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Thermo-Fluid Behaviour of Periodic Cellular Metals

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（周期性多孔金属材料的热流性能）

With 150 figures

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Preface

Exploring and developing ultralight engineering materials has been an important academic subject for decades. In 1990s, the emphasis has been put on developing ultralight multifunctional materials, which combine mechanical, thermal, electrical, acoustical, and possibly other functionalities. Cellular solids are a group of ultralight materials with multifunctional attributes. Multifunctionality of cellular solids is an interdisciplinary research area that requires a concurrent-engineering approach. The aim is to establish structure-property relationships for tailoring material structures to achieve properties and performance levels that are customized for defined multifunctional applications.

The subject of this book is the thermo-fluid behaviour of periodic cellular metals, which didn't attract wide academic interests until late 1990s. The book, for the first time, systematically adopts experimental, numerical, and analytical approaches, presents the fluid flow and heat transfer in periodic cellular metals under forced convection conditions. Thermal attributes in these materials include the high thermal conductivity of the metals comprising the borders, in combination with the high internal surface area and the propitious fluid transport dynamics. These enable high heat transfer rates that can be used effectively for either cooling or heat exchange.

This book is in the context of exploring multifunctional applications of cellular solids, which means that periodic cellular metals are regarded as a member of cellular solids. The book introduces the forced convective heat transfer capability of periodic cellular metals with the final aim of developing multifunctional materials. Therefore, this book should be beneficial to both academic and industrial readers.

Tian Jian Lu
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Chapter 1
Introduction

1.1 Introduction and Synopsis

In late 1990s, driven by the needs of minimizing manufacturing and operational costs in satellites, a revolutionary concept — Multifunctional structures (MFS) — was developed, which combines electronic components (multi-chip modules, or MCMs) and signal and power distribution cabling within a load bearing structure with embedded thermal control. This design concept dramatically changed the design approach for space systems, and in addition, led to a paradigm shift in the design methodology of the structures and control community[1~4].

Significant efforts in incorporating the MFS concept into materials engineering have led to an entirely new category of materials: multifunctional materials. Cellular solids are a group of materials with multifunctional attributes, which have tailorable structures to achieve system-level performance as materials that combine mechanical, thermal, electrical, acoustical, and possibly other functionalities. Recently, there has been an increased interest in the use of cellular solids as multifunctional materials for two reasons[5]: (i) novel manufacturing approaches have beneficially affected performance and cost; (ii) higher levels of basic understanding about mechanical, thermal, and acoustic properties have been developed in conjunction with associated design strategies.

Multifunctionality of cellular solids is an interdisciplinary research area that requires a concurrent-engineering approach. The aim is to establish structure-property relationships for tailoring material structures to achieve properties and performance levels that are customized for defined multifunctional applications[6]. One significant application area is ultralight multifunctional heat exchangers or heat sinks in large-scale integrated electronic packaging, where cellular solids appear to be more attractive than the conventional heat dissipation media as the heat dissipation material is also required to support large structural loads. The multifunctional design inherently facilitates the increase of integration scale, which results in increasing power densities in electronic packaging. Therefore, highly effective and robust thermal management via these cellular solids is crucial. With the requirements on capability of carrying both mechanical and thermal loads in mind, the challenges are to establish relationships between topology and properties, and to optimize the geometric parameters applicable to various thermo-mechanical applications[7~9].

1.2 Cellular Solids

Cellular solids are defined as those made up of an interconnected network of solid struts or plates that form the edges and faces of cells. They are found in many natural (wood, cork, sponge, bone, etc.) and man-made structures.

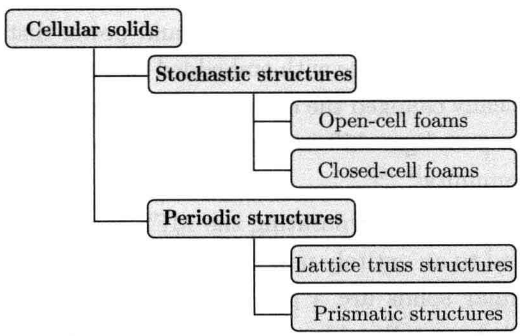

Figure 1.1 Two classes of cellular solids

Basically, there are two broad classes of cellular solids, as shown in Figure 1.1: one with a stochastic structure and the other with a periodic structure[10~13]. Cellular solids with stochastic structures are mainly foams, which can be further classified into two types based on their pore structure: open-cell foams and closed-cell foams, as shown in Figure 1.2(a) and (b), respectively. The former contain pores that are connected to each other and form an interconnected network; while the latter do not have interconnected pores. Cellular solids with periodic structures are found in a variety of structures, among which the most frequently mentioned are those with lattice truss structures, as shown in Figure 1.2(c), (d) and (e), and prismatic structures, as shown in Figure 1.2(f), (g) and (h).

