ADVANCED
ENGINEERING
MATERIALS

Cellular Metals Manufacturing**

By *Haydn N. G. Wadley**

Open cell, stochastic nickel foams are widely used for the electrodes and current collectors of metal – metal hydride batteries. Closed cell, periodic aluminum honeycomb is extensively used for the cores of light, stiff sandwich panel structures. Interest is now growing in other cell topologies and potential applications are expanding. For example cellular metals are being evaluated for impact energy absorption, for noise and vibration damping and for novel approaches to thermal management. Numerous methods for manufacturing cellular metals are being developed. As a basic understanding of the relationships between cell topology and the performance of cellular metals in each application area begins to emerge, interest is growing in processes that enable an optimized topology to be reproducibly created. For some applications, such as acoustic attenuation, stochastic metal foams are likely to be preferred over their periodically structured counterparts. Nonetheless, the average cell size, the cell size standard deviation, the relative density and the microstructure of the ligaments are all important to control. The invention of more stable processes and improved methods for on-line control of the cellular structure via in-situ sensing and more sophisticated control algorithms are likely to lead to significant improvements in foam topology. For load supporting applications, sandwich panels containing honeycomb cores are much superior to those utilizing stochastic foams, but they are more costly than stochastic foam core materials. Recently, processes have begun to emerge for making open cell periodic cell materials with triangular or pyramidal truss topologies. These have been shown to match the stiffness and strength of honeycomb in sandwich panels. New cellular metals manufacturing processes that use metal textiles and deformed sheet metal are being explored as potentially low cost manufacturing processes for these applications. These topologically optimized systems are opening up new multifunctional applications for cellular metals.

1. Manufacturing Methods Overview

As the engineering applications of cellular metals grows, many methods for their manufacture are being developed.[1] They result in materials that can be classified by the size of their cells, variability in cell size (stochastic or periodic), the pore type (open or closed) and the relative density of the structure. Figure 1 summarizes the range of cell size and relative density for materials created by established and emerging manufacturing methods. Those with high relative density, $\rho/\rho_s > 0.5$ (where ρ is the cellular metals density and ρ_s is that of the solid from which it is made) include Gasars made by the solidification of metal-H_2 alloys[2] and expanded, entrapped gas materials.[3] Interest in the structural uses of both materials has declined because of the difficulty of creating the low relative densities (0.05–0.20) needed for these applications.[4]

Manufacturing methods based upon the foaming of a liquid metal, either by injecting a gas (the CYMAT process)[5] or by the decomposition of gas releasing particles (e.g. the Alporus or Alulight materials)[6] are the most widely used for making stochastic cellular aluminum. Efforts are underway to extend the method to other metals. Both approaches result in closed cell stochastic foams with cell sizes in the 0.5 to 15 mm range and relative densities from 0.04 to 0.4.

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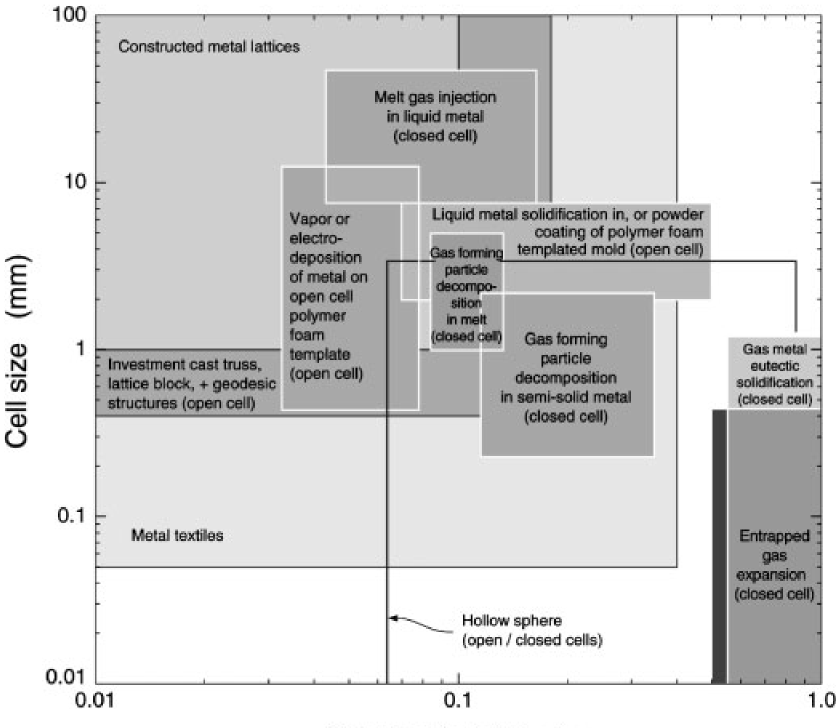


Fig. 1. Many cellular metal manufacturing processes have been developed. Each covers a part of the cell-size – relative density space.

