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# METAL FOAMS – A NEW PROMISING MATERIAL FOR ENGINEERING DESIGN APPLICATIONS

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## 1. Introduction

Porosity in metals and alloys is not always a bad thing: bubbles or open pores make metals lighter, give them good energy and sound absorption properties, and make their use possible in structures, filters, catalysts and other engineering design applications. Interest in cellular metal materials has thus seen a steady increase over the past decade.

This can be illustrated by the evolution of the MetFoam conferences. The kickoff conference called Metallschäume took place in 1997 in Bremen, Germany with about 90 participants, most of them from German speaking countries, listening to and discussing 18 papers. This year the fifth MetFoam conference took place in Kyoto, Japan with 170 participants from 24 countries, who contributed 144 papers.

## 2. Making metal foams

Metal foams can be made by one of the following nine processes:

- Bubbling gas through molten metals or alloys (aluminium and magnesium foams)
- By stirring a foaming agent (typically $TiH_2$) into a molten metal or alloy and controlling the pressure while cooling (aluminium foams)
- Consolidation of a metal powder with a particulate foaming agent ($TiH_2$ again) followed by heating into the mushy state when the foaming agent releases hydrogen, expanding the material (aluminium, zinc, iron, lead, gold)
- Manufacture of a ceramic mould from a wax or polymer-foam precursor, followed by burning-out of the precursor and pressure infiltration with a molten metal or metal powder slurry which is then sintered (aluminium, magnesium, nickel-chromium, stainless steel, copper)
- Vapour phase deposition or electrodeposition of metal onto a polymer foam precursor which is subsequently burned out, leaving cell edges with hollow cores (nickel, titanium)
- The trapping of high-pressure inert gas in pores by powder hot isostatic pressing (HIPing), followed by the expansion of the gas at elevated temperature (titanium)
- Sintering of hollow spheres, made by a modified atomization process, or from metal-oxide or hydride spheres followed be reduction or dehydridation, or by vapour-deposition of metal onto polymer spheres (nickel, cobalt, nickel-chromium alloys)
- Co-pressing of a metal powder with a leachable powder, or pressure-infiltration of a bed of leachable particles by a liquid metal, followed by leaching to leave a metal-foam skeleton (aluminium, with salt as the leachable powder)

- Dissolution of gas (typically, hydrogen) in a liquid metal under pressure, allowing it to be released in a controlled way during subsequent solidification (copper, nickel, aluminium)

Only the first five of these are used commercially. Each method can be used with a small subset of metals to create a porous material with a limited range of relative densities and cell sizes.

## 3. Properties of metal foams

The characteristics of a foam are best summarized by describing the material from which it is made, its relative density and stating whether it has open or closed cells (Figure 1.). Beyond this, foam properties are influenced by its structure and its anisotropy. All metal foam properties belong as properties of other materials among elementary engineering design properties which comprise one class of internal properties of technical products (systems).
Above common material properties the following are used to characterize foams:

- Relative density [ - ]

$$\rho_r = \frac{\rho}{\rho_s} \tag{1}$$

  where $\rho$ is foam density and $\rho_s$ is the density of the solid material from which it is made.
- Cell size [ m ] or pores per inch (ppi)
- Anisotropy ratio [ - ]
- Surface per volume [ $m^{-1}$ ] (this is a key property for open cell foams)
- Densification strain (compression) [ - ] (this is the compressive strain at which cell walls are forced into contact with each other, when the stress-strain curve rises steeply)
- Compressive stress @ 25% and 50% strain [ MPa ]
- Energy absorption at densification [ $J/m^3$ ]
- Heat deflection temperature at 0.45 MPa and 1.8 MPa [ K ] (this is another property tested according to ANSI / ASTM D648-72/78 which gives data useful for ranking purposes only, the heat deflection temperature is the temperature at which a given creep deflection 0.25 mm appears under a given bending stress 0.45 or 1.8 MPa when a specimen of standard dimensions is heated at 2 K/min)

