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Towards Smart Green Blue Infrastructure

COMPREHENSIVE OVERVIEW ON ADDITIVE MANUFACTURING OF LATTICE STRUCTURES USING SELECTIVE LASER MELTING

Ahmed M. Halaby (1), **Yehia M. Youssef** (2) **and Mahmoud A. El-Sayed** (3)

(1) Department of Industrial and Management Engineering, Arab Academy for Science and Technology and Maritime Transport, PO Box 1029, Abu Qir, Alexandria 21599, Egypt, ahmed.halaby88@gmail.com
(2) Department of Chemical and Petrochemical Engineering, Arab Academy for Science and Technology and Maritime Transport, PO Box 1029, Abu Qir, Alexandria 21599, Egypt, yehia.youssef@staff.aast.edu
(3) Department of Industrial and Management Engineering, Arab Academy for Science and Technology and Maritime Transport, PO Box 1029, Abu Qir, Alexandria 21599, Egypt, m_elsayed@aast.edu

ABSTRACT:

Additive Manufacturing (AM) has emerged as a revolutionary technology for creating a wide range of geometries, especially complex-shaped ones. The intrinsic characteristics and potential benefits of AM techniques can improve manufacturing process sustainability through the reduction of material waste, machine emissions, and energy usage. This had allowed AM to be recognized as a potentially green technology. On the other hand, lattice structures are characterized by their intricate network of interconnected struts and nodes that are organized regularly and repetitively. They provide a unique combination of lightweight, high strength, and material efficiency. This makes them excellent candidates for many applications ranging from aerospace and biomedical to architecture and automotive parts. In addition, such cellular materials had found diverse applications within marine engineering, including lightweight ship components, customized underwater sensors, offshore platform structures, and energy-efficient propellers. In this paper, a detailed review of the fabrication of lattice structures using Selective Laser Melting (SLM), one of the most prominent AM techniques, will be presented. This paper explores the fundamental principles of lattice structure design. It also investigates the capabilities and limitations of the SLM technique in terms of accuracy, layer thickness, raw material, and process parameters. Furthermore, the advantages, challenges, and future prospects of integrating SLM-fabricated lattice structures are also thoroughly discussed. Such a comprehensive survey would provide a deep understanding of the current landscape of SLM for the printing of high-strength-to-weight ratio lattice structures that would meet the demands of modern engineering challenges and promote innovation and sustainability across various fields.

Keywords: Additive Manufacturing, Lattice Structure, Selective Laser Melting, Sustainability

1 ADDITIVE MANUFACTURING

Manufacturing development has a major impact on the global economy and enhanced living standards. By transforming raw materials into finished items, the manufacturing industry adds 28.4% of global value addition compared to 67.1% for the service and 4.5% for the agriculture sectors [1], [2]. Before 1950, there were conventional procedures in use, and since the 1950s, non-conventional techniques have been embraced and put into practice [3]. Today's manufacturing environment includes Additive Manufacturing (AM), Subtractive Manufacturing (SM) like milling or turning, and Formative Manufacturing (FM) like casting or forging [4], [5].

The term AM refers to technologies that add material layer by layer while being directed by a digital model to create three-dimensional (3D) items. Layers are added throughout these procedures to create customized and complicated structures like lattice structures, which come together to produce the final product. This technique works with any type of material, including metals, ceramics, and polymers[6], [7], [8].

1.1 AM evolution

AM has its roots in the growth of two essential fields: **topography** and **photo sculpting** [9], [10]. Charles W. Hull's stereolithography patent in 1986 marked the true beginning of commercial AM, as we know it today. Due to this advancement, the first SLA "Stereolithography Apparatus" equipment appeared in 1987, and ever since then, the number of systems, technologies, and materials available has increased exponentially annually [11], [10], [12].

Recently, as industrialized nations want to innovate their way back to manufacturing leadership, AM is becoming a key area of study interest. In addition, AM is considered one of the nine technologies fuelling the "Industry 4.0," or the fourth industrial revolution that controls the current global economy. Because Industry 4.0 is about industries shifting their attention from conventional manufacturing processes to advanced manufacturing processes, 3D printers are being created for intricate structural applications [13],[14].

