Optimized internal geometries for lightweighting and multifunctionality in additive manufacturing – an ideal processing target

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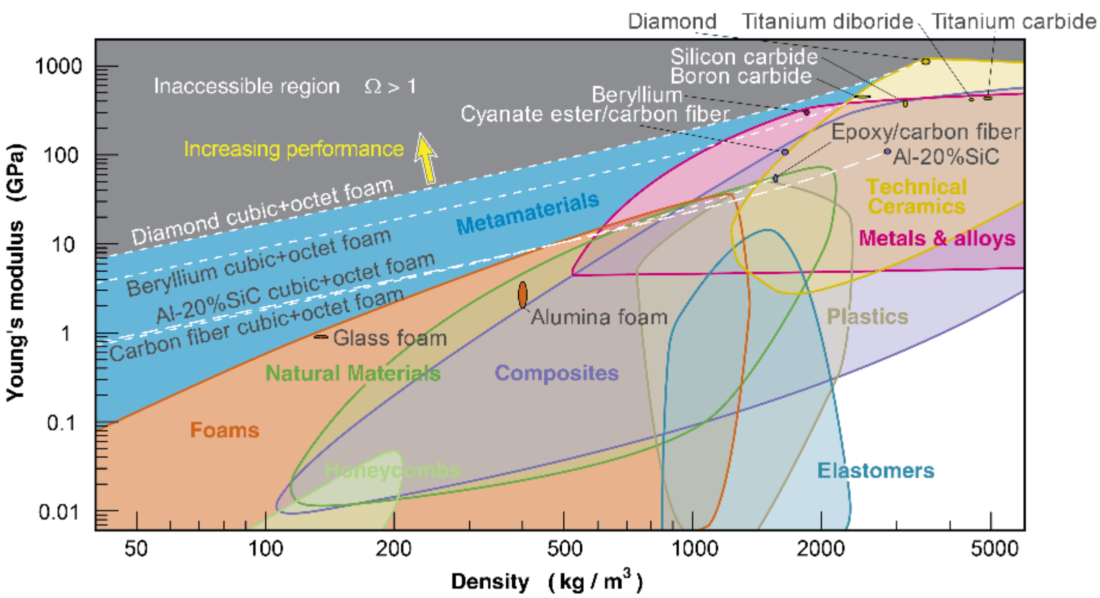

Figure 1 – Lightweight materials are critical technologies in a vast range of applications. There is an energy cost associated with every gram of material in any object that experiences even some dynamism. This is of primary and obvious importance in aerospace, personal protection, and transportation, where the majority of the energy budget, i.e., fuel, is used to accelerate and decelerate mass. When looking at the design space of lightweight materials—here plotted in terms of isotropic (directionally independent) and nearly isotropic elastic stiffness—the vast majority of property space is dominated by composites, where orders of magnitude improvement over more conventional materials are theoretically possible. Theoretical upper bounds [1] ($\Omega = 1$ in this plot) for two phase composites of solid and void, i.e., honeycomb and lattice materials, reveal a large region in the lightweight high-stiffness regime that is unoccupied by traditional, fully dense, solid materials. Only recently [2] has a design been identified that is capable of filling this space in its entirety, in the context of practical discussion [3], mathematical constructs withstanding.

ABSTRACT

We have identified an internal geometry that is the first and only known to be capable of achieving the theoretical upper bounds for lightweight stiffness and strain energy storage. Through unique symmetries and alignments of material, functionally graded designs can be achieved that maintain maximum or near maximum structural efficiency over a wide range in performances. This design uses a minimum amount of material to fill space when specific stiffness and strength are concerned. In the context of additive manufacturing, this results in a minimum amount of energy and build time to fabricate parts.

Keywords: lightweighting, additive manufacturing, cellular materials, metamaterials, structural materials

1 INTRODUCTION

One of the great opportunities in additive manufacturing is the ability to manufacture complex optimized internal geometries such as lattices and honeycombs for space filling applications. Structural design on the mesoscale—the intermediate scale between that sits between that of parts and loads, and the fine scale of microstructural features such as grain boundaries—enables some exciting opportunities to produce materials systems with extraordinary properties. The performance of engineering materials can be extended in dramatic fashion through the careful selection and fabrication of mesoscale designs [4]–[6]. Commonly this is seen in stochastic foams, including those made from polymers, but also metals and ceramics in more exotic cases. The properties of these