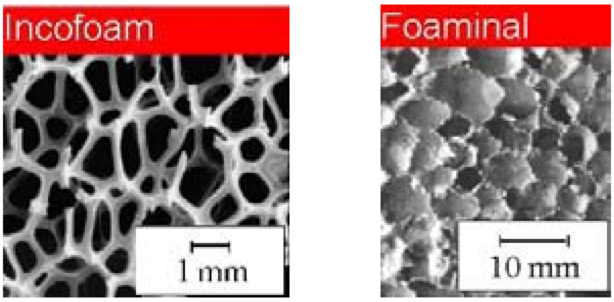

**Figure 1. Metal foams: Open cell foam – left view and closed cell foam – right view**

### 3.1 Scaling relations for foam properties

Scaling relations for foam properties are derived partly from modelling and partly from empirical fits to experimental data (Tables 1 a, b and c.). These relations are particularly useful in the early stages of design when approximate analysis of components, modules, parts and features is needed to decide whether a metal foam is a potential candidate.

The relations take the following form:

$$\frac{P}{P_s} = \alpha\left(\frac{\rho}{\rho_s}\right)^n \qquad (2)$$

where P is a property of foam, α a constant, ρ density of foam and n a fixed exponent. Symbol s means a property of the solid metal of which the foam is made, i.e. $\rho_s$ is the density of solid metal of which the foam is made.

**Table 1 a. Scaling laws for the mechanical properties of foams**

| Mechanical property | Open cell foam | Closed cell foam |
|---|---|---|
| Young's modulus E [ GPa ] | $E = (0.1 \div 4)E_s\left(\frac{\rho}{\rho_s}\right)^2$ | $E = (0.1 \div 1)E_s\left[0.5\left(\frac{\rho}{\rho_s}\right)^2 + 0.3\left(\frac{\rho}{\rho_s}\right)\right]$ |
| Shear modulus G [ GPa ] | $G \approx \frac{3}{8}E$ | $G \approx \frac{3}{8}E$ |
| Bulk modulus K [ GPa ] | $K \approx 1.1E$ | $K \approx 1.1E$ |
| Flexural modulus $E_f$ [ GPa ] | $E_f \approx E$ | $E_f \approx E$ |
| Poisson's ratio μ [ - ] | 0.32 – 0.34 | 0.32 – 0.34 |
| Compressive strength $\sigma_c$ [ MPa ] | $\sigma_c = (0.1 \div 1)\sigma_{cs}\left(\frac{\rho}{\rho_s}\right)^{3/2}$ | $\sigma_c = (0.1 \div 1)\sigma_{cs}\left[0.5\left(\frac{\rho}{\rho_s}\right)^{2/3} + 0.3\left(\frac{\rho}{\rho_s}\right)\right]$ |
| Tensile strength $\sigma_t$ [ MPa ] | $\sigma_t \approx (1.1 \div 1.4)\sigma_c$ | $\sigma_t \approx (1.1 \div 1.4)\sigma_c$ |
| Endurance limit $\sigma_{ec}$ [ MPa ] | $\sigma_{ec} \approx (0.5 \div 0.75)\sigma_c$ | $\sigma_{ec} \approx (0.5 \div 0.75)\sigma_c$ |
| Densification strain $\varepsilon_D$ [ - ] | $\varepsilon_D = (0.9 \div 1)\left(1 - 1.4\frac{\rho}{\rho_s} + 0.4\left(\frac{\rho}{\rho_s}\right)^3\right)$ | $\varepsilon_D = (0.9 \div 1)\left(1 - 1.4\frac{\rho}{\rho_s} + 0.4\left(\frac{\rho}{\rho_s}\right)^3\right)$ |
| Loss coefficient η [ - ] | $\eta \approx (0.95 \div 1.05)\frac{\eta_s}{(\rho / \rho_s)}$ | $\eta \approx (0.95 \div 1.05)\frac{\eta_s}{(\rho / \rho_s)}$ |
| Hardness H [ MPa ] | $H = \sigma_c\left(1 + 2\frac{\rho}{\rho_s}\right)$ | $H = \sigma_c\left(1 + 2\frac{\rho}{\rho_s}\right)$ |
| Initiation toughness $J_{IC}$ [ J/m$^2$ ] | $J_{IC} \approx \beta\sigma_{ys}l\left(\frac{\rho}{\rho_s}\right)^p$ | $J_{IC} \approx \beta\sigma_{ys}l\left(\frac{\rho}{\rho_s}\right)^p$ |

