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Cellular Metals for Functional Applications – an Overview

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Abstract.
Cellular metallic materials are a new class of materials which have been the focus of numerous scientific studies over the past few years. The increasing interest in cellular metals is due to the fact that the introduction of pores into the materials significantly lowers the density. These highly porous materials also possess combinations of properties which are not possible to achieve with other materials. Besides the drastic weight and material savings that arise from the cell structure, there are also other application-specific benefits such as noise and energy absorption, heat insulation, mechanical damping, filtration effects and also catalytic properties. Cellular metallic materials are hence multi-functional lightweight materials.

Introduction

Cellular metal materials feature properties and combination of properties far away from that one of their basic materials. Besides the drastic weight and material savings arising from the cellular structure, features such as noise and energy absorption, low heat conductivity and excellent mechanical damping properties, good filtration capability and catalytic properties demonstrate their striking application-specific benefits. Hence, in the past various technologies of manufacturing and applications of cellular metals have been explored [1,2].
Commonly, manufacturing technologies involve either the use of liquid metals in combination with blowing agents or bubbles, or the use of solid state methods. The term "solid state method" refers to the processing in the solid state. However, in some cases limited amounts of liquid phase appear in the process, i.e. during liquid phase sintering or brazing of single cells. Typically, solid state methods require a sintering step before the final cellular metallic structure is obtained. Thus, powder metallurgical methods play a dominant role in this area. The formation of the cellular structure can either be accomplished by building it up from single cells, which do not necessarily have to be in the final metallic state. Alternatively, the structure can be build up from bulk. The formation of the cells themselves can either be carried out with the help of a lost core, or in a coreless manner [3,4].

Technologies

The physical properties of cellular materials basically depend on their structure, their cell size and their porosity. Since these materials cover various types of structures and a wide range of pore sizes and porosities, miscellaneous applications were tested. In detail, metal fibre structures and network-like structures with open cell porosity as well as metal hollow sphere structures with more or less closed cell porosity were developed. Cell sizes in the range of 10^{-2} – 10^{1} mm and porosities in the range of 50 – 96 pct where produced. Figure 1 shows the classification concerning the cell size of these cellular materials.

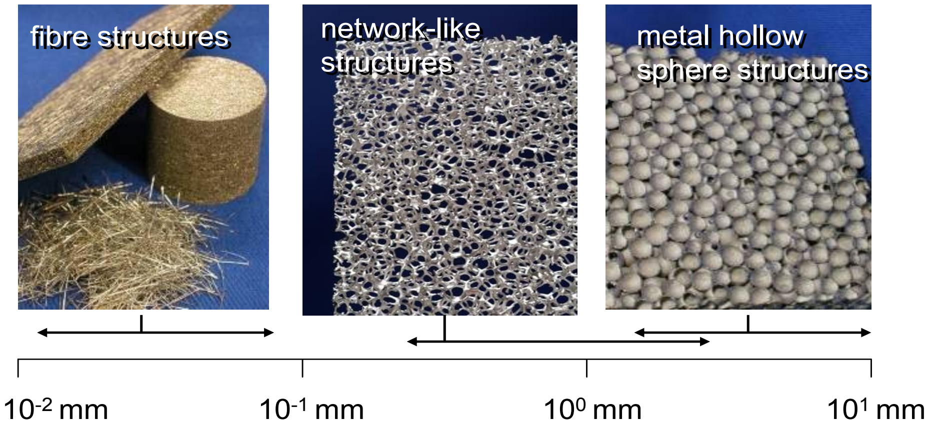


Figure 1. Types of structures and range of cell sizes for different cellular metals

Open porous metal fibre structures

In order to obtain open-porous fiber structures, crucible melt extraction is used to yield short metal fibers with equivalent diameters as low as 50 µm from almost arbitrary metals and alloys. Highly porous components can be made from such fibers by suitable deposition and sintering methods. This method is applicable to a wide variety of different metals and alloys. A thorough review of the manufacturing route can be found elsewhere [5].

