Chapter 1

Introduction to Porous Structures and Additive Manufacturing

1.1 INTRODUCTION

Porous structures, from a physical standpoint, can be viewed as composites comprising base materials that confer porosity and the surrounding media that fill the interstitial spaces. In the context of this discourse, we will refer to the individual pores as "cells" and the spaces they create as "voids." The concept of porous structures finds its inspiration in nature, where numerous natural constructs, such as bones and cork, inherently exhibit porosity. This characteristic arises from the biological process of constructing these structures through the growth of single cells. These natural constructs exhibit a wide spectrum of properties, enabling them to adapt to applications.

For example, nature employs porosity to optimize the structure and function of various organisms. In avian biology, bird bones exhibit a unique porous structure, combining strength with weight reduction, essential for aerial locomotion. This intricate network of interconnected pores within the bone matrix not only minimizes weight but also enhances the bone's overall strength. The porous architecture distributes stress evenly, preventing fractures and maximizing the bone's load-bearing capacity [1, 2].

Advanced Techniques in Porous Structure Design for Additive Manufacturing,
First Edition. Musaddiq Al Ali.

For plant structure, porosity plays a crucial role in the efficient transport of water and minerals throughout the plant body. Trees, in particular, rely on a complex porous structure of xylem vessels, which are characterized by their porous structure. These vessels, composed of dead, hollow cells, facilitate the upward movement of water from the roots to the leaves. The porous nature of the xylem vessels allows for capillary action, enabling water molecules to adhere to the vessel walls and be drawn upward against gravity. Additionally, the porosity of the xylem vessels provides a large surface area for the absorption of water and minerals, ensuring adequate nutrient supply to the entire plant.

Although the existence of porous structures dates back to ancient times, they have recently garnered significant attention, leading to the development of a novel class of materials in contemporary engineering. These materials offer a unique opportunity for achieving high performance relative to their weight, a characteristic highly sought after in advanced structural and other engineering applications.

By selectively designing the pore structure, it is possible to derive new desired properties from a base material that lacks such properties in its bulk form. This selective design essentially creates a composite of voids and solid materials. For instance, by manipulating the porosity, one can achieve materials with properties such as negative thermal expansion and apparent negative thermal conductivity. These properties can be tailored to specific applications, such as high-efficiency energy absorption [3, 4] and thermal insulation [5, 6].

Historically, the mastery of metals has significantly shaped human civilization, marking distinct epochs such as the Bronze Age and the Iron Age. The development and utilization of porous metal structures continue this legacy, presenting a modern frontier in material science and engineering.

As such, porous metals, in particular, represent a fascinating class of materials characterized by high surface area, high permeability, and tunable pore size and distribution. These attributes make them suitable for a diverse array of applications, including catalysis, filtration, energy storage, and biomedical engineering. Compared to polymers, porous metals exhibit superior mechanical stability, are lightweight, and have additional physical properties such as good electrical and thermal conductivities.

On the other hand, the high surface area of porous metals facilitates a greater number of chemical reactions at active sites, rendering them ideal for catalytic applications. In filtration, such as gas separation and water purification, the ability to tune pore size and distribution allows for the efficient separation of particles of different sizes. In energy storage, porous metals are used in batteries and supercapacitors due to their ability to provide high surface area and permeability, enhancing ion transport and storage capacity.

In biomedical applications, porous metals are employed for bone implants because their structure can promote bone tissue regeneration and integration.

How can porous materials exhibit extraordinary properties and characteristics that are absent in their bulk base materials? To address this question, it is essential to investigate the unique microstructural features of porous materials, including their

geometry, connectivity, and distribution, which govern their ability to achieve such remarkable functionalities. Porous structures exhibit a hierarchical organization that spans multiple length scales, from the atomic to the macroscopic. At the atomic level, the arrangement of atoms and the types of chemical bonds play a crucial role in determining the intrinsic properties of the material. Moving to the microscale, the size, shape, and distribution of the pores significantly influence the mechanical, thermal, and transport properties. Macroscale considerations include the overall geometry and connectivity of the porous network, which can produce a new collective property.

The phenomenal properties of porous materials may include materials with a negative Poisson's ratio, also known as auxetic materials, which expand laterally when stretched, a behavior opposite to that of conventional materials. This property can be engineered by designing the pore structure according to a specific function, leading to applications in protective gear, medical devices, and flexible electronics.

