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Mechanical properties of the metal foam

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ملخص

إن هذه الدراسة كرسست للتعرف بالرغوة المعدنية , انواعها و استخداماتها كما اهتمت بتطوير صناعة رغوة الألومنيوم ذات الخاليا المفتوحة بطريقة التسلل ثم دراسة خصائصها الميكانيكية و ذلك عن طريق اجراء اختبار الضغط لثلاث عينات مختلفة المسامية , وقد أظهرت النتائج تأثير حجم الخلية (المسام) على الخصائص الميكانيكية

الكلمات الرئيسية : رغوة الألومنيوم ذات الخلية المفتوحة ، عملية التسلل ، المسامية ، الخصائص الميكانيكية

Abstract

This study was devoted to the recognition of metal foam, its types and uses. It was also interested in the development of open-vacuum aluminum foam industry in the infiltration method and then the study of its mechanical properties by conducting a compression test for three different porous samples. Results have shown the effect of cell size (pores) on mechanical properties

Keywords: open cell aluminum foam, infiltration process, porosity, mechanical properties

Résumé

Cette étude a été consacrée à la reconnaissance de la mousse métallique, de ses types et de ses utilisations. Elle s'est également intéressée au développement de l'industrie de la mousse d'aluminium à vide ouvert dans la méthode d'infiltration puis à l'étude de ses propriétés mécaniques en réalisant un test de compression pour trois échantillons poreux différents. Les résultats ont montré l'effet de la taille des cellules (pores) sur les propriétés mécaniques

Mots-clés : mousse d'aluminium à cellules ouvertes, processus d'infiltration, porosité, propriétés mécaniques

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Nomenclature

dP	Pore diameter	[mm]
E	modulus of elasticity	[GPa]
F	force	[N]
h_0	initial height	[mm]
d_0	Material diameter	[mm]
ppi	Pore number per inche	
s_p	Specific surface	[m^{-1}]
v_p	vacuum volume (pore)	[m^{-3}]
v_t	Total volume	[m^{-3}]
w_v	Energy absorbed per unit volume	[MJ. m^{-3}]
ρ_g	density of porous media	[Kg/ m^3]
ρ_m	density of the foamed material	[Kg/ m^3]
Greek letters		
σ	Strain stress	[MPa]
ε	deformation	%
ρ	density	[Kg. m^{-3}]
φ	porosity	%

General introduction

In the 19th century, the widespread use of steel and other traditional materials had advantages in terms of mechanical strength, but their high density was a problem. Research was then carried out to develop materials with similar mechanical properties but with low density. Metal foams were born from this endeavor, imitating the cellular design of natural materials such as cork or foam, but using minerals. These foams provide good mechanical strength and excellent energy absorption. Improving the weight of ingredients was achieved by reducing the amount of solid matter while maintaining the structure geometry.

Tests have shown that the performance of metal foams can be improved by combining them with carbon fiber or aramide, creating lightweight and high-performance compounds. Extensive research is under way in many countries, including the United States, Germany, the United Kingdom, Japan and France, due to the numerous possible applications of these metal foams. These applications include lightweight construction, impact energy absorption, and high-performance composite manufacturing, indicating significant economic benefits.[1-2]

metal foam is one of the novel materials for which further research is being done . It is still unheard of in the engineering community and is created using methods that are constantly evolving. The majority of metal foams that are currently sold commercially are based on aluminum or nickel. However, there exist methods for producing magnesium foam, lead, steel, and even gold, which can be ordered specifically [3] . The metallic foam has not yet undergone complete characterisation, and the methods employed to characterize it frequently produce results with glaring diversity. This is a result of the intricate cell geometry that defines this structure. In response to technical advancements that address consumer demands for comfort, light weight, and versatility.

It finds applications in various fields as well civil as military; such as mechanical industries, naval aviation, aeronautics, civil engineering , etc. [4 -5]

This study aims to assess the mechanical properties of metal foam through compression tests

- This brings us to the problematic: What is metal foams. Their types and uses, and how to verify their mechanical properties ?

Chapter 01

Generalities on metal foam

1.1 Introduction :

Metal foam is characterized by its collection of hollow cells enclosed by solid walls or edges, capable of retaining up to 95% vacuum[6]. It falls under the category of porous media, denoting a solid material with intricate structures featuring pores or voids. These voids facilitate the exchange of information and accommodate one or more liquid phases. The structure is comprised of interconnected pores, giving rise to either an isolated or open foam configuration. Through the aggregation of these pores, a closed-cell foam is formed, wherein each distinct cell effectively entraps gas within its confines.[7]

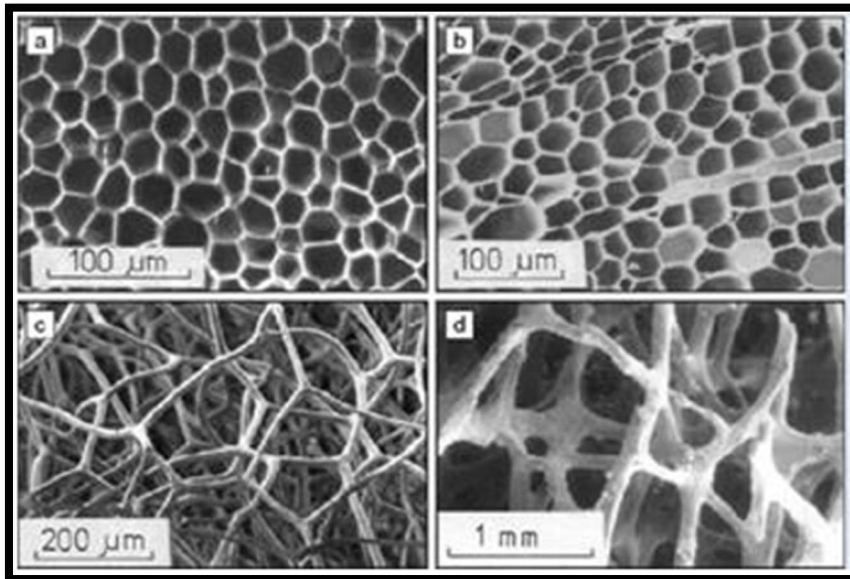


Figure 1.1: Natural materials: (a) cork, (b) balsa wood, (c) sponge, (d) bone.

A range of materials, including polymers, glasses, ceramics, and metals like nickel and aluminum, can exhibit foamy properties. However, synthetic and polymeric foams stand out as the most significant among cellular materials due to their extensive applications in diverse technological fields. These materials offer a remarkable blend of characteristics, such as exceptional rigidity, fire resistance, effective acoustic insulation, and easy recyclability, making them highly desirable for various purposes.[8].

Metal foams represent a promising and relatively recent class of materials, tracing back to the 1960s. Although early attempts lacked sufficient interest and investment for large-scale production, significant progress has been achieved over the past two decades. This progress is evidenced by notable improvements in product quality and manufacturing efficiency. Aluminum and its alloys have particularly emerged as popular choices due to their non-flammability and versatility. They find widespread use across multiple sectors, including thermal and acoustic insulation, sandwich core materials, mechanical damping, lightweight transportation panels, impact-resistant structures, stress isolators, and vibration control systems [9].

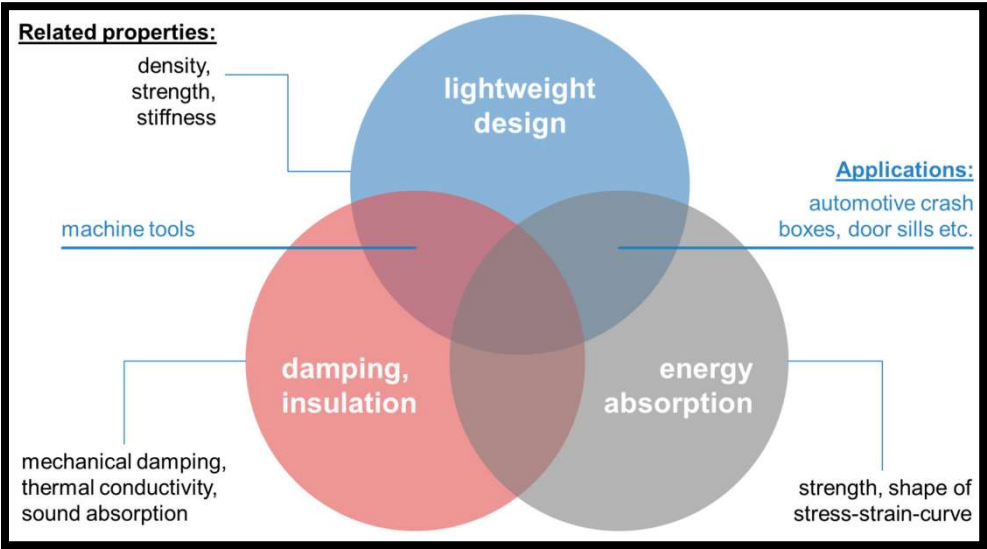


Figure 1.2: The main applications of metal foams

1.2 The different types of metal foam :

Metal foams are macroscopically cellular materials, characterized by their topological structures (open cells, closed cells), relative density, cell size and shape, and anisotropy.

There are three types of foam:

- Closed pore metal foams,
- Open pore metal foams,
- foams with reticulated pores

1.2.1 Closed pore metal foams :

Closed pore foams are characterized by their spherical cells isolated by often thick walls.

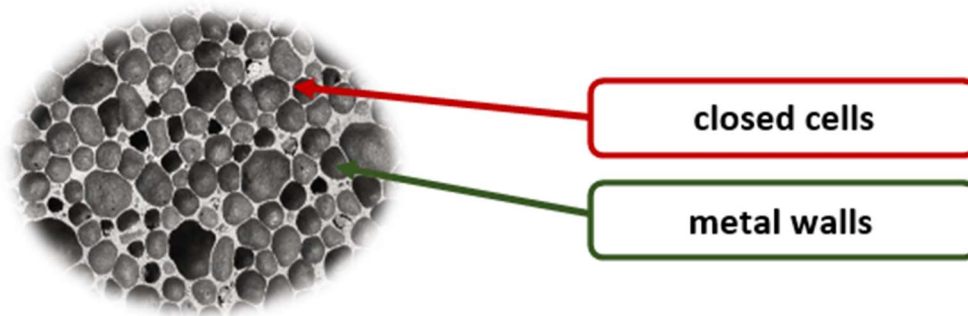


Figure 1.3 Closed pore metal foams

1.2.2 Open pore metal foams :

Open pore foams have connected cells. The geometric structure of open foam is generally more complex than closed-cell foam.

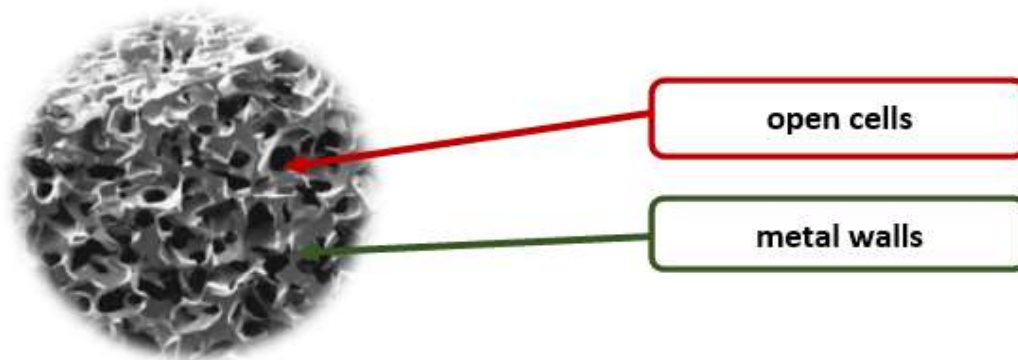


Figure 1.4 Open pore metal foams

1.2.3 Metallic foams with reticulated pores:

Crosslinked metal foams are similar to open pore metal foams, however they do not have pores but cross-linking. For the finest of these foams it is even possible to see through.. These metal foams are therefore the most porous of these cellular materials.