Open **cell network-like structures**

Open cell metal foams have been produced by the replication method using polyurethane sponge as a template. The replication method essentially consists of three production steps: First a reticulated polyurethane sponge is coated by slurry infiltration. In the next step, the template is thermally removed and the debindered brown structure is sintered. The method allows the manufacture of cell sizes in the range of 0.4 – 5.0 mm and porosities of 75 – 95 pct [6].

Hollow Sphere Structures

The manufacturing of metal hollow sphere structures is characterized by a three step including:

- powder coating of an styrofoam template
- shaping of the structure using the coated Styrofoam spheres
- debindering and sintering

A feature of the MHS technology is its suitability for a wide range of materials. A broad cell size spectrum from 0.5 - 10 mm is possible whereas the cell size distribution is very narrow. The cell wall thickness can be varied from approx 20 µm to 1,000 µm. The walls can be sintered fully dense as well as porous [4].

Characteristic properties

Cellular metal materials exhibit key benefits for applications where stringent operating conditions require extraordinary combinations of properties. Due to their porous structure, they are extremely lightweight (up to 95 pct porosity), combined with high specific strength and stiffness. At the same time, they feature low heat conductivities (approx. 1-5 pct of the matrix material) and sound absorption coefficients comparable to the values of polymeric damping material. Open cell metal foams are permeable, combined with high specific inner surface. This set of properties is the basis for a variety of applications.

Applications

Stirling Engine

Stirling engines for the combined production of heat and electricity are currently being developed by several companies. One of them is Enerlyt Technik GmbH of Potsdam, Germany. The Stirling cycle relies on the alternating heating up and cooling down of a fixed amount of gas. This is accomplished with the help of the so-called regenerator which acts as a temporary heat accumulator. To date, commercial wire mesh is cut, stapled and sintered together in order to build regenerators that are able to withstand the oscillating gas flow at temperatures up to 800 °C.

The overall efficiency of the Stirling engine is determined by the qualitiy of the heat transfer and the pressure drop in the regenerator, therefore a large degree of freedom in the design of the regenerator is desirable. Enerlyt Technik GmbH has thus carried out stationary simulations of the heat regeneration process with the help of the SolidWorks / FlowWorks software package. Fig. 2 illustrates the optimization approach. First, the heat transfer due to the flow around one fiber is modelled. Then, a volume element containing a number of fibers is constructed, this way determining the porosity of the structure. This allows to take into account a) the interaction between the gas flow around a single fiber and the flow around the neighbouring fibers, and b) the influence of the fiber orientation at a given porosity. The volume elements are then taken to model the regenerator in the Stirling engine.

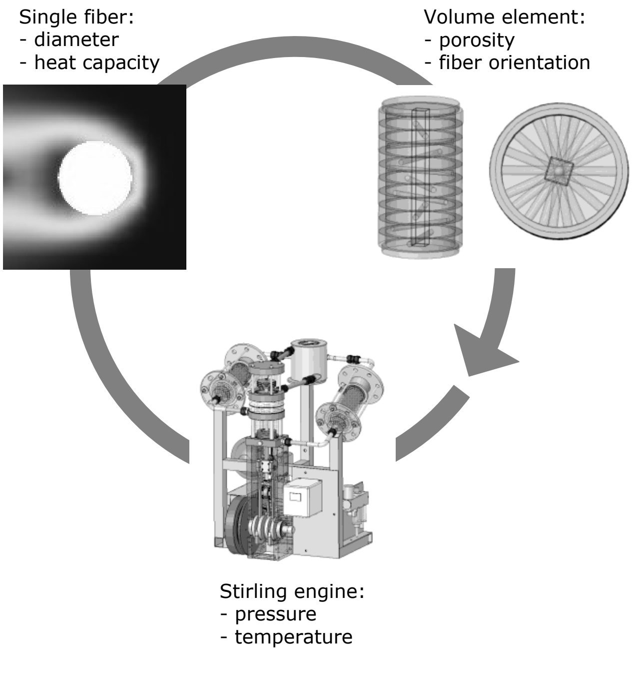


Figure 2. Iterative optimization cycle for a Stirling engine regenerator performance

