

Prospective Manufacture and Aircraft Applications of cast Metal Porous Materials

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Introduction

Aircraft weight reduction is achieved by two well-known ways, namely improving design, and using stronger and lighter materials. Reducing weight of metals and alloys may be effected, among other things, through developing sufficiently ordered porous morphology. Aircraft industry can use porous metals as functional materials also:

1. Heat sinks for electronic components
2. Cryogenic heat exchanger
3. Heat shielding for aircraft exhaust
4. Core structure for high strength panels
5. Water baffle in underwater launch missile
6. Containment matrix and burn rate enhancer for solid propellants
7. Energy absorber for shaped charges
8. Battery plates and spacers
9. Aircraft wing structure
10. Fuel tank baffles
11. Compact heat exchangers
12. Dead volume matrix in hard vacuum applications
13. Gas diffuser for semiconductor etch and deposition equipment
14. Porous electrodes
15. Pneumatic tool muffler
16. Silencer for jet engine intakes
17. Electromagnetic pulse (EMP) attenuation
18. Aircraft armor for fragmentation capture and absorption
19. Energy absorber for blast shock wave
20. Regenerator for thermal engines
21. Matrix for chemical beds and scrubbers
22. Mist elimination of water and oils
23. Flow straightener in wind tunnels
24. Air cooled condenser-cooling towers
25. Fluid pulse damper
26. Flash evaporator baffles in water desalination
27. Filters for sea water removal in surface ship
28. Energy absorber for auto bumpers
29. Race car deformable structures
30. Drone aircraft wet-wing structure
31. Ablative sealing compressor/turbine blades
32. Liquid heat exchanger
33. Catalyst surface
34. Vacuum chucks
35. Filters and filter supports
36. Flame arrestors
37. Fuel cells
38. Bearings
39. Fluid/particle separators

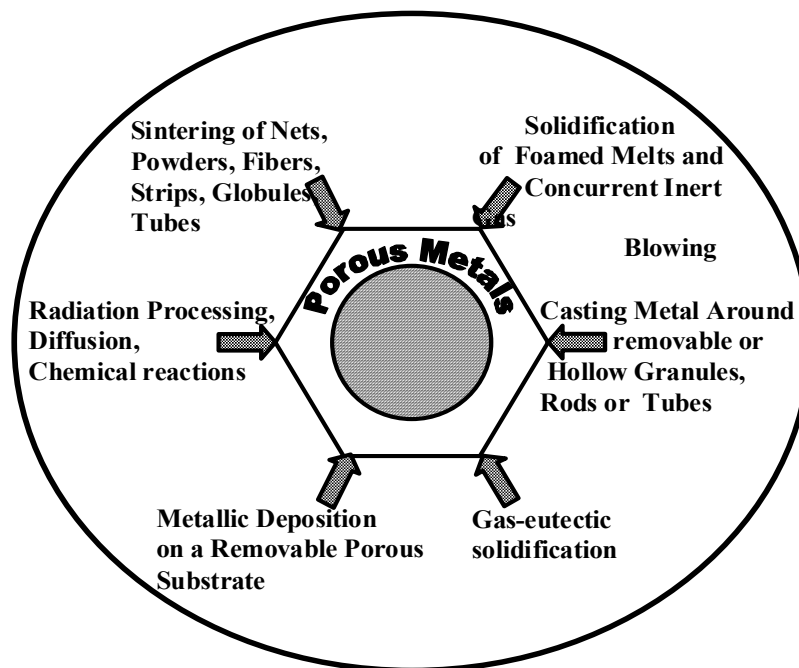
Porous metals are engineered materials; they are designed for special properties [1]. Technological progress necessitates expanding the choices of such materials, making the development of new porous metals a relevant challenge for materials scientists.

Although a wealth of information has already been accumulated on these materials, new results are published every year, extending the engineer's capability to manufacture porous metals and revealing their unknown and often unusual properties. This survey describes the state of the art and some recent accomplishments in the field. This paper discusses manufacturing practices, structure, properties, and applications of porous metals. Promising new research issues are also highlighted. Materials whose pores were not formed *in situ*, like honeycomb structures made by high-energy beams etc., and not covered.

Classification of porous metals

Porous metals are most often classified by the method of manufacture [1]. Here, a similar classification is given, although it differs from earlier ones because its criterion is the state of matter of the metal or alloy before the gas-crystalline structure of the porous metal is formed. We distinguish methods based on vapor deposition and melt solidification from the formation of pores which involves no change in the state of the base metal or alloy, such as sintering or radiation swelling. Apart from this classification, porous metals may be divided into two large groups, permeable and impermeable.