**Table 1 b. Scaling laws for the thermal properties of foams**

| Thermal property | Open cell foam | Closed cell foam |
|---|---|---|
| Melting point $T_m$ [ K ] | As solid | As solid |
| Max. service temp. $T_{max}$ [ K ] | As solid | As solid |
| Min. service temp. $T_{min}$ [ K ] | As solid | As solid |
| Specific heat capacity $C_p$ [ $\frac{J}{kgK}$ ] | As solid | As solid |
| Thermal conductivity λ [ $\frac{W}{mK}$ ] | $\lambda = \lambda_s \left( \frac{\rho}{\rho_s} \right)^{(1.65 \div 1.8)}$ | $\lambda = \lambda_s \left( \frac{\rho}{\rho_s} \right)^{(1.65 \div 1.8)}$ |
| Thermal expansion α [ $10^{-6}$ $K^{-1}$] | As solid | As solid |
| Latent heat, melting L [ kJ/kg ] | As solid | As solid |

**Table 1 c. Scaling laws for the electrical properties of foams**

| Electrical property | Open cell foam | Closed cell foam |
|---|---|---|
| Resistivity R [ $10^{-8}$ Ωm ] | $R = R_s \left( \frac{\rho}{\rho_s} \right)^{-(1.6 \div 1.85)}$ | $R = R_s \left( \frac{\rho}{\rho_s} \right)^{-(1.6 \div 1.85)}$ |

## 3.2 Ranges for properties of commercial metal foams

Many suppliers offer a variety of densities; the properties of foams, correspondingly, exhibit a wide range. This is one of the attractive aspects of such materials: a desired property profile can be obtained by selecting the appropriate foam material with the appropriate density. The ranges of properties offered by currently available metal foams are documented in Tables 2 a, b and c.

**Table 2 a. Ranges for mechanical properties of commercial metal foams**

| Mechanical property | Cymat | Alulight | Alporas | ERG | Inco |
|---|---|---|---|---|---|
| Material | Aluminium – silicon carbide | Aluminium | Aluminium | Aluminium | Nickel |
| Structure | Closed cell | Closed cell | Closed cell | Open cell | Open cell |
| Relative density $\rho_r = \rho/\rho_s$ [ - ] | 0.02 – 0.2 | 0.1 – 0.35 | 0.08 – 0.1 | 0.05 – 0.1 | 0.03 – 0.04 |
| Density ρ [ $Mg/m^3$ ] | 0.07 – 0.56 | 0.3 - 1 | 0.2 – 0.25 | 0.16 – 0.25 | 0.26 – 0.37 |
| Young's modulus E [ GPa ] | 0.02 - 2 | 1.7 - 12 | 0.4 - 1 | 0.06 – 0.3 | 0.4 – 1 |
| Shear modulus G [ GPa ] | 0.001 - 1 | 0.6 – 5.2 | 0.3 – 0.35 | 0.02 – 0.1 | 0.17 – 0.37 |
| Bulk modulus K [ GPa ] | 0.02 – 3.2 | 1.8 - 13 | 0.9 – 1.2 | 0.06 – 0.3 | 0.4 - 1 |
| Flexural modulus $E_f$ [ GPa ] | 0.03 – 3.3 | 1.7 - 12 | 0.9 – 1.2 | 0.06 – 0.3 | 0.4 – 1 |
| Poisson's ratio μ [ - ] | 0.31 – 0.34 | 0.31 – 0.34 | 0.31 – 0.34 | 0.31 – 0.34 | 0.31 – 0.34 |
| Compressive strength $\sigma_c$ [ MPa ] | 0.04 - 7 | 1.9 - 14 | 1.3 – 1.7 | 0.9 - 3 | 0.6 – 1.1 |
| Tensile elastic limit $\sigma_y$ [ MPa ] | 0.04 - 7 | 2 - 20 | 1.6 – 1.8 | 0.9 – 2.7 | 0.6 – 1.1 |

