Beautiful and Functional: A Review of Biomimetic Design in Additive Manufacturing

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This review article summarizes the current state-of-the-art for *biomimicry in additive manufacturing*. Biomimicry is the practice of learning from and emulating nature - which can be increasingly realized in engineering applications due to progress in additive manufacturing (AM). AM has grown tremendously in recent years, with improvements in technology and resulting material properties sometimes exceeding equivalent parts produced by traditional production processes. This has led to the industrial use of AM parts even in highly critical applications, most notably in aerospace, automotive and medical applications. The ability to create parts with complex geometries is one of the most important advantages of this technology, allowing the production of complex functional objects from various materials including plastics and metals that cannot be easily produced by any other means. Utilizing the full complexity allowed by AM is the key to unlocking the huge potential of this technology for real world applications – and biomimicry might be pivotal in this regard. Biomimicry may take different forms in AM, including customization of parts for individuals (e.g. medical prosthesis, implants or custom sports equipment), or optimization for specific properties such as stiffness and light-weighting (e.g. lightweight parts in aerospace or automotive applications). The optimization process often uses an iterative simulation-driven process analogous to biological evolution – with an improvement in every iteration. Other forms of biomimicry in AM include the incorporation of real biological inputs into designs (i.e. emulating nature for its unique properties); the use of cellular or lattice structures – for various applications and customized to the application; incorporating multi-functionality into designs; the consolidation of numerous parts into one and the reduction of waste, amongst others. Numerous biomimetic design approaches may be used – broadly categorized into customized/freeform, simulation-driven and lattice designs. All these approaches may be used in combination with one another, and in all cases with or without direct input from nature. The aim of this review is to unravel the different forms of biomimetic engineering that are now possible – focusing mainly on functional mechanical engineering for end-use parts, i.e. not for prototyping. The current limits of each design approach are discussed and the most exciting future opportunities for biomimetic AM applications are highlighted.

Keywords: biomimicry, biomimetics, bio-inspiration, additive manufacturing, powder bed fusion, freeform design, topology optimization, generative design, simulation-driven design, cellular, lattice

Preprint submitted to *Additive Manufacturing*, March 2019
Latest update: 28 March 2019 – Accepted for publication, in press
https://doi.org/10.1016/j.addma.2019.03.033

1. Introduction

The beauty found in nature is often inspirational - and this inspiration has found its way into functional mechanical engineering through the latest developments in additive manufacturing (AM). This beauty, especially when referring to natural structures, is often not only visually appealing due to rounded curves and organic shapes [1], but also beautiful in the sense of its engineering functionality or even multi-functionality. Other forms of engineering beauty are structural hierarchy, order or lack of order, and combinations with other structures. For more than 3.8 billion years [2], nature has optimized complex structures to fulfil specific function(s) within the constraints imposed by either the organism itself, or by the external environment. Learning from these biological structures may advance our use of efficient structures in engineering applications and may even help to provide new solutions to engineering problems, in a sustainable way.

A general definition of *Biomimicry* is "innovation inspired by nature," or alternatively, "the conscious emulation of nature's genius" [3]. *Biomimicry* in engineering involves the study of biological systems – specifically with the aim to use information learned (from nature) in solving engineering problems, or for use in engineering applications. In nature, structural features from nano to micro to macro scale defines an object's properties and functionalities and *vice versa*. Modern engineering design has the possibility to change the structural features and properties of the objects while maintaining functionality or to apply simulation to find a design for specific required properties. In an ideal case, AM is able to translate innovative biomimetic design into physical objects with the desired properties and functionality. Currently, nearly 2 million living species have been described although at least 10 million are estimated to exist [4]. The diversity in natural and living species constitutes a huge potential source of inspiration and information for engineers and designers [5]. Much of this potential has particularly realistic prospects when using AM, with its freedom of design and complex production capabilities. The capability to emulate the complex structures and hence the properties of biological materials is the aim of biomimicry.

In AM (and in engineering terms in general) the term "biomimicry" is often used in various contexts. Here it is important to clarify the different forms and approaches of biomimicry that are relevant to this field and to distinguish them from one another. This is critical to ensure correct reporting and interpretation, to prevent hype and misleading statements. For example, failure of a specific design that is claimed to be biomimetic but uses no input from nature, might undermine the credibility of biomimicry. The broad categories of biomimicry in AM are briefly described below and each category is further detailed and discussed in separate sections in this review paper.

Often structures with curves and rounded edges – in any way resembling something in nature (more than a traditional part with square edges) – are referred to as "biomimetic", "bionic" or "organic". This is not incorrect but it must be kept in mind that no biological input is present, and as such is not truly biomimetic or bio-inspired. Additionally, when a structure is designed for a biological application it may be termed biomimetic or bionic simply due to its intended biological role (e.g. a prosthetic device). Topology optimization, generative design and simulation-driven design – tools used to create optimized designs using (mechanical) simulation – often create unconventional and complex shapes and forms. These organic/bionic parts are often referred to as biomimetic or bio-inspired primarily due to their "strange" shapes, but it also happens that these shapes might resemble and consequently mimic natural structures (unexpectedly). The simulation-driven design process is in reality also biomimetic or bio-inspired in the sense that it is iterative and therefore mimics aspects of natural evolutionary strategies in a short timeframe. In the area of cellular or lattice structure design, some engineers refer to all porous engineered structures as biomimetic simply due to their resemblance to natural porous materials (e.g. honeycombs or trabecular bone), or their similarity to the biological equivalent. However, cellular and lattice designs have unlimited

https://doi.org/10.1016/j.addma.2019.03.033

design permutations and can therefore be tailored to the application. Currently, the most important application for these porous engineered structures is in dental and bone implants. The latter is a biomimetic application in the sense that the structure should emulate bone for best results, in terms of mechanical properties and permeability [6,7]. Finally, biomimetic lattice structures may also specifically refer to stochastic (random) design strategies which create structures with a random distribution of strut thicknesses and lengths – the randomness emulates nature [8,9]. Clearly, there are many different forms of biomimicry in AM, and the use of each will be further discussed in this paper, with emphasis on what is currently possible.

A biomimetic and bio-inspired approach to materials and design has attracted great interest from scientists in diverse areas: biophysics and biomaterials, sensors and chemistry, materials science and engineering, to name a few. Biomimetic research requires a multi-disciplinary approach and is a promising scientific field for coming years [10], which is demonstrated in Figure 1 by the consistent growth in the number of publications in this area in recent years. On the other hand, the exponential development of AM is also confirmed by the growth of publications on this topic: about four thousand review and research papers, encyclopedia articles and book chapters were published and presented in Sciencedirect in 2018. From 2016, with the progress in AM technology and wider understanding of the fact that complex designs can be realized in real AM products, biomimetic approaches began to be a subject of research in more than 150 papers per year. Interest in lattice structures produced by AM also increased year by year.

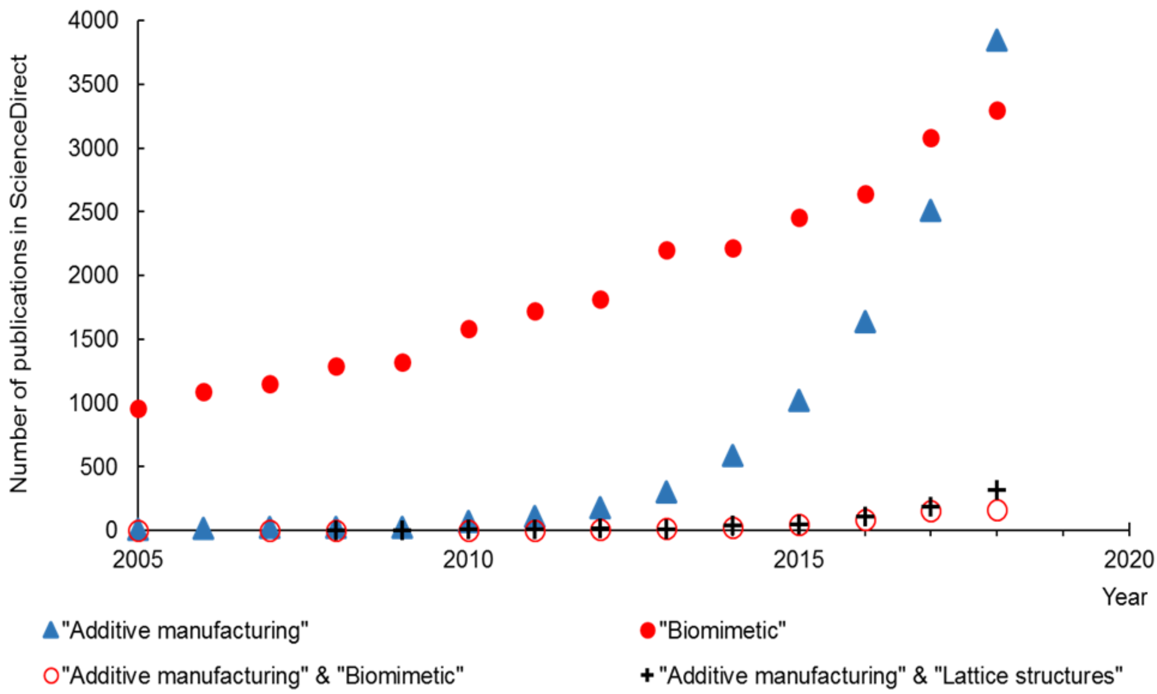

Figure 1: Number of publications for the period 2005-2018 in biomimicry and AM (Source: Sciencedirect.com)

In recent years AM has grown from a prototyping technology to a reliable direct production technique [11]. In particular, metal AM has developed tremendously, up to the point where it is now possible to produce functional metal parts for critical applications in medical and aerospace industries [12,13]. Powder bed fusion (PBF) is the term used to specifically describe metal AM using a

Preprint submitted to *Additive Manufacturing*, March 2019
Latest update: 28 March 2019 – Accepted for publication, in press
https://doi.org/10.1016/j.addma.2019.03.033

laser (LPBF) or electron beam (EB-PBF) to melt tracks and layers for the manufacture of detailed and complex shaped parts. The track-by-track and layer-by-layer PBF process allows the manufacturing of parts with intricate, complex designs. Part complexity allows designs to be optimized for specific applications such as light-weighting in aerospace parts or improving bone growth and implant success in bone implants. It has been demonstrated that the mechanical performance of PBF parts can be superior to traditionally manufactured equivalents [14] and lots of work has been done in particular in Ti6Al4V as shown in [15]. Laser powder bed fusion is limited to intricate parts typically smaller than 300 mm (although the maximum size of the working area reaches 800 x 400 x 500 mm^3) – for larger metal parts it is possible to use wire and arc AM with a reduction in detail possible. In addition to metals, various other materials can be reliably processed using AM including polymers, ceramics and various types of composites, as is discussed in more detail in [16]. Metals are highly likely to have practical uses in biomimetic structural applications in military, aerospace and automotive industries due to the light-weight and strong parts that can be produced, and hence much effort has been aimed in this direction. However, many biological systems are based on combinations of stiff and softer materials, and often have mechanical properties more like polymers and composite materials [17]. Therefore, many applications also exist for nature-inspired designs in materials other than metals.

Many design principles may be used to generate complex and biomimetic geometries and one of the aims of this review is to categorize these different approaches, and discuss their applications and practical uses as reported in the literature. Many of the examples presented in this review focus specifically on metal AM (both laser and electron beam powder bed fusion), due to the relevance for high-value functional end-use parts, but the same principles apply to all other additively manufactured materials. For products designed by biomimicry, it has been proposed that two broad approaches exist: the “biology-to-design approach” (solution driven) and the “design-to-biology approach” (problem driven) as outlined in [3,18,19]. In the first case, the designer/engineer is inspired by a biological concept or model and applies this to a new design idea. The second approach is when a specific problem at hand is solved through searching for a solution to this problem in nature and applying the concepts after a search for this particular problem. In addition to these approaches, three major ways of obtaining a designed biomimetic model in practice exist: customized/freeform design, simulation-driven design and lattice design. These are shown in Figure 2 and may be used in combination with one another but are nevertheless discussed separately in this review. For example, lattices may be incorporated in a freeform design process or in a simulation-design process. All these approaches may also be used with or without direct input from nature, with varying levels of biological input or bio-inspiration possible.

