Additive Manufacturing 19 (2018) 167–183

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Full Length Article

Topology-mechanical property relationship of 3D printed strut, skeletal, and sheet based periodic metallic cellular materials

Oraib Al-Ketan [a,b], Reza Rowshan [c], Rashid K. Abu Al-Rub [a,b,*]

[a] Institute Center for Energy, Mechanical and Materials Engineering Department, Masdar Institute of Science and Technology, Abu Dhabi, UAE
[b] Mechanical Engineering Department, Khalifa University of Science and Technology, Abu Dhabi, UAE
[c] Core Technology Platforms, New York University Abu Dhabi, Abu Dhabi, UAE

ARTICLE INFO

Article history:
Received 26 August 2017
Received in revised form 2 November 2017
Accepted 5 December 2017
Available online 17 December 2017

Keywords:
Additive manufacturing (AM)
Selective laser sintering (SLS)
Powder bed fusion
Triply periodic minimal surfaces (TPMS)
Architected materials

ABSTRACT

Recent advances in additive manufacturing facilitated the fabrication of parts with great geometrical complexity and relatively small size, and allowed for the fabrication of topologies that could not have been achieved using traditional fabrication techniques. In this work, we explore the topology-property relationship of several classes of periodic cellular materials; the first class is strut-based structures, while the second and third classes are derived from the mathematically created triply periodic minimal surfaces, namely; the skeletal-TPMS and sheet-TPMS cellular structures. Powder bed fusion technology was employed to fabricate the cellular structures of various relative densities out of Maraging steel. Scanning electron microscope (SEM) was also employed to assess the quality of the printed parts. Compressive testing was performed to deduce the mechanical properties of the considered cellular structures. Results showed that the sheet-TPMS based cellular structures exhibited a near stretching-dominated deformation behavior, while skeletal-TPMS showed a bending-dominated behavior. On the other hand, the Kelvin and Gibson-Ashby strut-based topologies exhibited a mixed mode of deformation while the Octet-truss showed a stretching-dominated behavior. Overall the sheet-TPMS based cellular structures showed superior mechanical properties among all the tested structures. The most interesting observation is that sheet-based Diamond TPMS structure showed the best mechanical performance with nearly independence of relative density. It was also observed that at decreased volume fractions the effect of geometry on the mechanical properties is more pronounced.

1. Introduction

Cellular metals are materials with voids deliberately integrated in their structure [1]. When voids are arranged periodically the material is referred to as architected cellular metals (or lattices). Architected cellular metals can have two-dimensional cell configuration like in the case of honeycombs or three-dimensional configuration (cubic symmetry) like in the case of strut-based lattice structures. Cellular metals offer unique functional characteristics including high stiffness to weight ratio, heat dissipation and heat transfer control, and enhanced mechanical energy absorption among others. Justifiably, they attract a great deal of interest in several engineering disciplines. For example, such metals are used as biomedical implants [2,3], scaffolds for tissue engineering [4], filters [5], electrodes [6], catalysts [7], heat exchangers [8–10], and lightweight structures [11–13].

The mechanical properties of cellular metals are a function of the relative density (defined as the density of the structure relative to the density of the base material), the solid constituent, and the unit cell architecture. When subjected to a macroscopic loading, the structure deforms by a combination of bending, twisting or stretching of the strut members [14]. In a stretching-dominated deformation mode, the stiffness/strength of cellular structures scales linearly as a function of the relative density and is higher than that of a bending-dominated deformation mode that scale quadratically with the relative density. On the other hand, the toughness of a bending-dominated deformation is larger than that in the case of stretching-dominated deformation mode [15].

When both the base material and the relative density are fixed, the mechanical properties of cellular structures depend highly on the architecture of the unit cell. Research efforts were invested to find the most optimum cell topology that can provide the best mechanical properties with the least amount of material invested in

* Corresponding author at: Institute Center for Energy, Mechanical and Materials Engineering Department, Masdar Institute of Science and Technology, Abu Dhabi, UAE.
E-mail address: rabualrub@masdar.ac.ae (R.K. Abu Al-Rub).

https://doi.org/10.1016/j.addma.2017.12.006
2214-8604/

order to maximize the stiffness/strength to weight ratio. As a result, several studies focused on the role of cell topology on enhancing the mechanical properties [16]. In tissue engineering specifically, extensive research has been done to identify the best topology that mimics the nature of bone and provides a viable environment to recuperate and regenerate damaged tissue cells [17,18]. For cellular metals with cubic symmetry, strut-based cell topologies such as the Octet-truss and the Kelvin have been vastly investigated [[25–40],19–24]. Recently, focus shifted towards cellular structures with mathematically defined architectures such as triply periodic minimal surface (TPMS) based topologies [25–40]. TPMS are complex 3D topologies that locally minimize surface area for a given boundary, and can be repeated periodically in three perpendicular directions [38,39,41–43]. These surfaces split the space into two or more interlocked domains, where each domain is a single connected and infinite component with no enfolded voids. Due to their novel topological features, TPMS have been employed in many engineering disciplines, for instance, in tissue engineering [37,44], and structural engineering [27,30,31,45,46], they proved to have optimal thermal and electrical conductivities [47], optimized fluid permeability [35], tunable acoustic attenuation and transmission [48], as well as visible photonic crystal properties [49]. TPMS-based structures can be created either by thickening the minimal surface to create sheet-based cellular structures or by solidifying the volumes enclosed by the minimal surfaces to create skeletal-based cellular structures [37].