Recently, the development of materials with the capacity to exhibit anomalous thermal behavior, such as apparent negative thermal conductivity, represents a significant advancement in the field of thermal management. These materials are engineered to manipulate heat flow in unconventional manners, allowing them to redirect thermal energy in ways that are not typically achievable with conventional materials. The redirection and dissipation of heat enable these materials to enhance the efficiency of cooling systems in electronic devices, ensuring that they operate within safe temperature ranges. Furthermore, these materials hold great potential for providing superior thermal insulation in extreme environments, such as space exploration or deep-sea applications, where traditional insulation methods may fall short.

The true industrial and engineering potential of porous metals began to be recognized in the early 20th century. The first commercially available porous metals were produced using sintered powder technology. This process involves compacting and heating metal powders to a temperature just below their melting point, allowing the particles to coalesce and form a solid mass with a network of interconnected pores. The unique properties of these sintered metals, including their high surface area and permeability, made them ideal for applications such as filters, batteries, and self-lubricating bearings. These early applications demonstrated the potential of porous metals to enhance performance in high-volume industrial processes, a promise that continues to be realized today in various fields.

Historically, the concept of porous metals is not a modern invention. The earliest known reference to man-made porous metals can be traced back to the work of Pliny the Elder in 77 AD, who documented a process known as granulation. This technique was notably used by Etruscan goldsmiths, who applied it to create intricate patterns and textures on jewelry, a process that involved the creation of fine, porous structures on the surface of metals [7, 8]. Although these early applications were primarily esthetic, serving decorative purposes in jewelry and religious artifacts, they laid the foundation for the understanding of porous metals and their potential applications [9].

The concept of metallic foams, which involves creating a metal structure with high porosity through the introduction of gas bubbles or other foaming agents, was

first formally introduced in a French patent in 1925. Metallic foams offer a distinct combination of lightweight, high strength, and excellent energy absorption characteristics, making them suitable for applications ranging from lightweight structural components to impact protection and thermal insulation. However, despite the early conceptualization, the commercialization of metallic foams did not begin in earnest until the late 1950s in the United States. This delay was primarily due to the need for extensive research and development to understand and optimize the foaming processes and to tailor the properties of the foams to specific applications [10, 11].

During the initial wave of research and development that started extensively from the 1950s, significant efforts were made to explore the potential applications of metallic foams across various industries [12, 13]. This period saw the development of foaming techniques for different metals and alloys, as well as the investigation of their mechanical and thermal properties. The versatility of metallic foams became apparent, leading to their adoption in a range of applications, including lightweight panels for aerospace structures, energy-absorbing layers in automotive crash protection systems, and high-efficiency heat exchangers.

Moreover, porous metals were created using electrochemical deposition. Historically, this was started as a series of studies to understand this "undesirable" feature in metal plating. However, it has found useful applications, such as in the creation of heat exchanger channels for space rocket engines [14–17].

The fabrication of metal foams presents a significant challenge due to the difficulty in achieving precise topological control of the cellular spatial configuration. To address this issue, various advanced manufacturing techniques have emerged to produce metal cellular structures with detailed and controlled cell architectures. The methods for producing porous metals are diverse and include powder metallurgy, foaming, chemical vapor deposition (CVD), electrodeposition, and chemical etching.

In powder metallurgy, a blend of metal powder and a sacrificial filler material is sintered, and the filler is subsequently removed to create pores. This technique allows for precise control over the pore size and distribution. Foaming involves the creation of a metallic foam by mixing a molten metal with a blowing agent, which generates gas bubbles within the metal, followed by rapid cooling to solidify the porous structure. This method is advantageous for producing lightweight materials with a high strength-to-weight ratio.

CVD is a process in which metal atoms are deposited onto a substrate from a vapor phase, forming a porous structure. This technique is highly effective in producing thin films and coatings with controlled porosity.

These methods have limitations, such as the requirement for specialized equipment, slow processing speeds, and incompatibility with large surface areas. Additionally, the mechanical strength of the resulting porous metals may be limited.

Alternatively, chemical and physical etching involves treating a metal piece with an etchant solvent to selectively remove materials and create pores. This technique allows for the processing of large surface areas using relatively low-cost resources. Chemical etching is effective for producing nano- and microlattice structures, making it suitable

for highly specialized applications such as sensors and microelectromechanical systems (MEMS).