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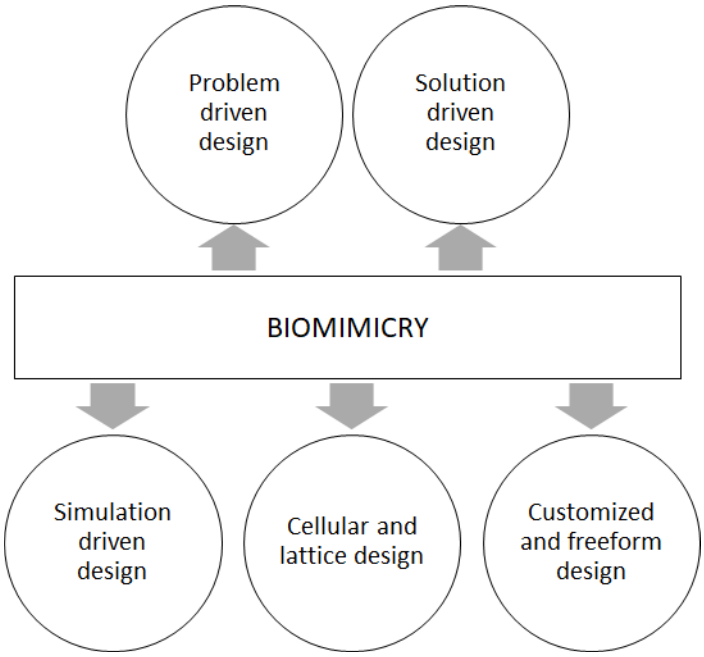


Figure 2: Biomimetic design approaches for AM

Customized and freeform design involves manipulation with curved surfaces and is typically used to create custom and unique designs fit for a particular application while maintaining functionality. For instance, customized implants aimed at directly replicating the bone shape for replacement, tree-like support structures, nervous-system-inspired shade or hierarchical networks where nodes constantly branch and merge [20,21]. This process is the simplest of the biomimetic design methods, particularly useful for customization such as in prosthetics or implants, and is also used in artistic design. With reference to prosthetics and implants, the design requirement is taken from a biological shape, hence the biomimetic description. In addition, freeform design results in organic shapes which can often resemble natural structures.

Simulation-driven design is a very promising approach which has emerged in recent years and is especially useful for light-weight design for engineering applications. This involves structural optimization (also termed topology optimization or generative design) and uses an iterative process of simulation and material removal to optimize the required material distribution or material stiffness [22–26] for a given set of expected load cases. This process of stepwise optimization is similar to most evolutionary processes in nature, and removal of material in areas of low stress is a similar optimization strategy as is used in natural systems, hence the motivation to categorize this process as biomimetic. In addition, the resulting designs have interesting curves and spider-web connections, strongly resembling natural structures. The field of topology optimization in AM was reviewed recently in [23], where the current limits of the practical use of this technique was discussed in detail, especially with regards to overhang angle, support removal, residual stress, build quality – including challenges in software tools that need to be solved for its more widespread adoption. Some other recent examples are shown in [22,27,28].

The use of additively-manufactured lattice or cellular structures is a highly relevant approach which is often combined with the former methods, i.e. the incorporation of lattices or cellular designs into optimized organic or topology optimized designs [29]. Natural systems often use cellular structures and these are widely used in bio-inspiration for the use of lattices in engineering parts, hence the categorization as biomimetic. Lattices have obvious light-weighting advantages, high specific stiffness, fracture toughness, crack growth arresting, amongst other desirable and tailorable properties [30]. One major application of cellular structures is their use in bone implants, to improve osseointegration [8].

The design theory for present-day AM in general was reviewed and limitations discussed in [31]. On the topic of biomimetic 3D printing, the review [32] gives a detailed overview of the use of biological inputs into the design process, discusses biological study systems used in biomimicry and focusses on applications of polymer and multi-material 3D printing, but does not discuss metal AM or simulation-driven design.

Biomimetic approaches for AM include the design of innovative materials and systems. In addition to simulation-driven design of single-material parts, fracture-resistant composite materials could be designed using simulation-driven design and validated by multi-material 3D printing as demonstrated in [33,34]. Multi-material biomimetic design for medical purposes has been demonstrated in [35].

All the above-mentioned approaches are referred to as biomimetic, but do not necessarily employ direct inputs from nature, therefore a clear distinction should be made when a design uses direct input from nature. In this case we suggest the term “true biomimicry”, while retaining the broad “biomimicry” description for all above-mentioned design approaches. Not all freeform designs, lattice designs or topology optimized designs include biological input, but they are still referred to as biomimetic in a broader sense.

True biological input in the AM design process is still rare in engineering due to the lack of biologists involved in engineering design in general [36]. Nevertheless, biological materials science is a mature field which focuses on studying biological systems to understand their properties and potentially employ these designs in engineering systems [37–39]. Biological materials often possess superior mechanical properties due to unique combinations of hard and soft materials [40] and gradients between them [41]. Biologically inspired design principles have been categorized recently into fibrous, helical, gradient, layered, tubular, cellular, suture and overlapping structures [42]. Besides broad design categories or guidelines, the use of X-ray tomography to study intricate details of individual biological structures in 3D for biomimetic applications is also a promising strategy to learn from nature [43]. Incorporating biological inputs into engineering design is a topic of continued effort and includes the development of biomimicry design databases [44,45]. Biomimetic design has also been named “eco-design”, as it has been suggested that these approaches may lead to the use of the minimum required materials, which is most environmentally sustainable [46].

Despite the access to complexity and freedom of design, which is often cited for AM, all the biomimetic approaches discussed here have practical manufacturability limits in the context of present-day AM systems. A recent review paper covers the use of AM to produce bio-inspired structures (also mainly using polymers) with the main aim to learn about and optimize the biological structures themselves [47]. In the area of biomimetic cellular design, various recent reviews are useful and relevant to bone implant applications in particular [48–50], and are more generally discussed for various applications in [51]. It is therefore the aim of this present review paper to fill the gaps between these areas and address all the above biomimetic approaches in one cohesive framework. Most examples used in this paper are focused on metal AM due to its ability to produce functional end-use parts, but the principles are broadly applicable to all additively manufactured materials. While most of the discussion and examples are using laser powder bed fusion, other AM technologies are equally applicable and the design “rules” and challenges vary slightly with each technology. For example, binder jetting has shown some promise for realization of complex designs cost effectively, but the obtained material properties require investigation. The fields of biomimicry and AM hold a unique synergy and inter-dependence on one another. The full benefit of both will become apparent when the techniques discussed in this paper are employed more widely, and in new applications.

2. True biomimicry

True biomimicry of natural form (as opposed to biomimicry of processes or ecosystems), involves the purposeful emulation of structure-function relationships in biological entities to solve engineering challenges, or to apply these to advanced engineering systems [3,52,53]. A review on biomimicry and bio-inspiration in the field of AM and 3D printing is provided in [32] and focuses on explaining different potential biological study organisms and associated applications with specific biological input, mostly by polymer AM. In addition, the review highlights the potential for different forms of AM technologies to mimic nature.

As mentioned above, the goal of biomimetic research is to learn generic design rules from natural systems to assist the development of optimized biomimetic materials which can be used widely in engineering systems. It is important to note that biological structures are by no means optimized to fulfil a specific function, but instead are subjected to constraints (i.e., mechanical, structural) and trade-offs among functionalities. To illustrate, osteoderms – thin plates of dermal bone that form protective natural body armour in various animal species – not only play a defensive role, but might also be involved in physiological processes such as thermoregulation [54]. The structural changes required for a physiological capacity might decrease the strength of osteoderms, rendering the structure less optimally adapted for protection than what would be expected [54]. When using a purely biomimetic approach, it is possible to address this issue by either incorporating the multi-functionality of the structure or to select natural structures in which the constraints and/or trade-offs are minimal. Alternatively, a bio-inspiration approach can be employed to alter specific properties of the natural structure resulting in an optimal design. An example of this is presented in recent studies on the osteoderms of the glyptodont – an extinct mammal with a thick carapace comprised of interlocking osteoderms that presumably evolved to withstand high-impact tail-club blows during fights [55,56]. Glyptodon osteoderms consists of a lattice core sandwiched between two compact layers that form a shell [55]. By printing and testing 3D models with varying lattice and shell parameters, the optimized shell thickness compared to lattice density and lattice strut thickness was revealed [55]. Similar procedures have been used to reverse-engineer a natural structure for application as a gripping device – the Aristotle's lantern structure as described in [57].

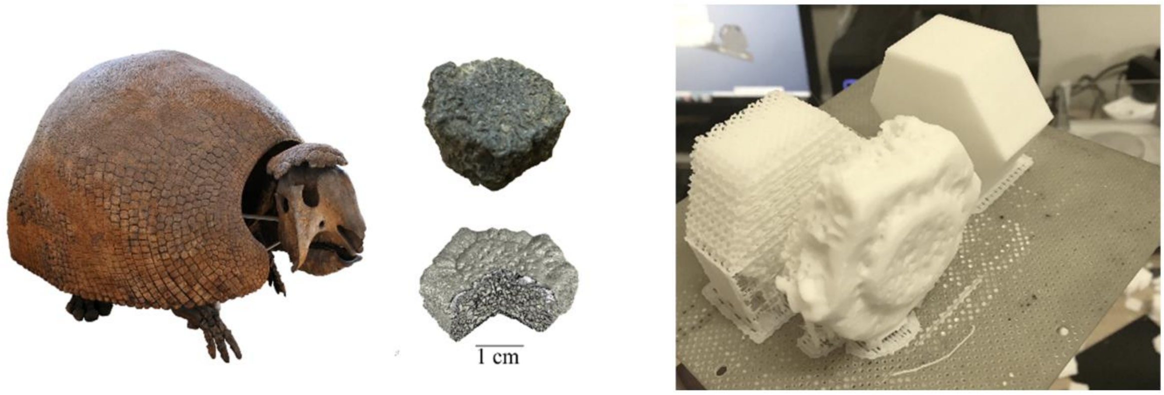
The mechanical properties of natural materials, particularly the superior fracture toughness, make biological structures highly suitable for biomimetic studies [38,58,59]. Nevertheless, a major advantage of AM is that a structure of interest can be further optimized by using materials that do not occur naturally in biological systems. In the case of glyptodont osteoderms, the use of biomimetic reverse-engineered metal (titanium alloy) models show remarkable strength and energy absorption capacity [56]. Besides material properties, the combination of hard and soft materials has been studied for improved fracture toughness properties using simulation-driven design tools [33,34,60]. In a recent study, pangolin scales were used as inspiration for bendable protective material for aerospace applications – different combinations of hard plates and soft connecting material were 3D printed and mechanically tested [61]. Lastly, the microarchitecture of biological structures, which can be categorized as one of eight forms: fibrous, helical, gradient, layered, tubular, cellular, suture and overlapping [42], plays an important role in determining the mechanical properties of biological materials. These structural organizations can be replicated by AM to study and optimize the arrangement of biological materials as discussed in [47]. Of particular importance to biomimetic engineering applications is the combination of these structures: the gradients between structures [41] and the multiscale hierarchical repetition of a structure [62]. Suitable combinations can provide superior properties compared to the structures alone and these are difficult to predict. Hierarchical structures such as functional graded materials, structures and surfaces can be produced directly by AM [63,64] or in combination with other methods. For example, LPBF and femtosecond laser surface modification makes it possible to produce complex hierarchical structures for

Preprint submitted to *Additive Manufacturing*, March 2019
Latest update: 28 March 2019 – Accepted for publication, in press
https://doi.org/10.1016/j.addma.2019.03.033

wettability applications [65]. Stereolithography and LPBF was applied for manufacturing of a multi-material arm orthosis; this approach can be used for manufacturing implants where the strength varies throughout the implant [35]. In general, AM of in-situ LPBF sintered composite objects also is a form of biomimicry since biological tissues are composite materials with stiff reinforcing elements and binding medium [66].

A pivotal tool to characterize structures for biomimicry or bio-inspiration is X-ray micro-computed tomography (micro-CT), as reviewed in [43]. MicroCT is ideally suited to obtain detailed microstructural information of natural structures in 3D [43], which can be used to (1) directly replicate natural structures (i.e., 3D printing nature), (2) measure 3D design values and implement these in engineering structures as bio-inspiration (i.e., reverse-engineering nature), or (3) in a broader sense to create a design principle without using any measurements (i.e., generic bio-inspiration). These three are shown in Figure 3, using the examples of (a) a direct replication of a structure printed on an entry-level FDM printer, (b) a reverse-engineered design based on measurements taken from a natural structure and (c) a generic bio-inspiration example in which honeycomb structures are used as light-weight design. The main aim of direct replication is to investigate the structure of interest (here: the impact protective capability). For reverse-engineering, the goal is similar to that of direct replication, but the techniques make the structure more practical for direct engineering applications. The generic bio-inspiration involves using design “rules” or guidelines from nature, which might be more beneficial when limits (e.g., manufacturing, functional) are imposed on the structure.