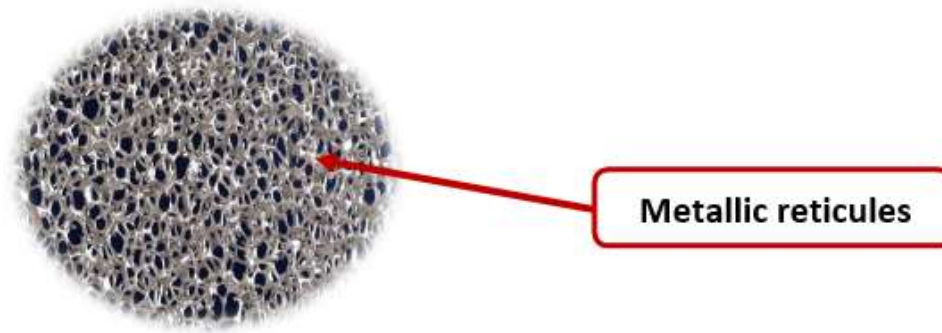


Figure 1.5 Metallic foams with reticulated pores

1.3 Multi-level study of cellular materials :

This description refers to how cellular materials, such as foams or alveolar structures, are analyzed and understood in different levels of detail.

- **Microscopic scale:**

This is the smallest level of surveillance, where the internal structure of the cellular material itself is examined. We can study the layout of cell walls, the size and shape of individual cells, as well as the presence of any particular material or component within cells.

- **Median Binary Eye Scale:**

At this level, we observe the distribution of cells in the material, as well as their overall size and shape. One can also examine how cells interact with each other and how their arrangement affects the optical properties of the material.

- **Eye scale:**

This is the widest level of surveillance, where the overall properties of the substance are analyzed. This includes properties such as the density of the material, its disproportionate behaviour (i.e. if it has different properties depending on the direction), and the type of cellular formation (open or closed), which can affect aspects such as the strength and rigidity of the material.

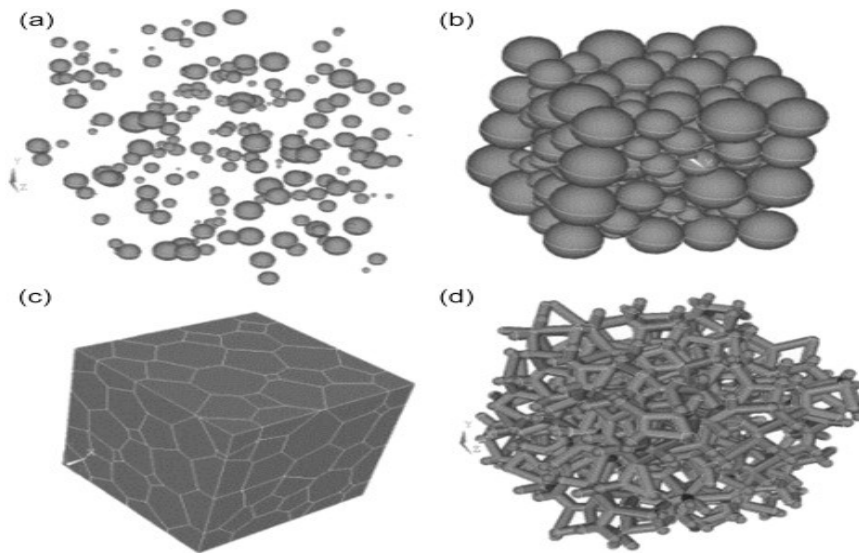


Figure 1.6 Multi-level view of the cellular materials

1.4 Applications of metal foams :

Open-cell foams are characterized by numerous burst bubbles, allowing for the passage of gases and liquids, rendering them suitable for a variety of applications. In contrast, closed-cell foams consist of intact bubbles, preventing the flow of gases and liquids. Their buoyancy enables some closed-cell foams to float on water. They hold great promise for applications such as chassis, automobile and aircraft fuselage components, train wagons, and cladding panels for building facades.

For these reasons, they are used in many applications in various industrial sectors such as:

- Automotive industry (figure 1.4)
- Aerospace industry (figure 1.6)
- Ship building (figure 1.5)
- Railway industry
- Construction industry
- Manufacture of machinery
- Sports equipment.
- Biomedical industry



Figure 1.7 : metal foam in Automotive industry

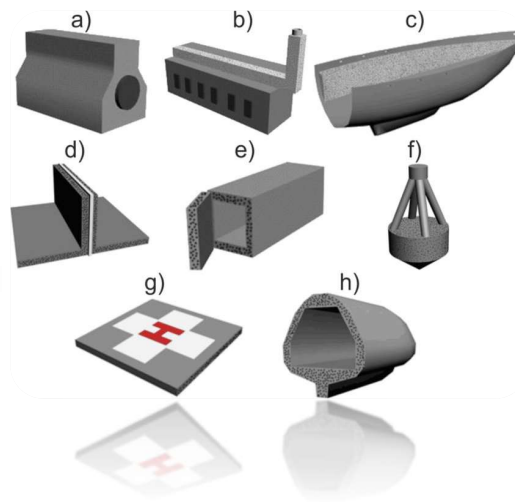


Figure 1.8 : Metal foam in ship building

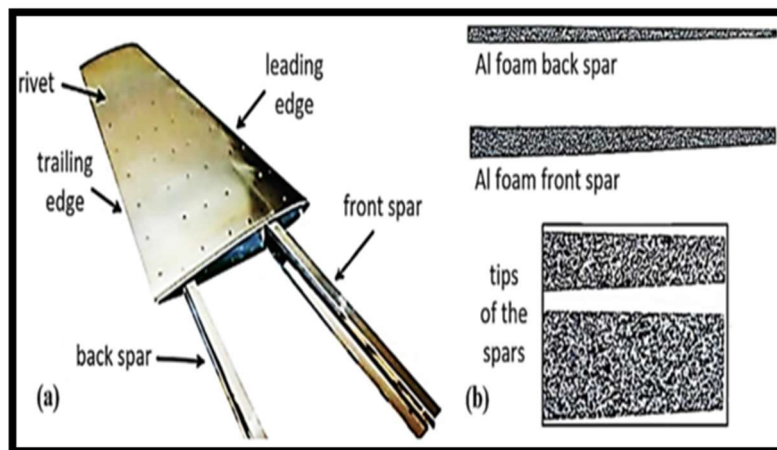


Figure 1.9 : Metal foam in Aerospace industry

The market offers a wide range of functional applications based on metal foams :

- Liquid storage and transfer
- Catalyst supporting structures
- The anti-bullying system
- The electrode for batteries
- Fuel tank electrodes
- The evaporator
- The filters (figure 1.7)
- The flame interceptor

- Rectifiers and flow and flow dividers (for gas pipes, liquids, specific interest in the fiber cooling process)
- Heat exchanger and cooling machines (figure 1.8)
- Silencers for control valves (pressure regulators), in the form of fittings or inserts
- Pre-mixed gas burners
- Rotary atomizers for ultra fine atomization
- Flame arresters and spark arresters (diesel engines)
- Silencers and acoustic control (exhaust, restrictive type, attenuators)
- Ultrasonic absorbers and deflectors, and many others



Figure 1.10: Metal foam in The filters

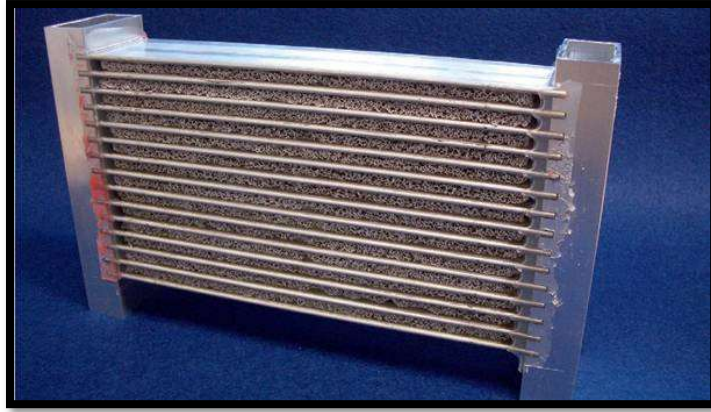


Figure 1.11 : Metal foam in Heat exchanger

The applications of metal foams are closely tied to the exceptional properties they can offer, some of which are unique. Many of these properties are inherently linked to those of the metal matrix itself. For instance, aluminum and copper foams exhibit excellent thermal conductivity, making them ideal for heat exchangers. Additionally, nickel foams are utilized as electrodes in nickel-metal hydride (NiMH) batteries, offering significant energy gains compared to conventional nickel-cadmium (NiCd) batteries. These nickel-based battery systems are now being adopted by leading global automotive manufacturers (such as GM, Toyota, Honda, PSA) for the next generation of electric and hybrid vehicles.[10]

1.5 Production methods of metal foam :

The production methods for metal foam encompass a range of techniques, some of which draw parallels with processes used for foaming aqueous or polymer liquids, while others leverage specific properties inherent to metals, such as their sintering activity or their ability to be electrically deposited. These methods can be categorized based on the state in which the metal is processed, leading to four distinct families of processes as illustrated in (Figure 1.9). Each family corresponds to one of the states of matter. This classification provides a framework for understanding the diverse approaches employed in the fabrication of metal foam.[11]

- from liquid metal,
- from solid metal in powdered form,
- from metal vapour or gaseous metallic compounds,
- from a metal ion solution.

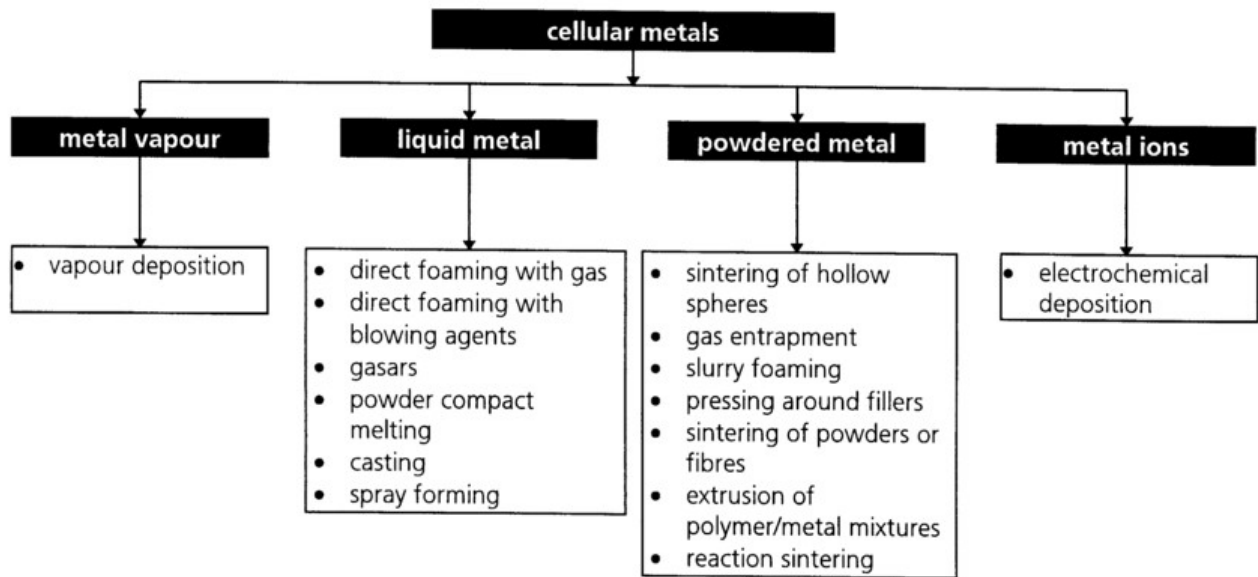


Figure 1.12: Overview of the various “families” of production methods for cellular metallic materials.

