Cellular Ceramics

Structure, Manufacturing, Properties and Applications

Edited by
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Cover Picture
Top left: Periodic cellular structure. Colloidal inks were extruded by robotic deposition. Sub-millimeter filaments of extruded colloidal gel are deposited layer-by-layer to assemble the structure in the *z* stacking direction followed by drying and sintering. The white-colored *x-y-z* axes are 400 μm in length (Image courtesy of Prof. J. Lewis, University of Illinois; see also Chapter 2.3).

Bottom left: Hierarchically built porous material. Rattan palm wood was transformed into char and infiltrated at high temperature with liquid silicon retaining its cellular channel structure. The Si/SiC porous material was then used for hydrothermal zeolite crystallisation under partial transformation of the excess silicon. MFI type zeolite was formed in the longitudinal channels of the material. The open channel diameter is 300–320 μm and the zeolite layer is 40–60 μm (Image courtesy of Dr. F. Scheffler, University of Erlangen-Nuremberg, Germany; see Chapter 2.5 and Ref. [29] in Chapter 5.4).

Right: Prototype of a silicon carbide foam heater element. The electrical conductive ceramic foam heats up when electrical power is applied to top and bottom end. Here a power of 750 W was applied. The ceramic foam is 30 mm in diameter (Photo taken by Friedrich Weimer, Dresden. Image courtesy of J. Adler, Fraunhofer-IKTS, Dresden, Germany).

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Foreword

For many years, the presence of porosity in ceramics was often seen to be problematic and a significant scientific effort was made to devise processing routes that produced ceramics with zero porosity. An exception to this philosophy was the refractory industry, in which it was understood that the presence of porosity is critical in controlling thermal conductivity. A sophisticated example of this concept was the development of refractory tiles for the thermal protection system of the Space Shuttle. In other branches of materials science, similar ideas were recognized. For example, rigid and flexible foams had been developed in polymer science and engineering. In these materials, porosity is controlled to optimize the elastic behavior and weight. In more recent times, scientific developments have touched on new areas such as biomimetics, in which scientists aim to duplicate natural structures. There has also been the push (and pull) to design materials and devices at smaller scale levels. Materials are becoming multifunctional with designed hierarchical structures, and porous ceramics can be seen in this light. The challenge now is for materials scientists to produce ceramics with porosity of any fraction, shape, and size. This also leads to new directions in the scientific understanding of porous structures and their properties. For the above reasons and my personal involvement in this field, I am pleased to see this new book on porous ceramics. This book takes a broad view of the field, while still allowing some detailed scientific aspects to be addressed. The book considers novel processing approaches, structure characterization, advances in understanding structure–property relationships and the challenges in all these areas. It is interesting to see the structural variety that forms the "pallette" for the materials scientist and the wide range of properties that are controlled by porosity and therefore require careful optimization. Finally, the book gives examples of technologies in which porous ceramics are being exploited and the demands that arise as products move to commercial use. I applaud the editors for their vision and the authors for sharing their insight. I wish you a successful outcome for your efforts.

David J. Green
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October 29, 2004

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Preface

Porosity in materials can be arranged in a well-defined and homogeneous manner or heterogeneously. It can be oriented, separated, or interconnected. From these possibilities pores of different shape, size, and interconnectivity arise. The three-dimensional assemblage of a large number of pores possessing a specific shape leads to a solid monolith displaying what can be termed a cellular structure.

A close analysis of materials found in nature reveals that most of them have a cellular structure and thus contain a significant amount of porosity, which plays a key role in optimizing their properties for a specific function. Indeed, Robert Hooke (1635–1703), a natural philosopher, experimental scientist, inventor, and architect, realized this in his investigations of the natural world and coined the term "cell" for describing the basic unit of the structure of cork, which reminded him of the cells of a monastery. In "Observation XVIII" of his book "Micrographia: or Some Physiological Descriptions of Minute Bodies Made by Magnifying Glasses with Observations and Inquiries Thereupon" (London: J. Martyn and J. Allestry, 1665), he wrote:

"... I could exceedingly plainly perceive it to be all perforated and porous, much like a Honey-comb, but that the pores of it were not regular ... these pores, or cells, ... were indeed the first microscopical pores I ever saw, and perhaps, that were ever seen, for I had not met with any Writer or Person, that had made any mention of them before this ..."

Similarly, with an updated pool of knowledge and equipped with higher resolution analytical instruments, 300 years or so later researchers around the globe are interested in investigating and exploiting the advantages and peculiarities of cellular materials. Indicators of the increasing importance of this field are the numerous international conferences devoted to all three classes of cellular materials (metals, plastics, and ceramics), special issues of various scientific journals, and a rising number of specific books discussing either cellular structures in general or, more specifically, cellular metals and cellular plastics, among them:

L.J. Gibson, M.F. Ashby, *Cellular Solids: Structure and Properties,* Cambridge University Press, 1999;
D.L. Weaire, *The Physics of Foams,* Oxford University Press, 2001;
S. Perkowitz, *Universal Foam: From Cappuccino to the Cosmos,* Walker & Co., New York, 2000;

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H.-P. Degischer, B. Kriszt (eds.), *Handbook of Cellular Metals: Production, Processing, Applications,* Wiley-VCH, Weinheim, 2002;
M.F. Ashby, A. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, H.N.G. Wadley, *Metal Foams: A Design Guide,* Butterworth-Heinemann, Oxford, 2000;
S.-T Lee, N.S. Ramesh, *Polymeric Foams: Mechanisms and Materials,* CRC Press, Boca Raton, FL, 2004;
A.H. Landrock, *Handbook of Plastic Foams,* Noyes Publications, Park Ridge, NJ, 1995.

The reason for this considerable interest in cellular materials derives from the recognition that porosity affords further functionalities to a material, ranging from an increased surface area, to permeability, to the control of heat transport within the structure, to the maximization of the strength/density ratio.

An analysis of the published literature by searching just the terms "ceramic" and "foam" revealed an exponential increase in scientific papers and patents with a total of 26 publications in 1977, 64 in 1992, 133 in 1998, and 167 in 2004.

Books dealing with porous ceramics have also been published (e.g., R.W. Rice, *Porosity of Ceramics,* Marcel Dekker, New York, 1998), but no publication specifically concerning cellular ceramics was available yet. Thus, the idea was born to fill this gap with a focused book and to provide students, researchers, manufacturers, and users with a comprehensive discussion of the most relevant aspects of this topic, covering manufacturing processes, structure characterization, analysis of the properties/structure relationship, and examples of applications. As such, this book does not deal, on purpose, with all classes of porous ceramic materials, disregarding, for instance, membranes, zeolites, and low-porosity solids, for which excellent reviews and books are already available. It is also not a collection of publications deriving from a conference, but rather represents the contribution of specialists from academia and industry who are at the forefront of this innovative field. This book contains an updated set of references allowing the reader to gain further insight into specific issues of this fascinating class of advanced materials.

We are deeply grateful to the authors for their enthusiasm and willingness to contribute to this project and to the referees for their critical involvement in the peer-reviewing process. Dr. Jörn Ritterbusch (Wiley-VCH) deserves special recognition for displaying the necessary foresight for embracing this endeavor, and we are indebted to Heike Höpcke (Wiley-VCH) for her graceful and helpful assistance throughout the editorial process.

Finally, we appreciate the patience, support, and encouragement of our families, to which this book is dedicated.

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19/11/2004

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