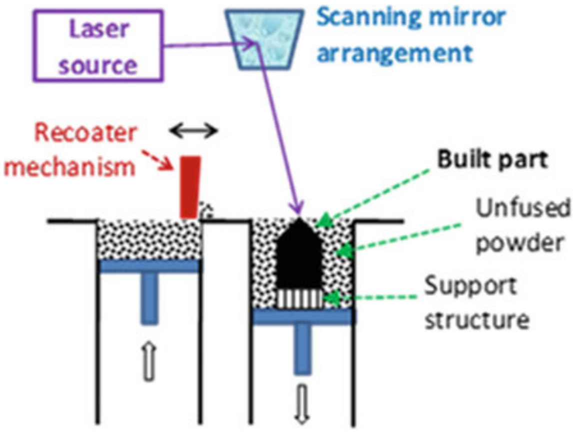

Fig. 7 Schematic representation of a powder bed fusion process. Reprinted with permission from Changdar and Chakraborty [1]

manufacturing methodologies". Currently, SLM or selective laser melting as shown in Fig. 7 is used mostly for manufacturing of porous part. The method is standardized as ISO/ASTM 52,900 and falls under powder bed fusion process [20].

Geometrically defined lattice structure porosity (GDLSP) and Geometrically undefined porosity (GUP) were the two approaches adopted for generating porous parts out of a SLM process. The part fabricated from GDLSP was entitled as non-stochastic cellular materials, whereas the parts out of GUP approach were termed as stochastic porous structure. Stochastic foams were mostly applied as filters and other functional applications, whereas the non-stochastic parts were applied biomedical utilities and heat exchangers [1, 21]. The process was quite efficient in developing customized cellular parts of aluminium, titanium and steel but was not efficient enough for processing alloys of the same. The process is still amateur, and its application for large-scale production of metal foams seems to be a distant dream [21].

3 Further Processing of Metal Foams for More Practical Manufacturability

Powder metallurgical route and additive manufacturing as discussed above are the two processes capable enough, to manufacture metal foam components in near net shape, while both the process offers flexibility in terms of foam structure and choice of the base metal, but are limited to small parts and tiny production volumes. Moreover, both the process involves high production cost, and are mostly limited to laboratory trials till date. A more practical approach of manufacturing metal foam is further processing of metal foams produced initially in the form of sheets and slabs. The foams can be further processed into the desired aesthetics either by cutting, joining or welding, as to tailor it in accordance to application. The approach apart from being more cost-effective, also guarantees better cell distributions and consistent densities.

3.1 Forming of Porous Metals

Capability of a material to form into desired shapes is very crucial to establish its firm foothold in industries. It has been reported that metal foams can resist fracture at severe deformation, which indicates their capabilities of getting formed into desired shape. Several studies successfully attempted forming of wide range of metal foams which include, aluminium foam (Alporas), porous nickel and lotus-type porous copper, plates. Cold extrusion was also applied to process porous metal by applying solid phase bonding of dissimilar metal wires. Though the possibility of mechanical forming exists but its yet not versatile. Studies revealed that corrugation of cell walls during mechanical forming leads to the formation of curvature at extrados. The curvature instigates development of very high tensile stresses, which eventually exceeds the tensile strength of metal foam [22]. Inability of metal foams to withstand such tensile stresses leads to its failure [1, 23, 24]. Limitations of mechanical forming of metal foam instigated utilization of laser forming, for bending metal foams. The process, utilizes non-uniform heating by laser to form a material by inducing non uniform strain within it. It eliminates the threat of mechanical stresses due to hard tooling instead relies on thermal stresses to produce the requisite deformation [1]. The recent studies are also affirmative and suggest that the process is capable of developing large bending deformations in the foam, without any detrimental effect on its structural robustness [3].

3.2 Joining Methodologies of Metal Foams

Several processes have been studied, in order to discover an optimal methodology for joining metal foam to another foam or a solid counterpart. Arc welding posed severe challenges when it comes to welding of metal foams. In order to successfully weld metal foam, heat must be confined to the thin struts and membranes of foam material, which is nearly impossible to achieve using arc welding [24]. As compared to arc welding, diffusion bonding served better results but its extreme processing time limits its usability. Diffusion bonding though delivered efficient joining [25]. Soldering was also attempted in several studies, but considering the porous structure of foam, wetting of soldering faces with molten solder was hard to achieve. As, a result the process failed to provide desired weld strength for any practical applications [24, 26]. Though use of adhesives were successful in joining metal foams with solid sheets, but the major drawback is it restricts utility of such part at higher operating temperature. Mechanical joints were also found not to be compatible. Attempt to rivet and mechanically fasten metal foams led to deformation and pre mature failure of the same [26]. Advanced joining methods like friction stir welding (FSW) and laser welding were found to produce better results in joining metal foams as compared to conventional methodologies. FSW was found to join metal sheets and foam at a single pass if the thickness of the foam was maintained within desired limits. On the other hand, laser welding due to its capabilities of confining heat input within a narrow region, stand out to be the most versatile process for welding metal foams. Laser welding process was found to offer the feasible solution to welding of metal foams on cautiously selecting the process parameters [1].

3.3 Cutting of Metal Foams

The application of metal foam can be enhanced if an appropriate method of machining it can be recognized. Several investigations were reported, wherein all the common methods were exploited. The processes include utilization of circular saw, band saw and disc grinding. But all of the processes tend to create localized plastic deformation and damaging of the surface. Wire electrical discharge machining (WEDM) and laser cutting were found to be more efficient process for machining metal foams. EDM was also found to exhibit higher rate of cutting metal foams, without any adverse effect on the structure of the metal foam. Whereas, laser cutting enabled obtaining cut surfaces which were burr free and with very narrow kerf [1, 25, 27].

4 Conclusions

The article enlisted the currently existing processing routes available for metal foams along with their prospects and limitations. The major insights exhibited by the article are as follows:

- Processes like additive manufacturing and powder metallurgical methods are capable of producing near net shape parts of metal foam, but their large-scale production prospects are limited due to low volume productivity and high cost. Products out of these processes are ideal for biomedical applications, dental implants or other sophisticated applications requiring less volume of part supply and high quality and precision.
- Solid-state processing of metal foam is gaining popularity as they are capable of developing controlled morphology metal foam and at standard volumes. Chemical vapour deposition (CVD) has already been applied for generating nickel foams at large volumes and are being applied by aerospace and automobile industries.
- Liquid-state processing is the most commercialized process, with least control over the morphology of the pores. The process is capable of producing metal foams at large volumes in generic shapes very cheaply. Currently, this processing method is the only sustainable method for large volume production. In order make the

process more versatile, a secondary manufacturing route must be added following the processing of metal foam to shape it as desired in an application. Processes like forming, cutting and welding are vastly studied for their compatibility with metal foam, without disturbing the structure of the material.
- The fragile structure of the material offers several limitations to the currently existing secondary processing methodologies. As this material is limited to deformation under compression, application of mechanical loads in any form to shape it tends to its failure. Similarly, welding, riveting or any other known joining processes turns out to be a challenge for these materials due their lesser contact surface. Laser-based processing methods turned out to be a success for this material and are currently being explored for complete process control.

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