CHAPTER ONE

General Introduction to Porous Materials

Porous materials widely exist around us and play a role in many aspects of our daily lives; among the fields they can be found in are energy management, vibration suppression, heat insulation, sound absorption, and fluid filtration. Highly porous solids have relatively high structural rigidity and low density of mass, so porous solids often serve as structural bodies in nature, including in wood and bones [1,2]; but human beings use porous materials more functionally than structurally, and develop many structural and functional integrative applications that use these materials fully [3,4]. This chapter will introduce the elementary concepts and features of this kind of material.

1.1 ELEMENTARY CONCEPTS FOR POROUS MATERIALS

Just as their name implies, porous materials contain many pores. Porous solids are made of a continuously solid phase that forms the basic porous frame and a fluid phase that forms the pores in the solid. The latter can consist of gas, when there is a gaseous medium in the pore, or of liquid, when there is a liquid medium in the pore.

In that case, can all materials with pores be referred to as porous? Perhaps surprisingly, the answer is "no." For instance, holes and crannies that are the result of defects will lower a material's performance. This result is not what designers want, and so these materials cannot be termed porous. So-called porous materials must possess two essential characteristics: one is that the material contains a lot of pores, and the other is that the pores are designed specifically to achieve the expectant index of the material's performance. Thus, the pore of porous materials may be thought as a functional phase what designers and users hope to come forth within the material, and it supplies an optimizing action for the performance of the material.

1.2 MAIN GROUPS OF POROUS MATERIALS

The number of pores (i.e., porosity) will vary for different porous materials. Porous materials can be classified as low porosity, middle porosity, or high porosity based on the number of pores. Generally, porous materials with low and middle porosity have closed pores (Figure 1.1) which behave like a phase of impurity. For porous materials with high porosity (Figures 1.2–1.4), there are two different cases according to various morphologies of the pore and the continuous solid phase. In the first case, the continuous solid constructs a two-dimensional array of polygons; the pore is isolated in space, taking on polygonal columniations accordingly; and the cross-sectional shape of the pore is commonly triangle, quadrangle, or hexagon (Figure 1.2). This structure looks similar to the hexagonal cell of a honeycomb, and such two-dimensional porous materials are called *honeycomb materials*. Porous materials with directional pores [5], which are called *lotus-type porous materials,* have a similar structure as honeycomb materials, but the cross-sectional shape of the pores for these materials is circular or elliptic, and the pore often cannot run through it, resulting in less uniformity of distribution and a lower density of the array. In the second case, the continuous solid presents a three-dimensional reticulated structure (Figure 1.3), and such porous materials can be termed *three-dimensional reticulated foamed*