Despite the high surface quality and accurate spatial configuration of the pores achieved through these methods, they are limited to certain types of metallic alloys. Moreover, achieving consistent results requires meticulous control over the processing parameters. The scalability of these techniques is also restricted, making them less suitable for producing large components and mass manufacturing.

Recent advancements in manufacturing technologies are fundamentally transforming the design and production landscape, addressing long-standing limitations inherent to conventional fabrication methods. Among these, additive manufacturing (AM), commonly referred to as three-dimensional printing, has emerged as a pivotal technology enabling unprecedented precision in the creation of geometrically complex and hierarchically porous structures. By leveraging layer-by-layer deposition techniques, AM provides unparalleled control over the topology and morphology of manufactured components, allowing for the meticulous customization of mechanical, thermal, and fluidic properties at both micro- and macroscales.

The defining capability of AM lies in its capacity to fabricate structures that were previously unattainable through traditional manufacturing methods, such as casting, machining, or injection molding. In particular, the ability to engineer controlled porosity is of immense interest due to the critical role it plays in optimizing material properties for specific applications. For instance, porous structures can be tailored to exhibit superior strength-to-weight ratios, enhanced thermal conductivity, and improved acoustic damping characteristics, attributes that are crucial for aerospace and automotive industries striving for high-performance, lightweight designs.

The versatility of AM extends to its capability to produce components with gradient porosity, where the distribution of pore sizes and densities varies spatially within a single structure. Such designs are particularly valuable in applications requiring multifunctional materials. For example, aerospace components can be engineered with denser regions for load-bearing purposes and more porous zones for thermal insulation. Similarly, in the automotive industry, gradient porosity can be utilized to optimize both crashworthiness and weight reduction in vehicle components.

Moreover, AM's potential for scalability and integration with computational design tools, such as topology optimization and generative design algorithms, has further augmented its impact. These tools enable the design of porous structures that are not only optimized for specific functional requirements but also manufacturable with minimal material wastage, aligning with sustainability goals. By seamlessly coupling advanced computational methods with AM, researchers can iterate rapidly between design and fabrication, significantly reducing development cycles and costs.

Despite these remarkable capabilities, challenges remain in standardizing the properties and reliability of AM-fabricated porous structures, particularly for load-bearing applications. Ongoing research is focused on improving material consistency, surface finish, and structural integrity to ensure broader adoption across industries. Nonetheless, AM continues to unlock transformative opportunities, pushing the boundaries of

what is achievable in engineering design and solidifying its role as a cornerstone of modern manufacturing.

Furthermore, hybrid manufacturing techniques that combine traditional methods with modern technologies are being developed to enhance the efficiency and scalability of porous metal production. These innovations hold the promise of creating robust, high-performance materials suitable for a wide range of engineering applications, from structural components to advanced functional materials.

1.2 WHY DESIGNING POROUS STRUCTURES

Porous structures present a remarkable potential for achieving a high performance-to-weight ratio, offering the capability to attain high stiffness with low weight. This unique characteristic arises from the inherent porosity within these materials, which provides a complex network of voids and solid regions. These voids can significantly reduce the overall density of the material, thus lowering its weight, while the solid regions maintain structural integrity and stiffness. Consequently, porous structures are highly desirable in applications requiring materials that are both lightweight and strong.

One of the significant advantages of porous materials is their ability to facilitate multiphysics phenomena, for example porous heat exchangers, such that the interconnected pores allow for fluid flow through the material, enhancing convective heat transfer. This feature is especially beneficial in systems such as internal combustion engines, where the material can bear mechanical loads while simultaneously aiding in cooling. The pores provide pathways for the coolant to pass through, effectively dissipating the heat generated during combustion processes and maintaining the structural integrity of the engine components.

Furthermore, porous materials exhibit high surface area-to-volume ratios, which are advantageous in thermal, chemical, and biological processes. The extensive surface area allows for more significant interactions with surrounding environments, enhancing reaction rates in various applications. In thermal processes, this can lead to more efficient heat exchange. In chemical processes, it can increase the rate of reactions, making porous materials ideal for use in catalysts and reactors. In biological processes, the high surface area can support cell attachment and growth, making these materials suitable for biomedical applications such as tissue engineering.

These benefits, however, only scratch the surface of the potential advantages offered by porous structures. One of the most critical aspects determining the structural behavior of these materials is their spatial configuration or the material distribution within the domain. This aspect profoundly influences the physical properties and functionality of the structure. To illustrate this concept, consider a 10-g mass of iron.

