Engineering Materials

ENGR 220

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Research Study on Syntactic Metal Foams

Abstract

Syntactic metal foams are drawing much attention because of their good strength, high compressibility, and especially their advantageous mechanical and physical properties. Syntactic metal foams will significantly improve the world around us and will be used in a large number of applications. The paper shows how syntactic metal foams are extremely useful for multiple applications and that they are capable of withstanding many internal and external impacts from the environment. The paper summarizes research based on the advantages of using syntactic metal foams due to their strong, light weight structure, and the paper will also introduce the materials and processes required to produce these various syntactic metal foams.

Table of Content

Contents

Table of Content 3

Table of Figures, Tables, and Equations 4

Introduction 5

Motivation 5

Applications 5

1. Definition 6

1.1 The Class of Materials 6

1.2 The Structure of Atoms 6

1.2.2. The Electronic Structure of the Solid: Energy Bonds and Chemical Bonds..... *8*

2.Physical Properties 8

2.1 Density 8

2.2 Thermal Conductivity 9

2.3 Electrical Conductivity 10

2.4 Superconductivity 11

2.5 Specific Heat 11

2.6 Melting Range 11

2.7 Thermal Behavior *12*

2.8 Magnetic Properties 12

2.9 Phase Transformations 12

3. Mechanical Properties 12

3.1 Yield Strength 13

3.2 Tensile Strength 14

3.3 Shear Strength 15

3.4 Elongation 15

3.5 Young's Modulus 16

3.6 Ductility 16

3.7 Impact Strength 16

3.8 Fatigue Resistance 18

3.9 Failure Analysis and Prevention 18

4. Manufacturing Process 18

5. Materials and Environment 20

6. Cost Analysis 21

Summary 23

References 24

Table of Figures, Tables, and Equations

Figure 1. Examples of marine structures, exhaust and generator systems, fire-resistant structures, etc. [5] …………5

Figure 2. (a) porous structure of syntactic metal foams (b) product blocks of syntactic metal foams [9] …………….6

Figure 3. Octahedral structure model for reticular porous materials [9] ……………………………………………7

Figure 4. Octahedral pore unit in reticular porous materials [9] ……………………………………………………7

Figure 5. Example of reticular tungsten foam [9] …………………………………………………………………..8

Figure 6. (a) physical model, (b) heating, cooling cycle [4] ………………………………………………………10

Figure 7. Engineering stress – engineering strain curves of (a) Al99.5 and (b) AlSi9MgMn [11] ………………… 13

Figure 8. (Left) Generalized compressive engineering stress – engineering strain curve (Right) Yield strengths [11] ….13

Figure 9. Simulated flow curves used for AlSi10 material [3] ……………………………………………………14

Figure 10. Experimented tensile test results compared with simulated stress-strain curves [3] ……………………..14

Figure 11. Pore unit of the porous body under shearing loads [9] …………………………………………………...15

Figure 12. Model for the tensile deformation of octahedral pore unit [9] ………………………………………...16

Figure 13. Brittle fracturing of 350-type metal foam [5] ……………………….………………………………17

Figure 14. Direct foaming of melts with blowing agents (ALPORAS process) [3] …………………………………19

Figure 15. Direct foaming of melts by gas injection [3] …………………………………………………………..19

Figure 16. Process scheme of the p/m space-holder methods [3] …………………………………………………19

Figure 17. Production scheme for high temperature alloy foams [3] ………………………………………………..20

Figure 18. Syntactic foam matrices [1] ……………………………………………………………………………20

Figure 19. Material strength plotted versus (a) specific cost and (b) volumetric cost [7] ………………………………22

Table 1. Density of the uniform syntactic metal foam samples [10] ……………………………………………………9

Table 2. Density of the functionally graded syntactic metal foam samples [10] ……………..……………………………9

Table 3. Thermophysical properties of paraffin RT27, RT58 and aluminum foam. [4] …………………………………10

Table 4. Properties of different metal samples that are used in metal foams, includes melting range. [6] ………………12

Table 5. Basic material properties and impact energies [5] ……………………………………………………………17

Table 6. Overview of cost figures for selected types of cellular metals and their base metals [7] ….……………………20

Equation 1. Constant heating, cooling and sinusoidal heating, cooling [4] ……………………………………………10

Equation 2. Equates to skin depth of sample, used with calculations of AC and DC magnetic fields. [8] ………………12

Equation 3. Young’s modulus of porous bodies [9] …………………………………………………….....................16

Equation 4. Estimation of volumetric cost of syntactic metal foams [7] ………………………………………………21

Equation 5. Estimation of specific cost of syntactic metal foams [7] …………………………………………………21

Introduction

Syntactic metal foams are becoming highly popular because of their distinguished mechanical and physical properties. Properties that describe the material of syntactic metal foam include low density, lightweight, low elastic modulus, high energy absorption capacity, and high specific strength. Syntactic metal foams have multiple benefits when it comes to using the material for structural and mechanical design.

Motivation

I was very motivated to research about metal foams because of its great advantages as a material and especially because of the strength metal foams have. Since metal foams are very lightweight and high in strength, I believe that they can be used for more future construction projects and designs. Metal foams have been considered to be used in constructing space colonies in the future, which can be crucial if our society progresses in residing in space. Not only has it been proposed for use in space colonies, but it can be used for more realistic real-world applications as well.

Applications

In a number of engineering fields, covering energy engineering, metallurgy, machinery, construction, electrochemistry, petrochemistry, bioengineering, environmental protection, transportation, aviation and aerospace, porous materials can have the own application advantages that other materials are difficult or impossible to replace them, among which the three-dimensional (3D) reticular metal foam occupies a very important position in production scale and practical applications [9]. Syntactic metal foams can be used for many different types of engineering fields due to the mechanical and physical property advantages the material contains [Fig. 1]. Syntactic metal foams may be used for higher-detailed, more specific applications which include lightweight structures, sandwich cores, strain isolation, mechanical damping, vibration control, acoustic absorption, energy management (compact or light energy absorbers), packaging with high-temperature capability, artificial wood (furniture or wall panels), thermal management (heat exchangers/refrigerators or flame arresters or heat shields), consumable cores for castings, biocompatible inserts, filters, electrical screening, electrodes and catalyst carriers, and buoyancy [2]. Syntactic metal foams have a wide range of use and capability that the material can be used in a large variety of different designs and projects.

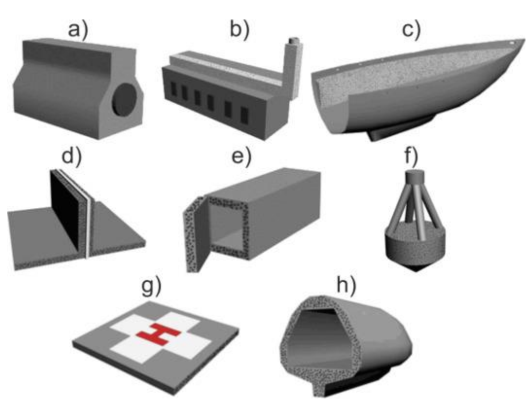
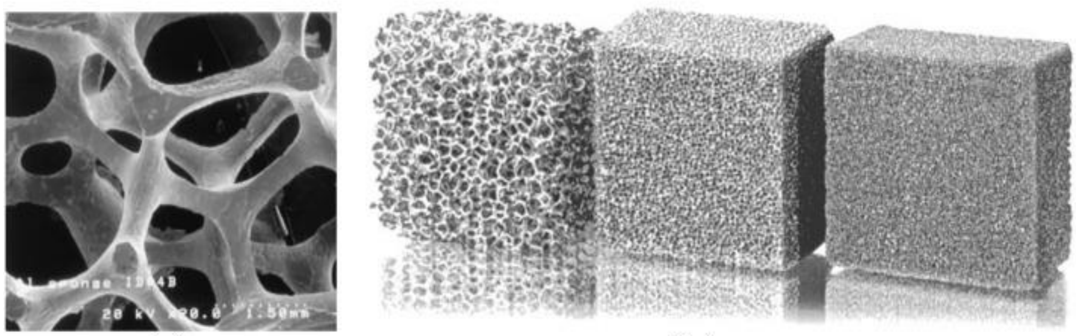


Figure 1. Examples of marine structures, exhaust and generator systems, fire-resistant structures, etc. [5].