1.5.1 metal vapour :

1.5.1.1 vapour desposition :

Metal foams can also be produced from gaseous metal or gaseous metallic compounds, necessitating a solid precursor structure that defines the desired geometry of the foam or cellular material. For instance, reticulated polyurethane foams or lattice block polymer precursors can serve this purpose. In a vacuum chamber, metal vapor can be generated and allowed to condense on the cold precursor. This results in a metal coating of a certain thickness determined by the density of the vapor and exposure time. One method to achieve this is through arc vapor deposition[12]. Alternatively, for manufacturing nickel foams, the highly efficient nickel

carbony route can be utilized to coat the precursor with nickel at relatively low temperatures.[13] Nickel carbonyl, a gas produced by reacting nickel with carbon monoxide, decomposes into nickel and carbon monoxide when heated above 120°C. By passing a stream of nickel carbonyl gas through the polymer precursor at such temperatures, the nickel formed during decomposition accumulates on the precursor, creating a metallic coating. Infrared heating can maintain the polymer at the required decomposition temperature[14,15]. After cooling, the polymer can be removed through thermal or chemical treatment, resulting in a material with hollow struts akin to those produced by the galvanic process. Nickel foams manufactured in this manner,[16] commercially available under the name "Incofoam," are offered in thin sheets up to 3.3 mm thickness, with densities ranging from 0.2 to 0.6 g/cm³ and very high material purity (99.97% Ni). Tensile strengths are approximately 0.6 MPa for a medium density. The appearance of "Incofoam" (shown in fig 1.10) closely resembles that of foams produced by electrodeposition. Currently, its primary application is as support material for pasted battery electrodes.

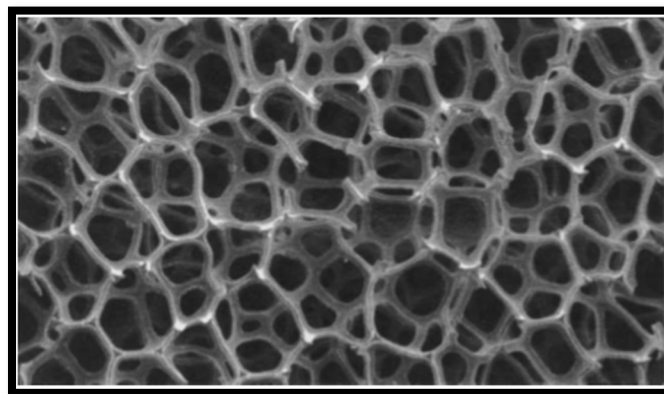


Figure 1.13 “Incofoam” sample made via nickel carbonyl process

1.5.2 metal ions :

1.5.2.1 electrochemical deposition :

Deposition techniques begin with the ionic state of metals, involving a solution of ions in an electrolyte [17]. The metal is electrochemically deposited onto a polymeric foam with open cells, which is subsequently removed, as depicted in (Figure 1.11). Similar to the investment casting route described earlier, the actual foaming process does not occur in the metallic state; instead, a foamed polymer is initially used, which is then replaced by metal during processing.

For electro-deposition onto a polymer foam, the initial polymer foam must possess some degree of electrical conductivity. This can be achieved by immersing the foam into an electrically conductive slurry containing graphite or carbon black, by using an electroless plating solution, or by coating the polymer with a thin conductive layer via cathode sputtering. Following electroplating [18,19], the polymer can be removed from the metal/polymer composite through thermal treatment, resulting in a three-dimensional arrangement of hollow metallic struts, as shown in (Figure 1.12). Various grades of foams can be fabricated, ranging from 2.5 to 30 cells/cm (approximately 6–70 pores per inch), with corresponding cell sizes ranging from 3.2 to 0.5 mm, and surface areas ranging from 500 to 7500 m²/m³[20]. Preferred metals for this process include nickel or nickel–chromium alloys, although copper foams can also be produced. Nickel–chromium foams are manufactured by alternating coatings of nickel and chromium, followed by a heat treatment process that induces alloy formation through interdiffusion of the two metals. Commercially available foams, such as Retimet (Dunlop, GB), Celmet (Sumitomo Electric, Japan), and Recemat (SEAC, The Netherlands), offer production volumes reportedly in the range of hundreds of tons per year at Sumitomo. These foams are available in sheets with thicknesses between 2 and 20 mm and densities ranging from 0.4 to 0.65 g/cm³ for nickel or nickel–chromium foams. Notably, the density of these foams has been observed to be virtually independent of the average pore size[21]. Mechanical properties and models for these materials can be found in relevant references.[22,23].

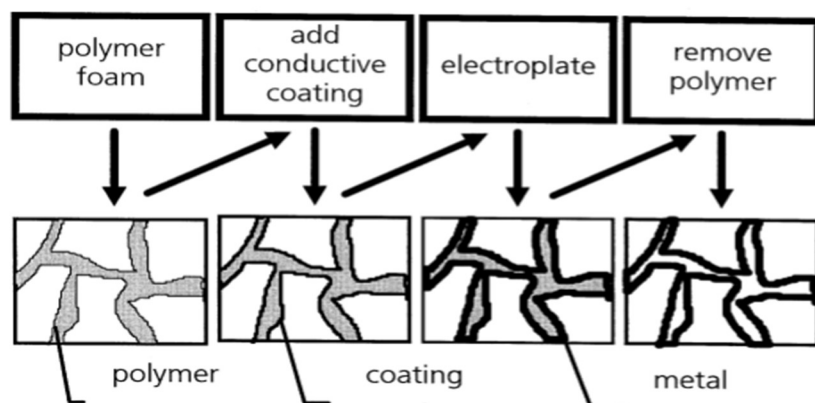


Figure 1.14 Electro-deposition technique for making metal foam.

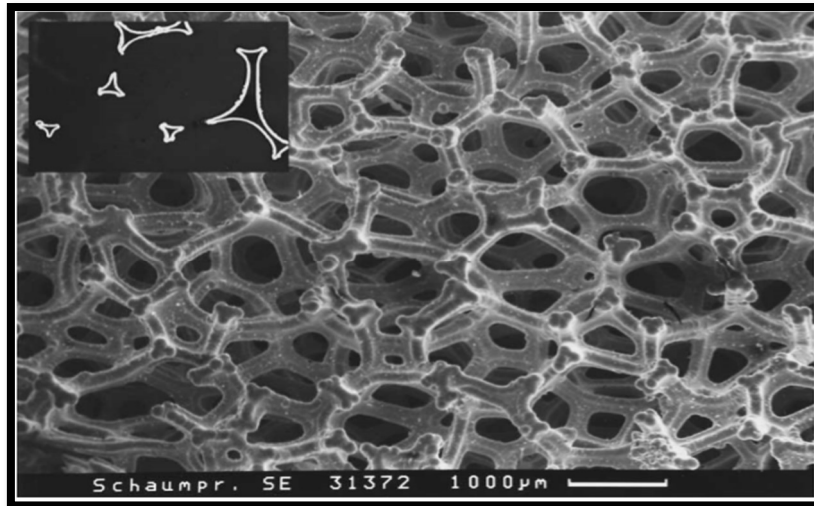


Figure 1.15 Nickel foam prepared by electro-deposition. Inset: micrograph of the edges of some of the hollow struts (source: Fraunhofer).

1.5.3 powdered metal :

Instead of relying on molten metal, cellular metallic structures can be produced using solid metal in powdered form. Throughout the process, the powder remains in its solid state and undergoes treatments such as sintering or other solid-state operations. This approach is fundamental for determining the morphology of the resulting cellular structure. In the liquid state, surface tension tends to promote the formation of closed pores. However, when using sintered porous products, the typical morphology consists of open structures composed of isolated, more or less spherical particles connected by sinter necks.

Presently, one of the simplest methods for producing porous metals is by sintering loose bulks of powders or fibers, which has become a well-established production technique in the powder metallurgy industry. Advanced technologies offer additional means of creating porosity, such as trapping gas within a powder compact, utilizing space-holding filler materials or hollow spheres, or employing metal powder slurries for foaming

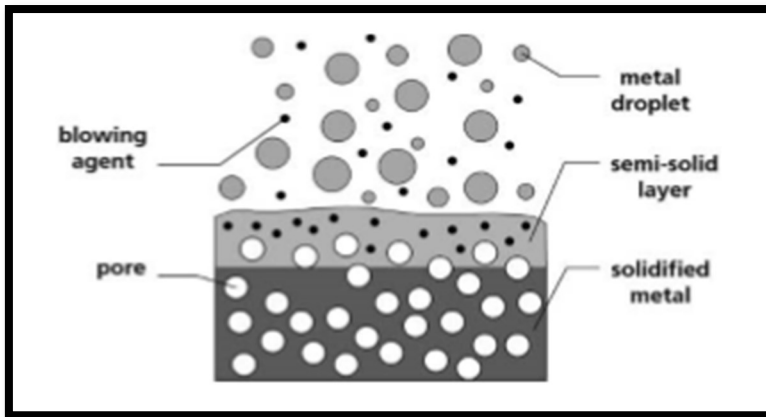


Figure 1.16 Manufacture of metal foam by spray forming

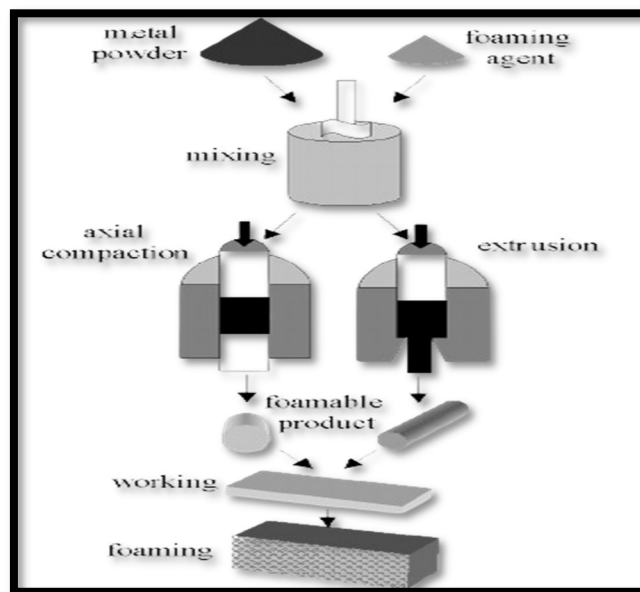


Figure 1.17 Processing steps involved in powdered metal foaming with a blowing agent

1.5.3.1 Sintering of metal powders and fibres :

Porous metallic products are widely used today, made from various metals including titanium, superalloys, bronze, and stainless steel. The production process involves powder fractioning, compaction, and sintering. For bronze, gravity sintering is common, yielding porosities of 20-50% with low strengths. Techniques like axial die compaction and isostatic pressing enhance strength. Wet powder spraying achieves fine porosities down to 1 mm. Producing porous

aluminum alloys is challenging due to oxide layers, addressed by mechanical deformation or sintering aids. Metal fibers offer new possibilities, with various metals commercially available in fiber form for sintered products.[23,24].

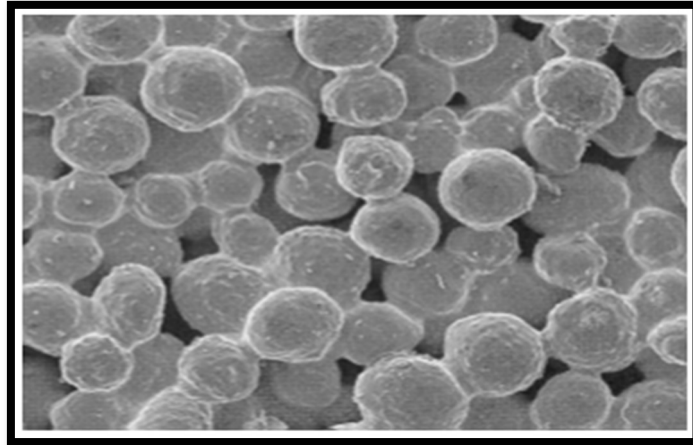


Figure 1.18 Porous sintered bronze made from particles with about 100 μ m diameter .