Classification by pore spatial distribution is also useful. Pore structure can be ordered or disordered, oriented or non-oriented. Porous metals may be distinguished by the geometry of individual voids that may be irregular, spherical, cylindrical, conical, or variable in section; straight or curved; closed, open, or dead end.



Porous metals also are categorized according to their applications, e.g., friction parts, electrical engineering components, etc. However, due to the rapidly expanding applications of porous materials this classification has provided inadequate and may mislead the designer.

Casting Porous Metals

Lost-foam casting is a unique process used to make cellular metals in Japan. Connected pores in plastic foam are filled with a castable refractory which is then cured. Upon heating, combustion of the sacrificial foam leads to formation of a spongelike solid. The solid is used as a mold for metal which solidifies in its pores. The process is primarily used for making cellular metals with low melting points.

A porous pattern for making refractory porous metals may be prepared by a different method not involving the use of organic material that is soluble at least in one solvent. The compact is heated, impregnated with the melt, and cooled to ambient temperature. The inorganic substance of the compact is then removed by a solvent.

Foaming. Already in 1948 (USA Patent #1434775, 1948) the mercury evaporation use has been offered for making foamed aluminum. This idea has been further developed (USA Patent # 2751289, 1956); due to that, foamed aluminum was obtained in 1951. According to this method, foamed metal is made by the foaming agent addition to a liquid metal and the subsequent mixture heating; as a result, the foaming agent releases some gas. The gas expands and causes the foaming of metal. The composition appeared after foaming is cooled with the formation of a solid foamed metal. Usually a metal hydride serves as a foaming agent, for example TiN_2 or ZrH_2 ; aluminum is subject to foaming, through this operation can also be executed with other metals, and the application of other foaming agents is possible. This process is very difficult to control, so the obtained foamed metal is characterized by non-uniform cellular structure. Large gas bubbles concentrate in the middle, while near the surface of cooling, the metal density rises. To remove these defects, several improvements were made.

The non-homogeneity of distribution and excessively large size of some cells were eliminated by several ways. Firstly, high-intensive hashing was resorted to (with the working body rotation frequency of 10000 rot/min); by doing this, the foaming agent was dispersed in the metal smelt in a rather short time, making about 10 sec (USA Patent #3816952, 1974). It was established, that the foamed metal quality improved as the hashing uniformity increased. The second method consisted of the smelted metal viscosity increase; due to that, the gas bubbles loss could be prevented on the subsequent stage of expansion. It can be achieved by using of alloys, possessing the large interval of solidification (200-400⁰C).

Another difficulty is connected with relatively short period of time between the foaming agent introduction in the smelt and the foam formation. It makes foundry especially difficult. One of the means, enabling to preserve the foamed metal in the heated liquid state for a relatively long time without foam destruction, is its thickening. Solid, liquid and gaseous materials are used as thickeners, for example silicon containing solid material, air, oxygen, nitrogen, carbon dioxide, argon and water (USA Patent #1392513, 1972). The smelt treatment with thickeners results in the essential increase of viscosity. The pores formed in the foamed metal under the addition of thickener, are smaller in size and more homogeneous. In the foam is subject to degradation after the gaseous thickener introduction, the foamed metal acquires more uniform porous structure (USA Patent #3692513, 1972).

The method, recently developed in Canada, should be specially mentioned [3]. A rare is entered into the vessel with smelted aluminum; through this pipe, a gas is blast and simultaneously the fine powder of silicon carbide is entered. In the zone of gas and pipe output, a tabulator is placed to foam the smelt. Due to the presence of a certain quantity of silicon carbide, with the given particles size, aluminum foam turns out very steady and is crystallized on a slowly moving saucer. To our mind, this way is the most promising one both as to technological parameters, and as to the quality of obtained foamed aluminum.

One should also mention the method, recently developed in the USA (USA Patent #4449901); according to it, a smelt is introduced through an outside nozzle into a special installation, the smelt entering in the form of a ring-like flow, and a gas is introduced through an internal nozzle.

The ratio between the smelt and gas flows enables metal bubbles to appear in the output. Downwards in a special container, they coalesce and then are crystallized, thus forming a material with cellular structure.