1. Definition

Syntactic metal foams are materials whose foam structure is provided by non-metallic spheres with a hollow or porous structure mixed into the base metal, therefore they can also be considered as a metal-matrix composite in which the primary role of the reinforcing material is to reduce density [6]. Any metals can be used as the base material in syntactic metal foams, however, aluminum is the most used for metal foams because of its industrial significance and its exceptional castability. Syntactic metal foams can differ in how porous they are which shows the wide range of capability they have depending on what applications they are used for [Fig. 2].



(a) (b)

Figure 2. (a) porous structure of syntactic metal foams (b) product blocks of syntactic metal foams [9].

1.1 The Class of Materials

Syntactic metal foams are considered to be categorized as composites. Composites are usually made up of two or more different materials. These different materials can contain diverse physical or chemical properties, so when combined together, they create a material with properties unlike any of the individual elements from the periodic table. These metal foams commonly consist of many various metals such as aluminum, silicon, manganese, magnesium, and some other metals can be included as well. All of the metals found in syntactic metal foams have similar and/or dissimilar physical and chemical properties from each other, thus defining the class of material for syntactic metal foams as composites.

1.2 The Structure of Atoms

Reticular porous materials with high porosity are of three-dimensional reticulated structures formed by mutually interlaced connection of pore struts. In these reticular porous foam products, pore struts connect in a complicated way and take various directions; and the resultant pore shapes are also varied, with irregular trend changes [9]. With experimentation done to finalize the structure of the atoms within three-dimensional porous metals, experts claim that the best structural model for reticular syntactic metal foams is the octahedral model. The octahedral model offers many benefits for metal foams. These octahedral pore units are closely packed to one another alternatively in three orthogonal directions to fully fill the space, and can extend regularly, thus forming three-dimensional isotropic porous uniform structure [9]. The octahedral model is a complex structure that features good shaping and form within the model itself. The octahedral structure contains two face-centered atoms, one on the top plane and one on the bottom plane of the structure [Fig. 3]. The octahedral pore units are all the same shape and size, but their axial directions are perpendicular to each other. Since the octahedron units extends in three orthogonal directions, the structure is considered three-dimensionally isotropic.

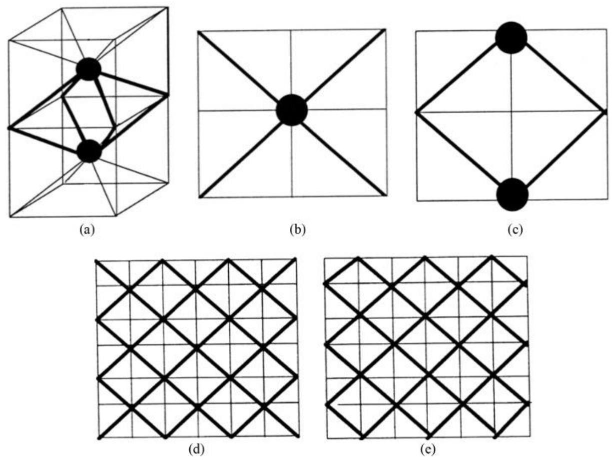


Figure 3. Octahedral structure model for reticular porous materials: (a) octahedral pore unit; (b) axial projection of the pore unit (top view); (c) lateral projection of the pore unit (side view); (d) direct projection of the set of pore units (face view); (e) lateral projection of the set of pore units (side view) [9].

1.2.1. The Electrons in an Atom

Defects within the internal structure of syntactic metal foams may cause problems with the strength and the allowable stress of the material. Since metal foams have high porosity, there is a possibility of production error of the material, which can cause the material to fracture easier. There is a low chance of error when producing foams, due to the structure having a uniform and structurally equivalent nodes and pore-struts within the matrix structure. All reticular porous materials, like syntactic metal foams, have equivalent nodes and struts. This is due to the composition of the nodes and the struts in the matrix, which results in an uniformly three-dimensional isotropic structure for syntactic metal foams [Fig. 4].

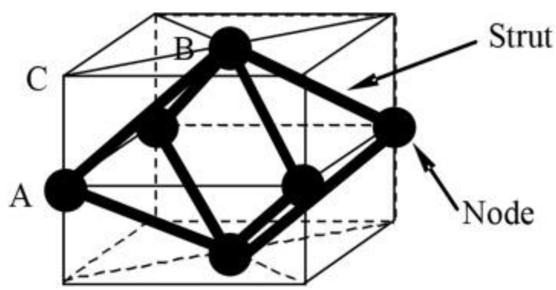
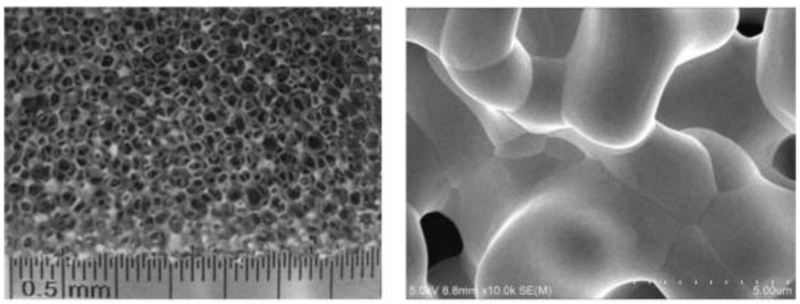


Figure 4. Octahedral pore unit in reticular porous materials [9].

When the porous material is anisotropic, the original octahedral unit in the analytical model would be thought to be stretched, flattened, or distorted in the axial direction. It can be seen that the electric current path of each pore-strut will be almost unchanged, that is, the total electric resistance of the octahedral unit will be unchanged, but the apparent total current path and the cross-sectional area for the total current flowing through the octahedral unit will both change [9].

1.2.2. The Electronic Structure of the Solid: Energy Bonds and Chemical Bonds

To produce a syntactic metal foam such as, tungsten foam, scientists use the improved vacuum sintering process. This process gives the metal foam little closed pores, good impregnation, high porosity (>58%) and good connectivity [Fig. 5] [9]. Tungsten foam and all other metal foams have strong grain bonding between the grain boundaries, which is why syntactic metal foams have excellent strength. In order to produce the hollow particles within the metal foams, experts must use other processes similar to improved vacuum sintering. These hollow particles can then be sorted by flotation methods, and consolidated by hot isostatic processing, by vacuum sintering, or by liquid-phase sintering. Liquid-phase sintering may be the preferred approach for some alloys since it avoids the compressive distortions of the thin-walled hollow powder particles that results from the hot isostatic processing process and avoids the prolonged high-temperature treatments required to achieve strong particle–particle bonds by vacuum sintering methods [2].