1.5.3.2 Gas entrapment technique :

Cellular metals can be produced without melting the metal or using a blowing agent. Powders are compacted into a dense precursor material, allowing gas to be entrapped. Heating the precursor causes metal expansion due to internal gas pressure. This solid-state process resembles creep rather than traditional foaming. Boeing has used this method to create porous titanium structures[25,26]. Titanium powder is compressed into a can filled with argon gas, then sealed and hot pressed. After densification, annealing causes gas pores to expand, resulting in a porous body with 20-40% unconnected porosity. The can walls also form a dense outer layer, enabling the creation of sandwich structures. These structures exhibit a relative density of about 66% of bulk titanium.[27,28]

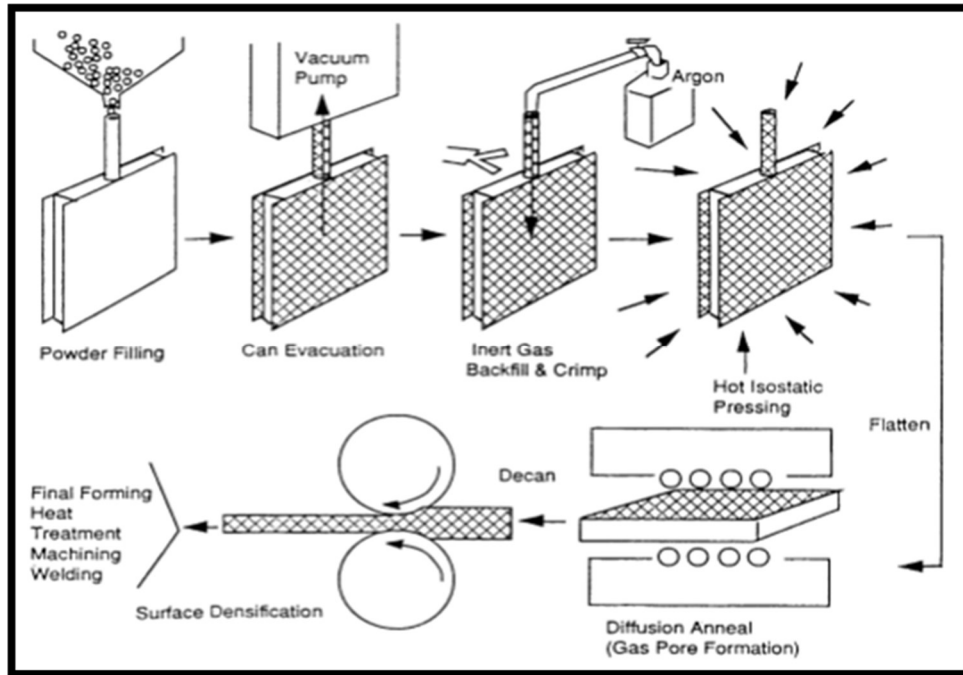


Figure 1.19 Gas entrapment technique

1.5.3.3 Foaming of slurries :

Metallic foams can be generated through a process involving metal powders, blowing agents, and reactive additives in a slurry. Initially, the slurry is blended and poured into a mold, then subjected to elevated temperatures. Through the influence of additives and blowing agents, the slurry thickens and expands due to gas evolution. With adequate stabilization measures, the expanded slurry can be preserved, dried, and subsequently sintered to produce a metal foam with significant strength. For instance, aluminum powders have been utilized with orthophosphoric acid and aluminum hydroxide or hydrochloric acid as a blowing agent[29], achieving relative densities as low as 7%. However, challenges like insufficient strength [30] and cracks in the foamed material may arise.

Another method involves utilizing slurries to create an open porous metallic foam. Here, a porous polymer foam is immersed into a slurry containing a mixture of silver and silver oxide powder[31] . After coating, the foam undergoes drying and heating, causing the polymer to burn out and the metal powder particles to sinter together, forming a rigid cellular metal structure.

1.5.3.4 Pressing around fillers :

Space-holding fillers are used to create cellular metals, akin to the process described earlier. Here, porous materials are formed by incorporating metal powders into the bulk of the fillers. Unlike the previous method where liquid metal fills the bulk[32], fine metal powder is used instead. The bulk can be filled with dry fillers or mixed with a solvent[33,34] or organic binder[35]. Various materials like ceramic particles, polymer grains, or metals can serve as space holders. After compaction, either at room temperature or elevated temperatures, a composite of metal matrix with embedded filler granules is obtained. If the metal content is low enough, the space holder material can be removed through thermal treatment, leaching, or using an aqueous solvent, leaving behind a porous metallic network. Further sintering may be employed to densify the structure.(Figure 1.17)

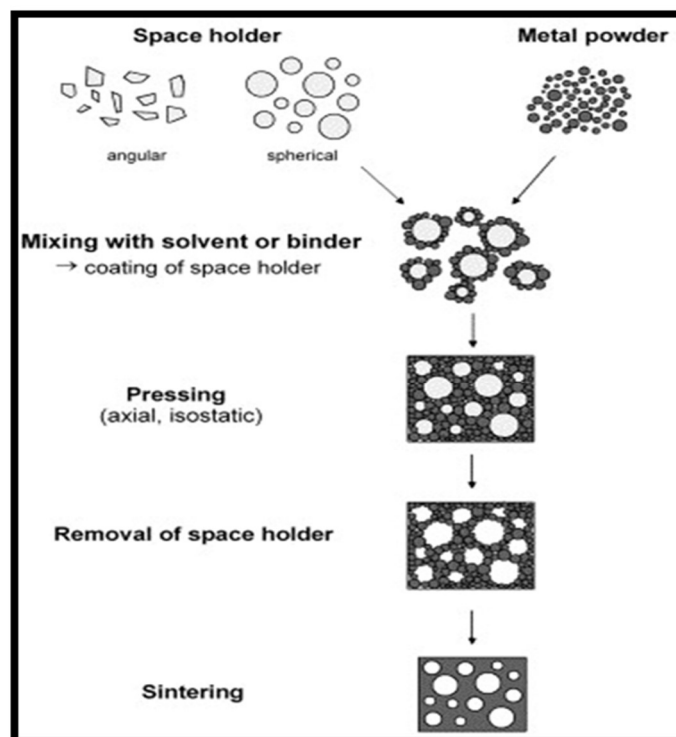


Figure 1.20 : Space holder technique for making porous metallic structures from metal

1. 5.3.5 sintering of powders or fibres :

Metallic hollow sphere structures can be utilized to create highly porous formations by bonding the spheres together through sintering. These hollow spheres, made from materials like copper, nickel, steel, or titanium, can be manufactured in several ways[36]:

1. Through combined chemical and electrical deposition of the metal onto polymer spheres, which are later removed.
2. Coating polymer spheres (e.g., polystyrene) with a binder/metal powder suspension and sintering the metal while removing the polystyrene[37].
3. Blowing metal powder, metal oxide powder, or metal hydride powder slurries into micro-spheres using coaxial nozzles, followed by drying and sintering or deoxidizing [38,39].
4. Atomizing metallic melts to form hollow spheres[40].

Typical sphere diameters range from 0.8 to 8 mm, with wall thicknesses from 10 to 100 mm. These hollow spheres enable the production of lightweight materials with open and closed porosity, organized in both ordered and disordered cell arrangements. Open structures are achieved by sintering a bulk of hollow metal spheres, creating sintering necks between adjacent spheres[36].

Ordered materials can be obtained by arranging spheres regularly on a lattice before sintering, often using wax honeycombs as a stacking aid. By applying forces during sintering, spheres are deformed into polyhedral bodies, increasing sintering contacts but reducing open porosity. Bonding slurry can enhance contact between spheres[41], either by bonding oxide spheres together with an oxide slurry and carrying out deoxidation and sintering in one step[41], or by bonding slurry-coated polystyrene spheres together and achieving debinding and bonding simultaneously. Spheres with thicker walls are preferred for open structures[42].

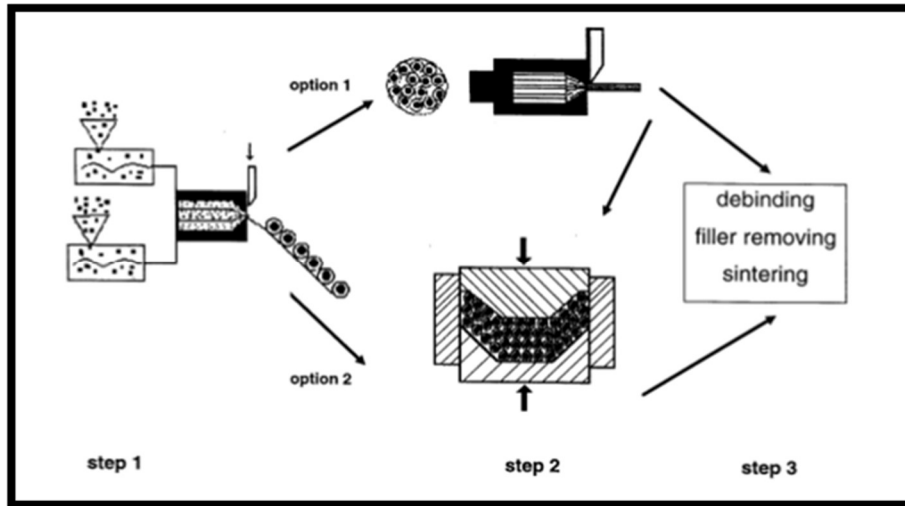


Figure 1.21 : Process for making cellular metals with oriented porosity from metal powders

1.5.3.6 Extrusion of polymer /metal mixtures :

Mixtures of metal powders and polymer binders can be shaped into porous materials and components by pressing or extrusion, followed by heat treatment[43, 44]. Despite the absence of space-holding fillers, porosities of up to 50% have been achieved. Additionally, materials with oriented pores, known as "micro-honeycombs," can be manufactured[45,46] with channel diameters spanning from microns to millimeters, using various metals and alloys.

The process involves several steps: first, bimaterial rods are prepared, comprising a core of a mixture of plastic binder with a volatile space holder and a shell of metal powder/binder mixture. Next, bundles of these rods are pressed to form a green part, either through extrusion or axial pressing, resulting in a green part of nearly any cross-section or complex shape. Finally, the binder and space holder are removed, and the metal powder is consolidated through sintering.

1.5.3.7 Reaction sintering :

Reaction sintering of metal powder mixtures such as Ti + Al, Fe + Al or Ti + Si is also known to yield porous structures [47–48]. This is due to different diffusion coefficients of the components of a multi-component system in each other

1.5.4 Liquide metal :

The next set of procedures forms the cellular framework using liquid metal. This molten metal undergoes various transformations to yield a porous substance. This transformation can occur directly through foaming, indirectly via a polymer foam, or by encasing the liquid metal around solid fillers that create voids once processed further. Another approach involves melting powder compacts containing a gas-releasing agent to induce foaming.

1.5.4.1 Direct foaming of metals :

1.5.4.1.1 Foaming by gas injection :

Hydro Aluminium in Norway and Cymat Aluminium in Canada employ a method [49–50], initially developed by Alcan International, for foaming aluminum and aluminum alloys. This process involves incorporating particles like silicon carbide, aluminum oxide, or magnesium oxide into an aluminum melt to increase viscosity[51,52]. The melt is then foamed by injecting gases (air, nitrogen, argon) using rotating impellers or vibrating nozzles, creating fine bubbles uniformly distributed in the mixture. As the mixture rises, it forms a stable liquid foam due to drainage of liquid metal, aided by ceramic particles. After solidification, the foam can be flattened into slabs. Care is taken to avoid damaging the pore structure[53–54]. The resulting solid foam can vary in size and thickness. The stability of the foam is ensured by the particles, which increase surface viscosity and are partially wetted by the melt, contributing to stable bubble/particle interfaces.

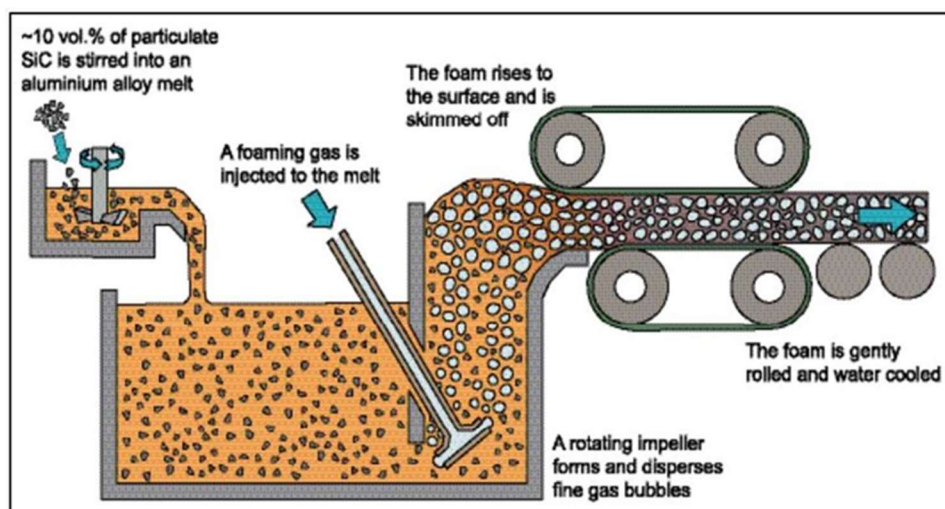


Figure 1.22 Direct foaming of melts by gas injection

The process involves incorporating ceramic particles into an aluminum melt to stabilize foam formation [55]. The resulting aluminum foams exhibit varying porosities, densities, pore sizes, and wall thicknesses[56,57]. Control parameters like gas flow and impeller speed influence foam characteristics. Foamed slabs often display density and pore size gradients due to gravitational drainage and diagonal cell distortion from conveyor belt shearing[58]. Direct foaming offers continuous, large-volume production, but cutting may be necessary, potentially compromising cell integrity[59]. Efforts to shape foam parts and research on foam properties are ongoing. Foaming pure metallic melts with inert gases has been suggested to avoid stabilizing additive drawbacks [60]. This requires close-to-melting-point temperatures and continuous casting processes to trap gas bubbles in the solidifying liquid.