(a)



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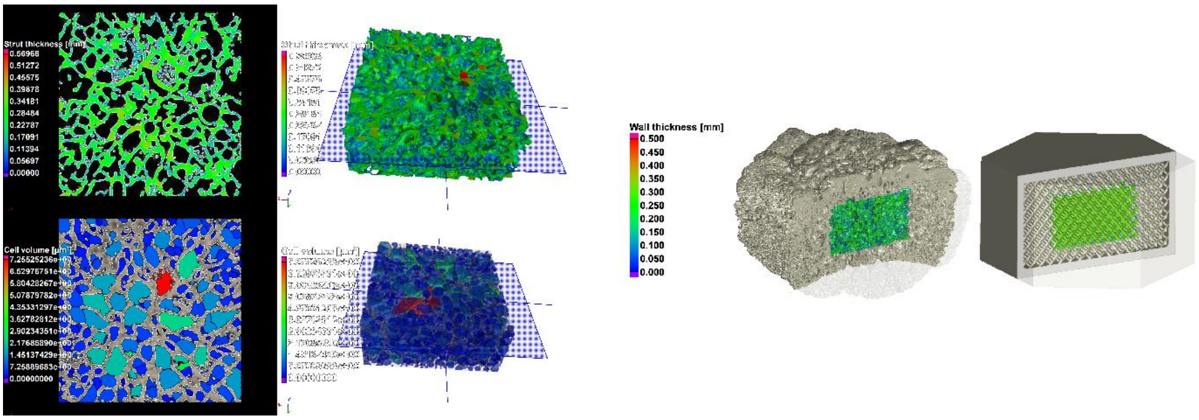

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(c)

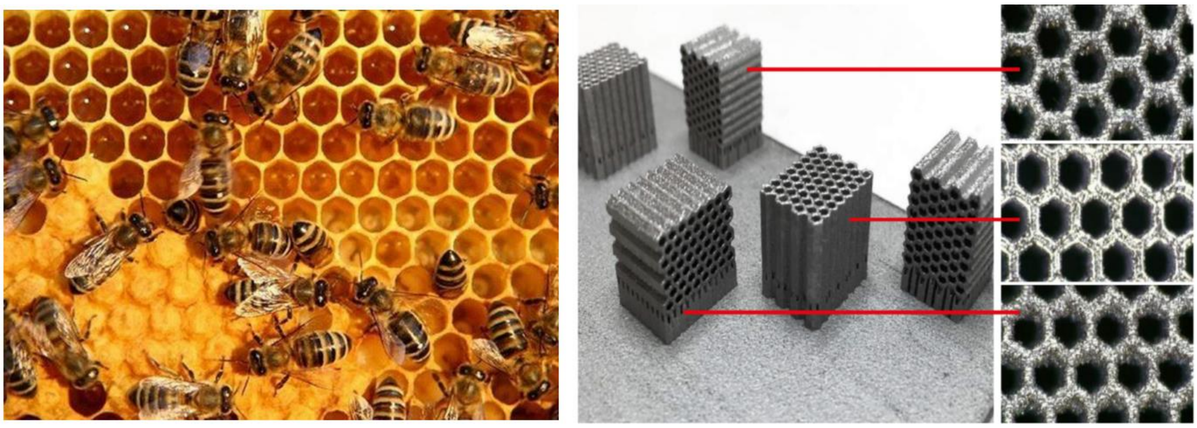

Figure 3: Three approaches – (a) direct replication [55] ; (b) reverse engineering [55] ; (c) bio-inspiration [51]

One biological structure that is of particular interest to biomimetic studies, and which has been studied extensively using microCT, is the lightweight structure of bird feathers and bones [67]. Here, bio-inspiration and design rules might be applied in engineering designs for aerospace applications. In recent work using topology optimization techniques, an optimized light-weight structure for an airplane wing was demonstrated through simulation and optimization, with the obtained structure having a strong resemblance to the structure of bird wing bones, i.e., a solid shell and connecting rods at angles inside the hollow structure [68]. While the optimality of bone design had been well described analytically [69], this was the first example of large-scale computational structure design: the rapid increase in computing power over the last years now allows for obtaining detailed structures from simulation-driven design tools, which for the first time nears the complexity of natural systems.

In conclusion, the complexity that AM allows makes it possible to manufacture true biomimetic structures, yet, knowledge of the biological structure is necessary. The greatest potential lies in taking “design rules” or guidelines from natural systems known for their excellent properties of interest, and use these in engineering parts.

3. Customized and freeform design

Traditional design for engineering involves individual part design in computer-aided design (CAD) tools, with engineering expertise and intuition required to understand the limits of traditional subtractive manufacturing. This most often results in traditional designs with right angles and flat surfaces – due to the simplicity for subtractive manufacturing of such designs. Over the last few years, advanced manufacturing techniques (e.g. AM, many-axes machining, advanced casting techniques, etc.) have become available and viable – which allows the design engineer more freedom to create parts with more complex designs.

These new design capabilities allow organic shapes and freeform designs, which are often also termed biomimetic due to their organic shapes resembling natural structures (see e.g. a lantern in Figure 4a) and sometimes, in the case of medical devices in particular, the forms are shaped to fit natural materials such as bone implants (see facial implant in Figure 4b). Natural structures tend to comprise of curves and organic shapes as they represent a balance between minimal energy expenditure and material used on the one hand, and maximal return of work on the other hand, all

https://doi.org/10.1016/j.addma.2019.03.033

within the organism's developmental limits [70]. Freeform and custom designs may be termed biomimetic as they resemble natural structures in these aspects, but without the constraints imposed by the organism itself.

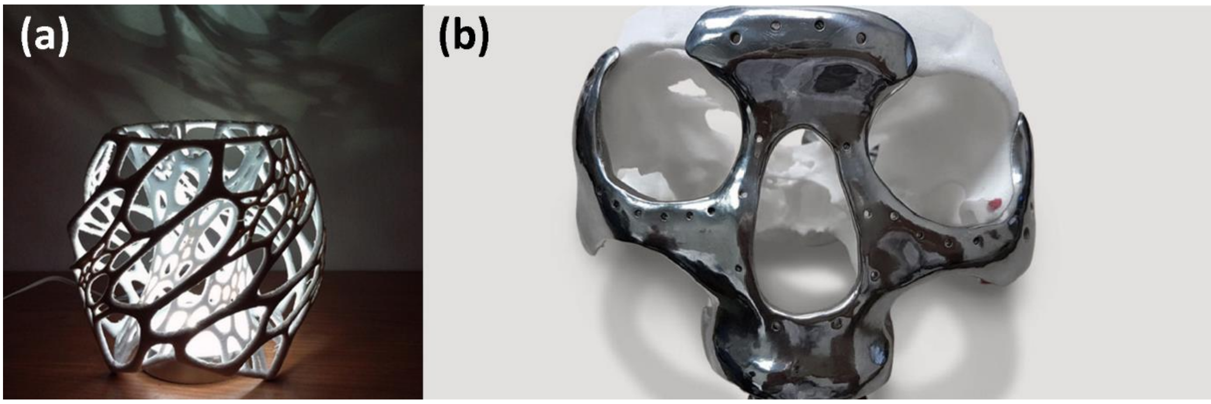

Figure 4: (a) Freeform organic design of a lantern [71] and (b) customized patient-specific facial implant. This implant was designed and manufactured in titanium alloy Ti6Al4V on an EOSINT M280 at the Centre for Rapid Prototyping and Manufacturing located at the Central University of Technology, South Africa. The Carl and Emily Fuchs Foundation funded this case study as this was a state patient without medical insurance.

Despite this freedom of design, traditional engineering thinking is often limited to experience of using right angles and flat surfaces. In order to optimally use this new design freedom, additional tools are needed. The most important contributing tools for freeform design are discussed here. One of these is the shaping of curved and organic surfaces by the use of T-splines and more recently polygonal non-uniform rational B-spline (polyNURBS). These tools allow organic designs with curved surfaces that often resemble natural structures. These are also critical tools in final steps of topology optimization and even true biomimetic reverse engineering structures, ultimately allowing for watertight models with curved geometries. Not only do these tools make custom curved shapes possible in a relevant workspace (the CAD environment), but they are also effectively translated into geometries suitable for simulation and/or AM.

In terms of custom design especially for implants – patient-specific implants are a special category and require a particular workflow involving the processing of medical image data, the use of CAD tools and design for AM knowledge to yield a good resulting implant as discussed in [72]. An example is shown in Figure 4(b) where a patient-specific facial implant was produced in Ti6Al4V.

Another important development with regards to design simulation, which has emerged in recent years, is computer-aided engineering (CAE). Increases in computing power, the availability of cloud computing and the wider availability of CAE tools (and improvements of these) all led to the sharp increase in advanced and complex design capability. One of the first examples was the "Design Insight Plot" from Solidworks [73], which demonstrates the main load paths in a designed part, as calculated from one or more applied loads by finite element modelling (FEM). This information was only visual, with the aim to assist in further refinement or modification of the design manually. This was a forerunner of topology optimization tools which will be discussed in more detail in the next section.

As mentioned above, AM releases much of the traditional limits of subtractive manufacturing allowing much wider allowed manufacturing complexity. This is already broadly acknowledged, and new design rules for reliable manufacturing in all forms of AM are emerging and in many cases are

Preprint submitted to *Additive Manufacturing*, March 2019
Latest update: 28 March 2019 – Accepted for publication, in press
https://doi.org/10.1016/j.addma.2019.03.033

already mature and well-defined. The design for AM (DfAM) rules and practical issues are discussed in detail in [20,31] and more recently in the context of topology optimization (discussed in more detail in the next section) in [23].

One major advantage of these new design tools for creating manually organic and curved surfaces and shapes is the ability to create artistic features – the resemblance to biological/natural and organic structures brings a new dimension to artistic designs for end-use products. The use of 3D printing in arts, fashion and jewelry is growing as is shown in [74] and artistic design is easily achieved by AM, without significantly adding to the cost of the product (e.g. it is possible to add Voronoi tessellation pattern to an existing shape without adding to the cost of the product – see e.g. [75]).

Freeform design tools can be used to shape custom-fit sportswear or footwear, with the first fully-AM footwear being produced by Adidas – Futurecraft [76]. The design of this shoe is entirely latticed – giving a futuristic and biomimetic visual appeal. A similar recent development is the production of latticed "foam" pads customized to the individual player for NFL players' helmets – the Riddell football helmet liners [77]. These are two examples of mass production and mass customization [78] by AM. Aspects of importance besides personal/custom design for fit, is the incorporation of logos or names, and the ability for the customer to take part in the design process – giving them some options making their product unique.

4. Simulation-driven biomimetic design

One of the first drivers of the concepts behind simulation-driven design was from the ideas of Julius Wolff, the 19th Century Orthopedic surgeon, who first suggested that, "As a consequence of primary shape variations and continuous loading, or even due to loading alone, bone changes its inner architecture according to mathematical rules and, as a secondary effect and governed by the same mathematical rules, also changes its shape" [79]. The concept of topology optimization sprung from here – from the concept that a structure can be optimized by following load paths and be modified to fit the particular mechanical requirement. The first industrial class software solutions incorporating the rules of design along with the ability to capture the 'loading', along with the constraints to automatically generate 'biomimetic' design was released in the early 1990's. This was primarily the beginning of CAE simulation driving inspirational designs.

Over the years many manufacturing constraints have also been added to shape these designs to be cognizant of the downstream manufacturing, and is relevant to different manufacturing processes (i.e. wider than AM alone). If the part is produced by an extrusion process, then using the extrusion constraints will generate a shape that is extrudable across the defined design space. Likewise, on specifying a casting constraint, the bionic shape that is generated will be free of undercuts for easy extraction from the casting molds. For AM, overhang constraints generate shapes that have minimal support requirement during build in a given print direction, with less horizontal sections, for example. There are various manufacturing constraints in AM that can be incorporated into the design optimization process – and it is the incorporation of these into the topology optimization process which will create designs ready for production.

Shown in Figure 5 are selected examples from Altair covering a variety of parts that illustrate the power of simulation in mimicking nature for product design that outperform conventional designs and are manufacturable and lightweight. The first example is the HardMarque automotive piston which was designed and optimized for production by additive manufacturing in titanium – the end result is reported to be 25% lighter and equally strong compared to the original aluminium part. The

Preprint submitted to *Additive Manufacturing*, March 2019
Latest update: 28 March 2019 – Accepted for publication, in press
https://doi.org/10.1016/j.addma.2019.03.033

second example from Renishaw is a seat post bracket of a mountain bike, meant to replace a cast aluminium part with additively manufactured titanium: the mass reduction was reported at 40%. The third example is a case study from the aerospace industry, in particular the optimization of a mechanical hinge for an Airbus A320 by the European Aeronautic Defence and Space (EADS) Innovation Works – in this case a 75% mass reduction was realized. The fourth example from RUAG space is a topology optimized satellite antenna bracket for the Sentinel-1 satellites, with a total length of 40 cm. The last example is a research project with Laser Zentrum Nord focusing on lightweighting of aircraft cabin brackets.

Figure 5: Examples of simulation-driven biomimetic design with weight savings. Image courtesy of Altair.

Simulation-driven design in the context of AM refers to the use of simulation to numerically ‘generate’ and ‘optimize’ a given space to meet some desired performance criteria under a defined set of constraints (loading and / or manufacturing). This currently refers to either of topology optimization or generative design, which can often be used interchangeably in the context of AM – both involve the use of simulation. Topology optimization refers to optimizing an existing “starting” shape or design space. Generative design is a broader definition of exploring a variety of possible designs within a given space with a desire to identify an optimal solution from various possible solutions meeting the same performance criteria. In the context of design for AM, both the approaches are aimed at creating light-weight parts which mostly contain material in areas were load is experienced and material is removed in areas which do not require it (low-load areas). This process of simulation and material-removal or addition is repeated iteratively until an optimization goal is achieved, and this iterative process may be seen analogous to the process of evolution. In fact, these simulations sometimes make use of genetic and evolutionary algorithms. Effectively, these algorithms incorporate rules like in nature to mathematically disallow weaklings to proliferate, but in

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Latest update: 28 March 2019 – Accepted for publication, in press
https://doi.org/10.1016/j.addma.2019.03.033

an accelerated fashion using clever computational methods. The technique has different variants with the most widely used form in AM initially described in [22]. More recently this was also described in terms of manufacturing challenges in [23] and in terms of available software tools and their differences and limits in [80].

