Reticulated foams expand the boundaries of cellular solids

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Picture a structure formed by fibres or ligaments that frame open cells. The structure would, of course, be lightweight, permeable and shock-resistant while retaining the properties of the parent material. Polymer foam, used for insulation, cushions and packaging materials, was perhaps the first manmade material to take advantage of the unique characteristics of cellular solids. Today, another type of foam – reticulated foam of either ceramic or metal – provides industry as well as the research community with an extraordinarily versatile material form that can be engineered for particular properties and tailored for specific applications.

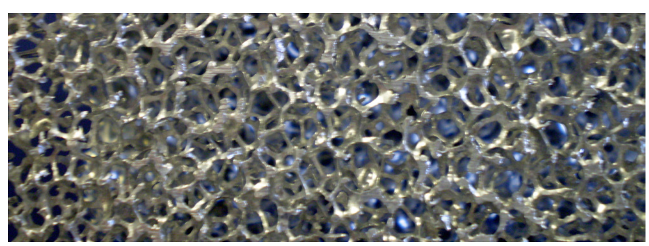
IDEALLY SUITED FOR HIGH-TECH APPLICATIONS

Reticulated foams have a number of features that benefit research and design engineers across many industries. The interconnected lattice of continuous ligaments within the cellular structure provides greater strength than shorter fibres and also ensures uniform material characteristics throughout the structure. Other characteristics that offer further benefits include:

High strength-to-weight ratio

Reticulated foam is particularly useful within cores of structural sandwich panels. The isotropic properties of the foam allow for a uniform response to impact, regardless of impact angle. These foams also add strength and structure when used as part of a three-dimensional network of reinforcing fibres in composites.

IN THIS WHITE PAPER



Reticulated foams are low-density, permeable structures of open cells and continuous ligaments – microscopically like three-dimensional mesh. It is the continuous nature of the ligaments that make the foam ‘reticulated,’ reticulum *being Latin for ‘network.’*

High surface area-to-volume ratio

Deposition of a high-cost catalyst such as platinum or silver onto the ligament surfaces of a reticulated foam allows contact of a gas or liquid with the catalyst over a vast surface area. This technique is cost effective and proves to be particularly valuable in the development of fuel cells. In addition, reticulated foam offers an exceptionally large surface area in a compact and lightweight structure for use as a scaffold for biological growth in pollution control and other devices.

Conductive or insulating

Depending on the material chosen, a reticulated foam can provide very low-bulk thermal or electrical conductivity as well as insulation against high temperatures. In particular, vitreous carbon and silicon carbide reticulated foams can endure the same extreme temperatures as solid material, but at a fraction of the weight. These characteristics lend themselves to use in aerospace applications, in heat exchangers, porous electrodes, and wherever an exceptionally efficient, lightweight conductor or insulator is required.

Low flow resistance

The uniform cell structure and rigid geometry of reticulated ceramic or metal foam contribute to a low pressure drop for fluid flow. This characteristic is useful in filters, demisters, gas diffusers and mixers, and liquid and gas separators, among other applications.

Resistance to fracture and thermal shock

Because the properties of the parent material extend throughout the foam in three dimensions, reticulated foam provides enhanced resistance to fractures and thermal shock. The continuous ligaments of the material deter crack propagation, since a crack encountering a continuous ligament (as opposed to a short fibre) is stopped from progressing through the structure.

TAILORING ATTRIBUTES FOR SPECIFIC USES

Although ‘standard’ reticulated foams of ceramic materials or metal are suitable for many high-tech applications, it is possible in the fabrication of a foam to tailor its properties for a specific application by adjusting the material composition, pore size, density, ligament structure, and even the shape of the component. In fact, the most exciting aspect of working with reticulated foams may be the opportunity to explore and exploit their properties for use in any number of new as well as established applications.

Matching the production process to the application

Recent advances in the production of reticulated foam and reticulated foam components are the lost carbonate sintering (LCS) process, sand-casting and 3D printing.