Stochastic open cell analogues can be created using open cell polymer foam templates (e.g. Duocel).[7] These templates are inexpensive and available with a wide range of average cell sizes. The templates can be used to create a mold for investment or pressure casting.[8] The relative density and cell size of the cast materials is strictly set by those of the polymer foam template (unless a post solidification deformation process is used to reduce the cell size and increase the density). The template can also be used as a substrate for vapor deposition. Both chemical vapor deposition using a nickel carbonyl precursor that decomposes at 120 °C (below the polymer softening temperature)[9] and directed vapor deposition[10] have been used. In the vapor deposition processes, the relative density is determined by the thickness of the metal deposited on the polymer ligaments. Applications of these materials for current collection in metal hydride batteries have favored thin ligaments with resulting relative densities in the 1–5 % range. A third approach based upon the coating of a polymer template with a metal powder slurry is beginning to become important.[11] In this process, the slurry contains metal powder, a binder, and various organic solvents/additives to control viscosity. The template is immersed in the slurry and the binder and other organic materials are removed by heating. The powder is sinter densified. The polymer templates can also be carbonized prior to either vapor deposition or application of a metal powder. This allows higher use temperature metals to be created with cellular topologies.[12]

Numerous other space holding structures can be created and used as temporary substrates. For example, significant efforts are being directed at the creation of hollow spheres using spherical polymer templates.[13] Hollow spheres can also be created from viscous metal oxide.[14] or metal hydride slurries. The infiltration of metals into sacrificial (e.g. water soluble salt) spheroidal particle aggregates is also being evaluated.[15] Hollow sphere structures are of interest in part because the fraction of open and closed porosity can be tailored to facilitate applications where both are desirable.[16]

Recently, the use of a sacrificial template has been extended to create periodic cellular structures with truss topologies.[17] Using polymer injection molding[18] or rapid prototyping,[19] these polymer templates provide a means for creating investment cast structures with precisely controlled metal ligament diameters and orientations. They allow the ultimate level of topology control, but the process is costly compared to metal foaming. Other, less expensive methods for forming these topologically optimized structures are under development. They include a method based upon the out-of-plane deformation of perforated/expanded metal sheets[20] and metal textile lay-ups.[21] In both cases, transient liquid phase sintering (brazing) is used to assemble the cellular structure. These processes may become competitive with those used to manufacture metal honeycomb cored sandwich panels. These honeycomb materials were the first use of a cellular metals concept for load supporting structures and remain widely used in aerospace where their high cost is compensated by their excellent structural efficiency.

These manufacturing routes are organized in Figure 2 and the names of the products associated with each are shown. Note the classification for Alulight as a solid route is problematic. In this increasingly important process[22] metal powder and a gas-releasing agent are blended and extruded to create a solid precursor material. This can be sandwiched between solid alloy sheets or pieces can be placed in a shaped container and the objects heated to release the gas and expand the component. Recent work shows that the best foam structures are achieved by heating above the solidus of the metal powder.[23] This process is therefore not strictly a solid state one, but since the structure is derived from a material that requires extensive solid state forming it is (for the moment at least) classified as a solid phase fabrication approach.

The cellular metals discussed above can be further classified by their metal topology, see Figure 3. Those created by