(a) (b)

Figure 5. Example of reticular tungsten foam: (a) macroscopic morphology; (b) grain bonding state [9].

2.Physical Properties

Syntactic metal foams feature very impressive physical properties that help it withstand much of its environment. Syntactic metal foams are lightweight, have low thermal conductivity, great energy absorption, great sound absorption, and more. Some tests that are used to find information and data of the physical properties of a material are compression testing, tensile testing, flexural testing, shear strength testing, peel strength testing, drop/impact testing, and more.

2.1 Density

All syntactic metal foams are very lightweight due to them having high porosity and having many empty sections throughout the structure. Most kinds of uniform syntactic metal foams have a density ranging between 1.90-2.20 $g \cdot cm^{-3}$ [Table 1].

Sample no	Density ($g \cdot cm^{-3}$)
EP-MSF-1	1.92
EP-MSF-2	1.99
EP-MSF-3	2.02
AC-MSF-1	2.13
AC-MSF-2	2.04
AC-MSF-3	2.15

Table 1. Densities of the uniform syntactic metal foam samples [10].

Samples of functionally graded syntactic metal foams have higher densities because of the change in filler type [Table 2]. The filler type in these samples is in the longitudinal direction rather than in the lateral direction. The overall volume fractions of matrix and particles in functionally graded syntactic metal foams fall between the values of two uniform syntactic foams. The functionally graded syntactic metal foam fractions are estimated based on the assumption that the particle volume fractions in each layer corresponds to the value of the uniform foam [10].

Sample no	Density ($g \cdot cm^{-3}$)
FG-MSF-1	2.11
FG-MSF-2	2.15
FG-MSF-3	2.15
FG-MSF-4	2.14

Table 2. Density of the functionally graded syntactic metal foam samples [10].

2.2 Thermal Conductivity

All syntactic metal foams have low thermal conductivity, which is highly advantageous for many applications. Non-combustible aluminum foams have a thermal conductivity coefficient that is 10-20 times lower than that of solid metallic materials, which significantly increases the fire safety of liquefied natural gas tanks, for example [5]. Metal foams can be embedded with phase change materials within their structure, meaning that small volumes of the metal foam would be able to store and release a large amount of heat during phase changes. To display the thermal conductivity of metal foams, an experiment using aluminum foam with embedded paraffin wax (phase change material), can be used as an example. A square cavity with the dimensions of 4cm x 4cm is filled with paraffin wax, RT27, and embedded in an aluminum foam with porosity of 0.93 and pores density of 40PPI. A heat flux is applied in the left wall cavity. There are a two types of cycling heating and cooling applied to the PCM/metal foam composite. The first is at a constant flux of +1800 W/m^2 provided from the heated wall at 60mins, and then its value becomes negative at the same magnitude for the next 60mins. The second, is a sinusoidal function having the similar area under the curve it is provided for the same time [Fig. 6]. The equation for the boundary condition in the left wall is presented in [Eq. 1]. The rest of the wall cavity is insulted. Initially, the metal foam and the PCM in the cavity are placed under a uniform melting temperature at 294.15K. The proprieties of paraffin RT27 used for the present study are given in [Table 3] [4].

$$q_w = \left\{1800\frac{W}{m^2}, (0 \leq t \leq 60 \text{ min})\right\},$$
$$= \left\{-1800\frac{W}{m^2}, (60 \leq t \leq 120 \text{ min})\right\} \quad Constant\ Heating, cooling$$
$$= 900\ \times \pi \times \sin(\pi \times \frac{t}{60}) \qquad Sinusoidal\ heating, cooling$$

Equation 1. Constant heating, cooling and sinusoidal heating, cooling [4].

a). b).

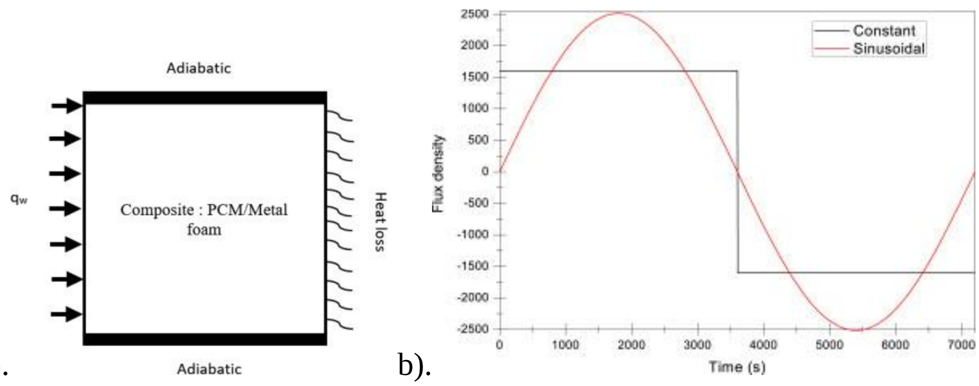


Figure 6. (a) physical model, (b) heating, cooling cycle [4].

properties	Paraffin RT27	Aluminum	Paraffin RT58
Density ($kg.m^{-3}$)	870	2800	850
Heat capacity–solid ($J.K^{-1}.kg^{-1}$)	2400	910	2100
Latent heat ($KJ.kg^{-1}$)	179		181
Melting temperature (K)	300.15		331.15
Dynamic viscosity ($Kg.m^{-1}.s^{-1}$)	3.42×10^{-3}		0.0269
Thermal conductivity –solid ($W.K^{-1}.m^{-1}$)	0.24	237	0.2
Density – liquid ($kg.m^{-3}$)	760		775
Heat capacity –liquid ($J.K^{-1}.kg^{-1}$)	1800		2100
Thermal conductivity – liquid ($W.K^{-1}.m^{-1}$)	0.15		0.2
β (K^{-1})	0.5×10^{-3}		1.1×10^{-4}

Table 3. Thermophysical properties of paraffin RT27, RT58 and aluminum foam. [4].

The thermal conductivity of metal foams is already low, but with phase change materials embedded within the structure of these metal foams, the thermal conductivity can be improved even more. In comparison to different solid materials, syntactic metal foams have lower thermal conductivity than materials like pure aluminum, pure steel, pure iron, etc.

2.3 Electrical Conductivity

Syntactic metal foams that are very porous are nonconductive, which would make their electrical conductivity lower than many other types of materials. Syntactic metal foams have lower electrical conductivity than other foams such as polymer foams and ceramic foams. Electromagnetic wave absorption for metal foams can be applied to electromagnetic shielding, electromagnetic compatible parts, and protection shields of electronic instruments. With additional electronic applications, including electrical appliances, the radiation from electromagnetic waves can disturb the operation of electronic instruments, cause leaking problems, and damage the human body [8]. Electrical shielding is very important for these electrical applications. Interconnected 3-D reticulated copper and nickel foams are mainly used in electromagnetic shielding due to their properties of good permeability, good heat dissipation, low density, and better shielding effects than metal wire nets. Due to their much smaller volume and greater portability, these metal foams are better suited for use in portable instruments [8].