A first performance optimum was detected at high porosities of approx. 90 pct, using small fibers with a diameter of 50 µm. For a regenerator of dia. 80 mm x length 80 mm, a heat transfer power of 19.6 kW corresponds to a power loss of only 28 W due to the pressure drop. However, recent simulations revealed that even lower losses can be achieved by switching to much larger fiber diameters and a lower porosity of the fiber structure. Further potential lies in the orientation of the fibers along the direction of flow.

Past tests of sintered short fiber structures in different Stirling engines have already shown that the overall efficiency reaches the order of the theoretically expected performance. Currently, field testing is underway and will be finished 2009/2010.

Porous Surface Burner

Porous surface burners for different kinds of fuels have very advantageous properties: compact design, very high power modulation and extremely low emissions. These properties are achieved by stabilising the combustion next to a macroporous surface structure (Fig. 3a). To date, these structures are made mainly from special ceramics. For non-stationary applications such as the auxiliary power unit (APU), the resistance to mechanical vibrations is not always sufficient. A metallic solution is therefore desireable.

The required longevity calls for an advanced high temperature resistant material. The properties of the well-known ferritic iron-chromium-aluminum alloys, containing up to 7 % aluminum, can be further enhanced by raising the aluminium content up to 15 %. This is only possible with melt extracted fibers Fig. 3b shows results of oxidation testing of sintered fiber structures in air at 1000 °C for 1000 hrs. It can be seen that both compositions show the same typical parabolic mass gain due to the aluminum oxide scale formation. However, the aluminum reservoir of the 5 % Al composition is consumed after roughly 600 hours, whereas the aluminum reservoir of the 15 % Al composition will last up to 2500 hours.

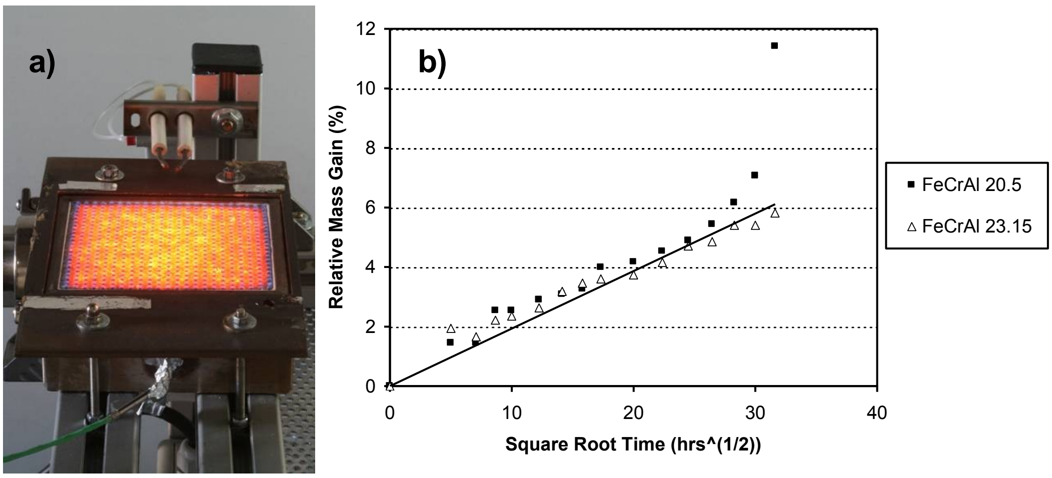


Figure 3. Burner test rig with IFAM fiber burner plate (Fig. a) and relative mass gain over time due to oxidation in air at 1000 °C for sintered fiber structures with a mean porosity of 75 % and different aluminum contents (Fig. b)

The preliminary experiments carried out with IFAM fiber mats towards an application as flame holders are very promising [7]. Future work concentrates on the fine tuning of the mat properties such as: low pressure drop, even gas distribution, high maximum temperature resistance, and good heat transport properties.