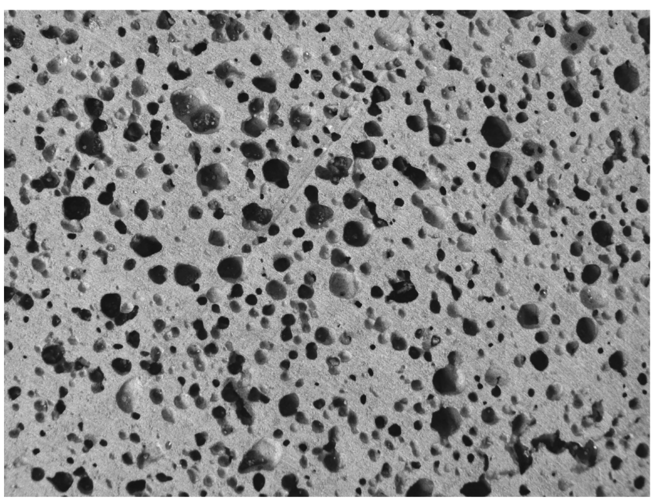
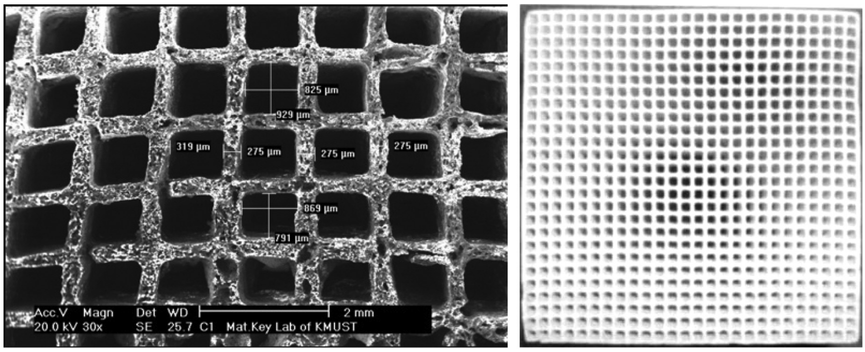
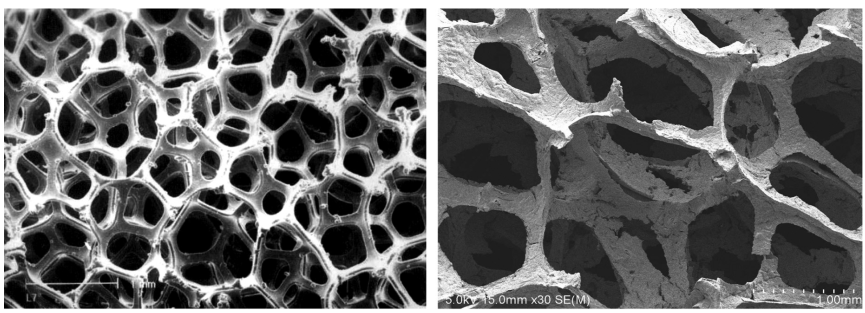


Figure 1.1 Porous composite oxide ceramics, which is a low-porosity material, shown as a cross-sectional image.



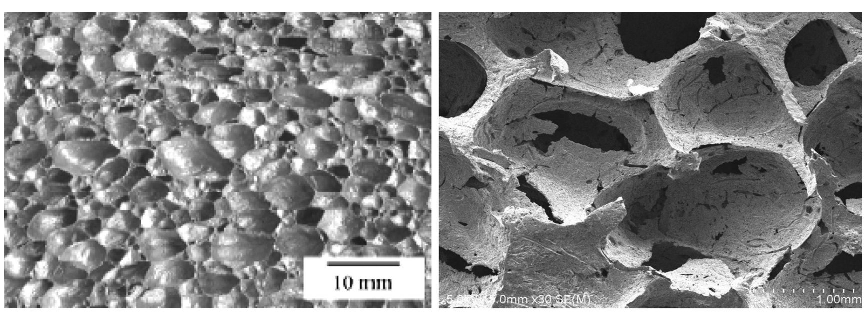
(a) (b)

Figure 1.2 Two-dimensional honeycomb materials: (a) conductive honeycomb TiC ceramics with quasi-square pores [6]; (b) thermal storage of honeycomb ceramics with square pores (with dimensions of 100 mm × 100 mm × 100 mm, cell-wall thickness of 1 mm, and square-pore side length of 2.5 mm) [7].



(a) (b)

Figure 1.3 Three-dimensional reticulated foamed materials: (a) nickel foam; (b) iron foam.



(a) (b)

Figure 1.4 Bubblelike foamed materials: (a) a closed-cell bubblelike foamed material of aluminum foam [8]; (b) an open-cell bubblelike foamed material of iron foam.

materials. These materials have connective pores that are of a typical open-cell structure. In the third case, the continuous solid shows the cell wall structure of pores of sphericity, elliptical sphericity, or polyhedron shape (Figure 1.4), and such three-dimensional porous materials can be called *bubblelike foamed materials*. Within these materials, the cell wall may separate many isolated closed pores or cells, forming a closed-cell, bubblelike foamed substance (Figure 1.4a). The cell wall may make up open-cell, bubblelike foamed material as well (Figure 1.4b). In the literature, three-dimensional, reticulated foamed materials are referred to as "open-cell foamed materials," closed-cell, bubblelike foamed materials are called "closed-cell foamed materials," and open-cell, bubblelike foamed materials are "half open-cell foamed materials."