2.4 Superconductivity

Super conductivity is the ability to deliver electricity with almost no resistance, which means that no electricity is absent throughout the process. The most common types of syntactic metal foams produced are made with aluminum. Aluminum is considered to be a superconductor due to its properties of being a metal. Through experimentation done on aluminum foil samples, a roll of aluminum foil was subjected to a special oxidation process which includes annealing in oxygen followed by annealing in vacuum and quenching to liquid nitrogen. The AC magnetic susceptibility and electrical resistance measurements have found metastable superconductivity of the sample at $T_c \approx 65$ K. The collection of experimental facts indicates that the superconducting phase is confined in the interfacial layer, between the oxide skin and the metallic Al interior of the foil. The superconducting interfacial layer consists of weak-linked superconductive grains embedded into a non-superconducting host matrix. [12]. Since aluminum is a superconductor, this makes its applications in other materials, like syntactic metal foams, advantageous.

2.5 Specific Heat

Many metals such as aluminum, iron, copper, etc. already have good specific heat capacities. Since syntactic metal foams are very porous in structure, this allows the material to cool at a faster rate due to the air pockets within the pores. Syntactic metal foams have higher specific heats than other pure metals, which gives this the material the upper hand when compared to other base metals.

2.6 Melting Range

Since syntactic metal foams have a higher specific heat than ordinary base metals, this would mean that the melting point and the melting range would be slightly higher. The melting points of aluminum foams are slightly higher than the melting temperature of a basic alloy at 780 °C. This is due to the presence of a thin layer of Al_2O_3 on the pore surfaces, which has a higher melting point. If the temperature continued to increase, the foams partially float and lose their cellular structure due to the presence of a uniform liquid aluminum solution. [5]. For example, the sample material within a specific metal foam, Silafont®-36, has a low melting point, and is an extremely good flowable cast aluminum alloy. In addition to its excellent castability, it is excellently hardenable, weldable, machinable and polishable, and is also highly resistant to corrosion [6]. Syntactic metal foams made from 99.5% of aluminum granulates has an impressive melting range Table 4]. The metal samples by themselves have a good melting range, and syntactic metal foams have a higher melting range because of its porous like structure.

Material	Tensile strength R_m (MPa)	Proof stress $R_{p0.2}$ (MPa)	Modulus of elasticity (GPa)	StrainA (%)	Melting range T (°C)	Density ρ (g/cm^3)
Al99.5	60	20	69	25	645–658	2.7
AlSi10MnMg	279	133	78	8.1	550–590	2.64

Table 4. Properties of different metal samples that are used in metal foams, includes melting range. [6].

2.7 Thermal Behavior

Syntactic metal foams have excellent heat transfer and go through little to no deformation when heated. These metal foams have high thermal resistance, because of their porous structure allowing heat to travel freely through the air pockets, which allows better cooling. Syntactic metal foams can withstand great amounts of heat, making it very applicable for various kinds of operations.

2.8 Magnetic Properties

The magnetic properties within syntactic metal foams are present due to their metal composite structure. Mostly all metal samples used in these metal foams are magnetic, and some of these samples can be non-magnetic at certain temperatures. In AC magnetometry of conducting samples, such as an aluminum foil sample that can be seen within metal foams, the susceptibility measured as a response to the AC drive magnetic field is a function of the skin depth of a sample after deformation [Eq. 2].

$$\delta = \frac{c}{2\pi}\sqrt{\frac{\rho}{\mu\nu}}$$

Equation 2. Equates to skin depth of sample, used with calculations of AC and DC magnetic fields. [8].

The variables ρ and μ are, respectively, the electric resistivity and the magnetic permeability of the material, ν is the ac magnetic field frequency and c is velocity of light in vacuum [8]. Frequently, these syntactic metal foams will mostly have magnetic properties within them since they remain at a steady temperature most of the time.

2.9 Phase Transformations

Syntactic metal foams do well with keeping their solid phase structure due to the thermal conductivity it possesses. Many syntactic metal foams can be embedded with different phase change materials as previously mentioned, in order to store and release large amounts of heat at one time during phase changes. These metal foams have a nearly impossible chance of becoming a gas, as it is mainly transformed from a liquid to a solid during the manufacturing process.

3. Mechanical Properties

Syntactic metal foams provide many advantageous mechanical properties such as having good bending stiffness, good strength, exceptional energy absorption, and more. In order to determine the mechanical properties of syntactic metal foams, experts conduct many tests, one being quasi-static compression tests. These tests measure the compressive capabilities of the material as well as measuring the energy absorption of the material. There are other types of testing that are conducted by experts to measure the mechanical properties of the material such as hardness tests, tensile tests, impact tests, fracture toughness testing, creep testing, and fatigue testing.

3.1 Yield Strength

Yield strength is the stress at which any amount of plastic deformation is produced within the material. The yield strength of syntactic metal foams is determined by using engineering stress and engineering strain curves. Most metal foams are made up of 99.5% pure aluminum (Al99.5) granulates and various AlSi9MgMn or AlSi10MnMg materials [6][11]. In order to find measurement of engineering stress and engineering strain for syntactic metal foams, Al99.5 and AlSi10MnMg must undergo standardized compressive testing. The engineering stress and engineering strain differ in each of the various samples [Fig. 7].

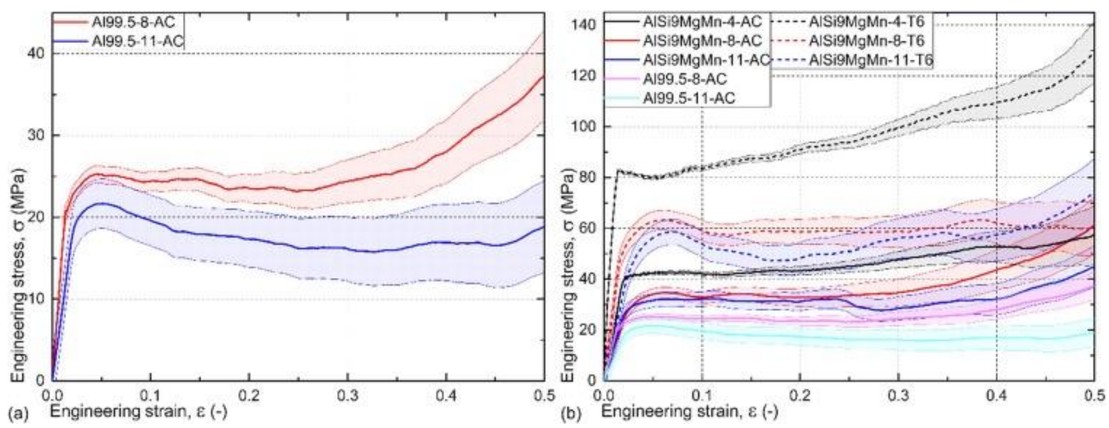


Figure 7. Engineering stress – engineering strain curves of (a) Al99.5 and (b) AlSi9MgMn of syntactic metal foams [11].

With the data found, the yield strength can be determined by comparing engineering stress versus engineering strain in syntactic metal foams. The yield strength is found at the point before the material undergoes plastic deformation. Each sample recorded different yield strengths due to slight changes in the structure and composition of the material [Fig. 8].