Another method of the porous metal manufacture on the basis of aluminum and its alloys with pores of small diameter, regularly distributed in the volume of metal, is of a certain practical interest. The authors have offered the foaming by a gas, consisting of the smelt saturation by hydrogen under the pressure of 0,5 MPa and significant overheating (350 K, with subsequent crystallization at the speed of 50 K/ sec in the atmosphere of argon at the pressure of 0,6 MPa. Then the metal is heated again up to the temperature of 1000 K, at the pressure of 0,01-0,1 MPa, in the state close to weightlessness; then it is crystallized again. In doing this, the particles of Al_2O_3 are previously entered in the smelt, making the centers of gas bubbles origin

The metal foam reinforcement provides for the increase of the foamed metal specific strength. Thus the technology is complicated by the reinforcing components preliminary introduction in the base smelt. For example, in the USA (Patent #3705030), the method of the foamed metal hardening was offered, implying the addition of an oxygen-containing agent in the smelt, thus promoting the oxide particles formation.

The means described permit to increase the strength of the composites with lightly built matrix. However, because of the cellular isometric structure of such a matrix, only a partial contact is realized between the reinforcing fibers and matrixes.

Infiltration of a granular bed is in many respects similar to lost-foam casting. It yields a continuous structure by melt infiltration of a bed of granules contained in the casting mold. The granules are made of soluble but thermally stable material that is removed by chemical treatment. To ensure free flow of the melt, it should be superheated. It is also desirable to preheat the granule bed and pressurize the melt or evacuate the spaces between the granules. An alternative method involves introducing granules into the melt while it is vigorously stirred.

This method permits to obtain a connected cellular structure, i.e. a spongy metal, by the smelt pouring between the granules can consist of soluble (but heat-resistant) material, which subsequently leaches, so porous metal is formed (USA Patent N 3236706, 1966). alongside with this, the granules can form a friable layer of an inorganic material easily compressible, for example of a foamed clay, of the balls of foamed glass, of empty corundum micro cylinders and etc. (Patent of Germany #1933321, 1971).

In Japan, a unique method is applied for the production of cellular metals-the casting against gasified patterns. The communicating channels of protoplast are filled in with a liquid refractory material, which solidifies. After heating, a body with rubber skeleton is formed. In this mould, the metals poured, which then solidifies inside. In such a way, the cellular metals with low smelting temperature are preferably obtained [6].

The method is known also (application of Japan #44-75165), implying the pouring into a construction, consisting of two plates with several pins, fixed with between them, in such a manner that the pins enter into the volume, where a smelted light metal is poured under pressure. After the solidification of metal, the casting is removed from the pins, as one of the plates is raised.

Stirred – in Granules. This method is opposite to the granules pouring with a smelt. According to it, a metal is smelted in a crucible, where granules are entered. After this, intensive hashing is

made, so that the granules were regularly distributed in the volume of metal. During the hashing, the composite can be cooled, in order to obtain the viscosity, sufficient to prevent segregation or lamination. Then hashing terminates and the mechanical mixture of metal with granules solidifies. If necessary, before the solidification, while the mixture has sufficient fluidity in liquid state despite its viscosity, it can be poured into an appropriate mould (USA Patent #30555763).

A similar method (Patent USA #3940262) implying the use of metal balls, entered in the smelt, is developed. According to it, plastic micro spheres industrially produced are used; they are heated up to the plastic charring, with empty carbon micro spheres appearance. They are covered by metal according to the method of precipitation from gaseous phase; after that, carbon is removed by the method of gasification, so that empty metallic micro spheres are formed. As a whole, this way is expedient to be used for refractory metals. In particular, it allows obtaining wolfram micro spheres 60-80 μm in diameter, possessing the uniform wall thickness of 2 μm .

Gas-eutectic transformation in metal-hydrogen systems is relatively recent discovery [4]. In this reaction, the liquid decomposes into a solid and a gas phase: $L \rightarrow S + G$. The transformation may take place if the phase diagram for the metal-hydrogen system involves a gas-eutectic equilibrium. Making the material consists of two steps [4]:

1. Melt charging with hydrogen to reach the eutectic composition, and
2. Melt solidification in a conventional or continuous casting mold.

No melt foaming occurs because the gas is evolved as the melt freezes (Figure 1).