Porous solids include two types of porous bodies (i.e., natural and artificial). Natural porous solids can be found universally [1], such as bones that support the bodies and limbs of animals and human beings (see Figure 1.5), plant leaves, wood, sponge, coral (Figure 1.6), pumice (Figure 1.7), and lava (Figure 1.8). Lava is a sort of natural porous material that can be used in construction or for creating artwork (Figure 1.9). It is not accurate to refer to the natural, porous solids of living animal bones and tree trunks as "natural porous materials." However, when a tree is cut down to make materials used by human beings to make things like furniture, it becomes natural porous materials. The fluid phase contained in the pores of plant leaves and living tree trunks always consists of liquid (namely sap), while that within

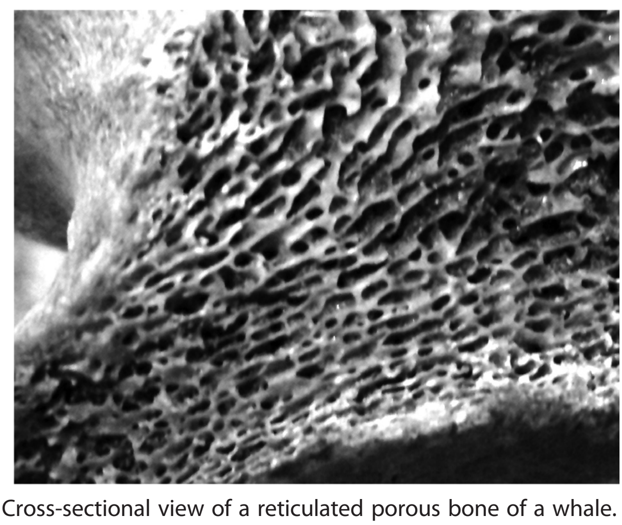


Figure 1.5 Cross-sectional view of a reticulated porous bone of a whale.

Figure 1.6 An optical photograph showing the porous morphology of coral.

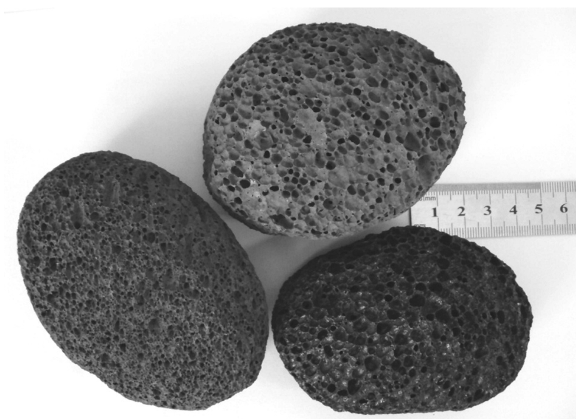


Figure 1.7 An image showing the porous morphology of pumice.

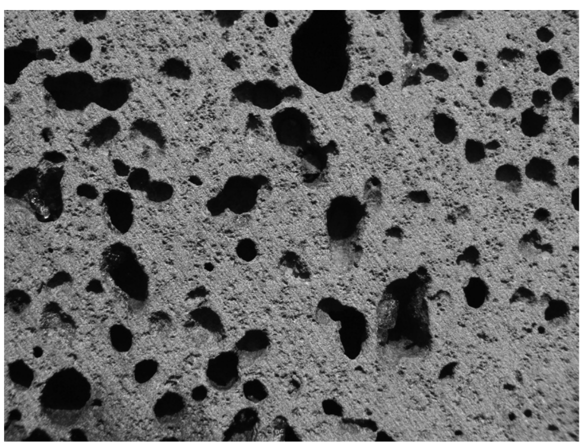


Figure 1.8 Cross-sectional view of the porous morphology of lava.

Figure 1.9 A vase made of lava.

artificial porous materials is mostly gas. Artificial porous materials can be subclassified further into porous metals, porous ceramics, and polymer foams.