| | | | | | |
|---|---|---|---|---|---|
| Tensile strength $\sigma_t$ [ MPa ] | 0.05 – 8.5 | 2.2 - 30 | 1.6 – 1.9 | 1.9 – 3.5 | 1 – 2.4 |
| Modulus of rupture $\sigma_{MOR}$ [ MPa ] | 0.04 – 7.2 | 1.9 - 25 | 1.8 – 1.9 | 0.9 – 2.9 | 0.6 – 1.1 |
| Endurance limit $\sigma_{ec}$ [ MPa ] | 0.02 – 3.6 | 0.95 - 13 | 0.9 - 1 | 0.45 – 1.5 | 0.3 – 0.6 |
| Densification strain $\varepsilon_D$ [ - ] | 0.6 – 0.9 | 0.4 – 0.8 | 0.7 – 0.82 | 0.8 – 0.9 | 0.9 – 0.94 |
| Tensile ductility A [ % ] | 1 - 2 | 0.2 - 4 | 1 - 6 | 10 - 20 | 3 – 10 |
| Loss coefficient $\eta$ [ - ] | 0.004 – 0.012 | 0.003 – 0.005 | 0.009 – 0.01 | 0.003 – 0.005 | 0.01 – 0.02 |
| Hardness H [ MPa ] | 0.05 - 10 | 2.4 - 35 | 2 – 2.2 | 2 – 3.5 | 0.6 - 1 |
| Fracture toughness $K_{IC}$ [ MPa $m^{1/2}$ ] | 0.03 – 0.5 | 0.3 – 1.6 | 0.1 – 0.9 | 0.1 – 0.28 | 0.6 - 1 |

**Table 2 b. Ranges for thermal properties of commercial metal foams**

| **Thermal property** | **Cymat** | **Alulight** | **Alporas** | **ERG** | **Inco** |
|---|---|---|---|---|---|
| Material | Aluminium – silicon carbide | Aluminium | Aluminium | Aluminium | Nickel |
| Structure | Closed cell | Closed cell | Closed cell | Open cell | Open cell |
| Relative density $\rho_r = \rho/\rho_s$ [ - ] | 0.02 – 0.2 | 0.1 – 0.35 | 0.08 – 0.1 | 0.05 – 0.1 | 0.03 – 0.04 |
| Density $\rho$ [ $Mg/m^3$ ] | 0.07 – 0.56 | 0.3 - 1 | 0.2 – 0.25 | 0.16 – 0.25 | 0.26 – 0.37 |
| Melting point $T_m$ [ K ] | 830 - 910 | 840 - 850 | 910 - 920 | 830 - 920 | 1700 - 1720 |
| Max. service temp. $T_{max}$ [ K ] | 500 - 530 | 400 - 430 | 400 - 420 | 380 - 420 | 550 – 650 |
| Min. service temp. $T_{min}$ [ K ] | 1 - 2 | 1 - 2 | 1 - 2 | 1 - 2 | 1 - 2 |
| Specific heat capacity $C_p$ [ $\frac{J}{kgK}$ ] | 830 - 870 | 910 - 920 | 830 - 870 | 850 - 950 | 450 - 460 |
| Thermal conductivity $\lambda$ [ $\frac{W}{mK}$ ] | 0.3 - 10 | 3 - 35 | 3.5 – 4.5 | 6 - 11 | 0.2 – 0.3 |
| Thermal expansion $\alpha$ [ $10^{-6}$ $K^{-1}$] | 19 - 21 | 19 - 23 | 21 - 23 | 22 - 24 | 12 - 14 |
| Latent heat, melting L [ kJ/kg ] | 355 - 385 | 380 - 390 | 370 - 380 | 380 - 395 | 280 - 310 |