One may argue the difference between the periodic engineering *structures* and the cellular *materials* with periodic structures. Ashby[14] pointed out that they differ in one important regard: that of scale. Scale of the unit

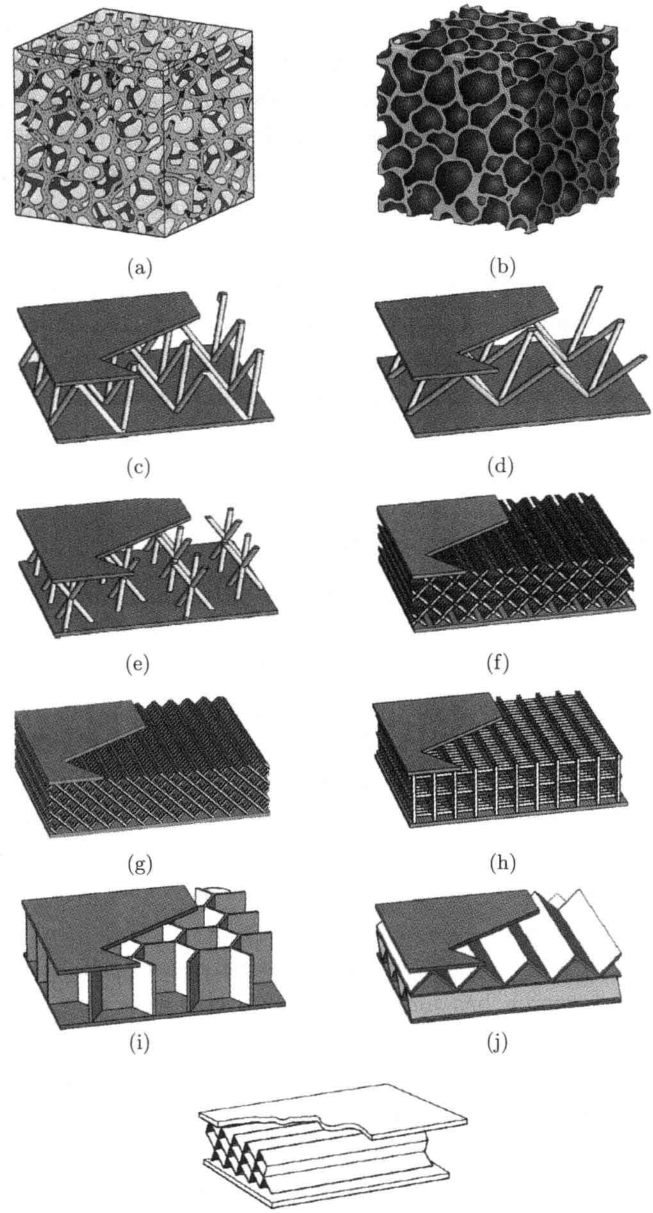

Figure 1.2 Examples of different cellular solids: foams as (a) open-cell foams; (b) closed-cell foams; and periodic cellular solids (sandwich panels with core structures) as (c) tetrahedral lattice; (d) pyramidal lattice; (e) Kagome lattice; (f) diamond textile; (g) diamond collinear lattice; (h) square collinear lattice; (i) triangular corrugation; (j) and (k) 2D cellular material[15~17]

cell of cellular solids is one of millimeters or micrometers, and it is this that allows them to be viewed both as *structures* and as *materials*. At one level, they can be analyzed using classical methods of mechanics, just as any space frame is analyzed. But at another we must think of the cellular structures not only as a set of connected struts, but as a 'material' in its own right, with its own set of effective properties, allowing direct comparisons with those of fully dense, monolithic materials.

Various properties of a cellular solid depend on two separate sets of parameters: those describing the geometric structure of the cellular solid, and those describing the properties of the material of which the cellular solid is made. In other words, for cellular solids with different structures or different materials, the underlying mechanisms governing structure-property relationships can be very different.

1.3 Periodic Cellular Solids

While commercial metal foams with open cells, which are typical stochastic cellular structures, are good compact heat exchangers and relatively cheap when made by sintering, their load-bearing capability is much inferior to periodic structures having the same weight. This arises because their deformation under mechanical loading is dominated by cell wall bending as opposed to cell wall stretching in most periodic structures[18]. Nonetheless, as cross-flow heat exchangers they can provide a high thermal conductivity path for heat transport, a very high surface area for dissipation into a cooling fluid located in the pores and a contiguous path for forcing the coolant through the structure.

The rapid advance in manufacturing techniques such as lithography and rapid prototyping has made possible to construct new types of cellular materials with periodic microstructures. These cellular structures have thermal and structural advantages over other conventional heat dissipation media and other performance characteristics[13,19~23]. The precise control of topologies during the manufacturing stage differentiates the new cellular materials from conventional heat dissipation media. A wide variety of process-routes have been developed to manufacture cellular metals with relative densities of 1%~20% and cell sizes from 100μm to several centimetres[12].