A good example of topology optimization, applied to an extreme lightweighting requirement is the design of a titanium alloy (Ti6Al4V) drone frame, with larger dimensions than can be produced on typical powder bed fusion systems (in this case 500 x 500 mm^2). This was produced on the large-scale laser powder bed fusion system called Aeroswift [81] and the design done in collaboration with Altair. The design iteration process is shown in Figure 6, done in Altair Inspire.

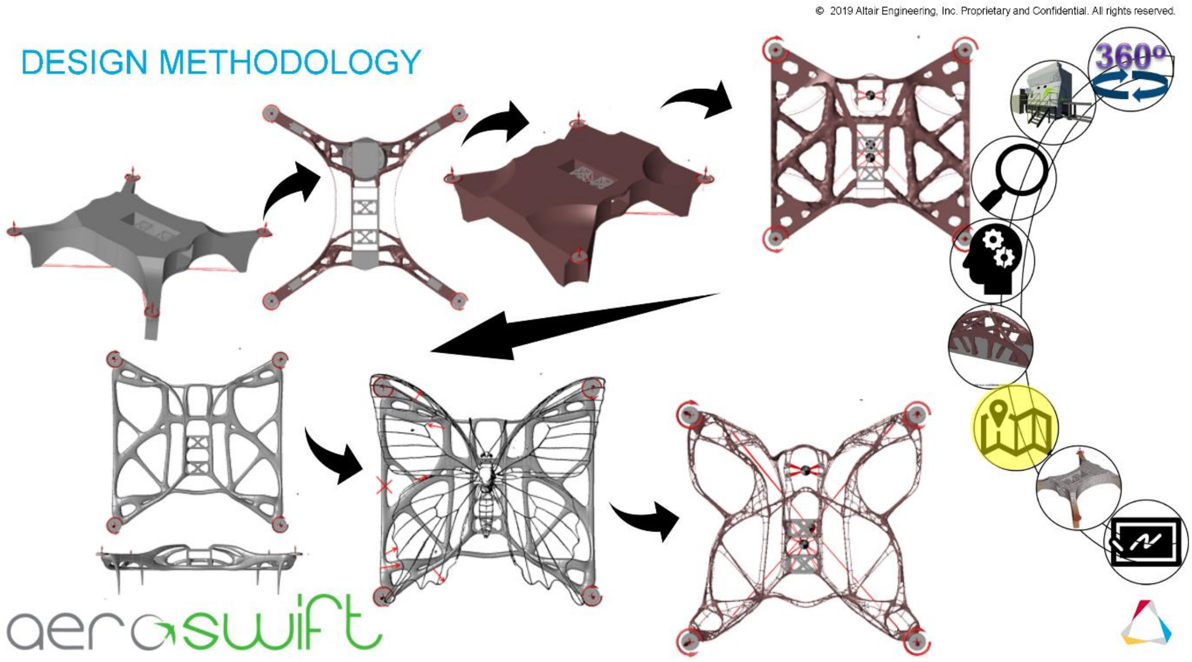

Figure 6: Example of topology optimization process from original design space (top-left) to light-weighted optimized design (bottom-right). In this case a butterfly shape was used to refine the final design. In steps: design space is defined; load cases are defined; optimization process is applied; results are smoothed using polyNURBS tools; design is refined according to butterfly geometry. Example is used with permission from Altair and Aeroswift.

Another example of a topology optimized part – a load bearing bracket – is shown in Figure 7, which is taken from [27]. This titanium alloy bracket was designed to replace a traditional composite bracket in an experimental vehicle for the Shell eco-challenge (South Africa). The design process schematic here shows the original composite part, the design space, the optimized “raw” solution and the final smoothed solution, after application of connections and polyNURBS to the surfaces. This part was also used in a round robin test whereby the same bracket was produced at various commercial laser powder bed fusion systems and detailed analysis performed using microCT [82]. The study highlighted the need for testing AM parts to ensure structural integrity (to be discussed in section 7 in more detail).

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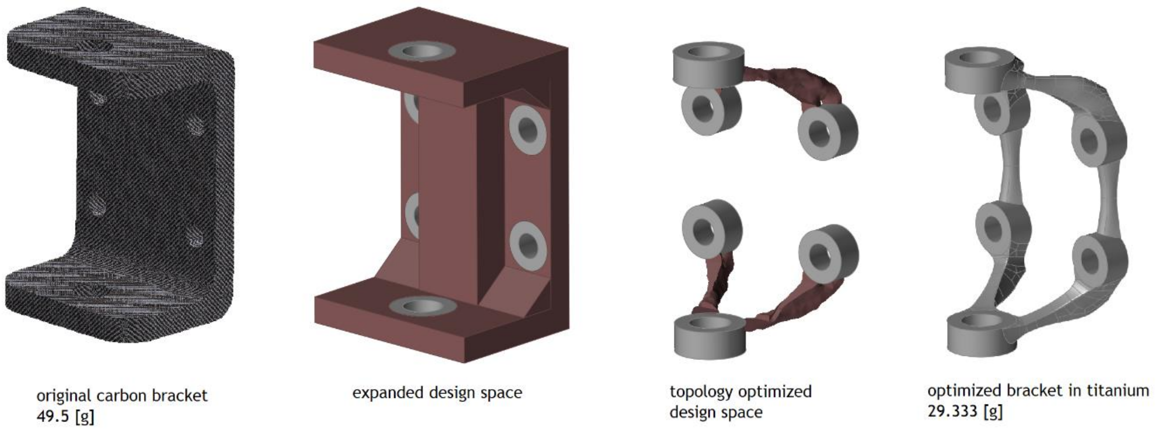

Figure 7: Topology optimized bracket – replacing a traditional carbon-fiber composite with a titanium bracket of lower mass – original bracket on the left, topology optimized Ti6Al4V bracket to the right. Taken from [27]. Image Courtesy of Altair and Nelson Mandela University.

Another example is the design for a large bracket for the same vehicle related to the above-mentioned example. Figure 8 shows the optimized topology itself which is also latticed: this is a sequential process in most software packages and the area to be latticed and the lattice parameters are selected by the user. Latticing will be discussed in the next section and holds many advantages but must be carefully implemented in a design, due to issues such as requirement for supports inside the lattice region, and struts which are potentially too thin (indicated in red in image).

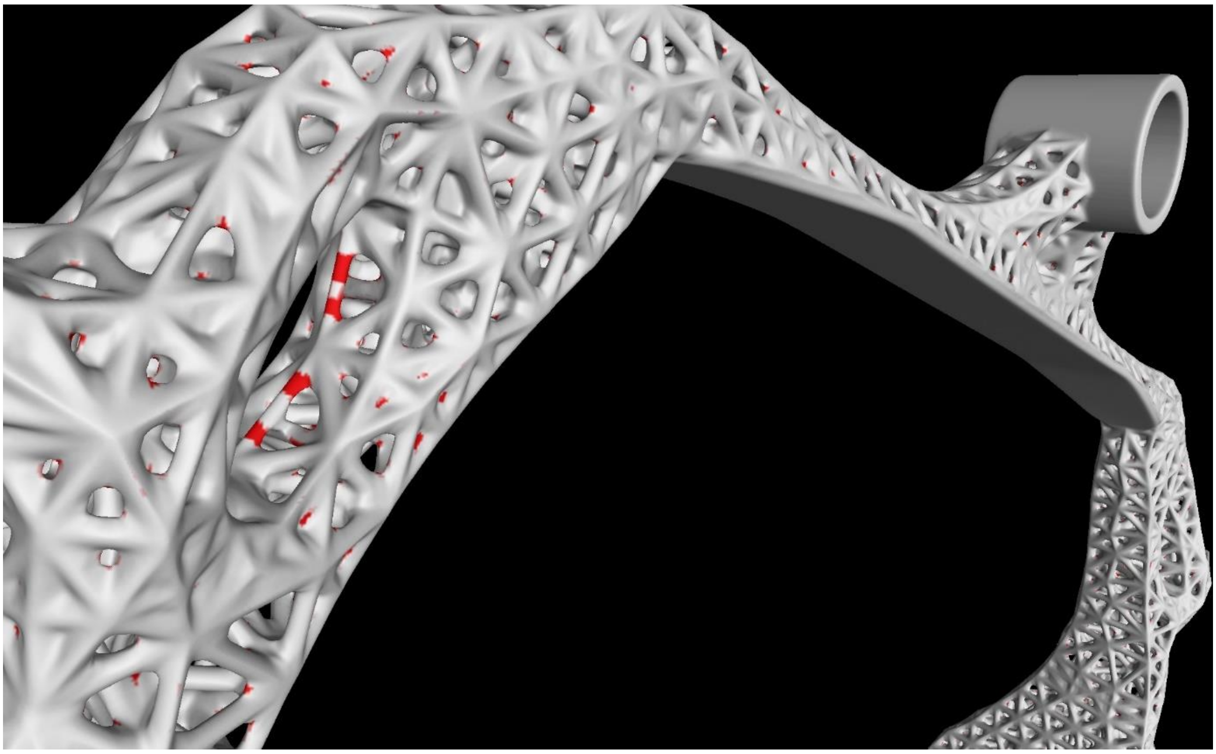

Figure 8: Large topology optimized bracket with latticing implemented after topology optimization. The entire bracket is 410 mm wide, 220 mm high and 70 mm wide – this is the design for steering arch for a light-weight vehicle described in [27]. Red areas show wall thickness of < 1.2 mm.

Preprint submitted to *Additive Manufacturing*, March 2019
Latest update: 28 March 2019 – Accepted for publication, in press
https://doi.org/10.1016/j.addma.2019.03.033

Optimization lattice is courtesy of Altair, with smoothing applied using Volume Graphics software [83].

Commercial examples are widely publicized at present and two representative examples are highlighted here. The first is the Bugatti brake caliper which is shown in Figure 9, and which is currently the world's largest functional part produced in titanium by AM. In this case the use of Ti6Al4V titanium alloy is especially useful for light-weighting, as this material is already strong and relatively light. Its use for automotive and aerospace applications is well known, but manufacturing complex designs by traditional manufacturing methods in this material is extremely challenging (e.g. machining or casting). The topology optimization result is visually impressive, the performance of this caliper has been validated in various tests and is used in production vehicles, with a 40% mass reduction compared to the previous version made of aluminium.

Figure 9: Bugatti brake caliper – currently the world's largest functional part produced in titanium alloy Ti6Al4V by AM – for the Bugatti Chiron vehicle. Example used with permission from Bugatti [84].

Another example, where the advantage of part consolidation is particularly highlighted, is from Autodesk and is shown in Figure 10. In this case 8 components are merged to one with a 40% mass reduction in total and 20 % stronger resulting part.

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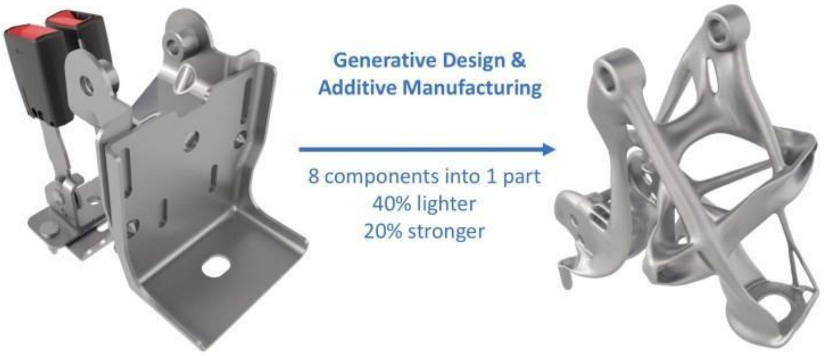

Figure 10: Part consolidation by topology optimization – clear advantage in simplification of parts. Example used with permission from Autodesk and General Motors [85].

5. Cellular and lattice design

Cellular structures exist in nature in numerous shapes, sizes and packing arrangements – some of the most well-known examples are the bee's honeycomb, wood cells and spongy bone (trabecular bone), all of which are discussed in a book by Gibson et al. [86]. MicroCT scans of some natural cellular materials are shown in Figure 11. In fact, one of the first true observations of cellular structures in nature can be traced back to 1665, when Robert Hooke published his observation of the cellularity in cork and suggested that the unique behavior of cork was attributable to its underlying cellular structure [87]. Humans have been using cellular materials such as wood, cork and bamboo, several millennia before we realized the underlying structural basis for their interesting behaviour [86]. Lattices today owe much of their origins and design selection to mathematics and crystallography [51], as well as following Maxwell's stability criterion, which was primarily developed in the context of large engineering structures [88]. The main utility of cellular or lattice structures lies in their ability to meet performance targets while enabling significant mass reduction, something that is a principle commonly embodied in nature [19]. While cellular materials do tend to have lower effective material stiffness and strength properties, this reduction is often acceptable and can be tailored to the application, as well as varied locally. Lattices may also be useful for other purposes besides light-weighting: they have interesting thermal, acoustic properties and energy absorbing properties under compressive loading – they perform a crucial protection role in nature [30,86]. Cellular materials have also been seen as a crucial enabler for large system-level multi-functional design optimization, such as in an aircraft wing [89]. The categorization of natural cellular structures is discussed in more detail in a recent review article which focuses on biomimetic design of cellular materials – utilizing cellular designs in engineering systems [51].