1.3 POROUS METALS

Porous metals are a relatively new class of engineering materials that can serve functional and structural purposes [9–11]. They have undergone rapid development over the last thirty years. These lightweight materials not only have the typical characteristics of metals (weldability, electrical conductivity, and ductibility), but also possess other useful characteristics, such as low bulk density, great specific surface area, low thermal conductivity, good penetrability, energy management, mechanical damping, vibration suppression, sound absorption, noise attenuation, and electromagnetic shielding. Consequently, these materials have increasing applications, and have emerged as a focus of great attention in the international material field [12]. The next sections describe the main characteristics of these types of metals [11,13–15].

1.3.1 Powder-Sintering Type

The powder-sintering type of porous metallic material is commonly made from metal or alloy powder with spherical or irregular shapes via molding and sintering. The porous bodies obtained in this manner will have various porosities, pore sizes, and pore-size distribution due to differences of the selected raw materials or technological systems. However, all of them have the characteristics of good penetrability, controllable pore sizes and levels of porosity, and great specific surface area, as well as endurance under high or low temperatures and resistance to heat fluctuation.

Powder-sintering porous metals were developed early, with pore size usually less than 0.3 mm and porosity mostly less than 30%. However, the production with porosity much higher than 30% can be prepared by using special technological processes, e.g, the space-holder method. In the metallurgy and chemical engineering fields, high-temperature and high-pressure environments are frequent, and accordingly, filtration and separation materials are needed; during catalysis reactions, catalyzer materials with great specific surface area are needed to supply the reactive interface area; and many types of oils and working gases must be filtered strictly to guarantee that the aviation and hydraulic pressure systems work safely. The areas of aviation and rockets demand that porous materials with great heat endurance and heat fluctuation resistance and well-proportioned pore structures be used as the basic structural material for volatilization cooling. In general, porous polymer or ceramic bodies are difficult to adapt to these conditions, which require great strength, plasticity, and high temperature tolerance at the same time, but powder-sintering type porous metallic materials can do this well, and therefore scientists worked to develop them speedily.

The first patents mentioning powder-sintering porous components were approved as early as 1909, and patents dealing with the techniques to make powder-sintering filters were developed until the early 1930s. During World War II, powder-sintering porous materials underwent rapid development for military applications. Powder-sintering filters were applied to airplanes and tanks, porous nickel was adopted to make radar switches, porous iron was employed to make cannonball hoops instead of dense metallic copper, and iron filters were used as flame extinguisher. In the mid-twentieth century, porous materials with oxidation resistance were applied to the fireboxes and blades of jet engines for volatilization cooling to heighten the efficiency of engines. In response to developments in chemical engineering, metallurgy, atomic energy, aviation, and rocketry, many types of powder-sintering porous materials with high penetrability and resistance to corrosion, high temperatures, and high pressure were created. Some more advanced porous materials were produced in the 1960s, including the corrosion- and heat-resistant porous materials of Hastelloy, Inconel, titanium, stainless steel, tungsten, tantalum, and other refractory metals and alloys. At present, powder-sintering porous materials of bronze, stainless steel, nickel, titanium, and aluminium alloys have been mass-produced and employed. Figure 1.10 shows a powder-sintering type of porous titanium alloy.

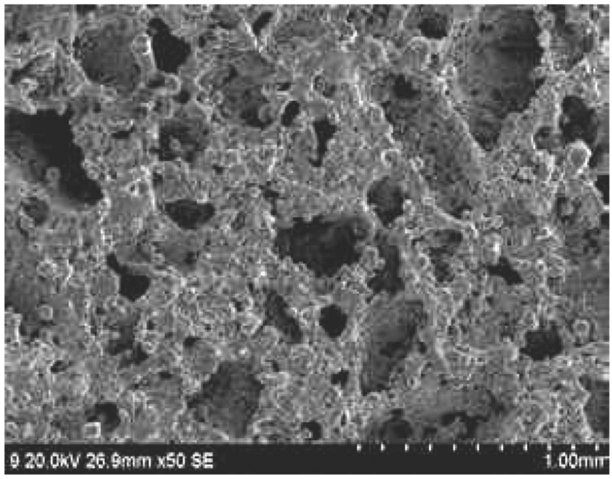


Figure 1.10 SEM image of the porous TiNiFe alloy fabricated by powder sintering [16].