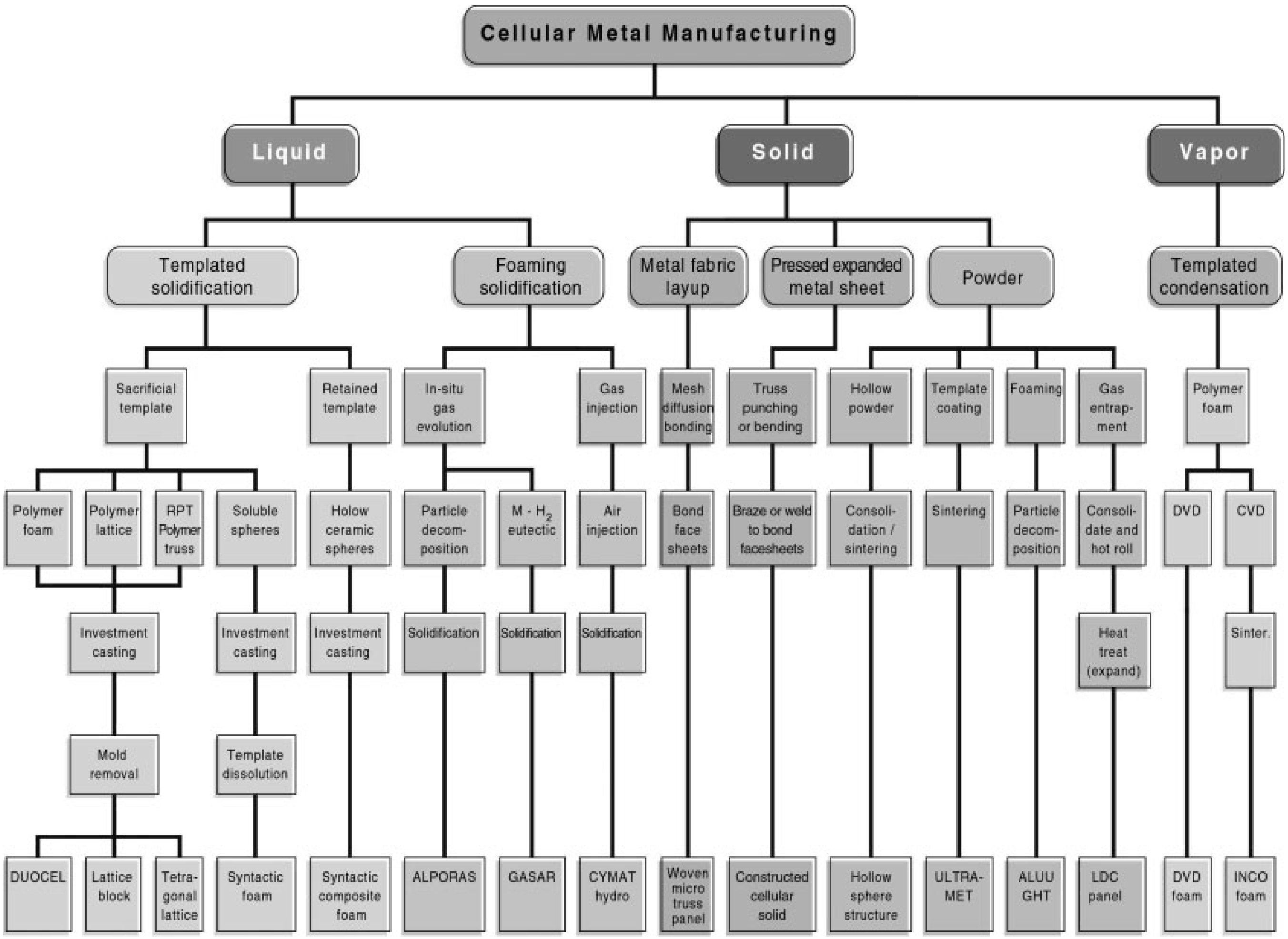


Fig. 2. A taxonomy of cellular metal manufacturing processes. They exploit liquid, solid and vapor phase processing routes.

foaming or from foamed templates, or from random size/dispersed spherical powders or from sacrificial random templates have a statistical variation of cell size and shapes.[24] These materials cannot be characterized by a single unit cell and are referred to as stochastic foams. Materials made using templates characterized by a unit cell that can be translated through the structure are referred to as periodic materials. Periodic materials in which the cell is translated in two dimensions are prismatic (honeycomb is the best known example). Those with three-dimensional periodicity are either ordered closed cell arrays such as hollow spheres or open cell truss structures with three (tetrahedral), four (pyramidal) or more struts. The latter are frequently referred to as lattice or micro-truss materials.

The properties, and therefore applications of stochastic cellular metals are a sensitive function of relative density, cell type (open/closed) and cell size distribution.[24] Applications where load support or thermal management dominates are optimized by periodicity.[25] Those for acoustic damping, catalyst support, batteries and perhaps impact energy absorption are well served by stochastic materials. Comparisons of the heat transfer and fluid flow characteristics of stochastic foams and periodic micro-truss materials made by the metal textile route indicate have similar heat conduction characteristics but significantly reduced pressure drops for the latter. They appear promising for use as cross flow heat exchangers.[26]

2. Stochastic Foams

Examples of the topologies of a number of stochastic cellular metals are shown in Figure 4. Figure 4a shows the cross section of Cymat material made by gas injection into a melt.[27] This micrograph is of material made early in the development of the process and shows a wide variation in the size of the cells.