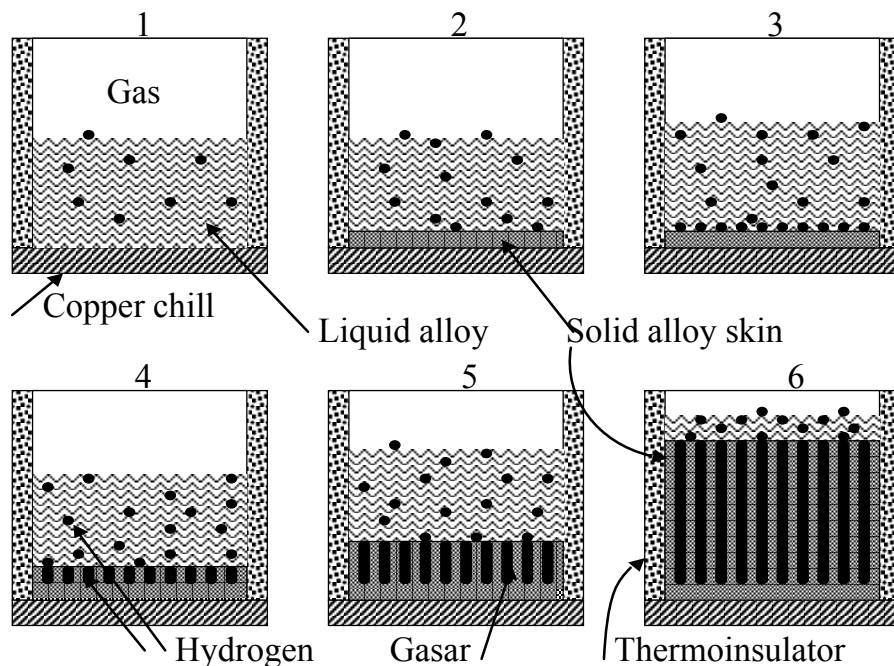


Figure 1. A schematic sketch of gas eutectic transformation at direction solidification

The process is in many ways similar to conventional eutectic transformation, the distinction being that the liquid decomposes into a solid and a gas rather than into two solids. The main process variables that govern the amount of porosity and the size, shape, and

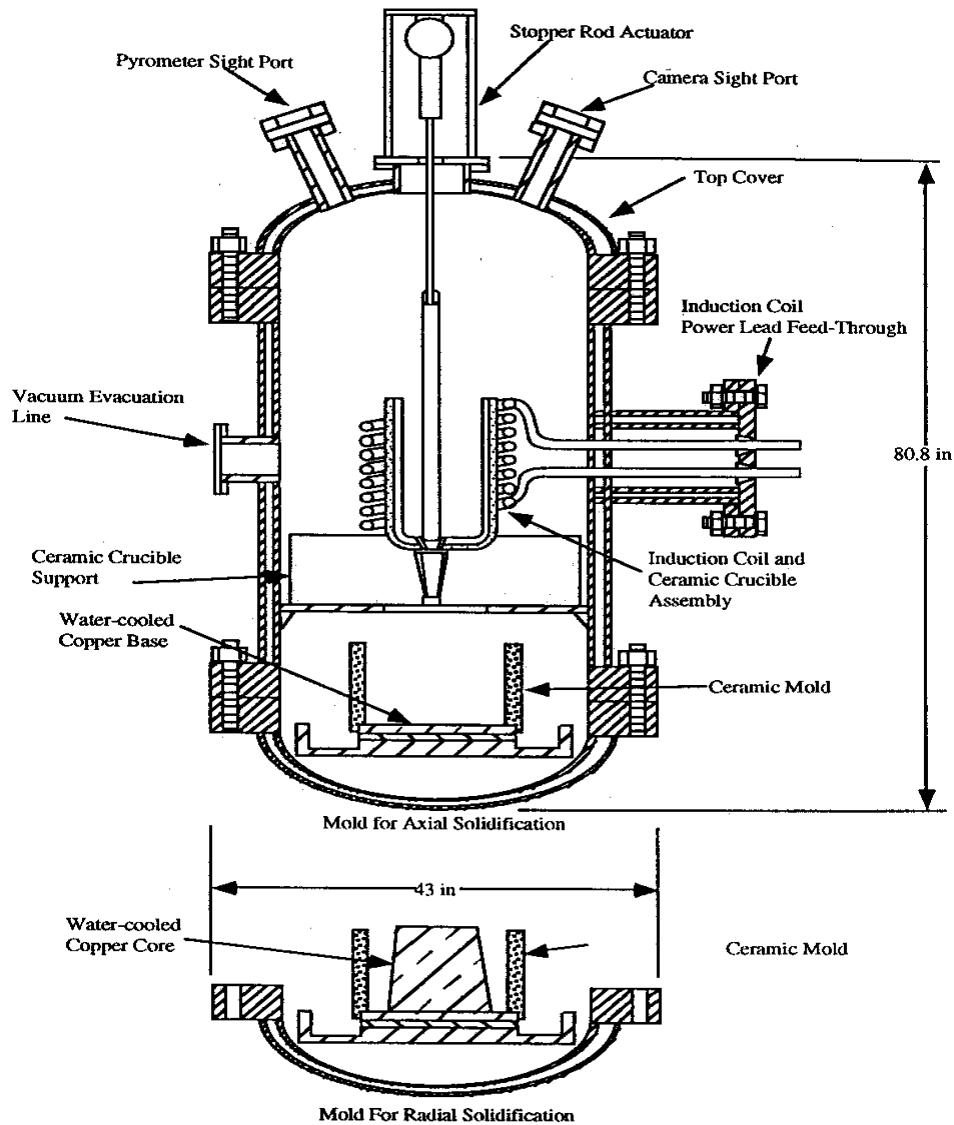


Figure 2. Sandia National Laboratories furnace.