1.3.2 Fiber-Sintering Type

The fiber-sintering type of porous metal is an improvement over powder-sintering porous metals for the above mentioned purpose. Porous materials made of metallic fiber may be superior to that of metallic powder in some ways. For example, filtration materials fabricated of metallic fiber will have a much greater degree of penetrability than those made of metallic powder with the same diameter as the metallic fiber. In addition, they have a higher mechanical strength, corrosion resistance, and thermal stability. These materials can reach a porosity of over 90%, with all through pores, good plasticity and impact toughness, and a high dust retention capacity. Known as *second-generation porous metallic filtration materials,* they may be used by many businesses under rigorous filtration conditions. Figure 1.11 shows a porous structure crafted by metallic fiber sintering.

1.3.3 Melt-Casting Type

The melt-casting type of porous metal is formed via cooling molten metals or alloys, which can include a very wide range of porosities and have diversely shaped pores with different casting manners. One example of this is aluminum foam produced by melt-foaming and infiltration-casting processes. Materials made from melt foaming are mostly closed-cell or half open-cell porous

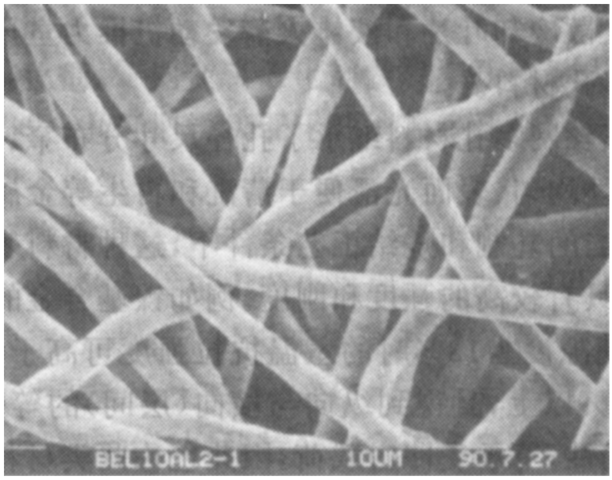


Figure 1.11 Micrograph of a porous material fabricated by metallic fiber sintering [11].

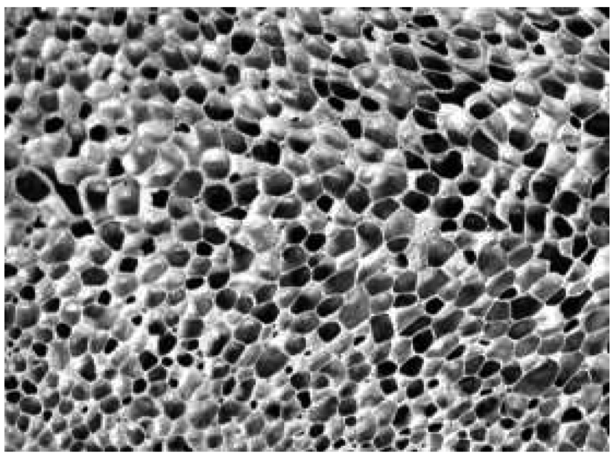


Figure 1.12 An aluminum foam produced by melt foaming [17].

materials (Figure 1.12), and those made from infiltration casting commonly take the form of three-dimensional, reticulated, open-cell ones with high porosity.