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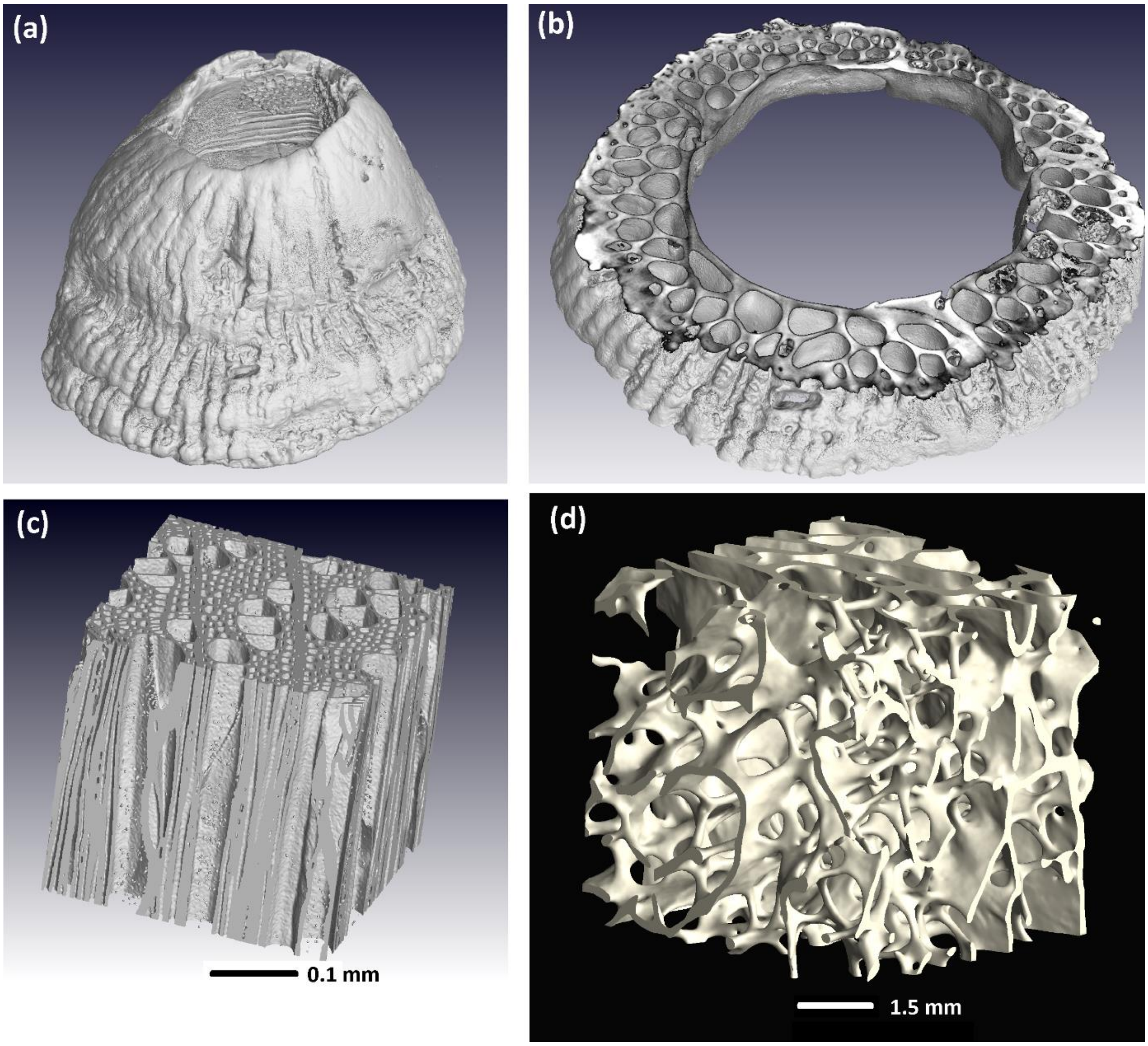

Figure 11: Examples of natural cellular structures (a-b) barnacle, (c) wood microstructure, (d) human bone trabecular structure. Images from microCT data from Stellenbosch CT facility [90].

Perhaps the most commonly used, and well-known bio-inspired cellular material is the honeycomb, which has found a wide range of applications in architecture, transportation, chemical engineering and more, as compiled in a review article [91]. With regard to additively manufactured cellular materials, the emphasis in the past decade has been on lattice structures (lattices), and their use for medical bone-replacement implant applications. In this application, the primary role of the lattice is to allow for osseointegration of bone into the implant, thereby causing better fixation. A recent book chapter describes the most important criteria for bone regeneration in titanium implants produced by powder bed fusion [50] and the production of topologically designed and otherwise designed porous lattices for this application was also reviewed in [48,49].

From an engineering standpoint, cellular materials are realized practically in commercial software packages using different approaches. Traditional CAD software uses mesh-based representation, but recent developments in software are exploring the use of volumetric object representation to generate surfaces, and in at least one case, the use of implicit modeling via the definition of fields (equations) that then generate cellular structures [92]. Mesh-based approaches can generate visually impressive lattices which conform well to the original surface design, and is relatively easily implemented for complex part geometries. The disadvantage here is the limited design options (only

Preprint submitted to *Additive Manufacturing*, March 2019
Latest update: 28 March 2019 – Accepted for publication, in press
https://doi.org/10.1016/j.addma.2019.03.033

struts, lack of control on build angles), the difficulty predicting the mechanical behavior of the structure and the high computational expense associated with representation of the geometry itself, making it difficult to make and evaluate changes rapidly. The volumetric object representation approach allows for the user to select a unit cell from a wider variety of cellular designs (struts, sheets, varying angles, varying unit cell size and number of struts, number of nodes, etc.). The repeated unit cell approach also allows relatively easy prediction of mechanical properties of the structure, easing the design process.

A series of unit cells and corresponding repeated lattice structures are shown in Figure 12. These are all designed with the same total density, but the different designs result in different minimum feature thickness and pore sizes. The first four are strut-based and the next four are minimal surface designs. The latter are found in nature [93], and have been shown to have good properties for bone implant applications [94]. These minimal surfaces are sheet-based designs which are often self-supporting and tend to have zero average curvature at every point on the surface, which makes for a more even distribution of stresses within these structures.

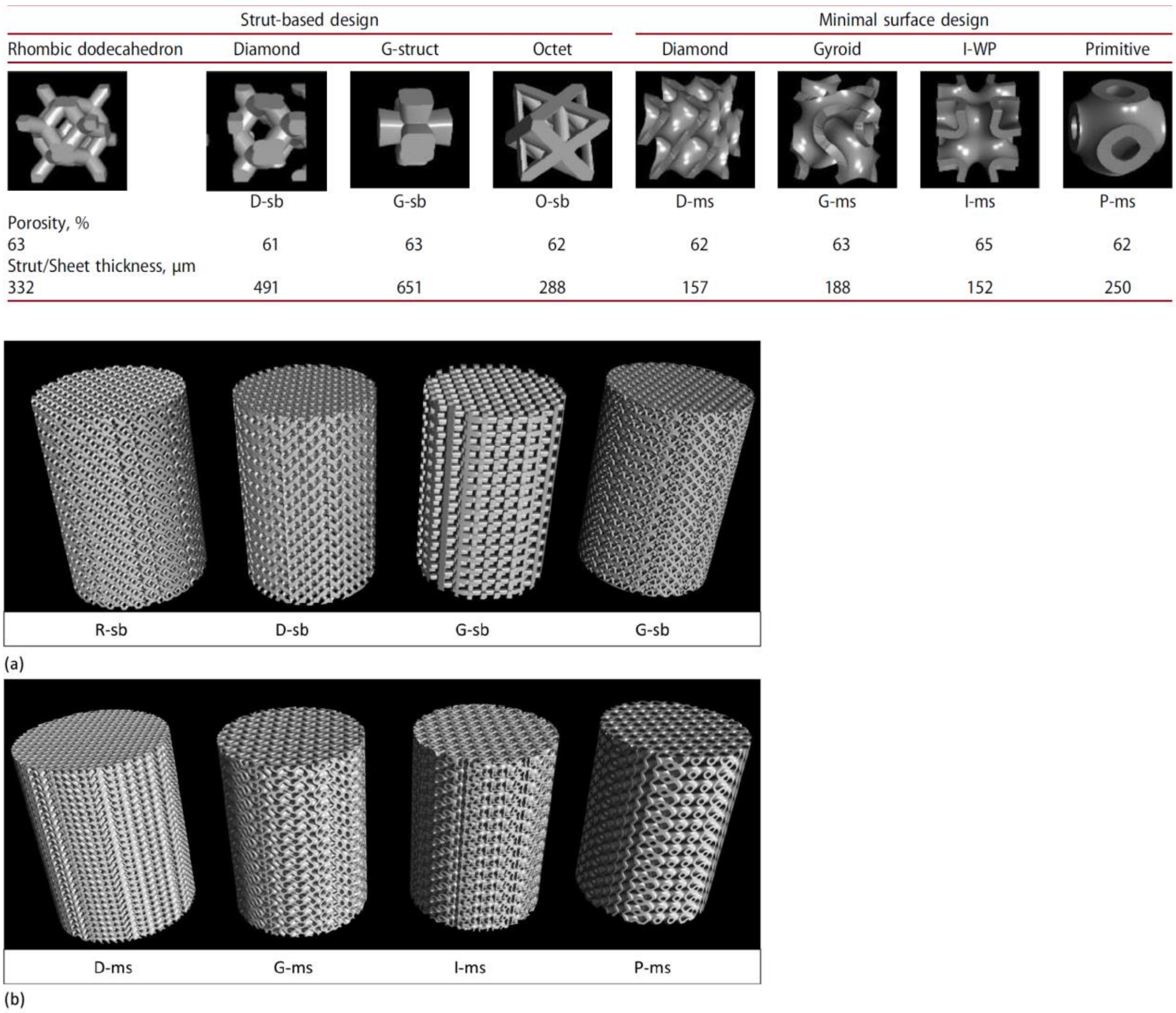

Figure 12: A series of different lattice designs with the same total density, from [7]. Shown here are the unit cell designs (top) and the uniformly tessellated lattices including at least ten unit cells in each direction.

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Despite the growing prevalence of design software capable of generating cellular structure designs, it is not always apparent what the best unit cell for a specific application is – and this becomes even more challenging in the context of multi-functional design. It is in such a context that biomimetic design can play a key role, in helping develop structure-function relationships based on observations of cellular materials in nature, and using these to guide selection of cellular materials [30]. Natural cellular materials span the range of parameter space used in design, from beam or strut-based materials to surface based ones, including structures that combine both types, as shown in Figure 13. These cellular materials occur in nature both internal to a form (such as bone), as well as externally on the surface.

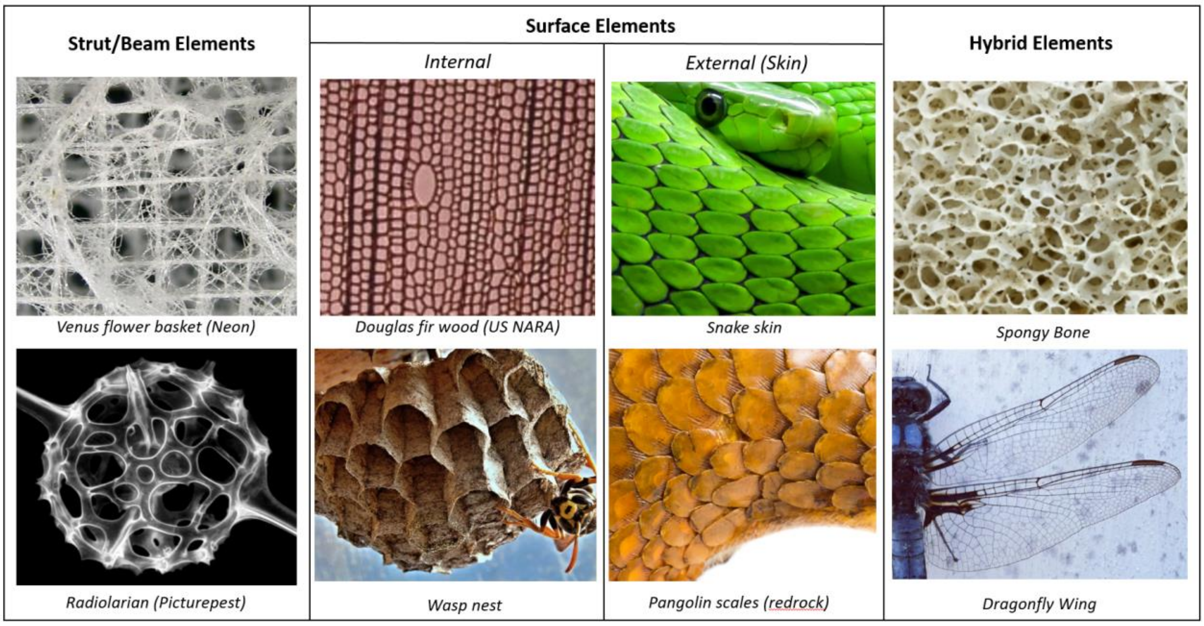

Figure 13: Some of the natural cellular materials found in nature, classified according to the type of element they are composed of (beam or surface) and whether they occur internal or external to the form in question, modified from [51].