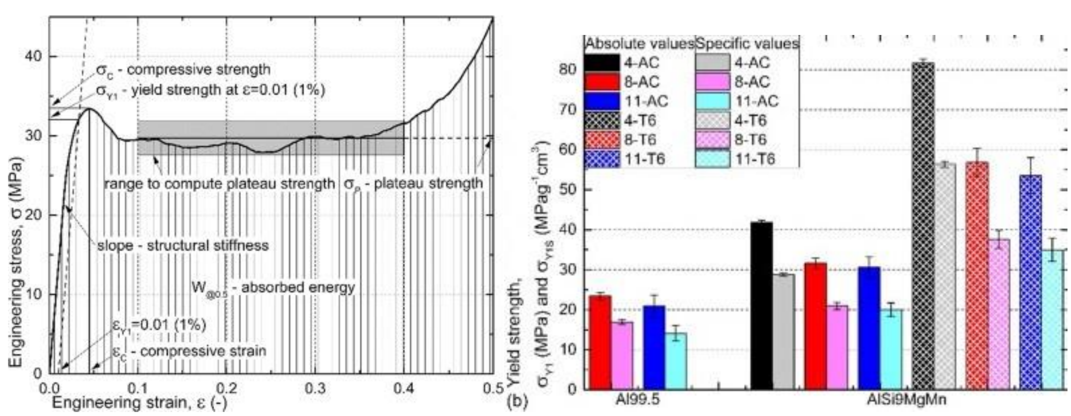


Figure 8. (Left) Generalized compressive engineering stress – engineering strain curve of syntactic metal foams. (Right) Yield strengths of multiple material samples [11].

3.2 Tensile Strength

Syntactic metal foams have excellent compressibility, but their tensile strength is not as impressive as their yield strength. An experiment to find the tensile strength in a sample of AlSi10, a syntactic metal foam, was done by cutting a longitudinal oriented strip of the metal foam, and a transverse oriented strip of the metal foam. These two different orientations of the metal sample were put under a tensile testing simulation and then actual tensile testing, then the results were compared. The simulation shows the curves for the AlSi10 sample, having a tensile strength of around 160 MPa [3]. The results show different simulated flow curves for the AlSi10 sample, with each curve defined at different strain-hardening exponents (n) and then showing the plastic deformation at n = 0.15 as shown in [Fig. 8]. When the tensile tests were actually performed, the results were compared to the simulation flow curves [Fig. 9]. The results are not far of from the simulation, showing that the AlSi10 sample has a tensile strength between 160 MPa to 170 MPa. As the slope of the sample begins to decrease as more strain is present. This shows the elastic and plastic deformations of the AlSi10 sample, which is relative for all types of syntactic metal foams [Fig. 10].

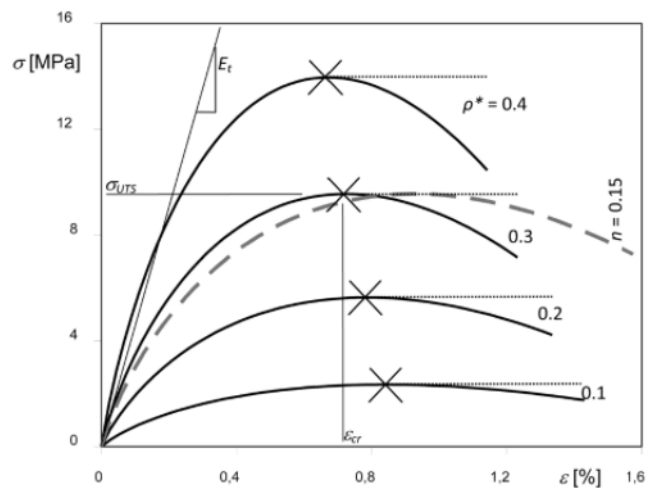


Figure 9. Simulated flow curves used for AlSi10 material, plastic deformation represented by dotted-lines, ultimate tensile strengths at different strain-hardening exponents represented by solid lines [3].

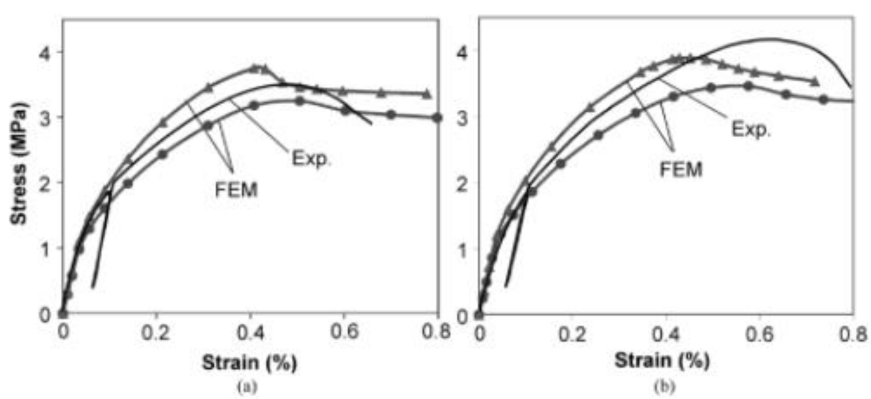


Figure 10. Experimented tensile test results compared with simulated stress-strain curves, (a) transverse sample, (b) longitudinal sample [3].

3.3 Shear Strength

Syntactic metal foams are very compressible, meaning that they can withstand large amounts of shear stress. The pore-struts within the structure of the syntactic metal foams provide excellent shear strength. If a pore-strut has exceeded its shearing stress due to shear loading, then this can cause fracturing throughout the structure of the syntactic metal foams. Under shearing load, the maximum nominal shearing stress for the whole porous component may cause the maximum tensile stress in the pore-strut to reach the allowable stress of the corresponding dense material species [9]. This will make the pore-strut failure, and such failure will develop a large number of pore-struts to ultimately lead to the whole failure of the porous body [9]. When the maximum tensile stress (σ_{max}) in pore-strut from the maximum nominal shearing stress (τ_{max}) in the porous component reaches the allowable stress ([σ], corresponding to the tensile strength (σ_0) for brittle materials) of the corresponding dense material species, the failure of pore-strut will germinate and grow to finally cause the entire failure of the whole porous component under shearing loads [Fig. 11].

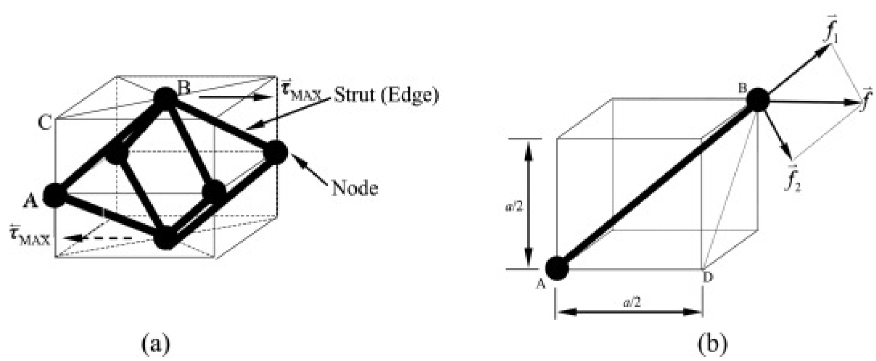


Figure 11. Pore unit of the porous body under shearing loads, (a) the octahedral unit; (b) the pore strut [9].

3.4 Elongation

Syntactic metal foams with higher porosity with have an increase in elongation rate of the whole porous body. With a gradual decrease of porosity, the pore-struts in porous materials will become thicker and shorter, and the contribution of the deflection of pore-struts to the elongation of the whole porous body will decrease, and that of the plastic stretching of metal species will continue to increase, eventually becoming the main contribution of the overall elongation [Fig. 12]. When this deformation makes the stress in the pore-strut reach a proportional limit (σ_p) of the corresponding dense material species, the nominal stress in the tensile direction of the porous body will be its apparent proportional limit (σ'_p), and the apparent strain will correspondingly be its apparent linear elastic strain limit (ε_{limit}) [9].