STANDARD TYPES OF RETICULATED FOAMS

Metal	Ceramic
Aluminium	Alumina
Copper	Silicon carbide
Nickel	Vitreous carbon
Stainless steel	
Zinc	

REPRESENTATIVE TECHNICAL DATA*

Silicon carbide foam

Bulk density: 0.29g/cm^3
Porosity: 91%
Pores/cm: 24
Thickness: 10mm

Aluminium foam

Purity: 98.5%
Bulk density: 0.2g/cm^3
Porosity: 93%
Pores/cm: 16
Thickness: 6.35mm

**Represents typical data for standard items.*

TYPICAL APPLICATIONS OF RETICULATED FOAMS

- Porous electrodes (electrically conductive materials)
- High-temperature insulation
- Filters
- Three-dimensional network of reinforcing fibres in composites
- Storage batteries
- Scaffolds for biological growth
- Acoustic control
- Cores in structural sandwich panels
- Heat exchangers

Lost Carbonate Sintering (LCS) process

Sintering a compact of copper powder and carbonate powder has proven to be a cost-effective means of producing copper foam with controlled cell shape, cell size and porosity. The particle size of the carbonate powder is selected to match the desired cell size of the final foam. The particle size of the copper powder is not critical, although it needs to be considerably smaller than the carbonate particles.

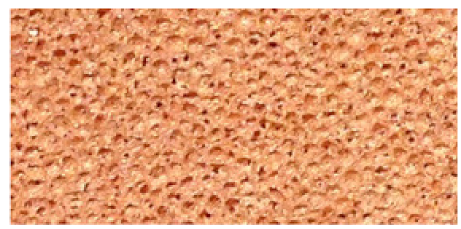
The compaction/sintering process yields a matrix of copper ligaments, in between which is the carbonate powder. After cooling, the carbonate is dissolved away in water and recycled, or decomposed using heat. The resulting structure is regular and uniform throughout, giving a rigid, highly porous and permeable structure with a controlled density of metal per unit volume.

This microporous copper foam structure is, not surprisingly, of particular interest to design engineers working in fields requiring heat exchange, where applications include but are not limited to liquid cooling, air cooling, heat exchangers, board-level electronics cooling, power electronics, and EMI shielding.

In addition to copper, the LCS process has successfully produced foams of other metals.

LCS Process

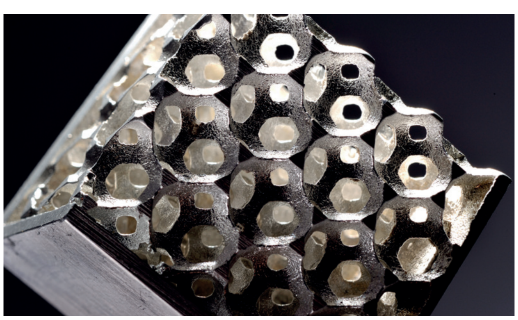
- Uses "space holder" method of foam manufacturing
- Cost-effectively controls cell shape, cell size and porosity
- Results in cell sizes between 300 and 600 µm and relative density of approximately 37% (vs. cell sizes between 0.8 and 2 mm and relative density of approximately 9% for traditional copper foam)



Microporous copper foam – LCS process

Sand-casting method

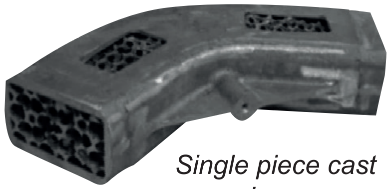
A recent development in the area of foam structures is a cost-effective "regular" aluminium foam with evenly spaced, open pores. It is made up of cells defined as regular tetrakaidecahedrons (polygons with 14 faces – 8 hexagonal and 6 square). The foam is manufactured using a sand-casting method, resulting in each manufactured piece being identical to and having exactly the same behaviour as other pieces from the same casting process.



"Regular" aluminium foam with solid base on three sides

Sand-casting

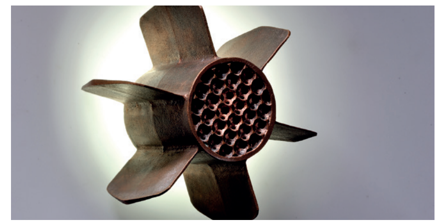
- Establishes exact form of foam part before its manufacture
- Optimises precise structure necessary for a specific application (e.g., impact absorption or heat exchange)
- Eliminates need for machining



Single piece cast crumple zone

For impact absorption, the advantage of this regular, reproducible aluminium foam product is that it can be designed with the end use in mind, making it possible to optimise the exact structure necessary to absorb the energy from an impact based on a specific application.