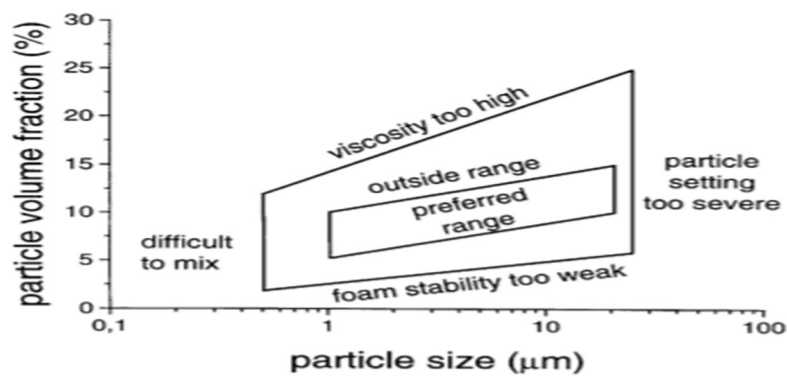


Figure 1.23 Selection of particle size and content for foaming MMC melts

1.5.4.1.2 Foaming with blowing agents :

This alternative method for producing foamed melts involves incorporating a blowing agent directly into the melt, which decomposes upon heating to release gas, driving the foaming process [61–62,63,64]. Initially developed in 1986 at Shinko Wire, Japan, this technique has seen small-scale commercial use with reported daily production volumes of up to 1000 kg of foam [65–66].

The process begins by adding calcium metal to an aluminum melt at 680°C, followed by stirring to increase viscosity, possibly due to the formation of calcium oxide or other compounds [67,68]. Typically, 1.5–3 wt% calcium is added, and titanium hydride (TiH₂) is introduced as a blowing agent (1.6 wt%). The melt gradually expands, filling the foaming vessel under constant pressure. After cooling, the liquid foam solidifies into aluminum foam, known

as "Alporas," renowned for its homogeneity. Zirconium hydride (ZrH_2) has also been suggested as a blowing agent [69].

Shinko Wire typically produces foamed aluminum in batches measuring $2050 \times 650 \times 450$ mm, with individual cast foam blocks weighing around 160 kg and having an overall density, including outer skins, of 0.27 g/cm^3 . Post-cutting, densities range between 0.18 and 0.24 g/cm^3 , with average pore sizes ranging from 2 to 10 mm. These blocks are often cut into sheets of various thicknesses (5–250 mm, standard thickness 10 mm) and used in various applications. Surface treatments, such as water or chemical vapor treatments, have been applied to enhance corrosion resistance [70].

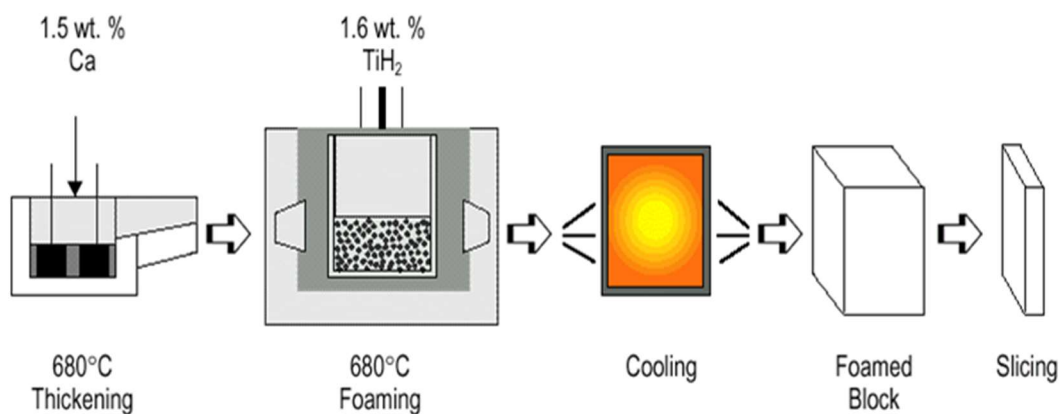


Figure 1.24 Direct foaming of melts with blowing agents (“Alporas”-process)

1.5.4.2 Solid–gas eutectic solidification (“gasars”):

The solid-gas eutectic solidification method, known as "gasars," utilizes the eutectic system formed between certain liquid metals and hydrogen gas, a technique developed approximately a decade ago [71,72]. By subjecting a metal to high pressure (up to 50 atm) in a hydrogen atmosphere, a homogeneous melt saturated with hydrogen is obtained. Upon cooling, the melt undergoes eutectic transition to a heterogeneous two-phase system of "solid + gas." The process parameters, including pressure and hydrogen content, must be carefully controlled to achieve optimal results. Directional solidification occurs as heat is removed from the melt, resulting in the formation of gas bubbles near the solidification plane. To ensure retention of bubbles within the solid, specific process parameters must be selected [73].

The resulting pore morphology is influenced by various factors, including hydrogen content, pressure, heat removal rate, and melt composition. Typically, elongated pores aligned with the direction of solidification are formed, appearing spherical only when viewed in this direction. Pore characteristics vary, with diameters ranging from 10 μm to 10 mm, lengths from 100 μm to 300 mm, and porosities from 5% to 75%. The pore distribution is non-uniform due to concurrent pore growth and coalescence, resulting in conical or corrugated pores. Gasars, or "gas-reinforced" materials, have been studied extensively for various metals and ceramics, with their pore morphology and microstructure well characterized [74–75].

Despite advancements, the homogeneity of gasars sometimes requires further improvement to expand their applications. Mechanical properties, including compression and tension strengths, Young's modulus, and Poisson's ratio, have been extensively characterized [76,77]. Gasars offer promising potential but necessitate ongoing research to optimize their properties for diverse applications.

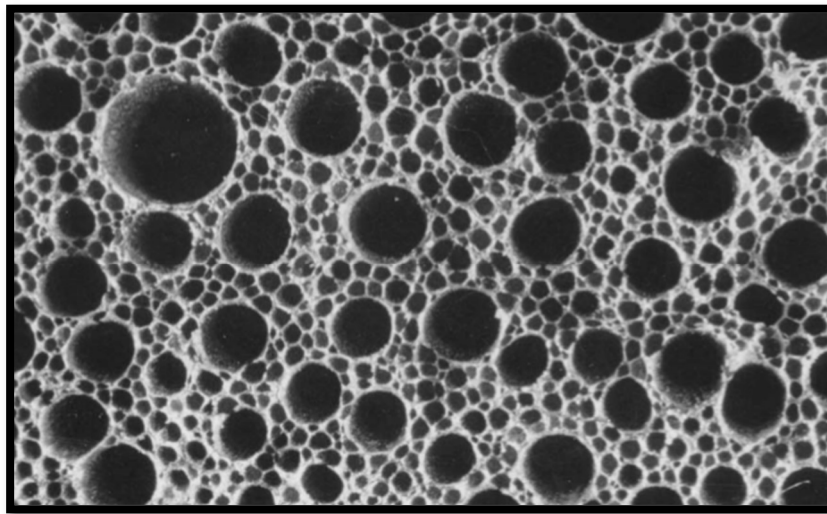


Figure 1.25 Pore structure of a “gasar”. Surface normal to direction of pores is shown [96].

1.5.4.3 Powder compact melting technique :

A method pioneered at the Fraunhofer Institute in Bremen, Germany, enables the production of foamed metals, a technique that has undergone significant development recently

[78,79]. Although the fundamental concepts of this method are relatively old [80,81], advancements have led to the production of foams or foam components of satisfactory quality. Termed "powder metallurgical," the process utilizes metal powders mixed with a blowing agent, compacted to form a dense, semi-finished product. Compaction methods such as hot uniaxial or isostatic compression, rod extrusion, or powder rolling embed the blowing agent into the metal matrix, with extrusion being the preferred method due to its economic efficiency [82,83].

Precursor manufacturing requires meticulous attention to eliminate residual porosity or defects that could affect subsequent processing. Heat treatment near the melting point of the matrix material initiates the expansion process as the blowing agent decomposes, resulting in the formation of a highly porous structure. Expansion curves demonstrate the volume increase over time, with adjustments in blowing agent content and foaming parameters controlling the foam density. Various metals and alloys, including zinc, brass, lead, and gold [84,85,86,87], can be foamed by selecting appropriate blowing agents and process parameters, with pure aluminum or wrought alloys being the most common choices.

Foaming can be tailored to achieve near-net shaped parts by limiting expansion in specific directions, either through molding or injection into suitable molds. Careful process control is essential to avoid defects in the pore structure of the foamed parts, but this method holds potential for economically mass-producing complex volume parts [88,89].

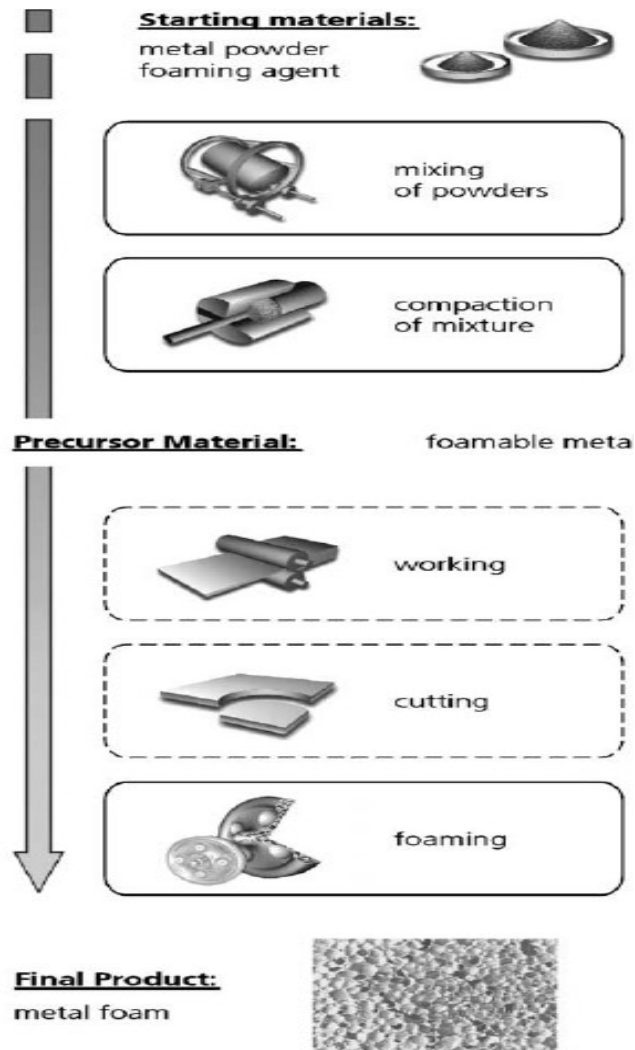


Figure 1.26 Powder compact melting process

Sandwich panels, comprising a foamed metal core and two metal face sheets, can be easily obtained by bonding the face sheets to a piece of foam using adhesives. Alternatively, for pure metallic bonding, conventional sheets of metal — such as aluminum or steel — are roll-clad to a sheet of foamable precursor material [90]. Subsequently, the resulting composite can undergo optional deformation, such as deep drawing. Following this, a final heat treatment, where only the foamable core expands while the face sheets remain dense, results in sandwich structures, as depicted in. Aluminum foam can be paired with steel [91] or titanium face sheets, as well as aluminum face sheets. In the latter scenario, precautions must be taken to prevent melting of the face sheets during foaming, for instance, by selecting alloys with different

melting points for the core material and the face sheets. A significant development in this area was a large aluminum/aluminum foam sandwich created through collaboration between the German car manufacturer Karmann in Osnabrück and the Fraunhofer Institute in Bremen, showcased in a concept car demonstrating structural aluminum foam applications [92]. One such part is illustrated in. These sandwiches are 3D-shaped, up to 2 meters in length, and approximately 1 meter in width. Tubes or nearly arbitrarily shaped columns can be filled with aluminum foam in several ways:

1. The simplest method involves inserting a rod of foamable precursor material into the column to be filled and placing both into a furnace. The precursor material will then foam, eventually filling the section completely. However, this method is limited to tubes with significantly higher melting temperatures compared to the material being foamed for example, steel tubes if aluminum is foamed.
2. An alternative approach is to insert a foamable hollow section closely fitting into the section to be filled with foam, instead of using a simple rod. This allows the foam to expand only towards the center of the outer section, providing mechanical support during foaming. Additionally, thermal contact between the section and foam prevents overheating of the section during foaming.
3. A third option involves co-extruding two concentrically arranged tubes to form a composite with a metallurgical bond between the two components. The inner tube is made of foamable material, while the outer tube is a normal aluminum alloy. During the subsequent foaming step, the inner layer expands towards the center of the tube, eventually filling it.
4. Another method for creating composites is to produce an aluminum foam component with a dense outer skin by thermally spraying aluminum onto a pre-shaped aluminum foam body, thereby creating a composite. shows one such sample. This technique is not limited to tubes; almost any foamed body can be coated.
5. Finally, using aluminum foam parts as cores in conventional sand-casting allows for the creation of structural composites in which the foamed core remains completely enclosed in the cast component [93,94].

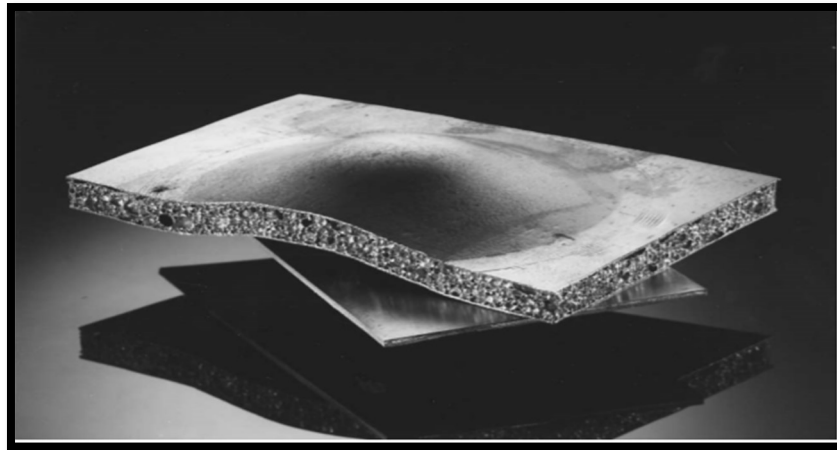


Figure 1.27 Sandwich panel having an aluminium foam core (thickness 12 mm) and two steel face sheets

1.5.4.4 Casting methods :

Foams offer versatile options in metal casting techniques. One method involves creating metal structures by casting around polymer foams. Initially, a polymer foam like polyurethane is used, which may undergo reticulation treatment to open its pores. Then, a heat-resistant slurry, such as a mixture of mullite, phenolic resin, and calcium carbonate[95], or simple plaster[96], fills the open-celled polymer foam. After curing and removing the polymer foam, molten metal fills the voids, replicating the original foam's structure. Pressure and heating may aid casting if needed. This process yields precise metallic replicas of the foam, though challenges include ensuring complete filling of filaments and controlling directional solidification. These foams, exemplified by ERG's "Duocel,"[97] offer diverse pore densities and are compatible with various metals like aluminum, copper, and magnesium, leading to products with porosities typically ranging from 80% to 97%. Despite high initial costs, recent casting advancements hint at potential price reductions.

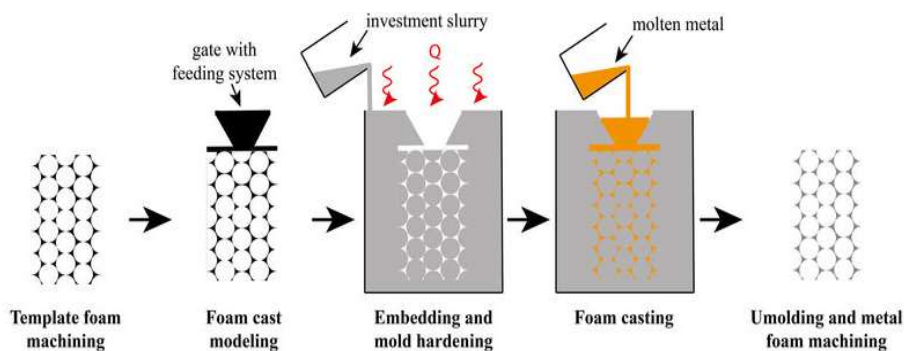


Figure 1.28 Production of cellular metals by investment casting.

Another method involves casting around space holder materials to create lightweight porous metals. In this technique, granules or hollow spheres of low-density materials, either inorganic (e.g., vermiculite, foamed glass spheres) or organic (e.g., polymer spheres), are cast with liquid metal. These fillers either remain within the metallic product, forming syntactic foams, or are removed post-casting through leaching or thermal treatment. The choice of space holder and casting conditions determines the resulting morphology, typically characterized as sponge-like. This method allows for precise control of pore size distribution but is limited to achieving porosities below 80%. The resulting materials find applications in various industries, offering advantages such as isotropic properties and potential for composite structures.

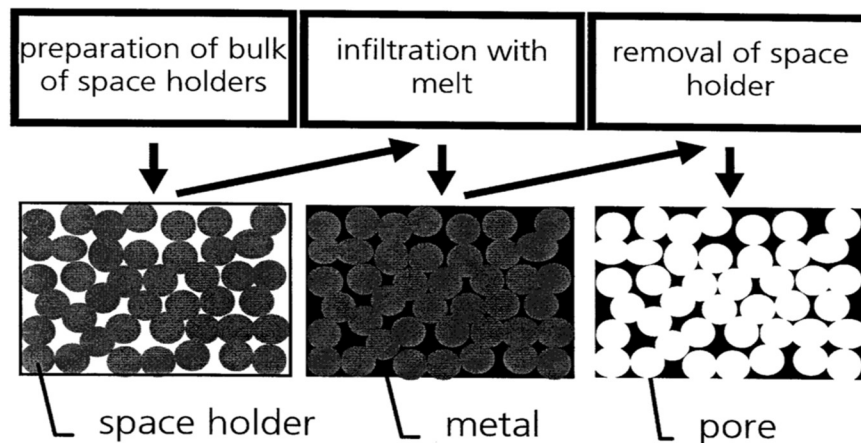


Figure 1.29 Production of cellular metallic materials using space-holding fillers

1.5.4.5 Spray forming (“Osprey process”) :

Spray forming, also known as the "Osprey process," is a versatile method for processing various metals and alloys. It involves continuously atomizing a metallic melt to create a spray of small, fast-flying metal droplets, which are then collected on a substrate to form a dense deposit in desired shapes like billets, sheets, or tubes. This technique offers advantages such as low oxide content, fine grain size, or high content of metastable alloy phases[98], properties often unattainable through conventional casting methods. One notable advantage of spray forming is the ability to modify deposit properties by injecting powders, such as oxides, carbides, or pure metals, into the spray. These powders can react with or be wetted by the liquid

metal droplets, incorporating them into the deposited metal. This capability enables the production of metal matrix composites (MMCs) if carbides or oxides are added. Alternatively, injecting powders that decompose upon contact with the molten metal and release gas can be utilized to intentionally create pores in the deposit, useful for making porous metallic materials. While this effect is typically undesired, it can be harnessed for specific applications. For instance,[99] research has explored injecting powders like BaCO₃ into copper-tin alloys to induce porosity or introducing silicon oxide or manganese oxide into carbon steel sprays to generate large amounts of carbon monoxide, resulting in porous steel. The achieved porosities can range up to 60%, although pore morphologies may lack uniformity.

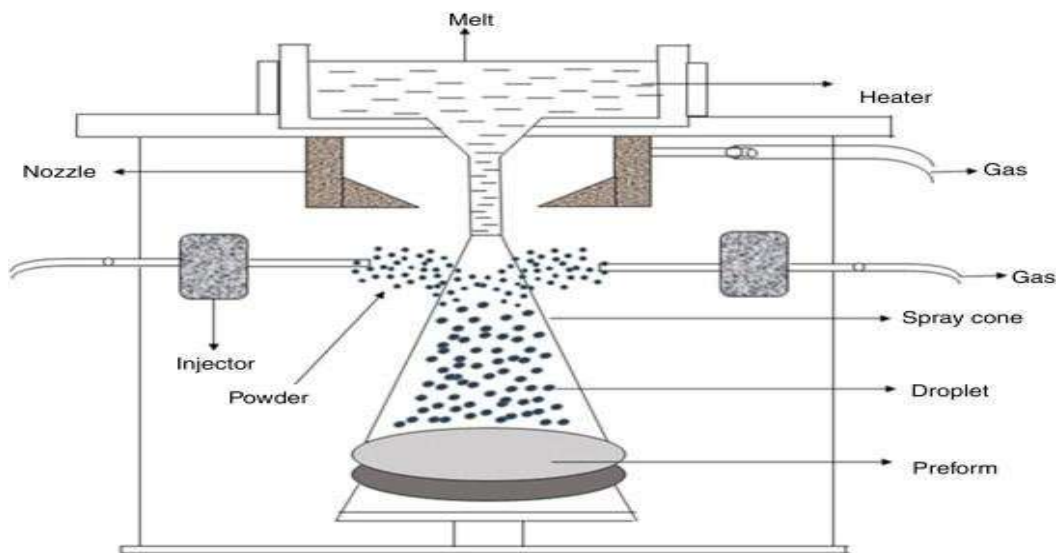


Figure 1.30 The Sandvik Osprey Spray forming process for creating AlSi alloys

Chapter 02

Manufacturing of the metal foams

2.1 Introduction :

This chapter outlines the manufacturing process of aluminum foam, focusing on the infiltration method utilized to produce open-cell aluminum foam. Within this chapter, the apparatus employed for foam production will be detailed.