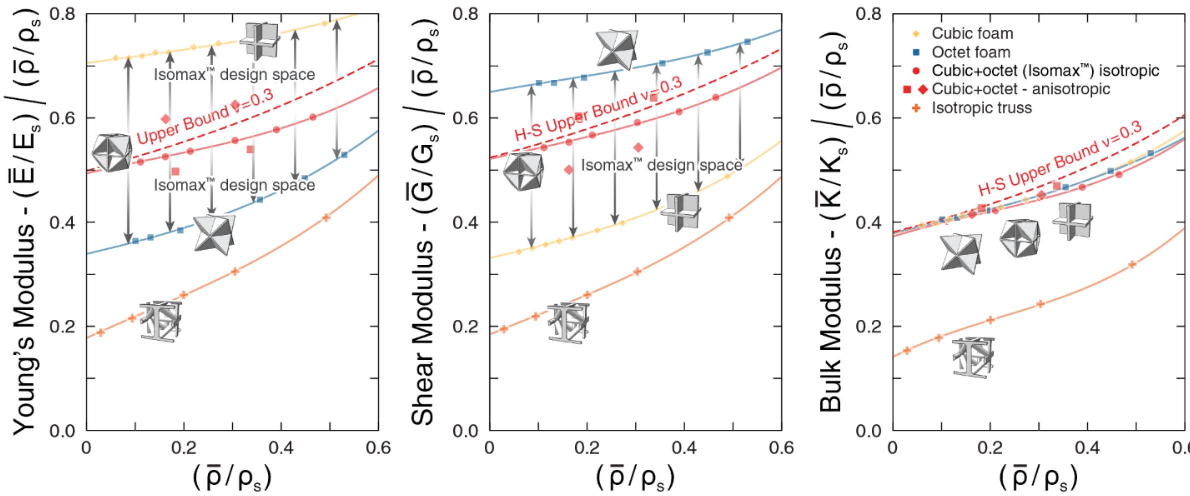

Figure 3 – The normalized moduli of maximally efficient material geometries. Closed cell materials outperform trusses by more than a factor of 2. A large design space exists, by varying the wall thicknesses of the subgeometries, for the Isomax™ material.

systems vary greatly from the fully dense constituent (Fig. 1), and can be tailored to a large degree through the sensible arrangement of cell edges and faces into various lattice and honeycomb designs [7].

Some obvious applications for these systems include sandwich panels for lightweighting and multifunctionality, energy-absorbing structures, buoyant materials, heat exchangers, implantable medical devices, and building materials, to name but a few [8]. Highly tailored and optimized materials will allow access to new design space and capabilities.

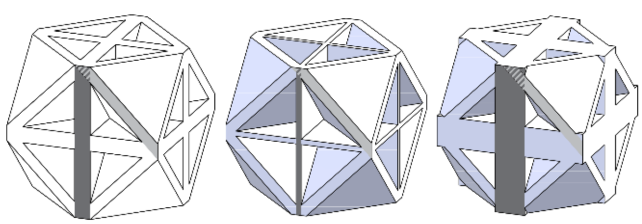

Figure 2 – Anisotropy can be tailored through the relative wall thickness of the cubic and octet subgeometries. The geometry of the left is achieved when the ratio of the cubic to octet wall thicknesses is, $t_c/t_o = \sqrt{3}$. However, isotropy by the Zener ratio is achieved when, $t_c/t_o = 8\sqrt{3}/9$ [2].

In the context of additive, an optimized design would use a minimum amount of material to achieve design requirements, minimize the energy required to complete a build, and minimize the build time. To this end, we have identified the first and only material geometry that achieves theoretical bounds for strain energy storage and linear elastic structural efficiency, maximizing the use of a given quantity of material for structural purposes.

This design, a combination of cubic and Octet foam, and known as Isomax™, has the advantageous attributes of being composed of sheets of material, providing a relatively simple geometry that can be formed form sheet stock, not just by additive processes. The design maintains essentially maximum structural efficiency over the entire range of relative densities that are practical for cellular materials, 0 to 40+% [2]. The Isomax Material Geometry™ is composed of two unique and highly anisotropic but maximally efficient subgeometries, whose relative contribution can be modified through the wall thicknesses to create functionally graded designs (Fig. 2), with locally varying stiffness, strength, anisotropy, conductivity, and other properties that relate to the material geometry.

Initial experiments of additively manufactured unit-cell test specimens composed of FDM ABS plastic agree well with numerical and analytical predictions for stiffness. Through the NSF Innovation-corps (I-corps) program [9], potential applications, ranging from aerospace to biomedical devices have been explored, and some of these efforts will be discussed, as well as some of the barriers to the adoption of additive and this type of technology.

2 MECHANICAL PROPERTIES & DESIGN SPACE

The theoretical upper limit in specific stiffness is achieved, in essence, over a wide of relative densities in one design [2]. A combination of a cubic foam and an Octet Foam, each of which have been shown to have maximum performance in terms of Young's modulus and shear modulus respectively, achieves the Hashin-Shtrikman (H-S) upper bounds in the low-density limit (Fig. 3). Isotropy is achieved in the low-density limit when the ratio of the cubic to octet wall thicknesses is, $t_c/t_o = 8\sqrt{3}/9$. Furthermore, variation of this term (Fig. 2) and/or one of t_c or t_o (Fig. 4) allows for the creation of functionally graded structures. Each of the two subgeometries both maintain very near maximal structural efficiency over a wide range of relative densities (Fig. 5).