In heat exchange, this metal foam potentially has the greatest advantages. Its high porosity (80-90%) and its very high relative surface area of up to 500 m^2/m^3 facilitate the movement of fluids and the recovery of heat, even at low speeds.



Heat exchanger

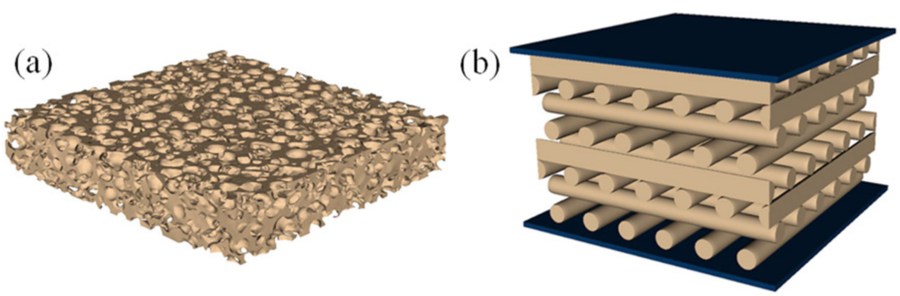
3D Printing

3D printing appears to be the next frontier in the creation of cellular solids, as evidenced by work being done by materials scientists at Lawrence Livermore National Laboratory (LLNL). They have developed a 3D-printed polymeric foam (filled polymethylsiloxane elastomer) that they report is superior in almost every way to stochastic foam of the same material.* The 3D-printed foam has a uniform structure with well-defined cellular shapes and dimensions down to the microscale level.

To test the durability and long-term mechanical performance of the 3D-printed foam, the scientists performed accelerated aging experiments in which samples of both traditional stochastic foam and the 3D-printed foam were subjected to elevated temperatures under constant compressive strain. Results showed that the 3D-printed foam aged more slowly, retaining its mechanical and structural characteristics better than the traditional foam. It is reasonable to expect that knowledge gained from work with polymeric materials will be applied in the production of ceramic and metal foams in the near future.

3D Printing

- Uniform structure has well-defined cellular shapes and dimensions down to the microscale level
- Retains mechanical and structural characteristics better than traditional stochastic foam
- Offers the potential for programmable architectures and mechanical response



Microstructures of a) open-cell stochastic foam, and b) 3D-printed foam.

**Maiti, A. et al. 3D printed cellular solid outperforms traditional stochastic foam in long-term mechanical response. Sci. Rep. 6, 24871; doi: 10.1038/srep24871 (2016).*

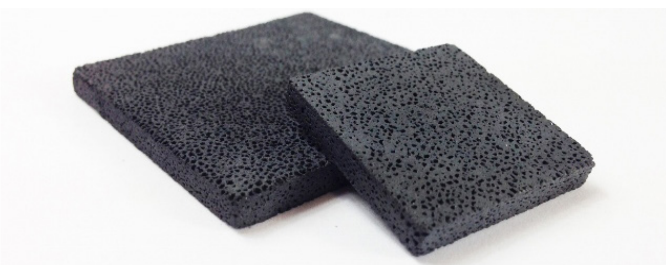
Coating for enhanced performance

Coating the underlying structure of a foam is an economical way to enhance the performance of the structure for a particular application. Once the coating fills approximately 5 percent of the original pore space, the entire foam takes on the mechanical, thermal and electrical properties of the coating. Typical coatings include pyrolytic carbon or graphite, refractory metals, ceramic compounds, and certain precious metals. Applying a dense coating of a platinum group metal to a ceramic foam protects the underlying foam material from highly oxidizing, corrosive and high-temperature environments at a fraction of the cost of a 100% platinum group metal foam.

The following are just a few examples of how such coating is being done commercially with metal, polymer and ceramic foams.