1.3.4 Metal-Deposition Type

The metal-deposition type of porous metal is created via depositing atomic metal on open-cell polymer foam, followed by eliminating polymers and sintering. The main features of such metals include connective pores, high

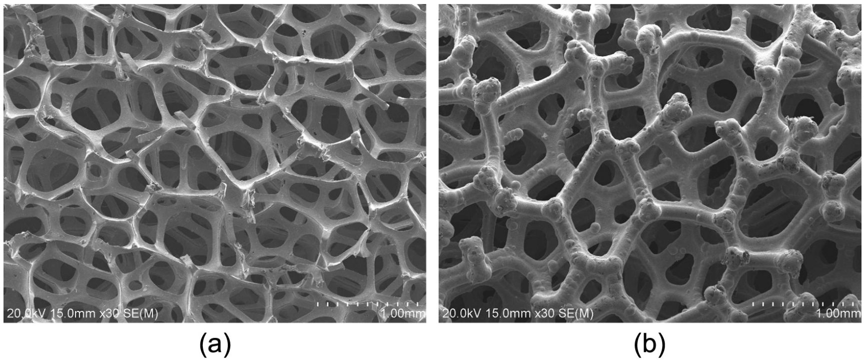


Figure 1.13 SEM images of nickel foam samples of various thicknesses made by the metal deposition process: (a) a thinner nickel layer; (b) a thicker nickel layer.

porosity, and a three-dimensional, reticulated structure. This porous material, a new type of functionally and structurally integrative substance with excellent properties, is a very important class of porous metals. When used in certain settings, its merits include low density, high porosity, great specific surface area, good pore connectivity, and uniform structure, which is difficult to achieve for other types of porous metals. However, the feature also results in some limits to the strength of metal-deposition type porous metals. These materials first were manufactured and utilized in the 1970s, and then, during the 1980s, they were speedily developed for a wide variety of applications and demands. At present, these porous materials are produced on a large scale in many countries, with the products of nickel and copper foams typically made by the electrodeposition process. Such metal foams are shown in Figure 1.13.

1.3.5 Directional-Solidification Type

The directional-solidification type of porous metal forms via dissolved gas in molten metal releasing in the course of directional cooling [5,18], namely by GASAR. The resultant products have a very similar structure to plant lotus roots (Figure 1.14), so they are called *lotus-type porous metals, porous metals with directional pores,* or *Gasarite.*

1.3.6 Composite Type

Composite-type porous metals are porous metal composite materials. They can be obtained by compositing different metal species or metal species and

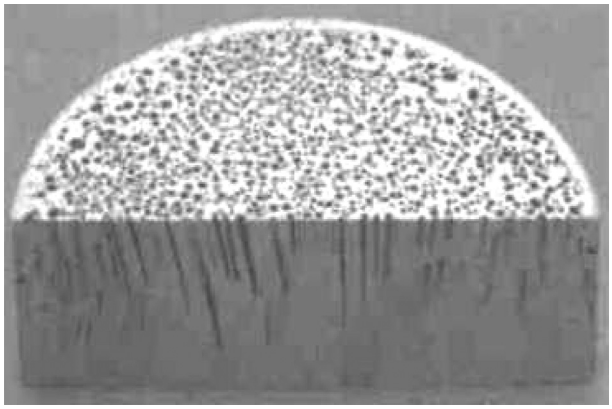


Figure 1.14 A lotus-type porous metal formed by gas-metal eutectic directional solidification [18].

nonmetal species to form a porous body. Examples of this type of metal include graphite-nickel composite porous material created by electroplating a nickel layer onto a graphite felt, and a composite of aluminum alloy and nickel foam made by pouring a melted aluminum alloy into a three-dimensional, reticulated nickel foam. Such materials also can be fabricated by using porous metals as a core to form a metallic composite porous "sandwich"; for example, by putting together stainless steel fiber felt and wire netting or by integrating aluminum foam and metallic panels. Compositing makes the materials acquire the respective merits of these different ingredients and improved their properties; the result is a completely new synthetic material that better meets the demands placed on products made from this substance.

In addition, certain porous metallic materials are prepared by particular routes, some of which can be ascribed to those of the above mentioned types, and others can be those of new types.

1.4 POROUS CERAMICS

Porous ceramics, also known as *cellular ceramics,* began developing in the 1970s. They are comprised of a kind of heat-resistant porous material with many gaseous pores. Their pore size mostly ranges between the angstrom and millimeter levels, the porosity usually spans from 20% to 95%, and the serving temperature varies from room temperature to 1,600 C [19,20].