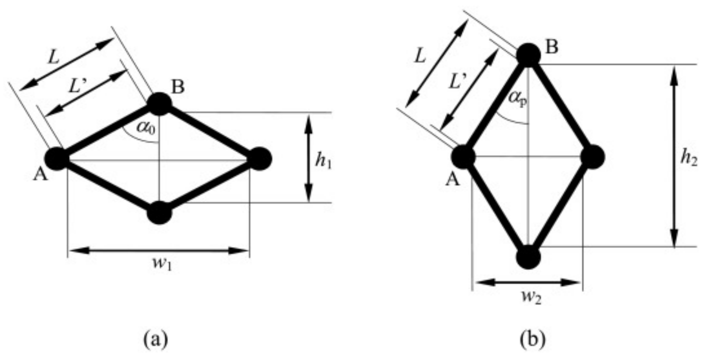


Figure 12. Model for the tensile deformation of octahedral pore unit: (a) before tension; (b) after tension when the stress in the pore-strut arrives at the proportional limit of the corresponding dense material species. [9].

3.5 Young's Modulus

Young's modulus relates to the elongation and elasticity of the syntactic metal foam body. The ratio of the apparent proportional limit (σ'_p) to the apparent linear elastic strain limit in the tensile direction (ε_{limit1}) is the apparent Young's modulus (E_a) of the porous body [9]. The negative value of the transverse apparent linear elastic strain limit (ε_{limit2}) divided by ε_{limit1} gives the apparent Poisson's ratio (v_a) of the porous body [9]. The Young's modulus of porous body foams, such as syntactic metal foams can be obtained using [Eq. 3].

$$
\begin{aligned}
E_a &\approx \sigma'_p / \varepsilon_{limit1} \\
&\approx [K_p \cdot (1-\theta)^m \cdot \sigma_p] / \left\{ \left(\sqrt{3}\cos\ \alpha_p - 1\right)\left[1 - \sqrt{\sqrt{3}/2\pi}(1-\theta)^{1/2}\right]\right\} \\
&\approx \left[K_p \cdot \sigma_p / \left(\sqrt{3}\cos\ \alpha_p - 1\right)\right] \cdot \left\{(1-\theta)^m / \left[1 - 0.53(1-\theta)^{1/2}\right]\right\}
\end{aligned}
$$

Letting

$$K_E \approx K_p \cdot \sigma_p / \left(\sqrt{3}\cos\alpha_p - 1\right)$$

we have

$$E_a \approx K_E \cdot \left\{(1-\theta)^m / \left[1 - 0.53(1-\theta)^{1/2}\right]\right\}$$

Equation 3. Young's modulus of porous bodies [9].

3.6 Ductility

Syntactic metal foams are not very ductile, due to their porous metal bodies. These syntactic metal foams that consist of highly porous metal bodies cannot elongate as much as base metals. Their porous structure causes the metal to become easier to fracture under elongation since there is lots of empty space throughout the material. Syntactic metal foams are show brittle fracturing due to having lots of empty space from the pores within the structure of the material.

3.7 Impact Strength

The design of syntactic metal foams consisting of highly porous bodies are excellent for absorbing high impact energy. At different pore sizes and foam types, most aluminum syntactic metal foams can withstand an impact energy of about 500 Joules (J) as shown in [Table 5].

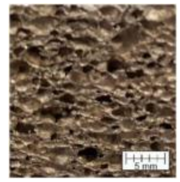
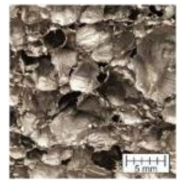
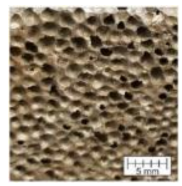
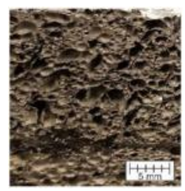
Density [kg/m^3] Manufacturing method [−] Pore size [mm] Foam type [−]	Cross-section	Impact energy [J]
242 Foaming in the liquid state 1–3 Aluminum foam		500
245 Gas foaming and continuous rolling Avg: 4–20; max: 40 Aluminum foam		500
350 Casting metal around granules 1.5–2.5 Aluminum foam		500
445 Foaming in the liquid state 0.5–2 Aluminum-ceramic, composite foam		500

Table 5. Basic material properties and impact energies [5].

Although syntactic metal foams have great impact strength, they can still undergo fracturing with enough force applied to do so. For example, with 350-type metal foams, these metal foams can undergo intense brittle fracturing with lots of applied force acting on it. These are weaker types of metal foams but can still withstand lots of force [Fig. 13].

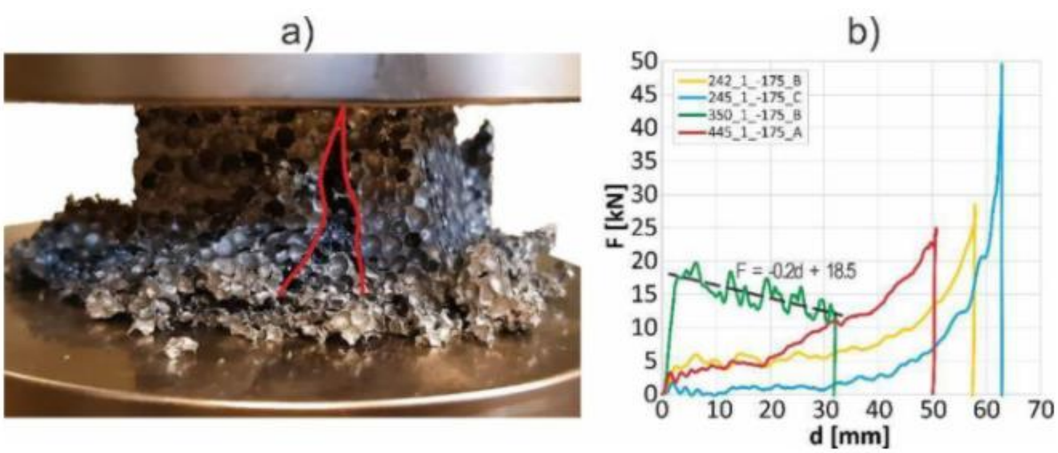


Figure 13. Brittle fracturing of 350-type metal foam, (a) foam fracture during compression, (b) graph F = f(d) [5].

3.8 Fatigue Resistance

Syntactic metal foams have excellent strength and are able to withstand high amounts of impact force. They can compress to 80% of their total volumes, which shows how strong they can be, thus showing little fatigue. As stress is continually cycled onto syntactic metal foams, they will face little fatigue due to their flexibility and compressibility characteristics.

3.9 Failure Analysis and Prevention

If any of the pore-struts fail within the structure of the syntactic metal foam material, this can cause more failure for the other remaining pore-struts. When the maximum stress at a weak position of the pore-strut exceeds the failure strength of the corresponding metal species, the strut will begin to break from one side of this position and presents its whole fracture process in a tearing form [9]. Such fracture of struts one by one shows a macroscopical tearing phenomenon for the overall behavior of the porous body [9]. Each strut is equivalent in structure, and roughly equivalent in the loading state; therefore, this tearing will be developed in a random direction to a large extent, so the overall fracture morphology is zigzagged [9]. The syntactic metal foam will undergo brittle failure if too much force is applied onto the material. To prevent failure, the metal foams can have lower rates of porosity in order to strengthen the syntactic metal foam, and the pore-struts can be thickened depending on the type of metal used for the production of the syntactic metal foam.