The total stiffness performance can be calculated relative to a material that performs at the theoretical upper limit,

$$\Omega = \frac{\bar{E}+2\bar{G}(1-\bar{\nu})}{E_{HSU}+2G_{HSU}(1-\nu_{HSU})}. \tag{1}$$

The term, $\Omega = 1$, for an isotropic material that achieves the upper bound, but also limits the performance of anisotropic designs [2].

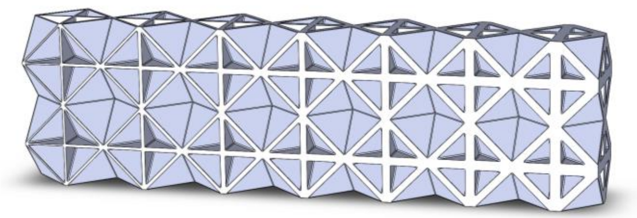

Figure 4 – Variation of the relative density produces graded structures. The self-similarity of the geometry over this range of morphologies and densities allows for efficient load transfer throughout the structure. Tailored and optimized cushioning for lightweight personal protection, for example, would have great utility. Note that the relative size of the overhang (horizontal faces) decreases left to right with relative density.

3 AN IDEAL ADDITIVE PROCESSING TARGET

Two of the primary challenges generic to the vast majority of current additive manufacturing processes are, 1) the production of overhangs with a large characteristic size, and 2) producing isotropic as-printed materials. Meeting these challenges will open the door to the manufacture of just about any shape of part. This does not speak to the reliability (strength), repeatability, nor uniformity of a process within the build chamber, which are points that must be addressed when producing additively manufactured (AM) parts.

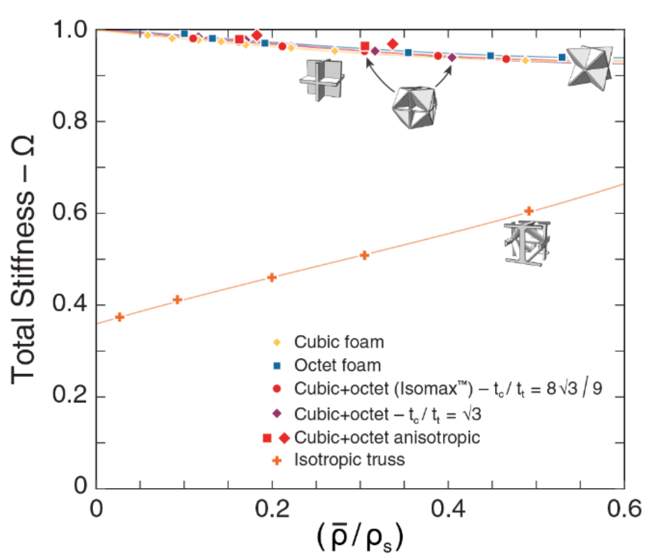

Figure 5 – Total stiffness (strain energy storage). Despite exhibiting a range of anisotropy, Isomax™ and its constituent subgeometries all have near, or maximal performance. The best isotropic lattice [10] is far less efficient.

The Isomax Material Geometry™ presents an ideal AM processing target in that it, a) is an ideal internal fill geometry, utilizing a minimum amount of material to fill space in the most robust way possible, b) producing the lower density and the highest efficiency designs requires larger overhangs (Fig. 4) with incremental payoffs in lightweight performance as technology advances, c) its isotropic nature can be exploited to create isotropic test specimens that can be used to assess the isotropy and robustness of a process. By using a single specimen type, printed in a single build orientation, loads can be applied along different but theoretically equivalent directions, e.g., a specimen can be compressed perpendicular or parallel to the build direction. The self-similarity of the design (Fig. 4) would allow for process resolution to be tested, along with any variations in as-printed properties associated with local part density (thermal effects, layer fusion) to be assessed.