The average cell size has been found to be a sensitive function of the way in which gas is injected into the melt (Figure 5) and the melt composition. Radiography[28] has revealed the existence of density gradients in early versions of the solidified material. These gradients are thought to result from drainage of the wet foam prior to its solidification. Correcting these deficiencies has exposed a need for an

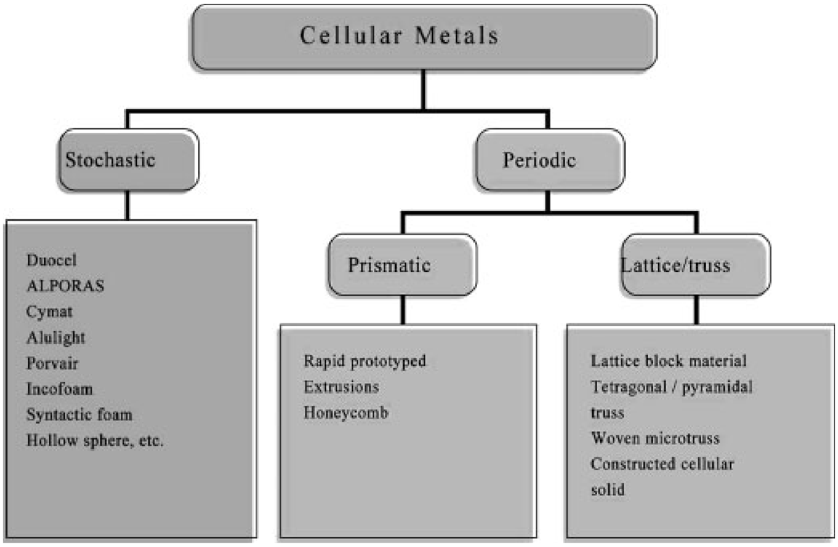
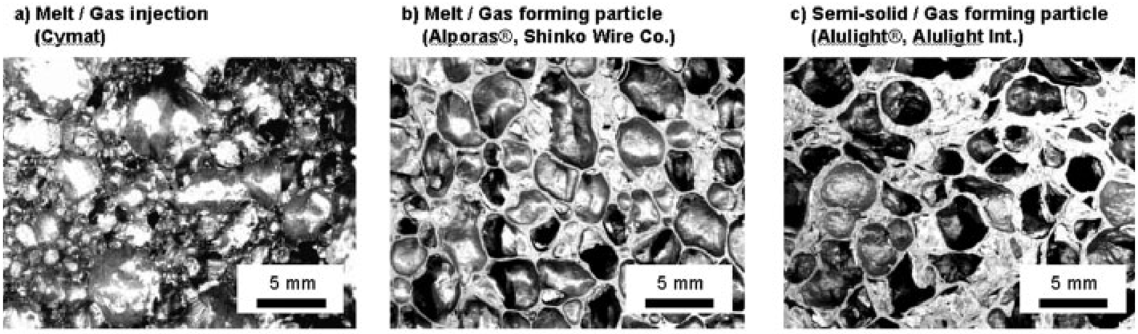


Fig. 3. Cellular metals can be classified as stochastic or periodic. The periodic materials are characterized by a unit cell that is repeated in two directions (prismatic structures) or in three directions (truss or lattice materials).

improved understanding of the formation and solidification of metal foams. The role of drainage and the evolution of cell size (coarsening) that accompanies it appear particular important.