Biomaterials: bone implant material

Bone replacement of large defects (eg. due to osteoporotic fractures) is an urgent clinical problem. Recently, such defects are filled by autogenic bone or massive metal implants. Former needs an additional surgical intervention, which is fraught with risk. Latter suffer from a stiffness mismatch between bone and implant (*stress shielding*), leading to implant loosening. Network-like metal foams exhibit a natural bone-like structure (Figure 4), which enables in grow of bone cells and blood vessels.

Thus, open cell metal foams out of steel and titanium have been developed. Since the stiffness of the cellular metal is comparable to that one of the bone material, stress shielding is inhibited (Figure 5). Recently, the new material was successful tested as vertebra replacement in a sheep model. Histological cross sections of the reimplanted artificial bone reveal an excellent ingrow of new bone cells.

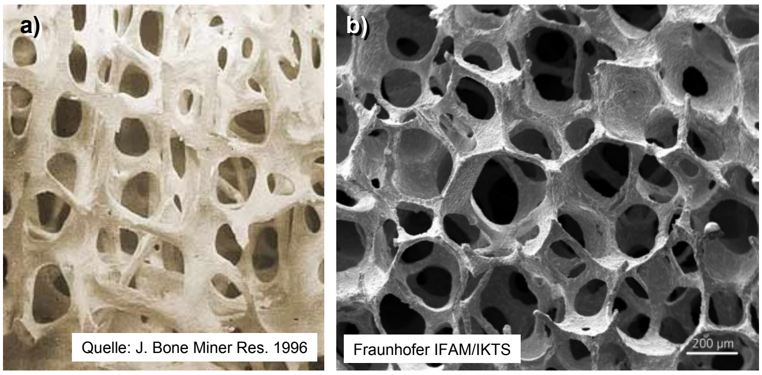
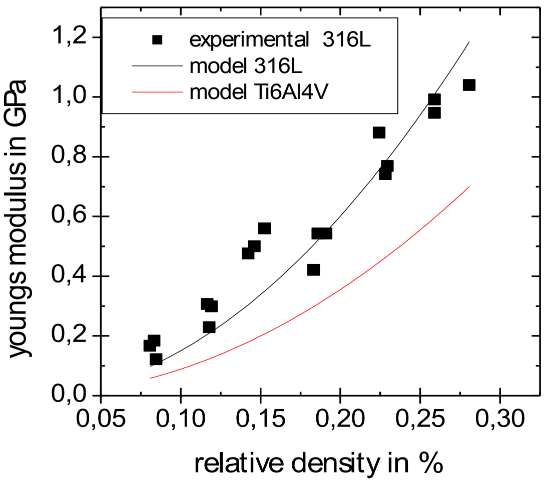


Figure 4. Spongeous bone (Fig. a) and open cell metal foam (Fig. b) show highly similar structures.



bone structure		youngs modulus [GPa]	compression strength [MPa]
cortical bone	Femur	12	180
	Radius	12	200
	Tibia	14	130
trabecular bone	Femur (Kondyle)	2.9	68
	Vertebra	1.5	4.1

Figure 5. Mechanical properties of open cell metal foam (316L) in comparison to different types of bone

Thermal insulation

Because of its high temperature strength molybdenum frequently is used in kiln engineering. E.g., hot plates, heating element support and shielding plates are manufactured out of molybdenum. Since the price of molybdenum rose by a factor 7 within the last 5 years, material costs became critical for manufacturer of industrial furnaces.