orientation of the pores are the hydrogen level in the melt, gas pressure over the melt in solidification, direction and rate of heat removal, and alloy chemical composition. Changing these variables, one can control the pore structure over a wide range. At This takes place, gasar process dos not need sophisticated equipment (Figure 2).

The structure of porous metals

Porous metal structure may be described by a number of special parameters, the most important being the amount of porosity, average pore size, pore shape, pore orientation, degree of pore

interconnection, pore distribution in macro- and microregions, pore-size distribution, connectivity, and specific surface. Pore structure is determined by processing, the emphasis of this survey.

Cellular metals are different from sintered porous metals in structure. Whatever the manufacturing process, the structure of cellular metal invariably features a continuous three-dimensional grid of the base alloy.

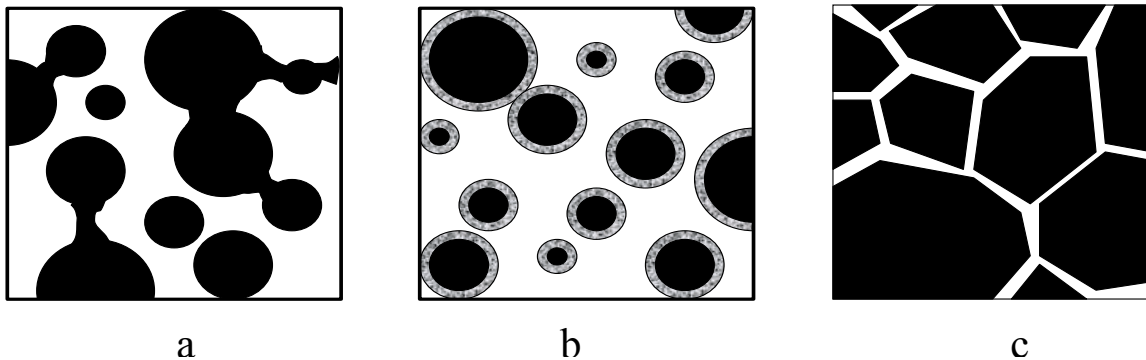


Figure 3. Cellular structure, obtained by the method of the smelt pouring on removed granules (a), method of smelt pouring on empty non-removed spheres (b), and by solidification of foams (c)

When produced by melt foaming, the cellular structure is described by the average values of cell (bubble) diameter and interpore wall thickness. The walls separating cells are poreless and may contain only the base alloy and particles introduced for reducing the surface tension at the gas-melt interface, if any (Figure 3).

In cellular metals made by melt foaming, pore walls have a clean, nearly lustrous surface and are not interconnected. Cellular metals made by P/M and deposition methods have interconnected pores and a gridlike structure. The pore wall surface is rough and contaminated with oxides and products of decomposition of the substrate material removed (Figure 3). Cellular metals may have a non-oriented general structure, which is always the case with foamed metals, or an oriented one depending on the structure of the substrate to be removed.

Materials produced by gas-eutectic solidification are so different structurally from all other porous metals that a new word was coined for them-gasar, which is an abbreviation of the Russian term for “gas-reinforced.” Gasars may be manufactured in diverse structural variations depending on the process variables previously discussed [4]. Figure 5 illustrates the main structural types embodied in gasars. Gasar pore size may be varied between $10\mu\text{m}$ and 10mm as desired, and the amount of porosity may reach 75%.

The pore wall surface is always entirely clean. In most cases it has high luster but is sometimes not so smooth due to the exposure of grown-old dendrites. The interpore walls are poreless and free of any secondary porosity or undesirable inclusions (Figures 4).

The relationship between the average pore diameter and the amount of porosity is an important structural characteristic of porous materials. No method is presently available for making porous metals that combine fine pore size with high void fraction. Clearly, the existing

technologies are complementary in that any of them is applicable to a specific are of engineering problems.