Copper oxide coating for heat sinks

Microporous copper foam coated with a thin, hard layer of copper oxide provides outstanding performance as a low-profile heat sink in passive cooling environments. The black copper oxide that coats the interconnected pores of the thermally conductive copper foam dramatically increases emissivity and therefore passive cooling performance.



Ideal where space is tight and performance is critical – a thin, hard layer of copper oxide on microporous copper foam dramatically improves performance.

Copper Oxide Coating

- Height of heat sink can be reduced with no sacrifice in performance, *or*
- Improved thermal performance can be achieved in same physical envelope
- A smaller footprint is possible, since size requirements of individual components can be reduced due to increased thermal efficiency
- Life of component can be increased through reduction in overheating

Refractory foams

Refractory foams are open-cell, low-density materials well suited for high-temperature aerospace and industrial applications. These foams usually begin as polymer foams pyrolized to create a reticulated vitreous carbon foam with the desired physical, thermal and electrical properties. The vitreous carbon foam can then be coated inside and out, if desired, with the refractory metal or ceramic material chosen to impart the desired properties for specific aerospace or industrial applications.

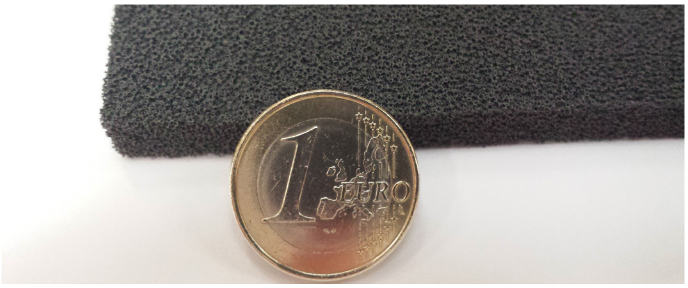
Vitreous carbon foam, also known as reticulated vitreous carbon, is a rigid, highly porous and permeable structure that has a controlled density of carbon per unit volume.

Refractory Foams

- High specific strength material for high-temperature, weight-sensitive applications
- Cost-effective method of imparting desired metal or ceramic properties to less expensive foam structure
- Thermally insulating, electrically conductive

Coating for highly active catalysis

Open-cell catalyst supports are often made from catalyst-coated foams of silicon carbide, silicon nitride, or metal oxides because of their low cost compared to the catalyst material. The foam structure allows the fluid excellent access to the large surface area of the catalytic surface, as well as providing excellent heat and mass transfer and minimal pressure drop on the flowing liquid. A high specific surface area can be achieved by increasing the foam cell density (number of pores per linear inch, or ppi).



Silicon carbide foam, shown here with a coin for size comparison, is one of several reticulated foams typically used for catalytic coating.

Foams Coated for Active Catalysis

- Outstanding fluid access to large surface area
- Excellent heat and mass transfer
- Minimal pressure drop
- Ability to tailor amount of surface area

SUMMARY

Strong yet lightweight, compact yet with a high surface area, conductive or insulating … reticulated foams have much to offer researchers and innovative engineers working in a broad range of fields.