If this mass of iron is shaped into a cube, it behaves as a rigid body, capable of withstanding considerable compressive loads. However, if the same mass is formed into a long wire, it becomes easily bendable due to its high aspect ratio and slender geometry. When shaped into a helical spring, the iron mass exhibits elasticity, capable of storing and releasing mechanical energy efficiently.

This variability in behavior is solely due to the different shapes and configurations given to the same mass of iron. By altering the spatial arrangement of the material, we can achieve a wide range of physical properties and functionalities beyond the scope of bulk materials in a similar manner to have a new material. This principle is equally applicable to porous structures. The distribution and connectivity of the pores within the material can be engineered to optimize specific properties, such as stiffness, strength, thermal conductivity, and band gap photonics, that depend on the intended application.

Designing bulk materials as cellular structures allows for precise control over their mechanical behavior. Consider iron shaped into a small plate with a honeycomb structure. This configuration results in a lightweight plate with orthotropic mechanical properties, meaning its behavior differs along different directions. The Poisson's ratio, a measure of the material's ability to expand laterally when stretched longitudinally, is positive in this case and is influenced by the intrinsic properties of the constitutive iron material.

Consider redesigning the honeycomb structure (as illustrated in Figure 1.1), where we can achieve even more remarkable behaviors. If we invert the upper triangular sections of the honeycomb so that the upper base becomes the lower and the two lower links become the upper, we create what is known as a re-entrant auxetic structure. This re-entrant design fundamentally changes the mechanical response of the material, giving it a negative Poisson's ratio. As a result, the structure expands laterally when stretched, contrary to the behavior of most materials.

This negative Poisson's ratio is due to the unique geometry of the re-entrant auxetic cells, which causes the structure to deform in a manner that increases its cross-sectional area under tension. This auxetic behavior has several practical advantages, including enhanced energy absorption, increased shear resistance, and improved fracture toughness.

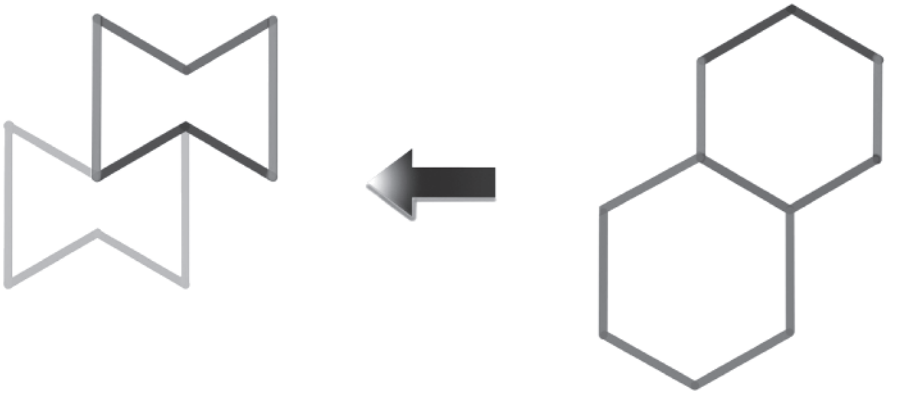

Figure 1.1 The effect of material distribution on material properties, with a positive-to-negative Poisson ratio.

1.3 TYPES OF CELLS

Cellular materials can be classified in multiple ways, including by topology and design methodology, with particular emphasis on volume occupation aspects. These classifications are vital in understanding the functional behavior of the materials in various applications. The primary classifications in terms of topology are closed-cell and open-cell structures.

Closed-cell structures are characterized by cells that are entirely encapsulated by their walls, forming discrete, impermeable units akin to bubbles. This encapsulation means that the internal volume of each cell is isolated from its surroundings, making the material impenetrable to environmental factors such as moisture or air. The impermeability of closed-cell structures leads to their widespread use in applications where water resistance and buoyancy are critical. For instance, closed-cell foams are used in flotation devices, life vests, and watercraft where buoyancy and the ability to remain dry are paramount. Their dense structure also provides excellent thermal insulation, making them ideal for use in environments where thermal management is essential, such as in the construction of refrigerated units and insulated shipping containers.

Conversely, open-cell structures feature cells that are not fully enclosed, with walls that have openings or are interconnected with other cells. This interconnectedness allows for the passage of fluids, air, or other substances through the material, leading to a range of unique properties. Open-cell materials excel in applications requiring compression set resistance and force relaxation, such as cushioning and shock absorption. The ability of these materials to absorb and gradually release air or moisture is beneficial in applications where gradual dissipation of absorbed substances is desired, such as in filters or moisture-wicking materials.