The main application of lattice structures, which has resulted in considerable research efforts, is their use in medical implants. For this application the pore sizes required are typically small, requiring small feature sizes in general. Other applications than medical, such as in light-weight structures for aerospace or automotive parts, might prefer thicker lattices to focus on mechanical reliability and strength. Experimental work with lattices with thick struts show excellent strength properties as shown in [95] for 50% density Ti6Al4V lattices of two strut-based designs.

Simple strut-based lattice designs can be classified according to the Maxwell criterion as either bending-dominated or stretch-dominated as illustrated schematically and by a few examples in Figure 14. The Maxwell criterion for simple strut-based 3D structures is [88]:

$$M = b - 3j + 6$$

Where b = the number of struts, and

j = the number of joints

When $M < 0$ the structure is bending-dominated

When M ~ 0 the structure is stretch-dominated and

When M > 0 the structure is over-rigid

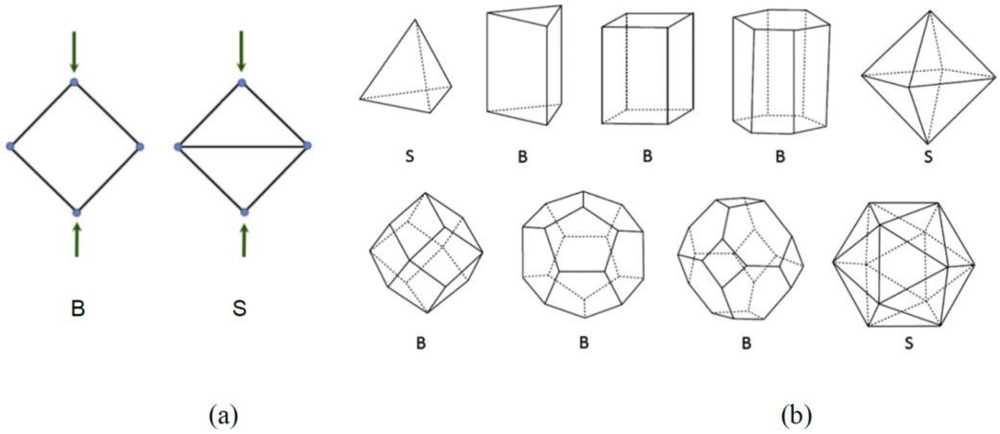

Figure 14: Lattices can be classified as bending (B) or stretch-dominated (S), which affects relative stiffness and failure mode. From [96].

Bending-dominated refers to the struts which tend to bend under compression of the lattice – resulting in shear failure, while stretch-dominated structures are stiffer and fail in a layer-by-layer mechanism. These failure modes have been observed in relatively thick-strut lattices and imaged by microCT in their initial failure locations [95]. The mechanical response of lattice structures in general follows a linear elastic response up to the first point of buckling or failure, followed by a plateau region (or sometimes repeated cycles of recovery and yielding as layer-by-layer failure occurs), followed by final densification. This is shown in the example in Figure 15, which also shows why cellular materials are useful for energy absorption – as they can handle significant yielding without catastrophic failure, under most circumstances.

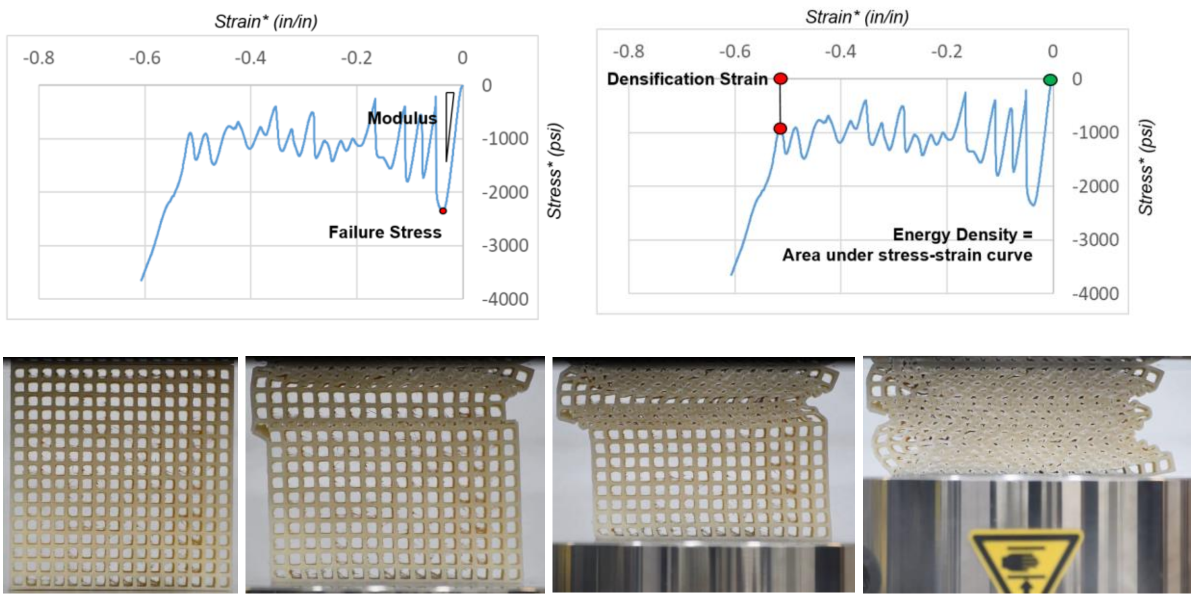

Figure 15: Effective stress-strain plots obtained from compression of a regular square honeycomb, indicating the typical metrics of interest: effective modulus, failure stress, densification strain and energy density, adapted from [97].

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Latest update: 28 March 2019 – Accepted for publication, in press
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A lattice structure can be approximated as an open-cell foam (as long as more than six unit cells in each direction are used), with effective elastic modulus E of the lattice related to the density of the structure (for the linear elastic response region) and the elastic modulus of the bulk material - solid (S) as follows [96,98,99]:

$$E = \alpha_2 \times E_{solid} \times \left[\frac{\rho}{\rho_{solid}}\right]^2$$

In this relationship, the constant α_2 depends on the manufacturing accuracy and material properties and varies between 0.1 and 4 – but is a constant for a specific material and process. What this relationship shows is that the effective elastic modulus can be controlled by the density alone – this means that a lattice with unit cell design of 50% density may use any unit cell size as long as the total space filled contains at least six unit cells in each direction – then the material stiffness will be the same. This means lattices with many thin struts might perform the same as lattices with less thick struts, an interesting design aspect – which can be varied by application requirement.

It is also important to note that the exponent “2” refers to ideal bending-dominated lattice while an ideal stretch-dominated lattice has exponent “1”. This is illustrated in Figure 16, for a range of lattice types – clearly this exponent may vary somewhat depending on the lattice design selected.

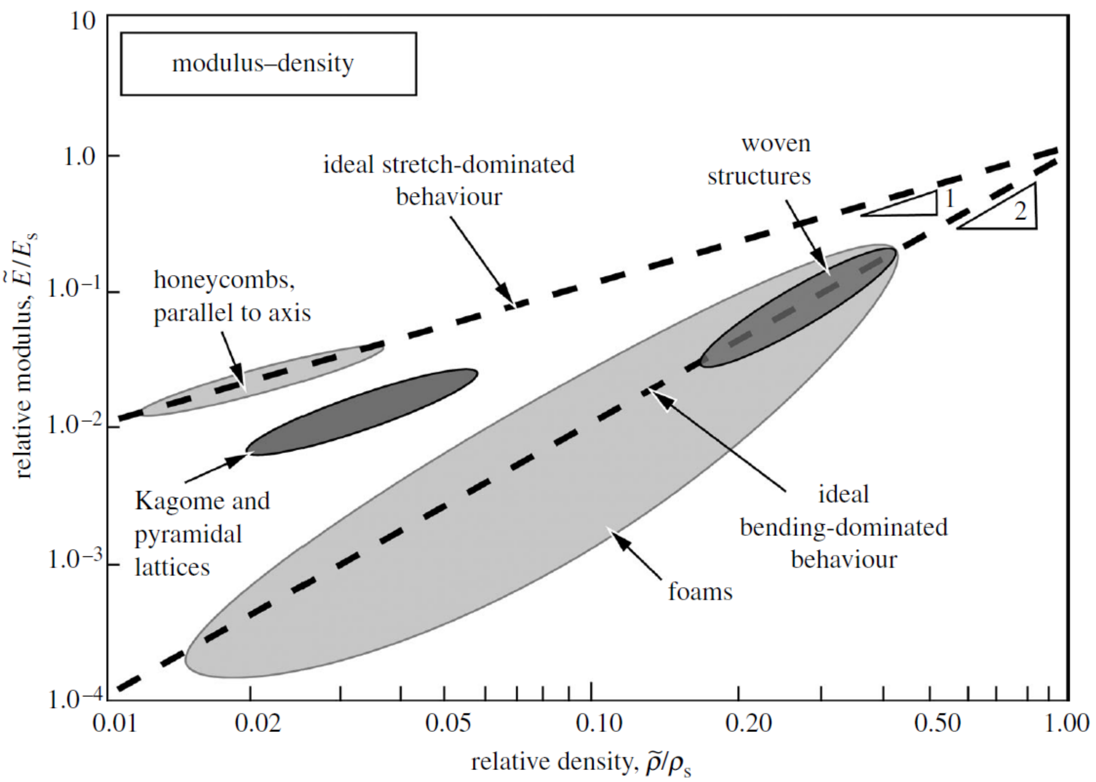

Figure 16: Relative modulus versus density for stretch-dominated and bend-dominated lattices [96]

Besides the relationships mentioned above, lattice designs must also be considered relative to manufacturing limits. For example, sheet-based designs (such as minimal surfaces shown in Figure 12) can typically print without supports, and strut-based designs can print without supports up to a certain strut length for horizontal struts. Therefore, manufacturing constraints are imposed on the

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design possibilities. The most important limits are the minimum feature size, which, in practice, is limited not only by the powder size and laser spot size, but also by the 3D model slicing accuracy and the resulting hatch and contour scanning employed. For example, in a recent study of thin-strut lattices, the standard processing parameters resulted in the inability to produce struts varying gradually from 0.2 to 0.4 mm [100]. Here, different designs were produced with approximately the same strut dimensions despite differences in design [100]. These thin-strut lattices also have relatively large surface roughness values compared to the strut thickness, which understandably affects the mechanical properties more than would be expected for a thicker-strut version. In this above-mentioned study the experimental elastic modulus values were significantly lower than predicted – mostly attributed to surface roughness and irregularity – which creates stress concentrations in notches and in locations of very thin wall thickness. Effectively for a metal laser powder bed fusion system with about 100 µm spot size, the minimum reliable wall thickness (strut size) should be 0.3-0.4 mm if no special precautions or optimization for strut manufacturing is done to enhance the manufacturability. The next section discusses material properties and will specifically mention limits with regards to lattice manufacturability.

6. Material properties of AM biomimetic parts

Biomimetic-designed and produced parts are visually so vastly different from traditional manufactured parts, that it causes mistrust and resistance to acceptance of this new technology, especially by engineers. In some ways this is to be expected, as AM has a history of over-hype and under-delivery in the past. The main question engineers ask is, can these parts be trusted? The answer is yes, when the manufacturing process is optimized and qualified for the purpose. In the qualification process, mechanical properties of the optimized process can be tested and validated as demonstrated for Ti6Al4V in [101]. In order to obtain defect-free and accurately produced parts, X-ray tomography can be used as outlined in [102].

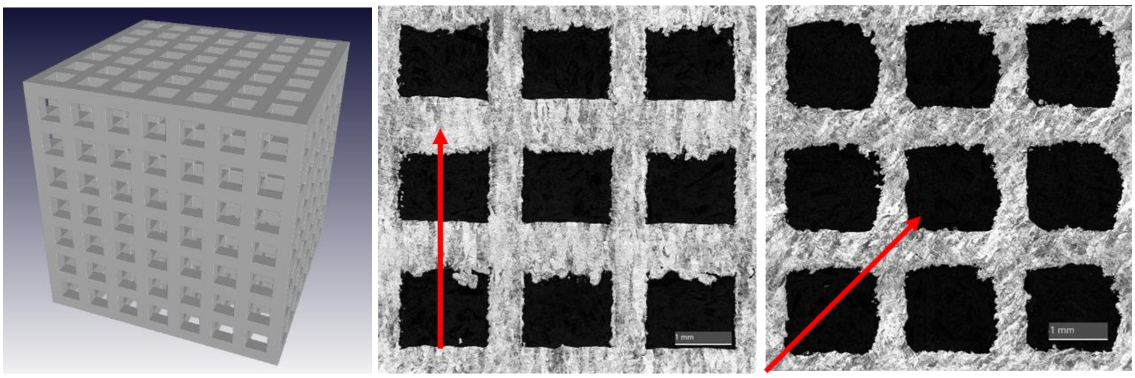
The specific process parameters which combine to create an object in AM all have an influence on the subsequent material properties and the manufacturing process of the object as a whole. This is true not only for fully dense objects, but also for complex or lattice design with biomimetic features such as custom or complex shapes, inner structures or surface modifications. The final LPBF object effectively consists of tracks that create layers built on top of one another. In this case, material properties and the properties of "construction" – i.e. single building blocks (tracks) and joints between them also influence the properties of the LPBF object. Defects and flaws such as porosity occurs in the LPBF process due to various reasons and this can influence the mechanical properties of the final parts [103,104].