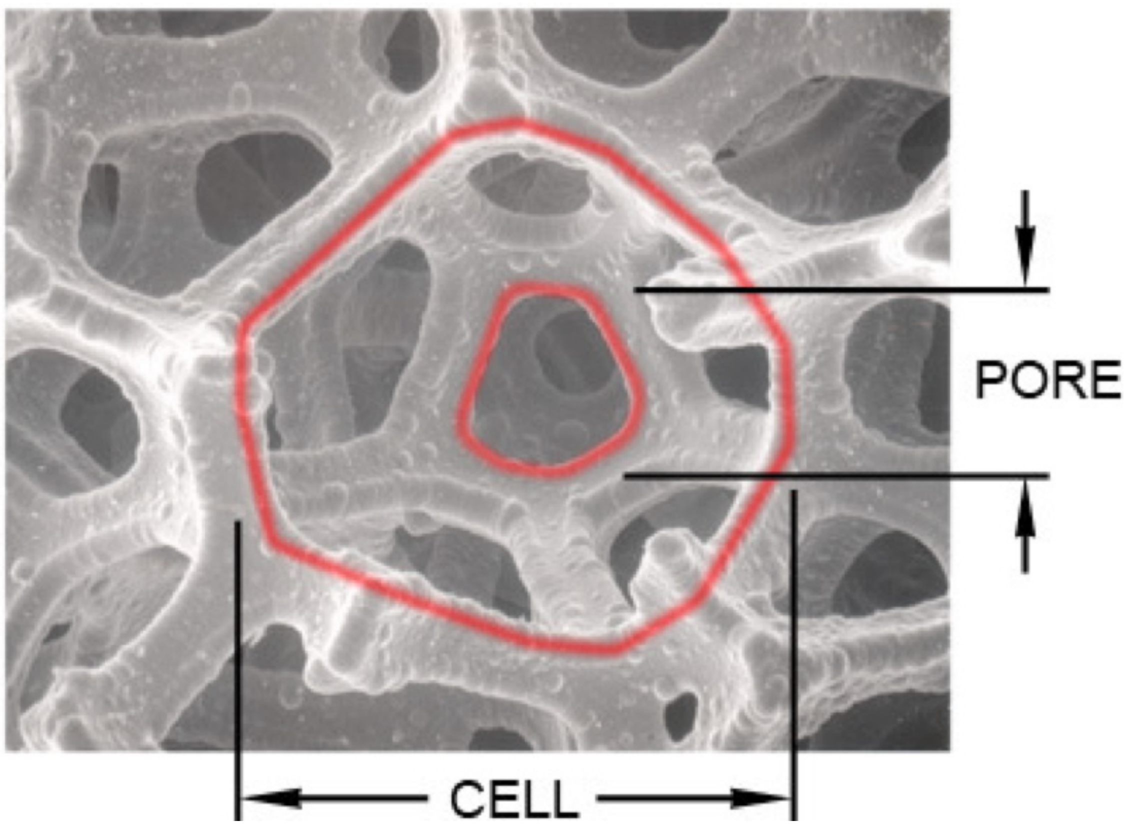
For more information regarding reticulated foams, contact the authors at Paul.Everitt@goodfellow.com or James.Taylor@goodfellow.com, or email info@goodfellow.com.

SEE APPENDIX A, EXPLANATION OF PORE SIZE, ON PAGE 7.

SEE APPENDIX B, EXAMPLES OF FOAM STRUCTURES, ON PAGE 8.

APPENDIX A: EXPLANATION OF PORE SIZE

Each bubble structure in the open-celled foam generally consists of 14 reticulated windows or facets. The polygonal opening through each open window is referred to as a “pore”. In any given bubble, the polygonal pores actually are of two or three different characteristic sizes and shapes, but for material designation purposes, they are simplified to an average size and circular shape. The number of these pores that would subtend one inch then designates the foam “pore size”. Metal foams are generally manufactured from 5 to 40 pores per inch, while carbon and ceramic foams are manufactured from 5 to 100 pores per inch. An average pore diameter is about 50% to 70% the diameter of its parent bubble, thus 10 pore per inch (PPI) foam would have roughly 5 to 7 bubbles per inch.