1.3.1 2D periodic cellular solids

Two-dimensional (2D) cellular solids, with the simplest structures amongst different cellular solids, are generally selected as the fundamental geometry for modelling more complicated cellular solids such as foams[24]. More importantly, certain structural and thermal properties of 2D cellular solids are superior to those of foams with equivalent densities[18].

2D cellular solids are composed of a two-dimensional array of polygons which pack to fill a plane area such as the hexagonal cells of a beehive honeycomb[25]. An example of a 2D cellular solid is shown in Figure 1.2(a). It is obvious that, topologically, 2D cellular solids are anisotropic. Two directions can be defined in 2D cellular solids: one is normal or lateral to the cell principal axes, y-z plane shown in Figure 1.2(b), which is *lateral direction*; the other is parallel to the cell principal axes, x direction shown in Figure 1.2(c), which is *axial direction.*

2D cellular solids, sometimes, are used as sandwich cores to form a sandwich panel. In these cases, correspondingly, the sandwich panel with face-sheets normal to the cell principal axes, as shown in Figure 1.2(g), is called a *sandwich panel with axial cores* since the loads (mechanical, thermal, etc.) are generally normal to the face-sheets and equivalently parallel to the cell principal axes; and the sandwich panel with face-sheets parallel to the cell principal axes, as shown in Figure 1.2(h), is named as a *sandwich panel with lateral cores* for similar reasons.

1.3.2 3D periodic cellular solids

For three-dimensional (3D) cellular solids, the most often used is lattice, such as tetrahedral lattice, pyramidal lattice, Kagome lattice and woven textile, as shown in Figure 1.2(c)~(e).

The potential use of a metal weave configuration as one of the periodic materials, coupled with a novel bonding scheme to fabricate periodic cellular structures was reported by Tian[11]. Diverse designs of this textile configuration have been attempted and some of results were reported by Li & Wirtz[26] and Xu & Wirtz[27]. The tetrahedral lattice, as shown in Figure 1.2(c), has three trusses each meeting at a face sheet node, while the pyramidal structure has four trusses meeting at a face sheet node, as shown in Figure 1.2(d). Both topologies have directions which are not obscured for fluid flow: three of these channels in a single layer of the tetrahedral structure and two in the pyramidal system[17]. Another example for the three-dimensional periodic materials was reported by Hoffmann[28], referred to as a Kagome topology. The basic topology is somewhat similar to that of the bank of cylinder arrays, showing structural and aerodynamic anisotropy, as shown in Figure 1.2(e).

Other lattice truss topologies have also been proposed based upon manufacturing considerations[17]. Figure 1.2(f)~(h) shows examples that are easy to make from wires. The diamond textile structure is made from layers of a plain weave metal fabric that have been bonded to each other.

1.4 Multifunctional Applications

Well established data on the mechanical properties of cellular systems with either periodic or stochastic microstructures demonstrate that the relatively high stiffness and yield strength achievable at low density creates an opportunity for lightweight structures[5,29~33]. Periodic cellular metals have been exploited for multifunctional applications[17]. For example, some, such as hexagonal honeycomb, are widely used to enable the design of light weight sandwich panel structures[34], for creating unidirectional fluid flows[35], for absorbing the energy of impacts[36], to impede thermal transport across the faces of sandwich panels and for acoustic damping, for blast wave mitigation[37~39].

In addition, the open topologies with high surface area density have thermal attributes that may enable applications which require a structure for heat dissipation as well as mechanical stiffness/strength. The structures have a high surface area density and may be constructed out of high conductivity materials. These combinations make the cellular materials capable heat dissipation media that can be used effectively for coupled thermal and structural applications, for example as a jet blast deflector on an aircraft carrier. In such an application, high mechanical compression is exerted on the deflector plate when an aircraft rolls over the retracted deflector and then subsequently a high thermal load from the jet is applied at take-off. The jet blast deflector is inclined at approximately 50° with respect to the deck surface during take-off. In this situation, the hot jet of surface temperature with radial variations impinges the flat plate that has convection cooling mechanism underneath to cool the plate down to a certain level of temperature in a short period of time. To enhance this convection heat transfer, a variety of structured lattice-materials can be used. However, conventional fin type heat exchangers are not suitable due to the mechanical loadings.

Whilst commercial metal foams with stochastic cellular morphologies are in general good compact heat exchangers and relatively cheap (if processed via the sintering route), they are not structurally efficient, as their deformation under mechanical loading is dominated by cell wall bending as opposed to cell wall stretching. Topologically configured ultralight metals with periodic microstructures have subsequently been developed, which have superior thermo-structural characteristics. Their weight efficiency is as good as the best competing concepts (with porosity of 0.9, it is higher than most of the existing heat exchanger media), with additional multifunctionality advantages.