Consequently, the Fraunhofer Institutes IFAM-DD and IKTS in cooperation with H.C.Starck Hermsdorf GmbH developed a lightweight molybdenum foam for heat insulation applications (Fig. 6), using the low heat conductivities of about 1-5 % of the basic material. Network-like structures with porosities up to 95 pct and cell sizes of 0.8-1.2 mm where synthesized.

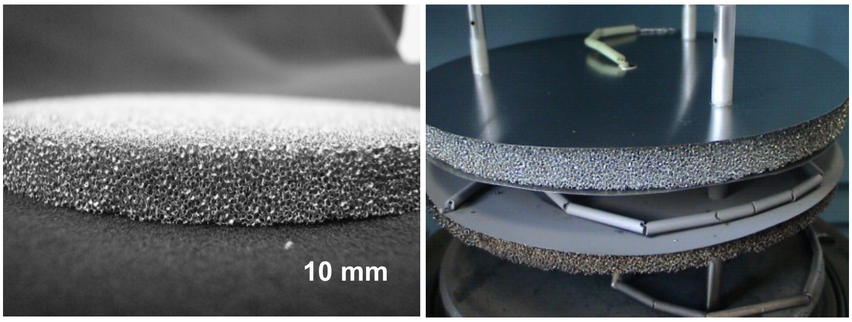


Figure 6. Open cell molybdenum foam as insulation material in industrial furnaces, using the low heat conductivity of the material.

In first tests, the heat insulation capability of the new material was tested in an industrial vacuum furnace. Therefore the molybdenum foam was laminated by a thin molybdenum foil. In comparison, to the conventional shielding plates, the temperatures at the cold zones only show differences of about 2 pct, when the molybdenum foam heat insulation was used. At the same time, the mass of the heat insulation package was reduced by factor 4.

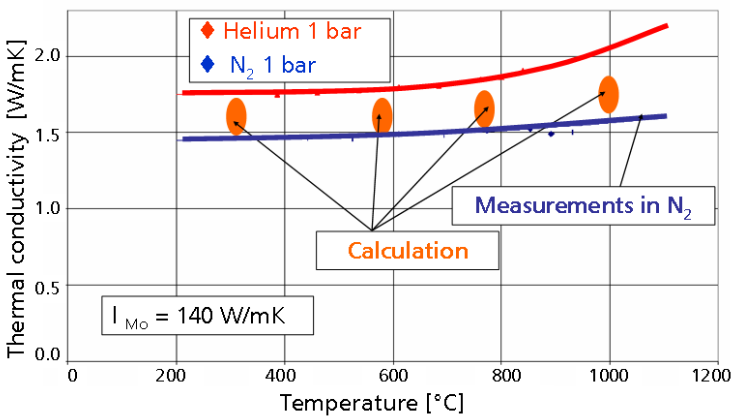


Figure 7. Heat conductivity of metal hollow spheres. The curves show good correlation between model calculations and experimental findings.

In the same way, metal hollow spheres (MHS) can be used in thermal insulation applications especially in high temperature environment. The heat conductivity values of the material range between 0.5 and 2 W·m^{-1}·K^{-1}. Furthermore the thermal conductivity of Molybdenum hollow sphere sandwich structures was calculated by FEM and verified by experiments afterwards (see Fig. 7). The results were in good correlation with the experimental findings.

Sound absorption

Investigations of the sound absorption of sintered 316L MHS-structures have been performed using the Kundt´sche tube, cold chopper engine as well as by hot engine tests. The results have shown that MHS-structures reveal a significant higher sound dissipation up to 1000 Hz compared to glass wool. The sound level could be reduced of about 10 – 15 dB [8].

The results of real hot engine tests (BMW 2.4 TDI) exhibit a considerable sound level reduction for engine revolutions lower than 1500 rpm, whereas in the range from 1500 – 4500 rpm the same sound level in comparison with glass wool could be measured (Figure 8).