There are many process parameters – the laser power, laser spot size and scanning speed, hatch distance, material properties, powder particle size distribution and powder layer thickness, the strategy, design and orientation of the 3D part and its supports, the scanning and building strategy, *etc.* – which all may influence the molten pool size, further solidification, microstructural grain growth and eventually the mechanical properties, lifetime and performance of LPBF parts. The details of the AM process are discussed in the comprehensive review paper [13]. It is already well known that variation of process parameters may influence the formation of porosity and may lead to extensive flaws and build imperfections, as is shown for example in a round robin test recently [82]. This highlights the need for process optimization.

Other properties such as corrosion are also strongly affected by processing conditions and are important for biomimetic applications, especially medical applications. For example, it was shown that a higher corrosion resistance of Co-Cr dental alloy was obtained by Selective Laser Melting (SLM) in comparison with the Selective Laser Sintering (SLS) process, due to a passive oxide protecting layer which formed on the surface of the SLM sample [105]. Takaichi *et al.* [106] found that metal elution from the LPBF dental implants was smaller than that of the as-cast Co-Cr alloy. Thus, it could be said that LPBF materials have superior corrosion properties. However, process-parameters can influence the corrosion behavior of samples produced with different process-parameters. It is already known that the level of microporosity affects the corrosion behavior as shown in [107,108]. Micro-segregation of elements under specific LPBF process-parameters can occur causing different corrosion behavior at materials processed under different parameters [109]. Since melt pool boundaries may differ in corrosion resistance compared to the center of the meltpool, more melt pool boundaries imply different corrosion resistance of LPBF material [110]. These statements have to be taken into account especially for smart AM advanced biodegradable implants that should degrade with spatial and temporal controllability to meet the requirements of different bone regeneration stages [111].

LPBF samples have varying surface roughness on side, top and bottom surfaces. Attached powder particles can be eliminated by post-process mechanical or chemical procedures. However, for LPBF parts with complex shapes and fine features or lattice structures, full powder evacuation and targeted accuracy and roughness values can be quite difficult to obtain. The surface roughness is dependent on the building and scanning strategy, material properties, powder size, layer thickness, *etc.* This can influence not only the mechanical properties but also the biological response of bone cells or soft tissues when such an object is implanted. Moreover, there is currently no general approach and agreement about preferred roughness values or surface micron-scale features and pore size for effective bone cell growth and functioning of implants [8,50,112].

For lattice structures, the geometrical characteristics of unit cells, the building direction, overhang angles, hatch and contour scanning strategy may all influence the obtained roughness in the scaffolds and may cause deviations from designed sizes. For example, in du Plessis et al. [113], the elemental cubic lattice was designed with a total 15 mm width, 0.75 mm strut thickness and 8 struts across one direction in total, resulting in 1.28 mm distance between struts and total 65% porosity (Figure 17a). One set of samples was built at standard process-parameters recommended for EOS Ti6Al4V (-45 μm powder) in vertical direction (17b), other ones – at 45° angle (Fig. 17c). Samples were heat-treated for stress-relieving as indicated in [101]. The differences in strut thickness, roughness and microstructure is clearly visible by cross-sections and also different columnar prior beta-grain orientations are clearly present. Samples that were produced at 45 degrees, had 25% lower ultimate compression strength in comparison with vertical samples.



(a) (b) (c)

Figure 17: Design of the cubic lattice structure (a) and cross-sections of LPBF Ti6Al4V ELI lattices manufactured in vertical direction without supports and 45° with supports. Red arrows indicate the building direction. Process-parameters were similar in both cases.

Preprint submitted to *Additive Manufacturing*, March 2019
Latest update: 28 March 2019 – Accepted for publication, in press
https://doi.org/10.1016/j.addma.2019.03.033

Bending and stretch-dominated lattices (Figure 14) fail respectively in shear and layer-by-layer failure modes, and this might depend somewhat on the material ductility. For a brittle material, shear failure is not desirable and layer-by-layer can be much preferred and even might act as protective mechanism. The layer-by-layer mechanism is more predictable as it is known where the next failure will occur (i.e. in the next layer). In general, manufacturing imperfections might affect thin features more than thick features, hence thin struts should be thickened or well-designed with sufficient safety margin.

The obtained texturization in LPBF materials - grain and sub-grain sizes - depend on the process-parameters used and scanning strategy in LPBF materials as shown by [114–117]. The microstructure of LPBF solid samples and their mechanical properties, fracture and fatigue behavior have some peculiarities in as-built and heat-treated AM parts, which have been widely studied. For example, the columnar boundaries of prior beta-phase were observed in as-built Ti6Al4V ELI specimens and remain even after heat treatment of 950°C for 2 hours [101].

Anisotropy in AM is often mentioned. For example, the mechanical properties of LPBF Ti6Al4V ELI was found to be strongly anisotropic – where three-point bending fatigue tests were used with parts produced in different orientations [101]. The crack propagation rate and fatigue life of as-built and heat-treated samples correlated with column boundaries and orientation of the layers, *i.e.* correlated with the building direction. For static tensile tests, lower ductility was observed experimentally for the horizontal specimens in comparison with vertical samples – this could be attributed to long prior beta-grain boundaries in Ti6Al4V which grow in the build direction and are hence perpendicular to the loading direction in horizontal specimens.

As it was noted in [118], the orientation dependency of the ductility in AM is not yet clear and further in-depth investigations need to be done. Mechanical properties are dependent on building and scanning strategies and these vary for different materials. For example, LPBF 316L stainless steel had maximum strength and Young's modulus under a 45 degree offset between the layer and loading direction, whereas AlSi10Mg revealed the lowest strength in this case [118]. In samples manufactured by LPBF from a nickel-based alloy, strong crystallographic texture resulting in anisotropic properties was found in creep behavior: specimens with loading parallel to the building direction were superior compared to specimens with loading axis normal to the building direction. The Young's modulus determined in measurements at room and elevated temperature was different during tensile testing parallel or perpendicular to the building direction [119]. The building direction and laser scanning direction / scanning strategy are important for the mechanical integrity and this adds complexity to the optimal processing protocol for parts of complex shape. Material type, particle size distribution and particle shape, process-parameters, protective atmosphere, building and scanning strategies, post-processing, etc. should all be optimized according to the specific LPBF process so that biomimetic objects can be produced with the desired properties.

Once material properties and structural integrity have been assessed, the parts produced can be trusted, especially when suitable design safety margins have been incorporated. There are some general suggested guidelines based on the experiences of the authors which can be used in addition to ensure safety and reliability of biomimetic parts in real world applications:

1. For lattices, thin struts might contain micro-porosity, rough surfaces and manufacturing imperfections which affect the mechanical properties sometimes more strongly than thicker features. It was found that the cyclic response of lattices (also known as meta-biomaterials) depend not only on the type of bulk material, but also on the roughness of the outer surface of the struts [120,121] and the distribution of the micro-pores inside the struts [120] which

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can both affect the crack initiation and crack propagation. Post processing chemical cleaning to decrease strut roughness can be used to minimize this [121]. The accuracy of various AM techniques are different since different laser spot size, powder layer thickness, process-parameters as well as powder material are used. Therefore, for a particular purpose where mechanical properties are critical, AM lattices should be tested stringently (as in implants). To improve mechanical performance of lattice structures for load bearing applications they must be well-designed. Van Bael *et al.* [122] showed that stiffness and compressive strength of lattice structures correlate well with volume fraction. Contuzzi *et al.* [123] proposed to use solid reinforcements in fine lattice structures that increase load carrying capability of the structure almost linearly with the number of the reinforcements. Bobbert et al. [94] proposed to use in these applications continuous sheet-based porous structures because they are expected to be less sensitive to such imperfections than beam-based porous structures, to improve fatigue resistance.

2. For lattices, selecting lattice parameters to ensure no supports are required on the lattice or inside the lattice area is critical. Here, strut angles and/or length is important.
3. For irregular geometries from topology optimization and freeform design, it is advisable to perform build-simulation to ensure no local heat accumulation occurs which might lead to residual stress and warping [122,124–126]. In this process, the optimal build angle and supports should be selected.
4. Residual stress can be minimized by design as mentioned above, and can be further improved by stress-relief heat treatment – a relatively simple recommended solution. Heat treatment can have a decisive role on higher ductility and load bearing capacity of lattice structures and might increase fatigue life [121,127].
5. Special attention must be given to the loading direction during use, because anisotropic mechanical properties of LPBF objects exists. This anisotropy might not only result from the material and its specific microstructure, but also from scanning and building strategies used for LPBF manufacturing, which might vary with different systems. Lattice structures built in different directions have non-identical mechanical properties [94,128].

7. Challenges in biomimetic AM

Despite all the potential for biomimicry in AM in its various forms, there are some challenges to its practical implementation. This section highlights some of the most important challenges and provides some perspectives on how to address these challenges, based on the authors' experiences. Most importantly, all forms of biomimetic design for AM involves complexity in various forms not previously encountered. While AM relaxes the traditional manufacturing rules, not any geometry or structure can be produced easily or reliably. Due to the complexity of design, design for AM (DfAM) becomes even more crucial to ensure manufacturability and might involve re-design in cases of difficult geometries [129]. This also varies with different forms of AM and even between different commercial system types. Metal AM and its limits in general are discussed in more detail in [13,130–132].

AM is still a relatively new manufacturing process which requires process optimization and quality control to ensure accuracy and reliability [133]. This requirement is critically important for parts with complex geometries which include curved surfaces, thin connecting features, hidden features and lattice structures. There are also many varieties of AM with different trade names, processes and differences in quality obtained. This quality refers in particular to material density and process induced pores, inherent process surface roughness, build errors such as uneven powder spreading or scan track errors leading to critical flaws, residual stresses and associated warping and cracking and microstructural inhomogeneity. A major limitation is the minimum feature size for the AM system used [134]. Some additional limitations are placed on the part designs, most notably the build angles [135]. All down-facing surfaces have typically rougher surfaces than upwards-facing surfaces, thin angled features suffer from stair-step effects, and small angles require supports [136,137]. Support removal is not a simple process: this post-processing “clean-up” is time consuming and may also affect the dimensional accuracy and quality of the resulting part. When supports are needed inside a complex part (e.g. inside a lattice), these supports might not be physically removable at all – as shown in the example in Figure 18. In this figure, two topology-optimized bracket designs were almost entirely latticed – but the build process required incorporation of supports – also inside the lattice region. Removing supports from lattice regions on the exterior can cause damage to the lattice struts, and removing them from inside the lattice region is entirely impossible. In this case, the brackets still met the mass target despite internal supports, but the aesthetic value (the appearance) is not as visually impressive as could have been achieved by appropriate design to eliminate supports.

Figure 18: Example of two topology optimized and latticed brackets produced by laser powder bed fusion in Ti6Al4V. These parts include internal supports in the lattice structure which cannot be removed. An improved design for the lattice is required to ensure no supports are needed inside the lattice regions.

Detailed inspection of these complex parts ensures their structural integrity and accuracy of production. Due to the expense involved in AM, non-destructive tools are especially useful to analyze parts without destroying them: the most widely used are X-ray techniques such as 2D digital radiography and 3D micro-computed tomography (microCT). Due to the complexity of the parts 2D X-ray images are difficult to interpret and smaller flaws which are typical to AM may be missed. As a result, microCT is often the preferred method of choice [102]. This technique works by acquisition of X-ray absorption images from many angles around the object, followed by reconstruction to produce a 3D representation of the object, including its interior. It is also known as X-ray tomography, CT scanning or X-ray microscopy (XRM). The most important issues that can be identified by microCT and which are relevant to biomimetic AM are:

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- Powder can get stuck in complex areas, especially inside lattices, and when heat-treated (e.g. stress relief heat treatment) they become stuck. This adds weight and might be unsafe (e.g. in medical implants). An example of this is shown in Figure 19.
- Rough surfaces which depend on build angle might affect mechanical properties, with rough surfaces in inaccessible areas being unable to be processed. Roughness can be measured quantitatively or assessed visually (e.g. to check for notch depth into the part).
- Manufacturing flaws such as porosity might also occur despite process parameter optimization and this may affect the mechanical properties. An example of porosity in a complex part is also shown in Figure 19. It is important to note here that process parameter optimization prior to building a part can limit process-induced porosity and this microporosity is expected to be the same in a test coupon than in a complex part [82].
- Residual stress cannot directly be seen in microCT images but can be seen indirectly in the form of warping and cracks. In extreme cases this can cause some parts to warp upwards during the build process which can cause damage to the coater blade of the system. Unnoticed residual stress in a part might affect its mechanical properties. Stress-relief heat treatment is therefore highly recommended.