However, the open structure of these cells also means that they are less effective at preventing water absorption when uncompressed. In certain situations, such as when a high level of compression is applied, the small openings in the cell walls can close off, creating an effective seal. This characteristic makes open-cell foams suitable for dynamic environments where materials are subjected to varying pressures. In addition to cushioning and acoustic absorption, open-cell structures are used in chemical reactors, where their ability to allow fluid flow is crucial, as well as in biomedical scaffolds, where the porous structure supports tissue growth and nutrient transport.

Beyond the basic classification into closed- and open-cell structures, modern engineering and material science have advanced to include the design and application of mathematically generated or “typical” cells (as illustrated in Figure 1.2). These are geometric shapes that form the building blocks of regular cellular structures and can be designed with specific mechanical or thermal properties in mind. Examples of such shapes include the cube, G7, diamond, truncated cuboctahedron, rhombic dodecahedron, and gyroid. Each of these shapes confers distinct mechanical properties to the resulting cellular material. For instance, the gyroid structure, known for its minimal surface area configuration, offers excellent mechanical strength and stiffness while

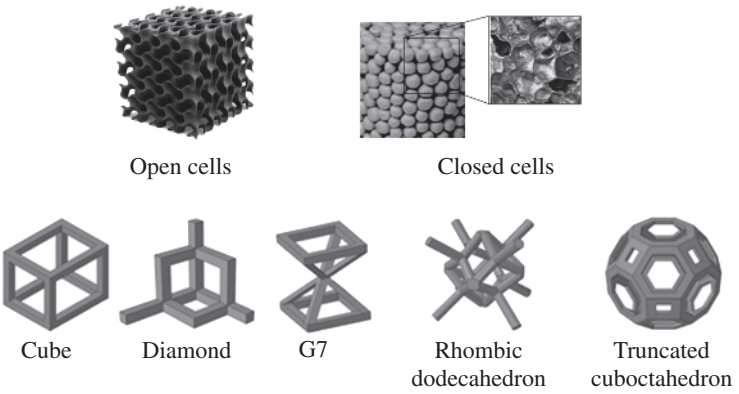

Figure 1.2 Common porous structure categorization.

minimizing material usage. This makes it an attractive option for lightweight structural components in aerospace and automotive industries. The rhombic dodecahedron and truncated cuboctahedron, with their high degree of symmetry, are favored in applications requiring isotropic mechanical properties, where uniform strength in all directions is necessary.

The application of these mathematically generated cells extends into various high-performance fields. In biomedical engineering, for example, the gyroid structure has been employed to design implants that mimic the porosity of natural bone, promoting osseointegration and reducing implant weight.

The integration of computational design tools and advanced manufacturing techniques, such as AM, has further expanded the possibilities for designing and fabricating cellular materials with tailored properties. Engineers can now optimize cellular structures at multiple scales, from the overall material geometry down to the microscopic cell configuration, to achieve the desired performance characteristics. This capability is particularly important in applications such as energy absorption, where the material must deform predictably under impact, or in lightweight strategies, where the material is removed strategically without compromising structural integrity.

Moreover, the field of non-parametric optimization, where the material distribution within a given design space is optimized to meet specified performance criteria, has seen significant advancements through the use of cellular materials. By incorporating closed- or open-cell structures into topology-optimized designs, engineers can create components that are not only lightweight but also exhibit superior mechanical properties compared to traditional solid materials.

Recently, many commercial software offer cellular structural design scale such as nTopology®, Abaqus®, ANSYS®, COMSOL®, and OptiStrct® solver, which have integrated specialized capabilities for creating porous structures. These tools are widely adopted in various industries due to their effectiveness in optimizing lightweight, high-strength materials. However, a notable limitation of these predefined structures is their fixed mechanical properties, which may not always meet the diverse demands of a specific

application. To address this, engineers can vary the thickness of the members and links within the cellular structure. This variation, when guided by an empirically driven predictive model of mechanical properties, enables the creation of a wide array of porous designs with enhanced robustness and for a specific application.