Until recently, the fabrication of complex cell geometries was a big challenge, and the challenge increases when the desired size scale gets smaller. The recent advances in additive manufacturing (AM) helped mitigating these challenges. Additive manufacturing or commonly-known as 3D printing refers to the process of fabricating parts layer by layer, adding materials only where it is needed, reducing considerably the amount of wasted material and allowing for much more design freedom. For metals, powder bed fusion techniques such as selective laser sintering (SLS), selective laser melting (SLM), and selective electron beam melting (SEBM) are used. In these techniques, an energy source (laser or electron beam) is utilized to selectively melt or sinter layers of metal powder to form a 3D structure. Using these techniques, several cellular structures with complex architectures were investigated for their mechanical properties using a range of 3D printable materials including aluminum [45,50], titanium [51] and steel alloys [46,52]. For instance, SEBM was employed to fabricate strut-based cellular structures made of titanium alloys with mechanical properties

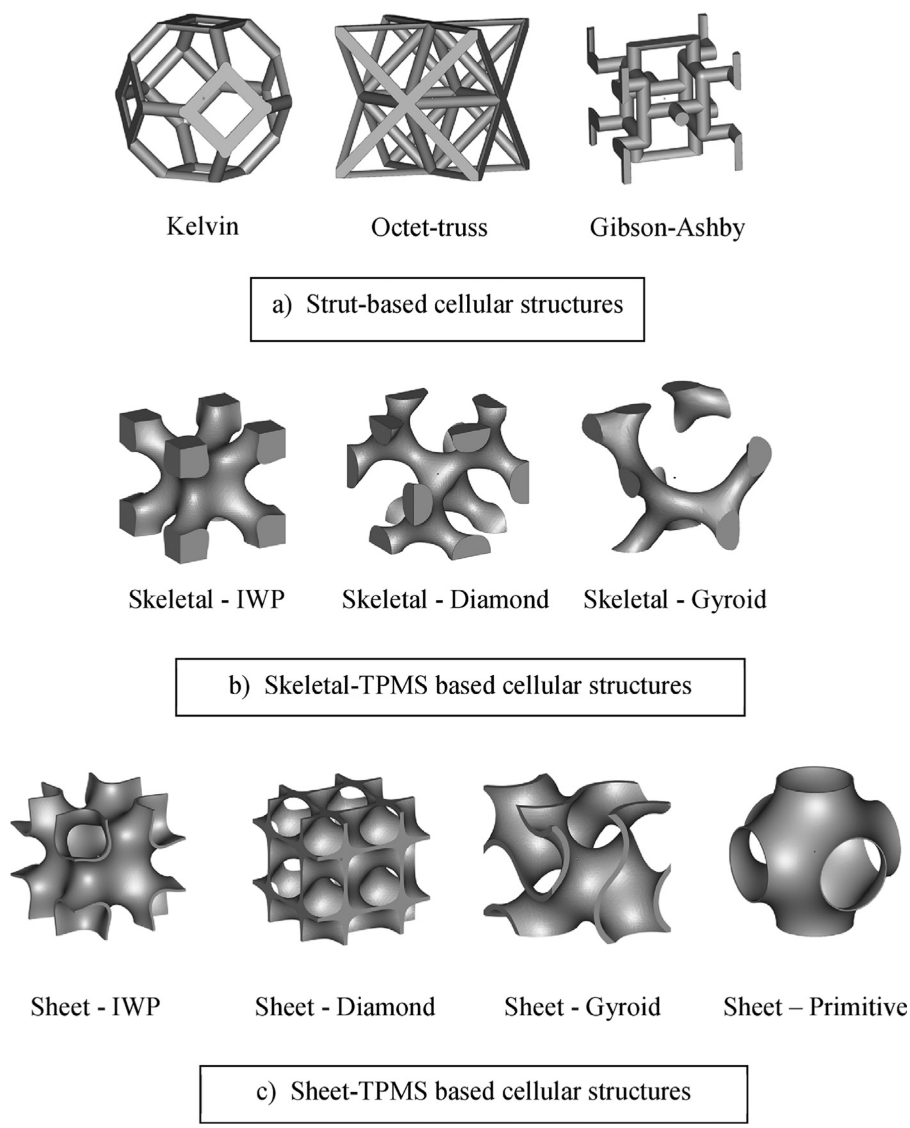

Fig. 1. Unit cell of the different cellular topologies. a) Strut-based cellular structures, b) Skeletal-TPMS based cellular structures and c) sheet-TPMS based cellular structures.