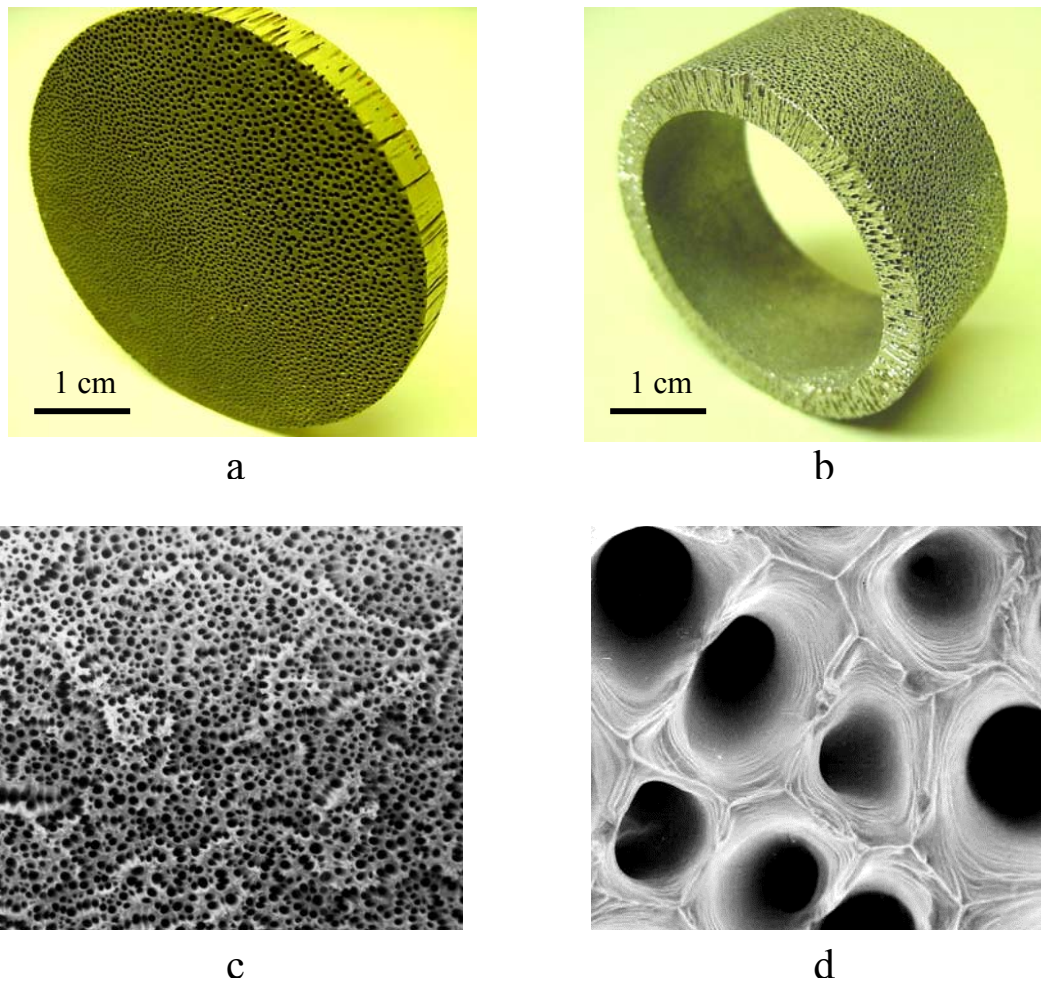


Figure 4. a- bronze gasar with parallel pore orientation (turning cutting); b- nickel gasar with radial pore orientation (turning cutting); c, d- cooper gasar, pore diameter 25 microns (fracture).