The field of natural inspiration, particularly in the context of material design, has gained significant attention due to technological advances in capturing the intricate details of cellular structures and modeling their mechanical properties. Most materials in nature, especially those utilized in engineering applications, are inherently heterogeneous. This heterogeneity arises from both structural and compositional variations, which are often random and complex, making it challenging to predict the material's overall response accurately. Nature-inspired materials aim to replicate the intricate structures or functionalities observed in natural materials, offering a blueprint for designing advanced engineering materials [18–22].

In the specific case of porous materials, the inherent randomness of their pore structures contributes to a wide range of mechanical, thermal, and fracture properties. This variability has captivated the interest of both engineering and scientific communities, as nature provides a rich source of inspiration for the development of cellular structures. Biological systems, with their optimized mechanical characteristics, often serve as models for high-performance structural designs. Nature-inspired cellular structures have diverse applications, ranging from biomimetic devices to specialized biomechanical medical implants. It is also worth noting that the concept of the first negative Poisson's ratio cellular design, which is fundamental to auxetic materials, originated from the study of the honeycomb structure—a classic example of a nature-inspired design.

Moreover, advancements in numerical methods for characterizing composite materials have expanded the possibilities for human ingenuity, leading to remarkable innovations in cellular design. For instance, the development of cellular structures in orthotropic materials has opened new avenues for achieving extraordinary properties, such as cloaking materials capable of rendering objects invisible or materials exhibiting negative thermal expansion.

These advancements underscore the transformative potential of combining natural inspiration with cutting-edge computational design methods. By harnessing the inherent complexity and optimization found in nature, engineers and scientists can develop materials with unprecedented properties, paving the way for innovations across a wide range of fields, from biomedical engineering to aerospace and beyond.

1.4 CHALLENGES IN THE DESIGN AND FABRICATION OF POROUS STRUCTURES

Porous structures, despite their extensive range of beneficial properties, present several significant challenges that need to be addressed for effective application. One of the primary concerns is structural failure. While the distribution of mechanical strain

across multiple cells theoretically limits mechanical deformation within design constraints, cells directly subjected to loadings, whether they are solid members or larger cellular voids, tend to experience higher strains. This localized strain increase can render such structures susceptible to elastic failure.

The intuitive approach of decreasing the cell size to enhance cellular performance holds especially true within the elastic deformation range. However, the fabrication of smaller cellular structures introduces considerable complexity. Smaller cells, particularly those subjected to high loading, are prone to plastic deformation, which can lead to premature failure. Furthermore, mechanical fatigue poses a critical issue. Unlike porous structures in living creatures, manufactured cellular structures lack the self-healing capability seen in biological systems [23, 24]. This absence of self-repair ability results in irreversible crack propagation within cell walls or linkages. The relatively small thickness of these walls exacerbates the situation, as cracks can propagate and cause rupture more rapidly than in bulk materials.

Additionally, the robustness of porous structures is influenced by the range of materials that can be utilized and the inherent manufacturing challenges. Despite advances in chemical and physical material preparation processes, producing robust solid materials as porous structures remains problematic. Factors affecting this robustness include cost considerations and the efficiency of the porous structure's performance. AM techniques, discussed in detail in Chapter 2, further complicate these issues.

Design decisions regarding the suitability of porous structures must consider various factors, including the intended purpose, time constraints, budget limitations, long-term objectives, and the multiphysics and physical chemistry of the problem [25–27]. These considerations require a comprehensive understanding of the multifaceted nature of the design problem. For instance, titanium alloys are favored for long-term biomedical implants due to their lightweight nature compared to materials like stainless steel, which have nearly double the density. However, porous stainless steel materials might offer a promising alternative by combining the lightweight characteristics of titanium alloys with enhanced mechanical properties, while their porous structure can function as a scaffold for bone cell integration, potentially mitigating stress shielding issues. Yet, without extensive long-term biomedical studies, the safety and efficacy of such alternatives remain uncertain. For example, the use of stainless steel materials in orthopedic implants over extended periods (5–10 years) has been shown to promote abnormal blood vessel growth, raising concerns about their long-term safety.

Moreover, design challenges extend to the representation and optimization of design variables for cellular structures. The objective is to develop methods for evaluating and optimizing the design of both individual cells and the porous structure as a whole. Advances in numerical methods and increasing computational power have led to the development of sophisticated methodologies for addressing these design challenges. Chapters 3 and 4 will explore recent advancements in this field and provide detailed discussions on contemporary numerical tools and software used in industry and research for the high-fidelity simulation and cost-effective evaluation of designs.

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