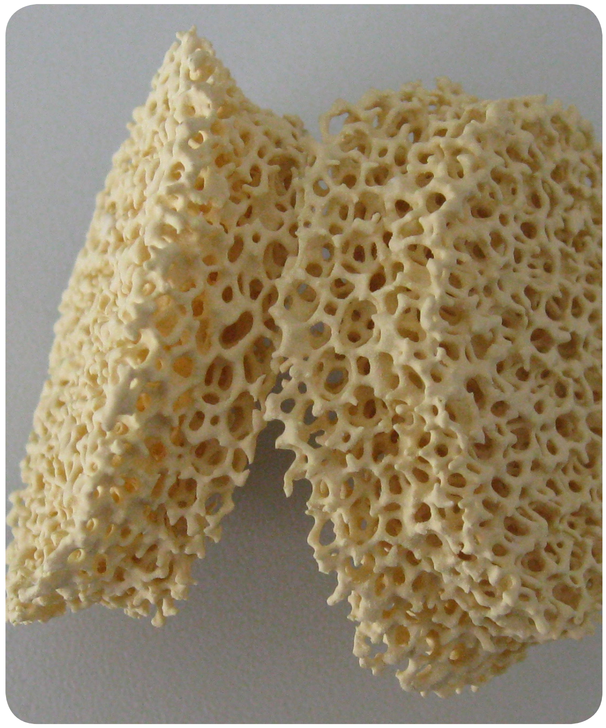
Effects of Pore Size

Foam pore size defines how finely the raw material of a foam is divided. The bubble and strut structural shape is always constant, but a 5 pore per inch* (PPI) will visually appear more open and coarse than a 40 or 100 PPI foam. Accordingly, the foam pore size directly affects nominal ligament length and cross section size, as well as pore diameter. In turn, these micro-structural features influence specific surface area, fluid flow resistance, and electromagnetic transmission or absorption. These are critical parameters when designing light diffusers, EMI shields, fluid flow diffusers, heat exchangers, stray light absorbers, laser dumps, filters, and porous electrodes.

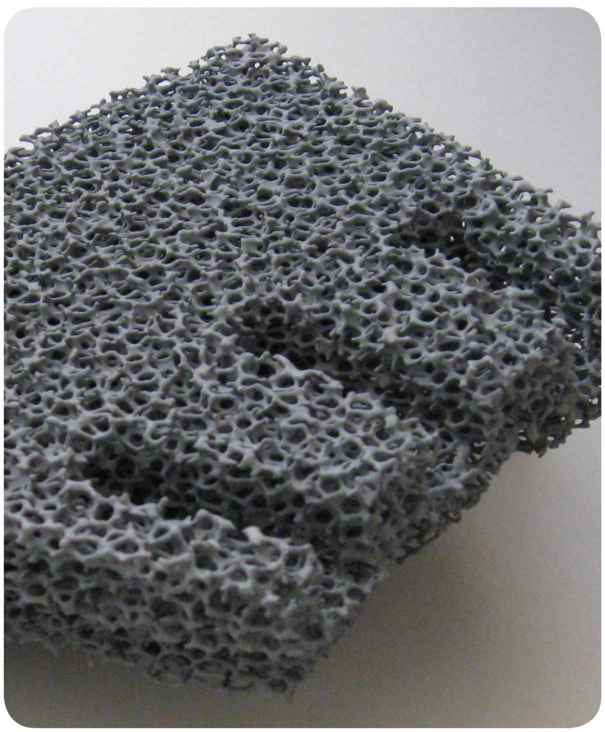
**A value for pores per cm can be calculated by dividing the pores per inch (PPI) by 2.54.*

APPENDIX B: EXAMPLES OF FOAM STRUCTURES

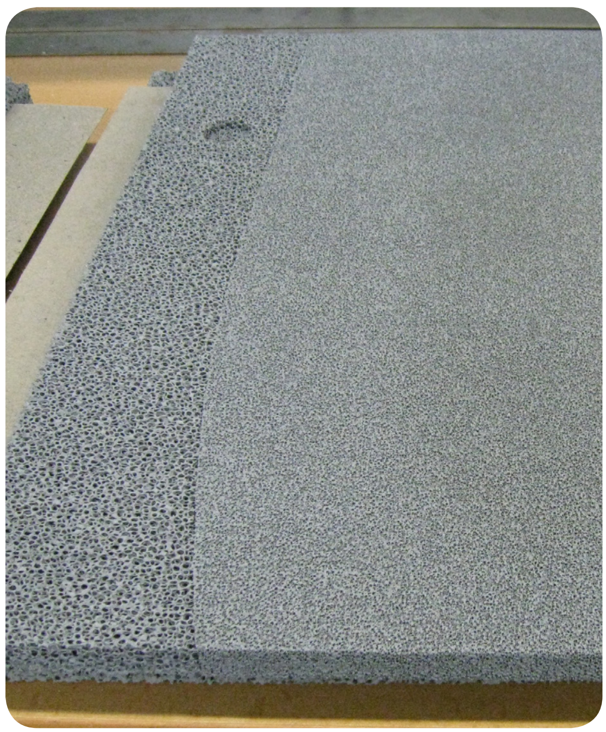
Silicon carbide foam with nonporous outer diameter



Zirconia foam with large pore size



Silicon carbide foam shaped for a particular application



Foam sheet designed with two different porosities