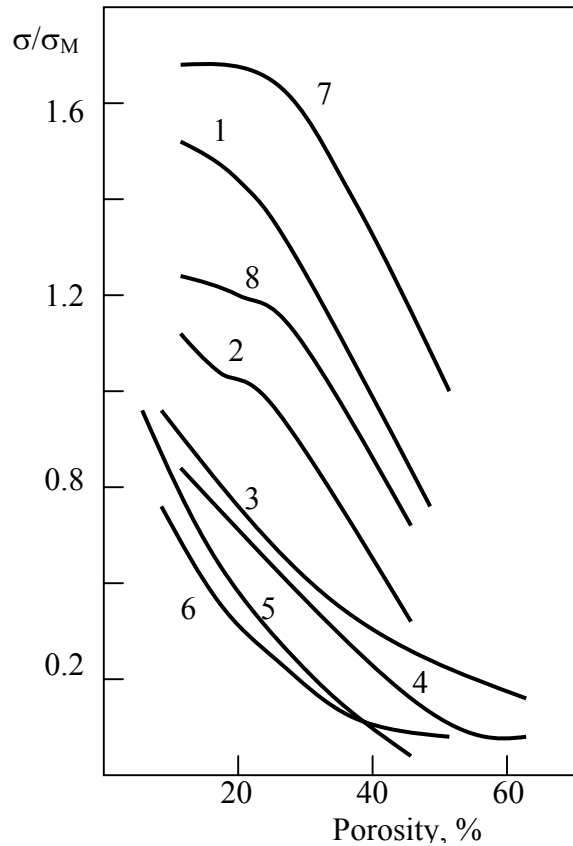
Properties of porous Metals

Mechanical Properties. Strength decreases faster than expected based on the volume fraction of the solid phase. The reason is that mechanical properties are highly sensitive to pore shape. Pore edges act as stress concentrators, reducing strength and especially plasticity.^{1, 2, 5, 6} The strength of porous metals made by powder sintering depends not only on the amount of porosity and the power material identity, but equally on the particle size and the sintering temperature and time. The greater the number and area of particle contacts, the better the mechanical properties of a sintered metal.

At a given porosity, sintered fibers yield far better strength properties than sintered powders. Sintered knitted meshes exhibit even greater strength. The general behavior of impact resistance and the plastic properties is similar to that of strength. Foamed metals and high-porosity cellular materials with a gridlike structure feature disproportionately low strength, particularly in tension.

Figure 6. Strength as a function of porosity for various porous materials:

- 1- yield stress, cooper gasar
- 2- tensile strength, cooper gasar
- 3- tensile strength, sintered cooper fibers
- 4- tensile strength, sintered nickel fibers
- 5- tensile strength, sintered iron fibers
- 6- tensile strength, sintered tungsten fibers
- 7- yield stress on the basis of specimen actual cross-section area, Cu-gasar, pore diameter 20 microns.
- 8- Tensile strength on the basis of specimen actual cross-section area, Cu-gasar



All factors being equal, gasars are the strongest. For the instance, at 20% porosity, the strength of copper gasar is 1.9 times that of sintered porous copper, and 4 times stronger at 45%. Moreover, strengthening was observed at porosities below 20% and pore diameter below 50 μm; a full understanding of this effect is yet to be achieved. Gasars far outperform other porous metals in impact resistance and plasticity as well.

Thermal properties. Heat transmission in porous materials may occur by solid conduction, convection, and radiation. In sintered porous metals, solid contact conduction predominates, although at high temperatures the contribution of radiation becomes substantial. Convection is of secondary importance here, so sintered porous materials always have lower conductivities than similar poreless metals.

In a gasar with closed hydrogen-filled pores, convection plays a far more important part. The reason is that hydrogen has high thermal conductivity and low viscosity. When its pressure in the pores is high enough, the contribution of convection will increase so that the gasar's thermal conductivity will exceed that of the similar poreless metal. The apparent thermal conductivity of

gasars may be controlled over a wide range by varying the amount of porosity and the pressure of hydrogen in the pores.