4. Manufacturing Process

There are multiple manufacturing processes that can be done to produce syntactic metal foams. Some of the types of production methods include making metal foams from metallic melts, solid metals, and electroplating. Each process can have various ways of manufacturing the metal foams, in which some can be more effective than others. Most foam making processes begin from metal that has been processed into a porous structured material by either foaming it directly, by using an indirect method by replication of a polymer form, or by casting the liquid metal around solid filler materials which reserve space for the pores, or which remain in the foam [3]. Each type of production method will be covered in this section very briefly. The different production methods have several types of processes within their categories, so this section only gives information on a few of the processes within these production methods.

To directly foam melted metallics, manufacturers add fine ceramic powders or alloying elements which form particles within the melt. This helps avoid the metallic metal from forming liquid gas bubbles too quickly and then resulting in the metallic melt to collapse or burst. There are two types of processes for directly foaming metallic melts. The first process consists of thickening, foaming, cooling, forming a foam block, and then slicing the block to correct size as shown in [Fig. 14]. The second process consists of inserting gases into a metallic melt, mixing it, then the foam floating up to the surface of the liquid onto a conveyor belt, and then solidifying as shown in [Fig. 15]. The second process provides more advantages, one being that it has the ability to produce large volumes of material at a relatively low cost and at the low density that can be achieved [3]. A disadvantage of this process is that when pulling the semi-solid metal foam from the melt surface, some shearing of the foam structure may occur [3].

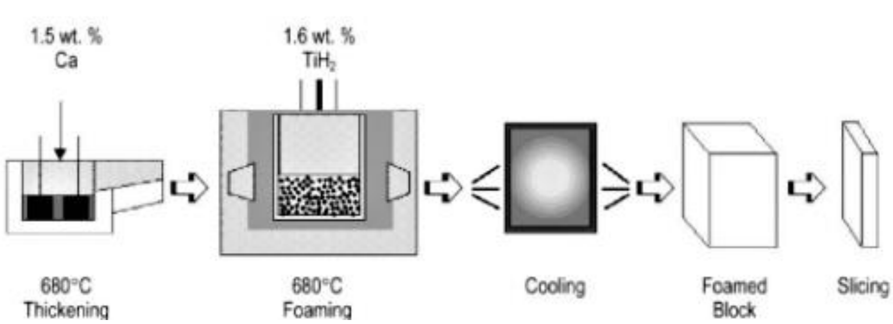


Figure 14. Direct foaming of melts with blowing agents (ALPORAS process) [3].

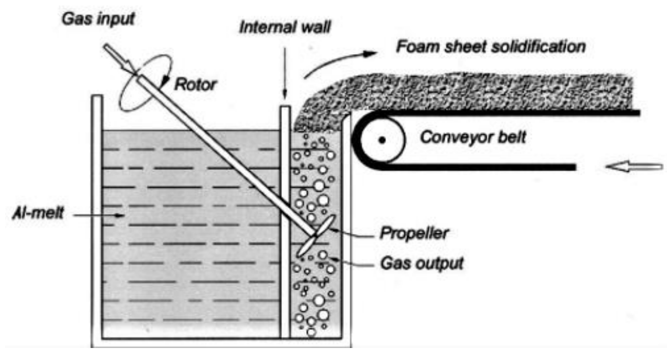


Figure 15. Direct foaming of melts by gas injection [3].

The production method of manufacturing foams from solid metals, mainly involves a sintering process and no liquid metal is involved. One process within this category is forming open porous foams using space-holders. A suitable space-holder is selected, and metal powders are added to the space-holders (placeholders). After this occurs, these are mixed, then compacted. Once this is completed, the placeholders are removed and the sintering process begins, as shown in [Fig. 16]. This process is an older process, but it is still very effective for making many applicable metal foams for things such as becoming medical material for bone repair and bone substitution [3].

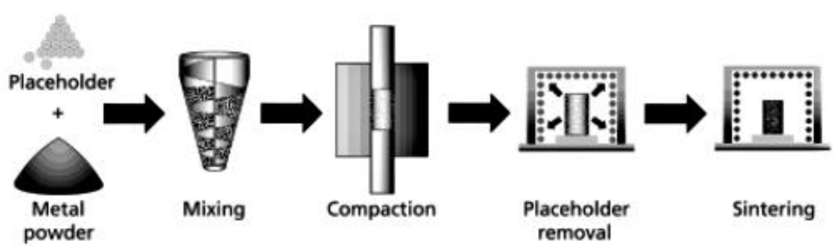


Figure 16. Process scheme of the p/m space-holder methods [3].

The production method of forming foams made by electroplating, is mainly used for manufacturing batteries. This process uses already processed metal foams and transforms them into alloy metal foams. Electroplating is a heat treatment method that de-binders and sinters the material. A metal foam is rolled out onto a conveyor belt. The metal foam is then sprayed with a binder solution spray and applied with an alloy powder shortly after. The metal foam is cut into sheets and put into heat treatment as shown in [Fig. 17]. The new alloy metal foam is thus formed [3].

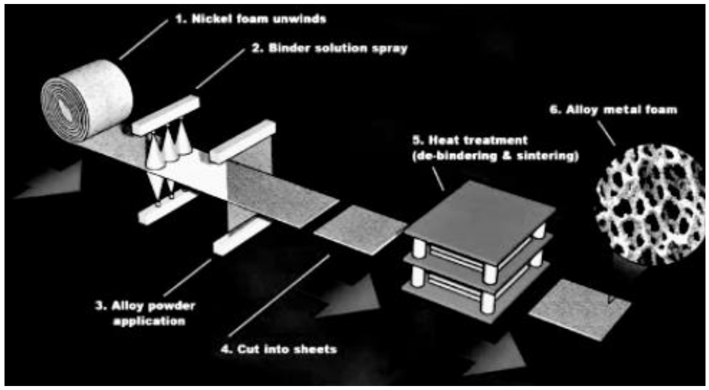


Figure 17. Production scheme for high temperature alloy foams [3].

These various methods of production are the basic methods for manufacturing syntactic metal foams. There are many more manufacturing method expects to be invented and established in the future.

5. Materials and Environment

Syntactic metal foams can be made up of almost any type of metals and mixed with different kinds of polymers and/or phase change materials. Most of the metals are purely mined and then manufactured to be sold for material usage in other productions. There are different kinds of syntactic foams that are made with metals, polymers, ceramics, or hybrid materials [Fig. 18]. The most common types of syntactic metal foams consist of aluminum, titanium, iron, magnesium, zinc, copper, continuous fibers, graphite, superalloys. Most of the metals can be recycled, rather than manufactured purely, which would reduce energy consumption. Syntactic metal foams have potential to be made from recyclable materials and be environmentally friendly. All metals contain very advantageous properties, which gives syntactic metal foams excellent strength, durability, and sustainability.