2.2 Steps of the general replication protocol (infiltration) :

2.2.3 The necessary equipment and materials :

In this work, the experimental equipment and protocols that have been used to produce aluminum foams through the infiltration process, are relatively easy to implement. In order to produce open-cell aluminum foam, the test bench (Fig. 2.1) was used. It consists of an argon gas cylinder for gas injection; a vacuum pump that was used to achieve a vacuum of less than 10 mbar in the mold to: avoid aluminum oxidation, facilitate the infiltration of molten aluminum between the particles, prevent the salt from reacting with oxygen; Oven and two stainless steel moulds, one of dimensions 70 x 70 x 400 mm and the other of diameter 60 and height 200 mm (Fig. 2.2). All of them were connected by stainless steel pipes, via appropriate valves and fittings. The gas pressure was controlled using a manometer and a needle vacuum gauge. Argon pressure can be regulated up to 10 bar and bottle argon flow can also be controlled

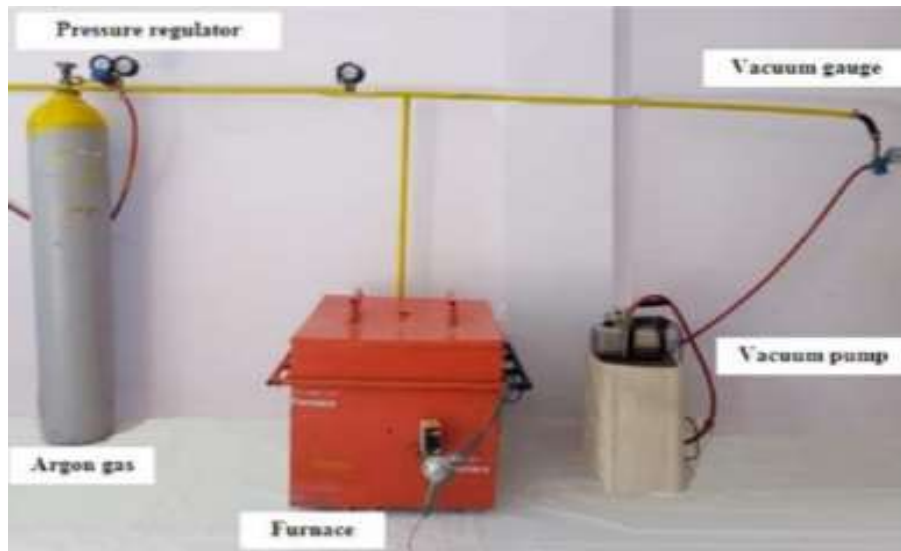


Figure 2.1 metal Foam making plate-shape

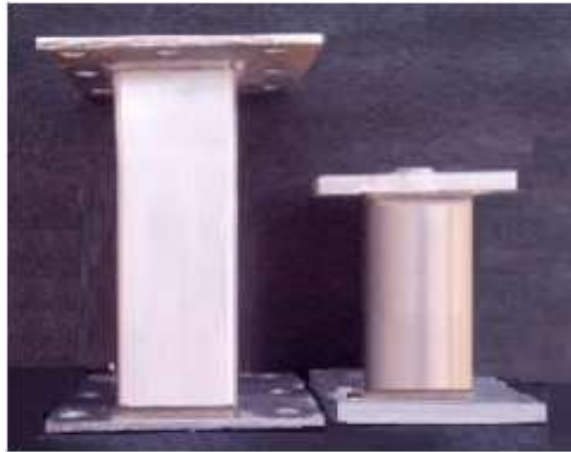


Figure 2.2 Moulds of cylindrical shape and rectangular block

➔ The type of aluminum chosen is Al99.5, physical properties are summarized in Table 2.1 :

Table 2.1: Main physical properties of aluminum

Caractéristiques physiques	
Masse volumique(g/cm ³)	2.70
Coefficient de dilatation linéique (0 à 100 °C) (10 ⁻⁶ /K)	23.6
Module d'élasticité(MPa) (1)	69000
Coefficient de Poisson	0.33
Conductivité thermique (0 à 100 °C) (W/M°C)	État O/H18 : 231
Résistivité électrique à 20 °C (μΩcm)	État O/H18 : 2.8
Capacité thermique massique (0 à 100 °C) (J/kg°C)	945
Limité élastique RP0.2 (MPa)	20
Limite à la rupture Rm (MPa)	60-95
Allongement(%)	25

2.2.2 Preform preparation :

The first step in the process of making foam by infiltration involves the preparation of the preform, which is the negative form of the foam, occupying all the space that will become the pores. The structure of the foam can be adjusted using different shapes and sizes of preformed materials. To be effective, the preformed material must meet three main requirements:

- Have a higher melting point than cast metal.
- Be chemically stable in contact with molten metal.
- Be easy to remove once the metal solidifies.

For our study, sodium chloride was chosen as preform material because it satisfies all these conditions. With a melting point of 801°C,[101] it remains chemically inert when in contact with aluminum during infiltration and leaching. In addition, the removal of salt from the foam does not generate toxic or dangerous by-products.[102].

For this purpose, ordinary rock salt was used, the properties of which are detailed in Table 2.2. Initially, it was ground and then sieved to obtain the desired preform size. To achieve salt particles in the required range, the salt powder was subjected to several passes through different sieves. A diagram detailing the sieve order is shown in Table 2.3.

Table 2.2: Salt Properties

Matériel	Propriété	Valeur
sel	Densité	2200 kg m ⁻³
	Conductivité thermique	7 Wm ⁻¹ k ⁻¹
	Chaleur spécifique	880 Jg ⁻¹ k ⁻¹

Table 2.3: The order of sieves used to separate particle size

2.8 mm
2 mm
1.6 mm
1 mm

2.2.3 Production process of metal foams :

The manufacturing process of metal foams is based on the infiltration technique, which is divided into three stages: injection, infiltration and solidification (see Fig. 2.3). This method uses sodium chloride (salt) particles as a space carrier to form the internal structure of the foam[103.105]. Known as the salt-aluminum method, this process was developed by Seliger and Deuther[106], praised for its lower cost and ease of use. In addition, salt is non-toxic and can be easily removed with water. It should be noted that porosity and pore size can be adjusted according to the size of salt particles, preform density and infiltration pressure[104]. In this study, aluminum foams were manufactured using the salt-aluminum method, using three different sizes of salt particles to obtain foams with various pore sizes. The preform was made by pouring salt into a mold, then allowing the molten aluminum to seep through the preform. Throughout this study, the infiltration method was improved and perfected to achieve the desired results.

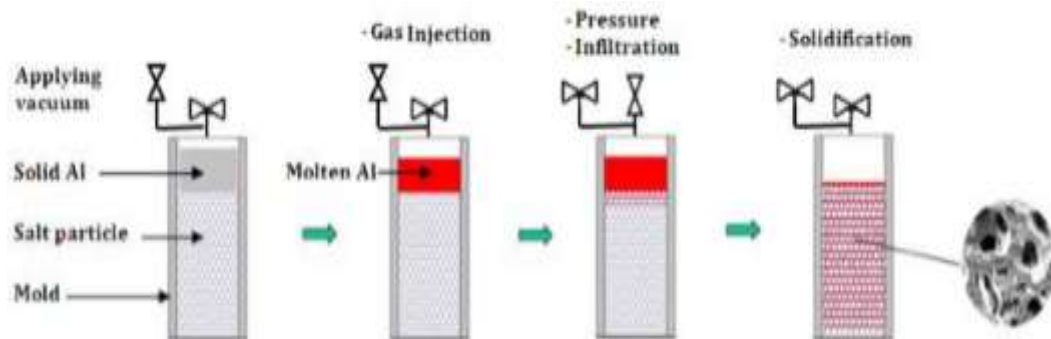


Figure 2.3: Main stages of production of open-cell aluminium foam

2.4 The process steps:

The steps to develop aluminum foam are as follows:

1. The NaCl powder to be infiltrated is introduced into the mold.
2. Pieces of aluminum are placed in the mould and on the NaCl preform.
3. A graphite seal in the groove of the mould cover.

4. Fixing Stainless Steel Studs
5. Fixing the Top of the Lid to the Valve System
6. Closing All Valves in the System.
7. Opening the valve leading to the vacuum pump and mould
8. The vacuum pump is turned on to the lowest possible pressure.
9. The vacuum pump is stopped.
10. If the vacuum loss in the system is less than 50 mbar for the first 10 seconds after the vacuum pump has stopped, then the seal is good enough for infiltration.
11. Without disconnecting the valve system, place the mould in the preheated oven and wait one hour until melting point (680°C) of the aluminum.
12. the vacuum pump valve is closed
13. The argon tank valve is opened and then the pressure and infiltration flow is adjusted using the control valves.
14. After 3 min, argon cylinder valve is closed
15. After 5 min, the mold is removed from the oven and then placed on a cooling surface (in this case, a brass block).

Note: During the cooling process, the pressure in the system may change at the beginning, so the pressure indicated by the regulator should be monitored and adjusted if necessary.

16. After 30 minutes, the valve system is detached and the lid is unscrewed
17. Sample extraction from the mould. Note that an aluminum-salt composite will be obtained
18. Finally, to extract salt from the prepared sample, the infiltrated foam is placed in a water beaker to dissolve the NaCl preform.

Note: To ensure that no more NaCl remains in the foam, the water has been changed more than 10 times until the NaCl is completely removed from the foam. It is also important to periodically check the weight of the sample after a brief drying phase

2.3 The porosity of the metal foams :

The porosity of a porous medium, symbolized by φ , represents the proportion of the total volume of the medium that is occupied by voids . Thus, fraction $1 - \varphi$ corresponds to the portion occupied by the solid. In the case of an isotropic medium, the "surface porosity" (that is, the fraction of the empty area relative to the total area of a typical section) is generally equal to φ . By defining φ in this way, we assume that all the empty space is connected. However, if part of the porous space is actually disconnected from the rest, an "effective porosity" must be introduced, defined as the ratio of the vacuum connected to the total volume. In natural environments, φ generally does not exceed 0.6. For beds of solid spheres of uniform diameter, φ can vary between 0.2595 (rhombohedral trim) and 0.4764 (cubic trim). Variation in grain size tends to result in smaller porosities than for uniform grains, as smaller grains fill the pores formed by larger grains. For artificial materials such as metal foams, φ can approach the value of "1 " [100].

We than have :

$$\varphi = v_p / v_t \quad (1)$$

Another method based on density measurements: this method is based on a simple equation :

$$\varphi = 1 - (\rho_g / \rho_m) . \quad (2)$$

With ρ_g overall density of porous media, ρ_m density of the material that forms the solid structure of the porous medium. To determine the coefficient ρ_g there are different techniques, for example geometric parameter measurements and sample weighing, or volumetric substitution (this technique involves immersion of the sample in a non-wetting liquid, for example mercury, which does not penetrate the porous medium), etc.

Chapter 03

Mechanical properties of Al foams

3.1 Introduction :

In this chapter the structural parameters, the mechanical properties of aluminum foams with open cells of moderate porosity obtained were determined

3.2 Experimental Setup and porosity :

In order to conduct this experiment, three cylindrical samples of metal foam were prepared in advance, but with a different porosity of each sample, as follows (0.62, 0.67, 0.7) as shown in the table (3.1) bellow . To calculate the porosity of the samples, the weight and size of the sample were first measured. Thereafter, the weight of the sample-like steel aluminum bar (the same size) was calculated by knowing the pure aluminum density (2.7 g/cm³ supplied by the supplier). Now porosity can be calculated by subtracting these two values and calculating the percentage of the vacuum within the sample .

Note : Length and diameter are equal in all the samples

3.2.1 Density :

The actual density of the foam was measured in ways that weighed the known volume sample (i.e., by measuring the density of the foam and normalizing it to that of the water)

3.2.2 The specific surface :

The specific surface of the aluminum foams was obtained by assuming that all the salt particles were spheres. Equation (3) was used to obtain the specific area.

$$S_p = \frac{6(1-\varphi)}{d_p} \quad (3)$$

d_p : pore diameter



3.2.3 Pore diameter :

The pore diameter was estimated by counting the number of pores in a given length of metal foam. It can be calculated using the following equations.

$$d_p = \frac{0.245 \text{ m}}{PPI} \quad (4)$$

PPI : pore number per inche

Table 3.1 Samples used and their properties

Samples	PPI	porosity	Diameter (mm)	Length (mm)	Density (g/cm^3)	specific surface (m^{-1})
	13	0.62	60	58	0.98	1167
	18	0.67	60	58	0.89	1403
	24	0.7	60	58	0.76	1701

3.3 Principle :

The mechanical performance of metal foams also depends on their relative density, cell topology, size and shape [107]. Relative density, according to Pinto et al. [108], is the most important factor in determining the mechanical behaviour and strength of a metal foam. For example, a denser foam has a higher modulus and yield strength [109-111]; however, the density and average cell size are not independent. Higher mean cell size leads to lower densities, but within certain limits, results in cell wall rupture [111], For example, the effects of cell size and shape were studied by Nieh et al. [110], and quasi-static compression tests were performed by Kang et al. [112], which evaluated the mechanical properties and deformation characteristics of open-cell aluminum foams. The latter showed that the mechanical behaviour of the foams is not very sensitive to the rate of deformation and the open-cell foams exhibited homogeneous plastic deformation. The compression test on an aluminum foam is the easiest to perform and therefore the most widespread and studied test. However, as it is not currently uniform, a

number of precautions must be taken to obtain more reproducible and comparable results. Indeed, there are multiple parameters that can influence the shape of the stress/displacement or stress/strain curve. The compression behaviour of aluminium foams has been studied in depth because of their energy dissipation capacity. In tension, aluminum foams generally exhibit a fragile behavior. The tensile load is also important in practice, because the structures can be subjected to bending and the brittle tensile behavior that results in energy absorption. Compression tests on several samples of different pore sizes allowed to draw the stress curve (in MPa) according to the deformation. This leads to the interpretation of the curves of the compression tests which present a peak Marchic and Mortensen [113] analyzed the relationship between relative stress and relative density. The most common test method for aluminum foams is the uniaxial compression test. The stress-strain curves obtained from the tests consist of three parts:

- 1- quasi-elastic region,
- 2- plateau region and
- 3- densification region.