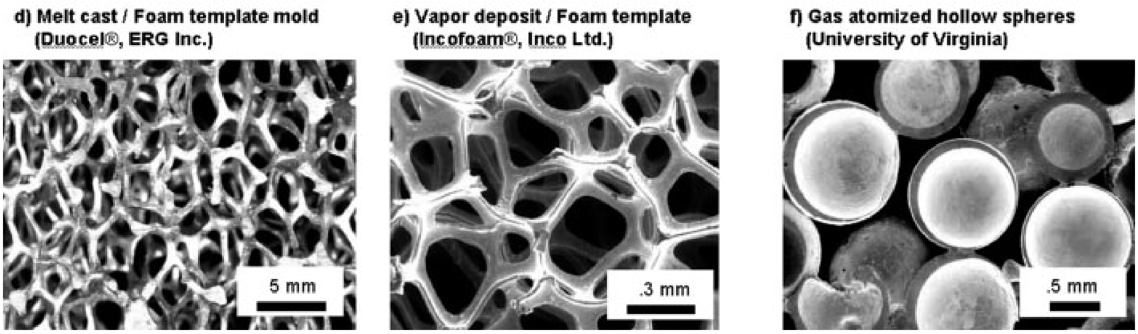
Several groups[29,30] have begun to address the drainage of liquid metal foams. Simplified melt constitutive properties are used in these early models. Drainage through the plateau borders is driven by gravitation and surface tension effects. However, the rate of drainage is liquid composition dependent and is a (nonlinear) function of the temperature and solid fraction content of the liquid. Incorporating these factors into predictions of the rate of drainage appears critical if the effects of melt composition and foam withdrawal rate are to be properly introduced. The pressure within the cells increases with decreasing cell size and the dispersion in a foams cell size therefore drives coarsening in nonequilibrium metal foams. Linking the final topology of a metal foam to the liquids composition and the environment sampled by the foam during its propagation through a manufacturing process will eventually provide powerful tools for optimizing metal foaming processes.

Unlike the majority of metal manufacturing processes, foaming is a highly dynamic process in which the transient topology one seeks to "freeze in" depends sensitively upon


a) Melt / Gas injection (Cymat)

b) Melt / Gas forming particle (Alporas®, Shinko Wire Co.)

c) Semi-solid / Gas forming particle (Alulight®, Alulight Int.)


d) Melt cast / Foam template mold (Duocel®, ERG Inc.)

e) Vapor deposit / Foam template (Incofoam®, Inco Ltd.)

f) Gas atomized hollow spheres (University of Virginia)

Fig. 4. Examples of the topologies of stochastic cellular metals made by different manufacturing routes.

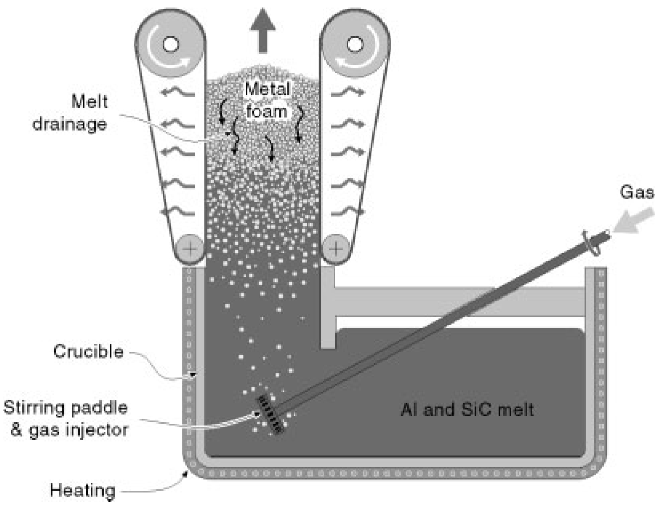


Fig. 5. Gas injection is used to create aluminum foams. Many phenomena combine to determine the cell size, its distribution and the relative density of the resulting stochastic foam.

many process parameters. As a result, this process appears well suited for the application of what has come to be known as intelligent processing of materials concepts.[31] In this now widely practiced approach, sensors are used to continuously monitor structure and process models are combined with feedback control principles to regulate the process variables in such a way that a desired material state is achieved. Radiography,[32] eddy current[33] or laser ultrasonic[34] sensors all appear well suited for monitoring relative density and interring cell size, even in the harsh environment of the foaming process. Reduced forms of the modeling efforts now underway promise a linking of the process to the structure so that on-line feedback control of a foams structure could eventually be achieved.

Similar issues underlie efforts to improve and perfect materials made by the decomposition of titanium hydride (and other gas releasing materials) in the melt.[35] Figure 4b shows the existence of a wide range of cell sizes in Alporus. Similar observations are seen in Alulight, see Figure 4c. Here, the rate of hydrogen release and the kinetics of its subsequent diffusion through the cell walls of the foam need to be convolved with drainage and the cell topology evolution issues alluded to above. Recent work has begun to identify the hydrogen release rate kinetics in both air[36] and in the metal where inter-diffusion through a transient titanium aluminide phase appears important.[37] Important insights into the foaming process are being revealed by dynamic radiography.[32] Promising modeling work is also well underway.[37]

The creation of stochastic open cell foams via casting into a mold made from a polymer foam template, Figure 4d, and by chemical vapor deposition, Figure 4e, are both mature processes. In the former case, improvements in the foams mechanical performance may be achievable by reducing the variability in the cell size of the polymer templates. These materials have been used as heat exchangers. The pressure drop encountered in thermal management applications of this material could be reduced if the occasional cell face membranes present in the original polymer template were removed. The INCO foam is already very well optimized for its major application as an electrode and current collector in nickel-metal hydride batteries. INCO foam is made from pure nickel and has a very low strength. It is therefore not well suited for structural applications. However, the ability to deposit alloys of other metals by directed vapor deposition,[10] or Ni_3Al/N_iAl intermetallics by reactive diffusion of aluminum[38] could open up interesting new opportunities for this system.