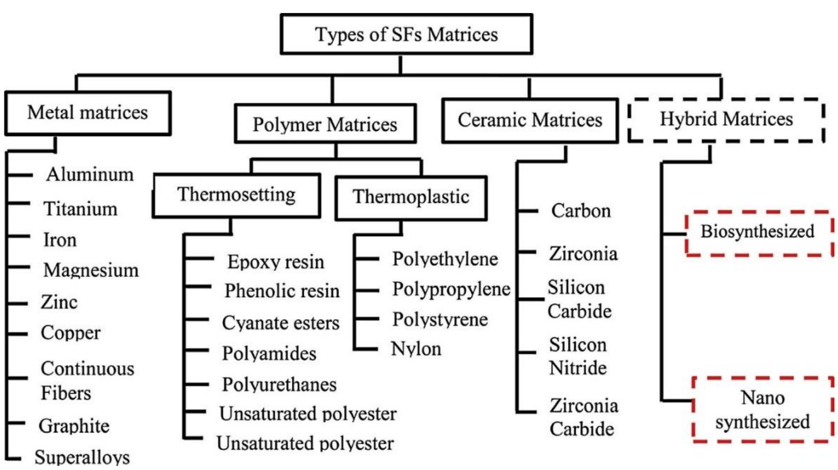


Figure 18. Syntactic foam matrices [1].

6. Cost Analysis

All metal products have a specific cost ($/kg) and a volumetric cost ($/m^3) that is calculated by the cost of the material, the cost of energy, the cost of other filler materials, and other types of expenses or role variables. Syntactic metal foams (P-MSF's) are manufactured by the combination of expanded perlite particles with melt aluminum. Typical volume fractions of aluminum and perlite are ϕ_{Al} = 40% and ϕ_{Pe} = 60%, respectively. The cost for aluminum (A356-standard casting alloy) is estimated at 8 $/kg (21,600 $/m^3) and the typical cost for expanded perlite is 0.1 $/kg (120 $/m^3). In the case of syntactic metal foams, no costs (C_{FA}) or a foaming agent or consumables (C_{Cm}) arise. Considering a starting temperature T_0 = 300 K, aluminum melting temperature T_M = 1023 K, density ρ_{Al} = 2700 kg/m^3, specific heat capacity C_{Al} = 0.91 kJ/kg·K, and latent heat Δh = 339 kJ/kg a total melting energy of 0.259 kWh/kg is required. Multiplication with an assumed energy price of 0.1 $/kWh yields the approximate energy cost (C_E) [7]. Accordingly, the volumetric cost (C_V) of syntactic metal foams can be calculated using [Eq. 4].

$$C_V = \underbrace{\phi_{Al} \cdot 21600 \frac{\$}{m^3}}_{\text{Aluminium cost}} + \underbrace{\phi_{Pe} \cdot 200 \frac{\$}{m^3}}_{\text{Filler particle cost } C_{FP}} + \underbrace{\phi_{Al} \cdot \rho_{Al} \cdot [C_{Al} \cdot (T_M - T_0) + \Delta h] \cdot 0.1 \frac{\$}{kWh}}_{\text{Energy cost } C_E} + C_{FA} + C_{Cm} = 8790 \frac{\$}{m^3}$$

Equation 4. Estimation of volumetric cost of syntactic metal foams [7].

The specific cost (C_m) of syntactic metal foams is obtained by the division with the material density (in this case the density of syntactic metal foams is, $\rho_{P\text{-}MSF}$ = 1080 kg/m^3) [Eq. 5].

$$C_m = \frac{C_V}{\rho_{P-MSF}} = 8.1 \frac{\$}{kg}$$

Equation 5. Estimation of specific cost of syntactic metal foams [7].

The material strength is plotted versus the specific cost and the volumetric cost in [Fig. 19]. The specific cost of the cellular metals is lower in cost when it is higher in strength, but the volumetric cost is higher for these cellular metals when the strength is higher in value.

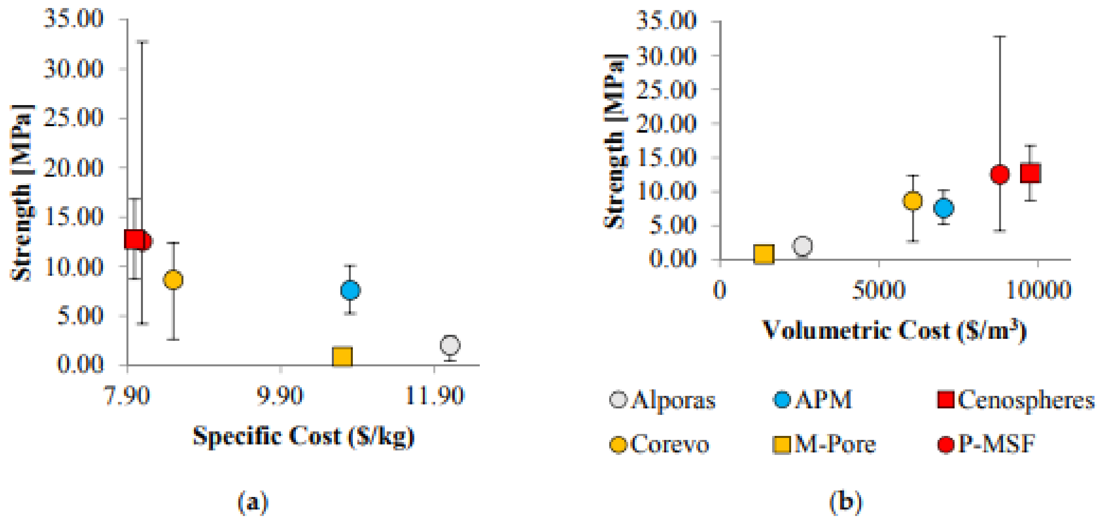


Figure 19. Material strength plotted versus (a) specific cost and (b) volumetric cost for selected types of cellular metals [7].

There are different ranges of prices for base materials that are put into cellular metals. Various cellular metals have differing amounts of base metals within the, which fluctuates the cost of the cellular metal. An estimate of cost for cellular metals and the base metals contained within them can be seen in [Table 6].

Property	Alporas	APM	Cenospheres	Corevo	M.Pore	P-MSF
ϕ_{Al} (%)	8	25	45	25	5	40
C_{FA} ($/m^3)	871	819	-			-
C_{Fp} ($/m)	-	-	free			120
C_{Cm} ($/m)	-	-	-	320	100	-
C_E ($/m)	6.0	18	33.6	19.8	3.7	29.9
C_V ($/m)	2600	7030	9750	6060	1390	8790
ρ (kg/m)	216	650	1215	715	130	1080
C_m ($/k)	12.1	10.8	8.0	8.5	10.7	8.1

Table 6. Overview of cost figures for selected types of cellular metals and their base metals [7].

Summary

In summary, syntactic metal foams are very useful for many applications of engineering and design, due to their strong, porous structure that can withstand great amounts of impact. Syntactic metal foams have advantageous physical and mechanical properties that can be compared as much greater than other types of cellular metals. There are various ways of manufacturing syntactic metal foams, but most commonly the production methods are directly foaming melted metallics, foaming solid metals, and electroplating. Each product method has several different types of process that can be done through different machinery and equipment. The materials used in syntactic metal foams are commonly seen metals, such as aluminum, iron, steel, and other kinds of base metals. Fillers are also mixed in within syntactic metal foams such as polymers, gases, and other kinds of various materials. Syntactic metal foams can be cost effective in some cases but cost more in other cases. The specific cost of syntactic metal foams is less compared to other cellular metals, in relation to strength of the material, but the volumetric cost of syntactic metal foams is more compared to other cellular metals, in relation to strength of the material. In conclusion, the advantages that syntactic metal foams contain make it a very useful and applicable material that can be used for many different types of engineering and design applications.

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