The quasielastic region is defined as the production of the weakest porous layer, usually called collapse stress. The plateau area is characterized by high energy absorption efficiency, where almost all deformation, energy is absorbed at a constant level of force. The densification region is characterized by a rapid increase in force to an almost constant deformation. However, the regions on the stress-strain curves are different due to density variability, structural defects, porosity, etc.

- Strain stress σ was calculated from force F using an apparent cross-sectional area S of the specimen:

$$\sigma = F / S \tag{5}$$

- the deformation ε was calculated from its height under compression is:

$$\varepsilon = \Delta h / h_0 \tag{6}$$

3.4 Experimental study of mechanical properties :

The experimental composition used in this study is shown in figures (3.1) and (3.2). The flat sides of each cylindrical material are designed to ensure that the two cylinder sections are perfectly parallel. Material diameter $d_0 = 60$ mm and initial height $h_0 = 58$ mm. The samples can then be compressed by forcing displacement using a traffic engine. The deformation rate is controlled and installed between two pillars, one mobile and the other fixed. For each test, pre-strain is applied to confirm the contact of the sample with the mobile part of the compression device and measures the force sensor, which has a maximum value of 200 kN, the resistance of the material under mechanical displacement of the support. and the reliable speed (velocity) of the experiment was $V=0.5$ Mpa/s

The whole of this experimental technique will allow us to characterize the materials after each manufacturing step and to make the link between the properties of the samples, the structure of the foams obtained and their mechanical properties. Knowing the contact surface S_0 (initial section of the cylinder before compression), the stress σ is deduced from the force according to equation (5). For the measurements made in this work, we will consider S_0 as invariant during compression. The deformation is defined according to equation (6).

$$\sigma_p = \frac{\int_{\varepsilon_0}^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon}{\varepsilon_d - \varepsilon} \quad (7)$$

Note : The experiment was prepared and carried out in the laboratories of the Civil Engineering Department in mohamed khider university of biskra



Figure 3.1 The compression machine used



Figure 3.2 Machine and tools used for experimentation

3.5 Mechanical properties :

The $\sigma - \epsilon$ curves are shown in Figure 1.4, which shows the compression load curves on aluminium foams and different porosities (0.62, 0.67 and 0.7) and pore densities(13, 18, 24 PPI) (PPI : pore number per inch) . As illustrated by the stress-strain curves, when the foam is loaded in compression, plasticization occurs at about 0.12 deformation followed by a long densification plateau up to about 0.5 deformation figure 3.3. During this densification phase, the foam undergoes strong deformations without substantial increase in stress. At about 0.5 deformation, the collapse of the ligaments of the foam is complete and the voids that were initially present in the material no longer exist. Once the densification is complete, the constrained deformation relationship shows a drastic increase in stiffness as the foam takes the elastic properties of the material base. That is, the slope of the stress-strain curve of the foam after densification is equal to the modulus of elasticity of the aluminum. The compression curve of an aluminum foam was broken down into three phases: elastic, plastic tray and densification. These three phases were at different modes of deformation of edges and walls and thus at the mechanical behavior of the base materials.



Figure 3.3 The sample before and after the deformation

The behaviour of aluminum foams in compression in the elastic zone can be described by the classic choice of Young E modulus, is due to a rearrangement regime at the beginning of the compression test. The second step, the plastic tray, When the stress exceeds a certain threshold, the foam cells collapse plastically, resulting in a long, almost horizontal tray on the stress/displacement curve from which the deformation is no longer recoverable. The third step, a significant plastic deformation in compression produces a densification of the collapsed cells, which leads to an increase of the stress which then tends towards infinity for a certain level of deformation ϵ_d . The densification of the material will be total when the overall volume of the material after compression is equal to the volume of solid . In addition, the influence of the structure of aluminum foam has an effect on the mechanical behavior of the material, that is, the curves of the three samples are different. It has been reported that the mechanical behaviour of foam materials is complex and depends mainly on three factors, namely porosity, density and microstructure . According to Table 3.2, aluminium foams with higher density (0.98 g/cm^3) and lower porosity (0.62) have the highest modulus of elasticity (0.60 GPa) and plateau stress σ_p (19.77 MPa). The solidification phenomenon occurs on the stress/displacement curve with lower porosity occurs at the plateau phase, leading to a significant increase in the plateau. Stress-strain curves for foams of different porosities showed that the yield strength of the samples varied as shown in Figure 3.3. It has been found that the most important factor in the compressive strength of foams is their porosity or relative density [112]. The discontinuous line shown in Figure 3.3 shows that the densification deformation of open-cell aluminum foams generally decreases with decreasing porosity. This is mainly due to the increase in the solid phase volume ratio, which produces the earlier densification step in the uniaxial compression test. With continuous foam cell collapse, the matrix begins to densely stack on each other, until the cells are completely compressed and the compression curve reaches the densification stage

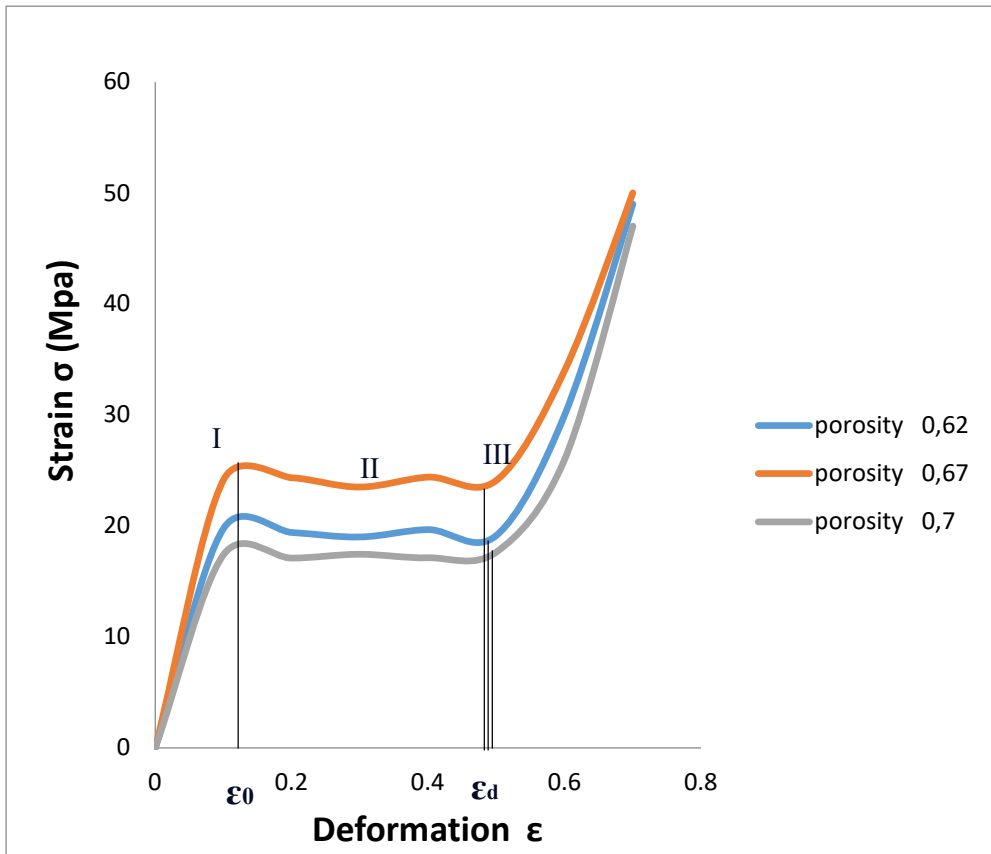


Figure 3.4 Stress curve/ deformation characteristic of aluminum foams obtained with different porosities.

It is clear that through compression testing, the mechanical properties and behaviour of the foam can be significantly improved by reducing porosity. Based on the model of Gibson et al. [114] and Ashby et al. [115], fit curves were proposed for the modulus of elasticity table (3.2), plateau stress and energy absorption capacity of the samples

Tableau 3.2 Paramètres mécaniques des mousses d'aluminium avec différentes porosités ϕ .

SPECIMEN OF AL FOAM	E (GPA)	σ_P(MPA)
0.62	0.55	19.77
0.67	0.68	24.15
0.7	0.49	17.38

3.6 Energy absorption capacity per unit volume :

As shown in Figure 3.4, open-cell aluminum foams show many energy absorption gains for the long compression stress plateau during the plastic deformation phase resulting from the progressive collapse of the cells, allowing enormous deformations when stress gradually increases. The area under the stress curve to a particular deformation represents the energy absorption per unit volume W_v , where the area under the curve is calculated by integration [116]:

$$W_v = \int_0^{\epsilon} \sigma(\epsilon) d\epsilon \quad (8)$$

The ability of aluminum foams to absorb energy is mainly due to cellular performance, friction between cell walls, bending and tearing [117, 118]. Low porosity foams have a higher yield and breaking power than higher porosity foams [17]. In addition, they include a higher solid matrix ratio, releasing more friction energy during cell degradation. Thus, low porosity aluminum foam has a greater ability to absorb energy than foams with higher porosity. Although the condensation deformation in the weakly porous foam is less, a higher plateau stress gives a higher condensation deformation energy value. Moreover, the porosity effect corresponds to the effect of the relative density on the deformation energy of the density. While density deformation decreases with increasing relative density (i.e. reduced porosity), density deformation energy increases significantly with relative density, mainly due to increased plateau stress. Therefore, a high relative density of open-cell aluminum foam should be used when you need to absorb a large amount of energy.

Energy absorption capacity is generally used to describe energy absorption until condensation deformation. It is mysterious to identify condensation deformation with low porosity, to avoid the condensation deformation factor, so it is reasonable to assess energy absorption capacity as a function of stress [119]. The amount of stress transferred to the protected element should be below a certain limit. That is, even if the absorbed energy is sufficient, protection will be useless if the protected element is damaged. Therefore, for applications involving protection, it is best to estimate the energy absorption capacity associated with the same stress in all samples. Low porosity open cell aluminum foam demonstrates the best ability to absorb energy.

3.7 Conclusion

In this part of study, open-cell aluminum foams with moderate porosity were studied. Their structural parameters, mechanical properties and main results can be summarized as follows:

- Porosity distinguish foam from the base material from which it is derived.
- Compression curves of aluminum foams showed three typical phases: elastic phases, plastic plateau and densification.
- Open cell aluminum foams with low porosity are particularly sensitive to work hardening phenomena, which results in significantly high plateau stress. Additionally, for the same strain, the ability of open-cell aluminum foams to absorb energy increases as porosity decreases.

The foams with porosity (0.67) have a higher Young's modulus, which contradicts the typical behavior of porous materials. In general, materials with lower porosity tend to have higher Young's modulus due to increased material density and structural integrity. Therefore, it is possible that the aluminum foam samples with low porosity (0.62) were fabricated under low pressure.

General Conclusion

Three samples were manufacturing for this investigation by packing the salt particles at random. Several parameters, including the size, shape, and friction factor between the particles, affect packing density. The preform packing density and the infiltration pressure affect the porosity of metal foam. As a result, altering the shape of the salt particles change the parametre of the foam porosity. Given that crushed salt particles were used to make the foams used in this investigation, it would be intriguing to observe how the shape of the particles affected the performance of the samples.

The study also addressed the issues of test compression in metal foams manufactured by the Replication method. The results of this study could help to improve the design and performance of metal foams in various applications, such as lightweight structural components, and energy absorption materials. By gaining a better understanding of test compression behavior in metal foams manufactured by the infiltration method, can optimize the material properties, structural integrity, and energy absorption capabilities of these foams. This knowledge can lead to the development of more efficient and cost-effective metal foam products that meet specific performance requirements in industries ranging from automotive, aerospace, construction and electronics.

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