**Table 2 c. Ranges for electrical properties of commercial metal foams**

| **Electrical property** | **Cymat** | **Alulight** | **Alporas** | **ERG** | **Inco** |
|---|---|---|---|---|---|
| Material | Aluminium – silicon carbide | Aluminium | Aluminium | Aluminium | Nickel |
| Structure | Closed cell | Closed cell | Closed cell | Open cell | Open cell |
| Relative density $\rho_r = \rho/\rho_s$ [ - ] | 0.02 – 0.2 | 0.1 – 0.35 | 0.08 – 0.1 | 0.05 – 0.1 | 0.03 – 0.04 |
| Density $\rho$ [ $Mg/m^3$ ] | 0.07 – 0.56 | 0.3 - 1 | 0.2 – 0.25 | 0.16 – 0.25 | 0.26 – 0.37 |
| Resistivity R [ $10^{-8}$ $\Omega m$ ] | 90 – 3 000 | 20 - 200 | 210 - 250 | 180 - 450 | 300 - 500 |

## 4. Applications of metal foams

Metal foams have a wide range of established and potential engineering design applications. They can be used in structures (e.g. sandwich structures), vibration, sound and energy absorbers, thermal insulation, heat exchangers, firewalls, filters, catalysts, battery electrodes, fuel cells, magnetic flux conductors.

**Table 3. Potential engineering design applications for metal foams – an overview**

| **Application** | **Characterization** |
|---|---|
| Lightweight structures | Excellent stiffness-to-weight ratio when loaded in bending |
| Sandwich cores | Metal foams have low density with good shear and fracture strength |
| Strain isolation | Metal foams can take up strain mismatch by crushing at controlled pressure |
| Mechanical damping | The damping capacity of metal foams is larger than that of solid metals by up to a factor of 10 |
| Vibration control | Foamed panels have higher natural flexural vibration frequencies than solid sheet of the same mass per unit area |
| Acoustics absorption | Reticulated metal foams have sound-absorbing capacity |
| Energy management: compact or light energy absorbers | Metal foams have exceptional ability to absorb energy at almost constant pressure |
| Packaging with high-temperature capability | Ability to absorb impact at constant load, coupled with thermal stability above room temperature |
| Artificial wood (furniture, wall panels) | Metal foams have some wood-like characteristics: light, stiff and ability to be joined with wood screws |
| Thermal management: heat exchangers/refrigerators | Open cell foams have large accessible surface area and high cell-wall conduction giving exceptional heat transfer ability |
| Thermal management: flame arresters | High thermal conductivity of cell edges together with high surface area quenches combustion |
| Thermal management: heat shields | Metal foams are non-flammable; oxidation of cell faces of closed cell aluminium foams appears to impart exceptional resistance to direct flame |
| Consumable cores for castings | Metal foams, injection-moulded to complex shapes, are used as consumable cores for aluminium castings |
| Biocompatible inserts | The cellular texture of biocompatible metal foams such as titanium stimulate cell growth |
| Filters | Open cell foams with controlled pore size have potential for high-temperature gas and fluid filtration |
| Electrical screening | Good electrical conduction, mechanical strength and low density make metal foams attractive for screening |
| Electrodes and catalyst carriers | High surface/volume ratio allows compact electrodes with high reaction surface area |
| Buoyancy | Low density and good corrosion resistance suggest possible floatation applications |

Figure 2. Example of application – car body part

Figure 3. Example of application – piston-rod

**Figure 4. Example of application – sound absorber for expressway**

## 5. Conclusion

In spite of a wide range of potential engineering design applications, metal foams are at present used rarely and even less in mechanical design applications. Where they are used the products successfully meet customer requirements. This gives engineering designers great opportunities and challenges for innovative solutions for technical products.

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