The above issues can be partially improved or solved by using AM simulations to highlight where thermal hotspots might be formed. A change in the build angle or design itself can contribute to eliminate these. Changing the lattice design or parameters can improve the requirement for supports and self-supporting lattice designs can be selected in some cases.

https://doi.org/10.1016/j.addma.2019.03.033

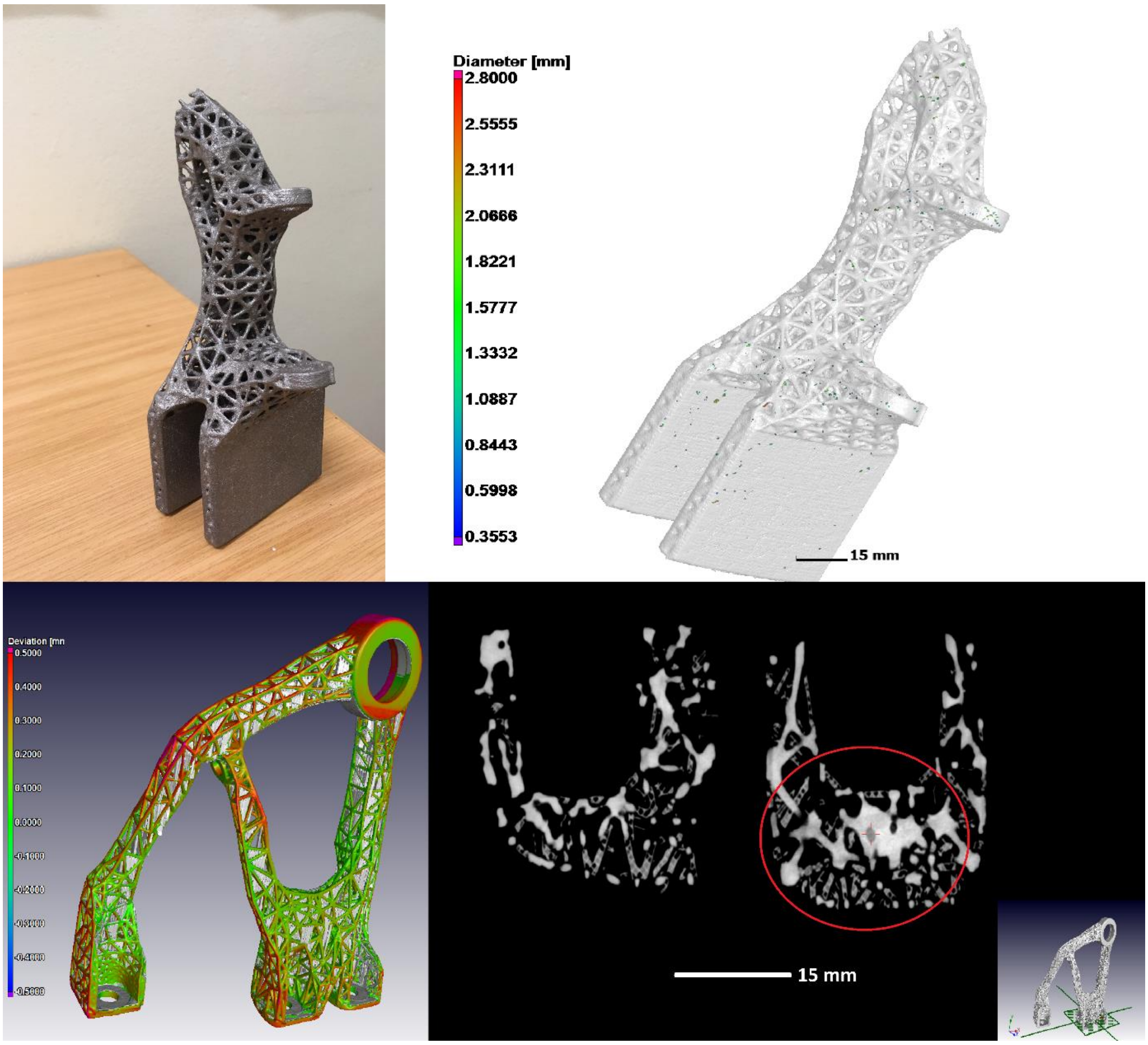

Figure 19: Examples of the use of microCT in inspection of complex biomimetic parts for (a) large lattice test part with struts 1.5 mm thick and containing microporosity evenly distributed in the struts, and (b) a similar smaller bracket with CAD variance analysis showing maximum deviation from design, support structures inside the designed lattice and powder stuck inside the lattice (circled in red).

Besides build orientation planning and simulation, the manufacturing process can be optimized to ensure high quality production on test cubes, which can be subjected to detailed analysis by sectioning, or preferably by microCT. When using microCT, however, it is also important to realize that while small porosity is acceptable when well distributed, only major flaws or those with specific location-specific clustering are important, as well as those in critical regions of the part. Optimization of processes using test cubes and microCT may assist in identifying the root cause of some types of defects which allows to improve the process. Simulations and experimental work done on lattice structures with artificially induced porosity in individual struts showed that this did not affect the yield strength of the lattice for up to 0.5 mm pores [113]. Despite this being a single study, it does show that even large pores are not necessarily detrimental, but improvements to processes and eliminating porosity is always desirable.

https://doi.org/10.1016/j.addma.2019.03.033

8. New trends in biomimetic AM

This section mentions some current interesting trends in biomimetic design for AM, with new developments expected in the next few years as the techniques are refined and new tools become available. The first worth mentioning is that most topology optimization software at present operates on the topology itself and subsequently certain areas can be selected for latticing, i.e. the latticing is not part of the simulation-driven design process. Some recent software tools have started to emerge where the two are combined (topology and lattice in the simulation-driven design process) – the most widely used one is CogniCAD™ by ParaMatters, Inc. Here, the latticing follows load paths and has a true organic/biomimetic visual appearance. This latticing is incorporated into the simulation-driven design process and will find application especially in light-weighting applications. Some examples are shown in Figure 20.

Figure 20: Combining topology and lattice optimization into one simulation-driven design process results in “lattice struts” which have a curved geometry following load paths. Parts designed by ParaMatters [138], manufactured by 3D Systems and XPonentialWorks.

The other useful development is the optimization of repeated lattices – gradient lattices and variations of strut thickness or unit cell size across a part, and conformal lattices to the surfaces of a part. In other words, the lattice is not simply cut off on the edge of the part but unit cells are stretched to fit the surface topology. An example hereof is shown in Figure 21 where the lattice is conformal to two opposing surfaces and the lattice density varies to allow denser lattice in areas where simulations show higher stress will be experienced. This example is from nTop Element from nTopology Inc [92].

Preprint submitted to *Additive Manufacturing*, March 2019
Latest update: 28 March 2019 – Accepted for publication, in press
https://doi.org/10.1016/j.addma.2019.03.033

Figure 21: Brake pedal of F1 racing car with gradient lattice conformal to the two opposing surfaces [92].

Recent research approaches for cellular material design have included the development of multi-scale optimization approaches as described by Osanov and Guest [139] and Cadman et al. [140]. In this approach, the unit cell domain is discretized into elements which are then themselves optimized using topology optimization methods [141], similar to discussions in the previous section. A unit cell so designed can then be used to compute effective properties, after which inverse homogenization is used to upscale the cellular geometry to the level of the larger structure [142]. These ideas have been recently extended to multi-material cellular structure optimization [143]. Cellular automata methods have also been developed to design materials [144] and microstructures [145], and machine learning methods are beginning to be applied to materials design [33,146].

Because of the very complex shapes of the parts having a biomimetic or bionic design, it is often necessary to use support structures for overhanging areas. This can be a big problem in the post processing of these parts — for removing the supports and surface finishing. However, there is some progress in this issue. First of all, it is possible to use the EBM technology (Arcam EBM), which, due to some features, requires much less support [147–149]. On the other hand, internal complexity and small features are limited in this process, since with constant preheating of each layer to a high temperature, the powder is partially sintered and later cannot be removed from the manufactured part. There are also quite serious limitations on materials for EBM technology. Also recently, companies such as EOS [150] and Velo^{3D} [151] (both use LPBF technology) have improved their softwares, scanning strategies and process control parameters, which allowed to realize designs with overhangs lower than 15°, and large inner diameters without supports. These developments are all very promising for the realization of increasingly complex biomimetic designs with improved structural integrity and surface quality.

An emerging trend is the development of software packages incorporating the entire workflow for advanced (biomimetic) design for AM, including freeform design, topology optimization, latticing and more recently also build simulation (to find optimal orientation for build process) and even support generation and slicing for build preparation. When all this is combined in one workspace the entire design process is simplified and this allows more frequent and improved biomimetic designs to be realized in practice.

The development of standards for AM and non-destructive testing in AM is emerging as an important aspect in the qualification of processes and ensuring reliability in AM processes. This is especially applicable to biomimetic designs and it holds the most advantage in optimizing process parameters

https://doi.org/10.1016/j.addma.2019.03.033

prior to building complex parts - using microCT test methods [152–154]. Inspecting complex parts is also valuable in critical parts such as for aerospace, and microCT is the best method to do this. It is worth mentioning that besides complex part inspections, which are limited in resolution by field of view, it is becoming standard practice to inspect witness specimens of smaller diameter built alongside complex parts. This allows for high resolution CT analysis with defects found in these specimens being indicative of problems encountered during the build. In-line monitoring of the build process is also something that is currently under intense investigation with various options, to highlight problems during the build process in real time.

Something that is becoming increasingly popular for improving part density is the use of hot isostatic pressing (HIPping), especially for additively-manufactured metal parts for aerospace – it is a requirement that all parts are HIPped. The HIP process closes pores and improves the microstructure, but it is important to realize that not all pores are necessarily closed by HIP: it has been shown that pores connected to the surface do not close properly, and is detectable by microCT [155]. The important point is that HIP should not be used as a blind solution – its performance especially in thin walled parts should be checked.

In general, the use of biomimetic AM is growing at a very fast rate, with practical engineering applications emerging almost daily. This is driven by the maturation of metal powder bed fusion AM, the development of appropriate software tools, and the huge interest from companies in investing in a technology with clear potential to disrupt various industries. The key to disrupting existing products is in significant advantages in the new design – which is possible by AM and biomimicry is key to unlocking this potential. Besides aesthetic appeal, actual light-weight advantage is likely the biggest drawcard in automotive and aerospace industries. In other industries the combination of multiple parts into one might be a significant advantage and it is expected that the multi-functionality of designs might be one of the big future growth areas.

9. Conclusions

It is clear that biomimicry in AM allows complex functional designs and various tools are currently available to easily achieve such designs. Biomimetic designs are therefore both beautiful and functional. Despite the high possible complexity, some design for AM (DfAM) rules have emerged which improve the manufacturability and reliability of these types of parts – and these should be incorporated into the design process. It is especially important that process parameters are optimized to ensure structural integrity and ensure high quality manufacturing, as manufacturing errors might affect these parts more than traditional parts – this requires an additional safety factor to be built into designs, and inspection is critical. Inspection is more challenging due to complex hidden features which are not accessible easily, therefore microCT is the best suited technique for this purpose. Post-processing of parts is also a challenge, and the options are limited – therefore depending on the application the complexity of the design might need to be constrained to ensure all surfaces are accessible by required post-processing techniques. One of the most widely used applications of biomimetic design in AM is light-weighting, but many other opportunities exist including parts customized for acoustic, thermal, optical or other applications, especially in combination with surface modification techniques. Lattice structures in particular have various applications which are still untapped and surely will emerge in the next few years. Most importantly, all examples in this work clearly demonstrate that biomimetic designs can be trusted and should be used more widely. Biomimetic designs are crucial for fully unlocking the power of metal AM in particular.

In conclusion, biomimicry in AM has been shown to be possible in various ways, with the most accessible tools currently being freeform design and simulation-driven (topology optimization) design. These tools allow complex forms to be created which often resemble natural structures, and the design engineer may incorporate “lessons from nature” in this design process. For example, in simulation-driven design, various outcomes are possible and selection of the design outcome most similar to a biological structure is most likely the best solution. The greatest future potential for biomimicry in AM lies in incorporating real biological input in some ways in the design process – and here biological materials science is crucial in providing “lessons from nature” which can be incorporated easily. Despite some of these “lessons” emerging, there is still a huge number of hidden “design rules” to be uncovered, and the most interesting of these might be in optimized multi-functionality. It is not only in the design process where biomimicry can be employed. The entire process of 3D printing may follow biological principles, including sustainability (re-use of used materials), and biomimetic design therefore forms part of and drives the bio-industrial revolution – which will become known as Industry 5.0.

Acknowledgements

The South African Department of Science and Technology is acknowledged for support through the Collaborative Program for Additive Manufacturing (CPAM).

Conflict of interest statement

One author (Ravi Kunju) is the Senior VP Business Development & Strategy – Simulation Driven Design at Altair Engineering Inc, a provider of software for simulation-driven (biomimetic) design amongst others.

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