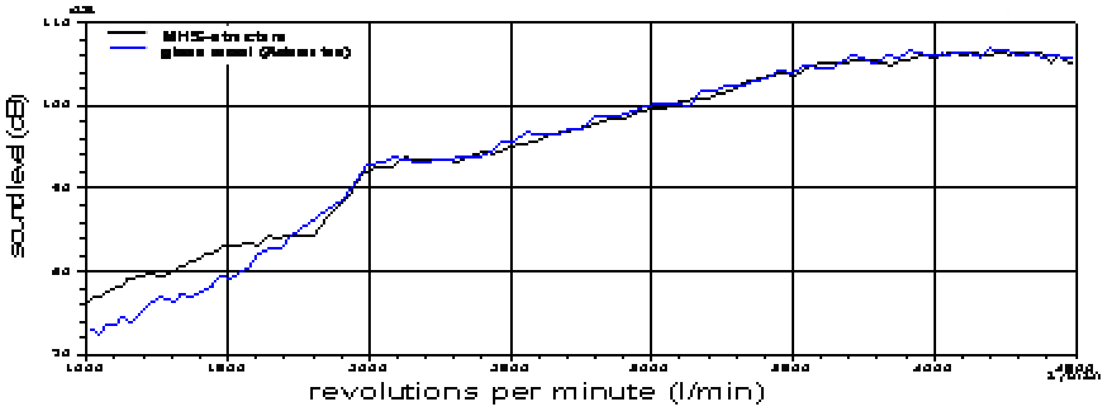


Figure 8. Sound level of Stainless Steel (316L) metal hollow sphere structures as a function of the revolution of a hot engine (BMW 2.4 TDI).

Compared with the state of the art mufflers a significant weight reduction (up to 25 %) and a simpler assembling of the whole muffler can be pointed out. The main parameters on sound absorption are the diameter of the spheres and the structural density. Smaller diameters of the spheres and a lower structural density lead to a more pronounced sound dissipation. Because of the low thermal conductivity of the MHS structures additional thermal insulation materials of the muffler can be omitted.

Conclusion

Numerous technologies have been developed in order to manufacture cellular metal materials. Because of the unique properties of the material (low density, excellent sound absorption, thermal insulation, energy absorption, high specific surface area, mechanical damping), a variety of new applications for the vehicle industry (diesel soot filtration, energy absorption, sound dissipation, heat insulation), for machine constructions (acoustic and mechanical damping, weight reduction), and for process engineering (weight reduction, sound absorption, catalytic reaction, thermal insulation, filtration, infrared burners) have been tested.

References

[1] Davies, G.J., Zhen, S.; J. Mat. Sci 13, 1983, p 1899

[2] Banhart, J., Progress in Materials Science 46, 2001, p 559

[3] Andersen, O., Stephani, G., in: Handbook of Cellular Metals, Ed. Degischer, P., Kriszt, B., (Viley VCH, Weinheim, Germany), 2002, p.56

[4] Stephani, G., Andersen, O., Göhler, H., Kostmann, C., Kümmel, K., Quadbeck, P., Reinfried, M., Studnitzky,T., Waag, U., Adv. Eng. Mat. Vol. 8, 2006, 847-852

[5] Andersen, O., Kostmann, C., Stephani, G., Conference Proceedings European Congress and Exhibition on Powder Metallurgy, Valencia, Spain, Octobre 20-22, 2003, Vol. 2, p 361

[6] Quadbeck, P., Stephani, G.,_Kümmel, K., Adler, J., Standke, G., Materials Science Forum 534/536, 2007, p. 1005

[7] Mößbauer, S., Wawrzinek, K., Andersen, O.: Conference Proceedings CELLMET 2005, Dresden, Germany, May 18-20, 2005 (Fraunhofer IRB Verlag) p. 12

[8] H. Göhler et. al.,: in Proc. European Powder Metallurgical Conference (European Powd. Met. Assoc. 2003) Vol. 2, p. 159