The final material shown in Figure 4f is made by the hot isostatic consolidation of hollow alloy powders.[39] The ones shown here were obtained as an undesired by product of inert gas atomization and can be inexpensively separated by floatation. However, the particle size is non-uniform, which results in a stochastic structure and reduced mechanical performance. The design of special purpose melt atomization processes[40] show promise for addressing this issue. Other strategies include using sacrificial spherical templates,[13] which are then coated with an alloy or the Georgia Tech approach, which utilizes metal oxide slurries.[41] In the latter approach, the slurries are used to form uniform size/relative density “green” ceramic spheres. A subsequent reduction process then creates a thin walled metal sphere. It remains unclear if the high cost of any of the hollow sphere routes is sufficiently compensated by properties that are superior to those of other stochastic foams.

3. Periodic Approaches

Interest in periodic structures has been driven by both structural and thermal management applications of cellular metals.[25] Honeycomb core sandwich panels are the benchmark for mechanically efficient structures. By flowing a coolant along the hexagonal channels of honeycomb structures, very effective cross flow heat exchangers can be created. However, when used as the cores of sandwich panels, maximum stiffness is obtained when the channels are perpendicular to the face sheets. These are then closed cell structures, and are therefore unsuited for multifunctional applications where both a load supporting and heat dissipating structure is required. Recent work with open cell truss structures with relative densities below 5 % has shown at least a 300 % increase in structural performance over stochastic foam sandwich panel analogues. These materials approach the mechanical stiffness of honeycomb-cored panels while providing opportunities for multifunctionality. Several approaches are being developed for their manufacture.

3.1 Investment Casting

The first materials with a three-dimensional truss structure and a cell size typical of cellular metals were developed by Jamcorp and are known as lattice block materials.[42] Thick

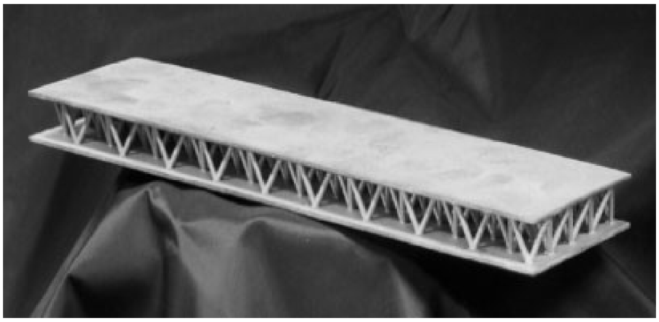


Fig. 6. A tetrahedral lattice structure made by rapid prototyping followed by investment casting. A Cu-2 % Be alloy was used for the 300 mm long sample shown. Struts are 1.2 mm in diameter.

(relatively low aspect ratio) trusses with many trusses (four or more) per node are features of these materials. These structures are well suited for investment casting. However, their topologies were not optimized for specific stiffness or strength[17] Wicks and Hutchinson[43] have designed optimized sandwich panels for supporting bending loads using a tripod (tetrahedral) truss core. The structures optimized for specific (in plane shear) stiffness have slender, higher aspect ratio trusses which are much more difficult to investment cast. Figure 6 shows an example made using rapid prototyping followed by investment casting using a high fluidity Be-Cu alloy.[19]

This is an expensive process and results in structures that contain significant casting porosity (a consequence in part of the complex topology which makes continuous fluid access to the solidification interface difficult). The use of a ductile Be-Cu casting alloy compensates for defects but not for the high cost and weight.

3.2 Constructed Trusses

More affordable approaches to the creation of the bend-load optimized tetragonal structure are being pursued.[20] In one approach, expanded or perforated metal sheet containing a two-dimensional ordered array of hexagonal holes are deformed out of plane at the nodes to create a triangulated (tetrahedral truss) core, Figure 7. Perforated metal sheet containing a square array of holes results in pyramidal truss cores. Transient liquid phases can be used to bond them together or to face sheets. The tetrahedral cored material has been found to match the performance of honeycomb core materials.