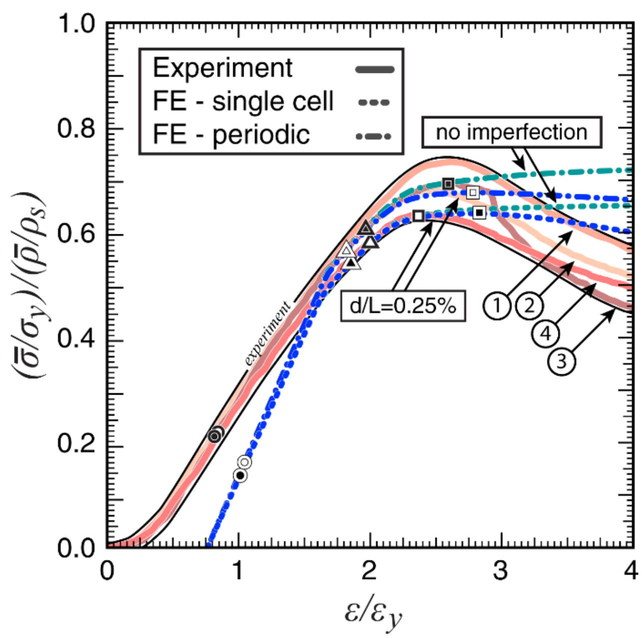

Figure 6 – No evidence of anisotropy is readily evident in the engineering stress vs strain response of 4 ABS plastic additively manufactured specimens [12]. FE models agree well for peak strength, and indicate little in the way of edge effects (single cell vs infinitely periodic).

The modeling of geometrically complex systems requires substantial computing resources. Global optimization routines [11] often do not find global optimum. Due to its flexibility in properties, its maximal performance over a wide range of relative densities (Fig's. 3 & 4), self-similarity and the resulting efficient load transfer properties, as well as the aforementioned relevance to AM, the Isomax Material Geometry™ appears to be an ideal processing target for the development of AM processes and the realization of truly extremal lightweight performance.

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4 TESSELATION AND MAPPING TO FORM COMPLEX STRUCTURES

To form the Isomax™ design into complex shapes, there are two obvious approaches. One can design with cuboid type cells where the resulting structure is truncated to conform to an arbitrary envelope. This may introduce some edge effects and/or non-uniformity in properties, but comparison of experiments and FE models suggest these effects are small (Fig. 6) [12]. The other option is to using tessellation and mapping to skew the cuboid basal geometry (see Fig. 7 for example). The analytical approach used to calculate the small strain behavior [2] can be adapted and incorporated into a finite element homogenization scheme as one possibility of designing and analyzing such geometrically complex structures.

5 DISCUSSION AND CONCLUSIONS

For the many aforementioned reasons, we believe the Isomax Material Geometry™ to be an ideal internal geometry for lightweighting applications, in addition to being an ideal processing target for the development of AM processes. Applications in aerospace have begun to be explored through the NSF I-corps program, with some interesting results.

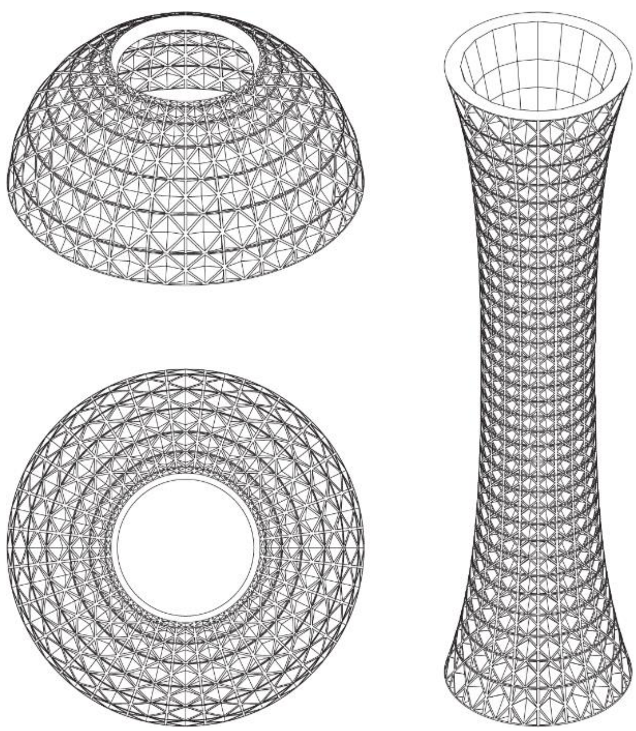

Figure 7 – Through tessellation and mapping, highly optimized structures can be created with little computational effort when compared with global optimization type schemes.

The current advantages that AM brings to the aerospace field is not directly related to performance, such that high-performance internal geometries, as we have described, are not in widespread demand. In general, current generation vehicles, e.g., the Lockheed Martin F-35, already meet performance requirements, so that cost drivers are what motivates the adoption of new materials and technology. AM technologies are attractive in their ability to reduce part count, and therefore cost. It appears as though the commercial attractiveness of these high-performance mesoscale material systems will depend heavily on the reliability of the AM processes themselves, including the ability to design with and predict the capabilities of AM parts. The will always be a driving force for the development of lighter materials and parts, but the economics of producing such systems is the limiting factor. We believe we have presented a strong case for the co-development of Isomax along with complimentary AM processes. The development and adoption of new generation of ultra-lightweight materials would have a dramatic impact on global energy needs and facilitate new and exciting capabilities.

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