1.5 Aims and Outline of the Book

In the current work, we are specifically interested in periodic metallic cellular materials, because the metallic cellular materials, due to the high thermal conductivity of metallic solid comprising the borders and the high internal surface area with propitious fluid transport, are promising candidates for ultralight multifunctional heat exchangers or heat sinks.

The outline of this book is as follows.

Chapter 2 gives detailed information on experimental characterization of the thermo-fluid behaviour of periodic cellular metals, including the setup of the experimental system, the experimental procedure, and the data analysis method.

Chapter 3 covers a comprehensive description of both the pressure drop and heat transfer characteristics of metallic 2D cellular materials based on analytical, experimental, and numerical results.

Chapters 4 and 5 covers the thermo-fluid behaviour of two types of 3D metallic cellular materials: pyramidal lattice and woven textile.

Chapter 6 proposes an approach for evaluating the overall thermal performance of various heat sink media, with which, the comparisons between periodic cellular metals and other cellular metals are provided.

Chapter 7 proposes an analytical approach for the optimal design of periodic metals subjected to single-phase forced convection. The model is validated by comparison with numerical results. Optimal results are reported for different flow configurations.

Chapter 8 suggests the directions of the future work.

References

[1] Das A, Obal M W. Revolutionary satellite structural systems technology: A vision for the future. Aerospace Conference Proceedings, IEEE, 1998, 2: 57–67.

[2] Barnett D M, Rawal S, Rummel K. Multifunctional structures for advanced spacecraft. Journal of Spacecraft and Rockets, 2001, 38: 226–230.

[3] Barnett D M, Rawal S P. Multifunctional structures technology experiment on Deep Space 1 Mission. IEEE Aerospace and Electronic Systems Magazine, 1999, 14: 13–18.

[4] Fosness E, Guerrero J, Qassim K, et al. Recent advances in multi-functional structures. Aerospace Conference Proceedings, IEEE, 2000, 4: 23–28.

[5] Evans A G, Hutchinson J W, Ashby M F. Multifunctionality of cellular metal systems. Progress in Materials Science, 1999: 171–221.

[6] Seepersad C C, Fernandez M G, Panchal J H, et al. Foundations for a systems-based approach for materials design // The 10th AIAA/SSMO Multidisciplinary Analysis and Optimization Conference. New York, 2004.

[7] Gu S, Lu T J, Evans A. On the design of two-dimensional cellular metals for combined heat dissipation and structural load capacity. International Journal of Heat and Mass Transfer, 2001, 44: 2163–2175.

[8] Hayes A M, Wang A J, Dempsey B M, et al. Mechanics of linear cellular alloys. Mechanics of Materials, 2004, 36: 691–713.

[9] Seepersad C C, Dempsey B M, Allen J K, et al. Design of multifunctional honeycomb materials. AIAA Journal, 2004, 42: 1025–1033.

[10] Sypeck D, Wadley H. Multifunctional microtruss laminates: Textile synthesis and properties. Journal of Materials Research, 2001, 16: 890–897.

[11] Tian J. Fluid Flow and Heat Transfer in Woven Textiles [PhD thesis]. Cambridge: University of Cambridge, 2005.

[12] Wadley H N G. Cellular metals manufacturing. Advanced Engineering Materials, 2002, 4: 726–733.

[13] Lu T J, Stone H A, Ashby M F. Heat transfer in open-cell metal foams. Acta Materialia, 1998, 46: 3619–3635.

[14] Ashby M F. The properties of foams and lattices. Philosophical Transactions of the Royal Society A, 2006, 364: 15–30.

[15] Queheillalt D T, Sypeck D J, Wadley H N G. Ultrasonic characterization of cellular metal structures. Materials Science and Engineering, 2002, 323: 138–147.

[16] Fleck N A. An Overview of the Mechanical Properties of Foams and Periodic Lattice Materials. Germany: Trans Tech Publications, 2005.

[17] Wadley H N G. Multifunctional periodic cellular metals. Philosophical Transactions of the Royal Society A, 2006, 364: 31–68.

[18] Evans A G, Hutchinson J W, Fleck N A, et al. The topological design of multifunctional cellular metals. Progress in Materials Science, 2001: 309–327.

[19] Bastawros A F, Evans A G, Stone H A. Evaluation of Cellular Metal Heat Dissipation Media. Cambridge: Harvard University, 1998.

[20] Ashby M, Evans A, Fleck N, et al. Metal Foams: A Design Guide. Boston: Butterworth-Heinemann, 2000.

[21] Tian J, Kim T, Lu T J, et al. The effects of topology upon fluid-flow and heat-transfer within cellular copper structures. International Journal of Heat