3.3 Metal Textiles

Recently, a metal weaving approach has been used to create lay-ups of metal textiles.[21] If these are coated with a transient liquid phase alloy powder (e.g., a Ni-P alloy for a stainless steel fabric), a simple vacuum heat treatment creates a periodic cellular metal with a unit cell that is square on two sides, pyramidal on two others and rectangular on the remainder, Figure 8.

This structure is much stiffer and stronger in compression than identical relative density stochastic foams.[44] Costs are driven by that of the wire and the bonding process. Methods for creating cellular metals from many metallic alloys appear feasible. When used as the cores of sandwich panels, specific stiffness approaching that of honeycomb appears feasible. The inherent anisotropic mechanical response may be advantageous, particularly in multifunctional applications. The structure shown in Figure 8 is close to optimal for a vertical

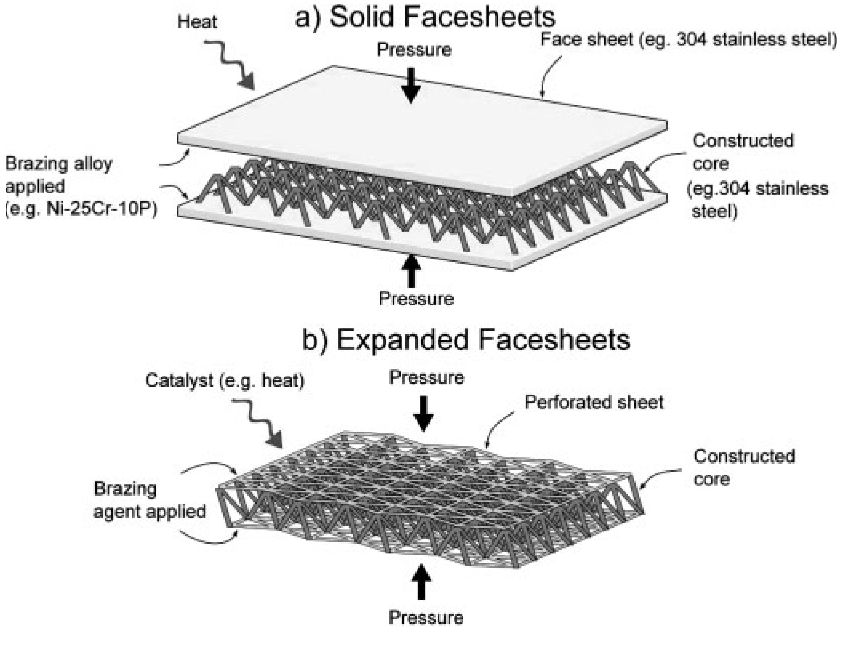


Fig. 7. Inexpensive tetrahedral truss cellular metal cores can be fabricated via the out of plane deformation of perforated/expanded metal sheets. These can be brazed to solid or expanded metal face sheets to create periodic cellular metals.

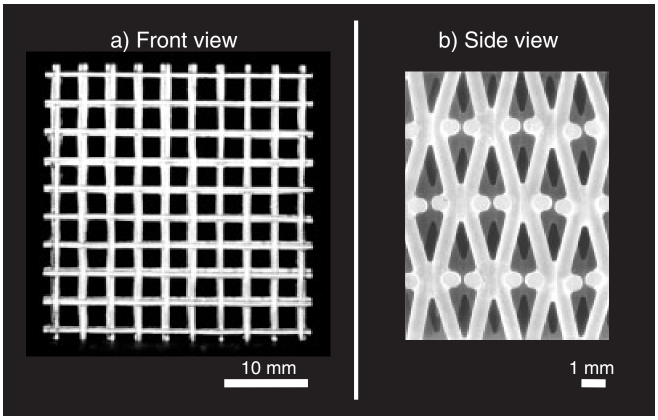


Fig. 8. Two views of a nichrome metal textile. It is an example of a periodic cellular metal made by liquid phase sintering metal fabric lay-ups.

compressive load and heat exchange to a fluid flowing parallel to the face sheets.

4. Discussion

The manufacture of cellular metals has rapidly emerged as an important new field of metallurgy. Numerous methods of processing utilizing the solid, liquid or vapor phase are all under development. Each process results in metal topologies that are classified as either stochastic or periodic. Many have overlapping cell sizes, relative densities and alloy chemistries. Not all the processes being explored to date will become commercially viable. Shakeout of manufacturing processes always follows the discovery of new material forms and this will undoubtedly be the case here.