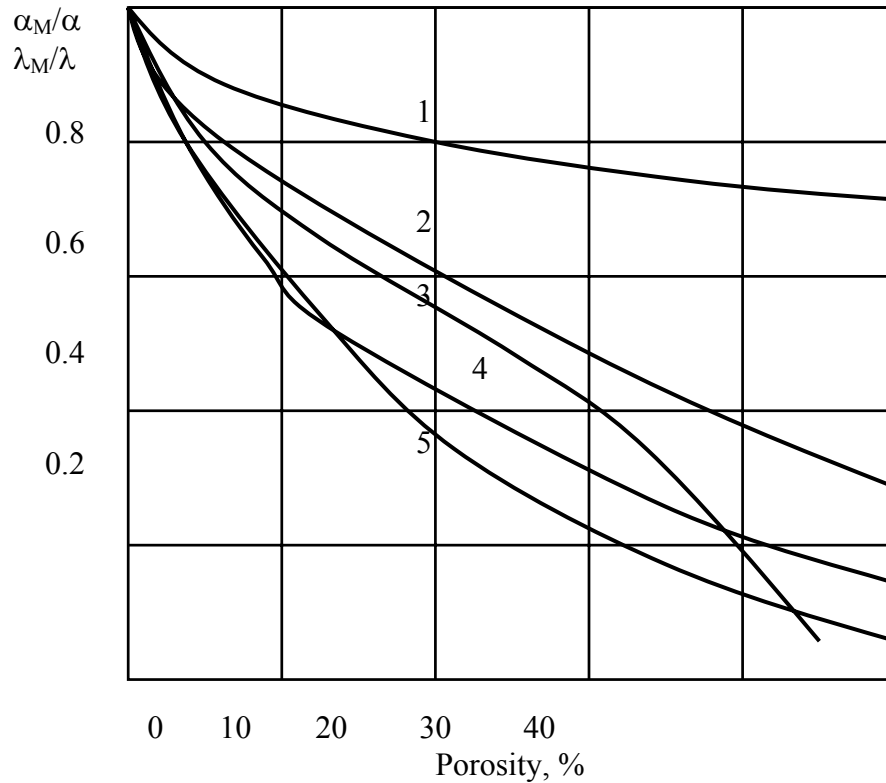


Figure 7. Relative heat conductivity (α) and temperature conductivity (λ) of porous metal materials:

1- gasar heat conductivity; 2- gasar temperature conductivity; 3- heat conductivity of sintered powders; 4- heat conductivity of cellular materials; 5- heat conductivity of sintered fibers.

Electrical conductivity. As the porosity is increased, the electrical conductivity of a porous metal declines in a disproportionate manner similar to that of the thermal conductivity. This decrease is due to the imperfect nature of particle contacts where energy of electrons is dissipated. In a gasar with its monolithic matrix, however, the reduction in the electric conductivity is almost strictly proportional to an increase in the amount of porosity.

Acoustic damping. Acoustic energy attenuation in porous materials is chiefly due to the internal friction of the gas filling the pores. Another energy sink results from the thermal conduction in the gas and the metal. An acoustic wave gives rise to the compression and expansion of gas in the pores. The compression is accompanied by gas heating, and the evolving heat is dissipated in the solid. When the solid is highly plastic, additional attenuation is possible owing to the deformation in the pore walls. Theoretical prediction of acoustic adsorptivity of actual porous metals is hardly feasible because of the complex shape of the pore space. Therefore, acoustic damping is evaluated in tests.

Corrosion resistance. Porous metals feature poorer corrosion resistance than poreless ones because they have large specific surface and many negative curvature. Another adverse factor is chemical inhomogeneity, which is particularly significant in powder porous metals. Corrosion test routinely used for solid materials are generally not suited for porous metals; porous metals are commonly evaluated based on changes of resistivity or mechanical strength. Basically, all factors contributing to corrosion resistance of poreless metals have a positive effect on porous metals.

Pressure drop. Flow resistance is highly important for the permeable porous metals that are frequently used in filters. This characteristic is very sensitive to the pore space topology. Pressure drag generally declines as the amount of porosity is increased. At a given porosity, however, a material with less tortuous pores will be more permeable. Ideal in this respect are those gasars that have parallel cylindrical pores of preset diameter in a monolithic matrix.

Applications of porous metals

Permeable porous metals have the widest range of applications. The development of solar and nuclear power generation technologies has made porous metals candidates for electromagnetic and neutron absorbers. It is highly probable that porous metals will be used for the inner walls of nuclear fusion reactors. Some experience has been gained in using porous metals in structural applications as filters for laminated panels in shipbuilding and aerospace constructions. Permeable porous metals may be used as matrices of composite materials.

Impermeable porous metals are used less extensively, limited to applications as lightweight structures capable of absorbing noise, vibrations, and shocks. High-porosity foamed metals, particularly aluminum, are well-suited for thermal insulation in construction and engineering. Impermeable porous metals are used for seals in turbojet engines. The development of hydrogen energy technologies suggests the use of porous metals for hydrogen storage.

Prospects

Several disadvantages prevent the application of porous metals on wider scale. The majority of porous metals are not strong enough, especially at porosities in excess of 50%. Another drawback is the high cost due to the multiple steps involved in the manufacturing process, and the low production rates. There are also difficulties in engineering a desired pore space structure. Problems are posed by the poor corrosion resistance, machinability and weldability, and by the complexity of mechanical joining with similar materials or poreless parts. Clearly, the prospects of porous metals depend on whether these and other disadvantages will be eliminated, be it through improvements in conventional process or by the advent of revolutionary technologies. Porous metals formed by gas-eutectic reaction are particularly promising. Among the advantages of gasars over conventional porous metals, are:

- Improved strength and rigidity,
- Flexibility in regard to the permeability,
- Possibility of making regular structures,
- Wide range of the pore diameter (10 m to 10mm),
- Feasibility of control over pore shape and orientation,

- Ease of fabrication and relatively low cost,
- Good weldability and fabricability, and
- Unprecedented formability.

Also, it is believed that the method of making foamed aluminum is highly promising because it eliminates some engineering problems which we considered intractable.

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