As an understanding of the relationships between ligament metal properties—metal topology and performance emerges, it is possible to identify preferred materials forms for the various application classes. Figure 9 compares the mechanical properties of the cellular metals described above. For structures designed to support significant mechanical loads and those intended for thermal management where fluid backpressures are a concern, a periodic truss structure results superior in performance to all other concepts. However, it is not yet clear if the increased cost of the periodic cellular manufacturing processes under development today can be compensated for by the reduction in weight. Furthermore, ongoing improvements to foaming processes may, overtime reduce the discrepancies in performance and further lessen the impact of the periodic materials. This may be off-set by the ability to fashion periodic materials from wrought alloys whose composition has been optimized for the many challenges confronted by a structural metal during its use in corrosive, oxidizing or cyclically loaded environments. Looking to the future, it is clear that for applications where the interior surface area is the key determinate of performance (e.g., a catalyst support or battery current collector) stochastic materials have a sustainable future and the development and perfection of low cost methods for their manufacture will continue to remain an area of significant importance. The same may also apply to impact energy absorption applications for automobiles where cost is a major consideration in materials selection. However, metal topologies for this application are far from optimized. New periodic concepts may pose significant competition to stochastic approaches.

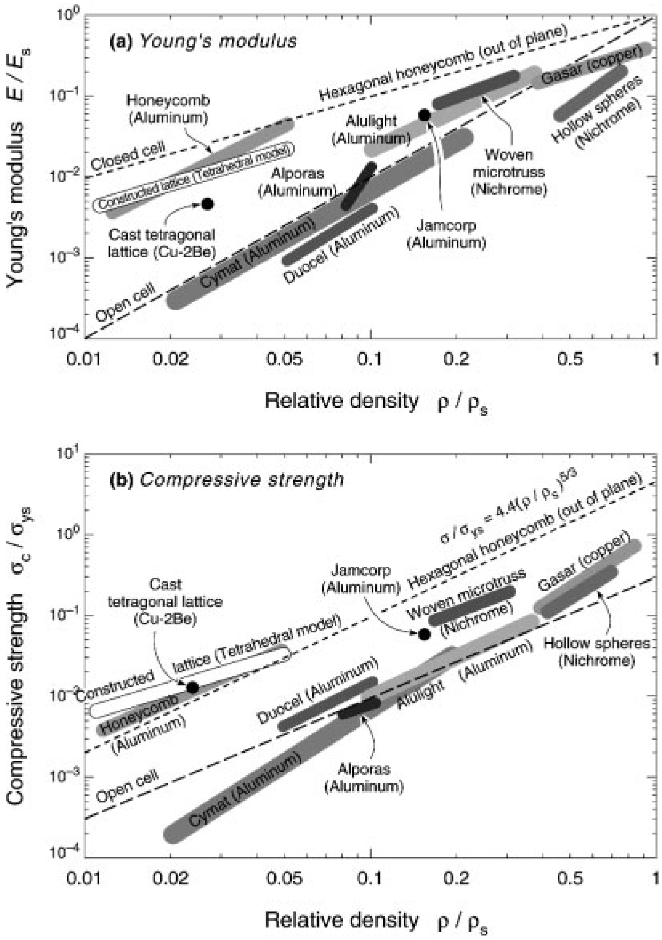


Fig. 9. A comparison of the mechanical properties of cellular metals. At low relative density, periodic systems have superior properties to their stochastic counterparts. The differences can be large. At 2 % relative density a tetrahedral cored material can be as much as 30 times stronger than a closed cell stochastic foam.

5. Summary

The properties of cellular metals depend upon those of the material in the ligaments and the metals topology. Many methods for manufacturing cellular metals are available and numerous others are under development. They result in either stochastic or periodic cellular metal topologies. Periodic structures appear to be superior for load bearing and/or thermal management structures. Stochastic structures are better for high specific surface area applications (e.g. electrodes for Ni-MH batteries or for catalyst supports) and for acoustic damping. The mechanical properties of stochastic structures can be improved by enhancing ligament properties which are determined by alloy selection and processing route. Improved understanding of foaming processes and better methods for on-line process control promise further improvements. Metal deformation processes used for periodic cellular metals appear better suited for the creation of load supporting structures subjected to sustained use in corrosive and fatigue loading environments but cost considerations need to be addressed. Periodic, open cell structures appear particular promising for multifunctional applications where the volume used for load support is also utilized for other purposes such as thermal management, power storage or shape actuation.

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