1.2 Generalized AM process chain

Using AM, a series of steps are taken to create a physical feature, starting with a 3D CAD model. A change in part type results in differences in the amount and method of AM utilization. For instance, AM could be necessary for certain basic items just for the visual aspect. However, careful planning and post-processing may be necessary for some complicated geometries. [5], [9]. Figure 1 shows the eight steps that are conducted in any AM process [15], [4].

Figure 1: AM process chain (based on [16])

1.3 Advantages and Challenges of AM

Table 1 summarizes the advantages and challenges of AM compared to other conventional processes based on various aspects [5], [8], [15], [13], [17]. Despite the numerous challenges that must be solved, AM will become increasingly popular in the future since it is simple to use, allows for the exploration of creativity, and offers several additional advantages. It is projected that in the coming years, the younger generation will take the lead in the development and global applications of AM technology, much as it did with the Internet [15].

Table 1: Additive manufacturing vs other conventional processes.

Point of Comparison	*Additive Manufacturing*	*Conventional Manufacturing*
Material	Applied on fewer classes of materials; (metals, thermoplastics, and some composites)	Applied on almost all classes of materials; (metals, polymers, ceramics, composites, wood)
Design freedom	There are no restrictions for any geometry, better for customized parts	There are restrictions for some geometries
Dimensional accuracy	Less accurate; tolerances are as low as 0.1 mm.	More accurately, tolerances are as low as 0.025 mm.
Surface finish	In most cases, post-processing is required (Heat treatment, polishing)	It produces parts with good surface quality.
Productivity	It is not cost-effective at large production volumes	It is economical for large-scale production.
Material wastage	Less or no material waste is produced because of near-net shape processing	More material waste is produced because of recycled materials (chips, scrapes, vapors, etc.)
Tooling	Can make parts without other tooling required	Need costly machining tools, dies, and molds.
Complexity	Complex parts can be manufactured effortlessly at a modest price	Limited capability in creating complex shapes
Lead time	The build rate is slower, especially for high-volume production	It has a high production speed
Part size	Restricted to machine size, so it is efficient for nanoscale parts	Large components are possible
Product assembly	Eliminating or decreasing the requirement for multiple-component assembly	The majority of products need the components' assembly
Part optimization	It has the capability of mesh production to produce parts (lattice structure) with a high strength-to-weight ratio	The lattice structure is difficult to produce with optimum characteristics.
Standardization	There is a lack of standards and quality assurance needs substantial consideration	There are massive standards for all processes, so these technologies well established
On-demand Manufacturing	Highly recommended for on-demand or customized manufacturing so reducing inventory parts	Not suitable for on-demand manufacturing
Green technology	It is more environmentally friendly because it reduces material waste, energy usage, and machine emission	It is less environmentally friendly than AM processes

1.4 Classification of AM Technologies

▪AM can be classified into seven categories, depending on the deposition method used by the printing technology as shown in Figure 2 [18], [19]. ***Material Extrusion*** pushes a semi-liquid or filament thermoplastic in a molten state through a nozzle and deposited layer by layer onto the print bed. ***Binder Jetting*** deposits liquid binder droplets onto a powder bed. ***Powder Bed Fusion*** applies a laser that is guided precisely on the metal powder bed to melt the powdered metal, which then solidifies into a layer. ***Sheet Lamination*** utilizes a laser or blade to cut sheets of printing materials and stacks these layers by applying an adhesive layer between them. ***Vat Photo-Polymerization*** utilizes UV light that is directed across the vat of photosensitive polymer resin to cure it into layers. ***Direct Energy Deposition*** applies a laser or other thermal energy source on the filament of extruded metal, continuously melting it. ***Material Jetting***, similar to inkjet printing, sprays photopolymer and/or wax droplets onto a printing platform using one or more jets, and a UV light source precisely focuses to achieve heating or photocuring [20], [21], [22].

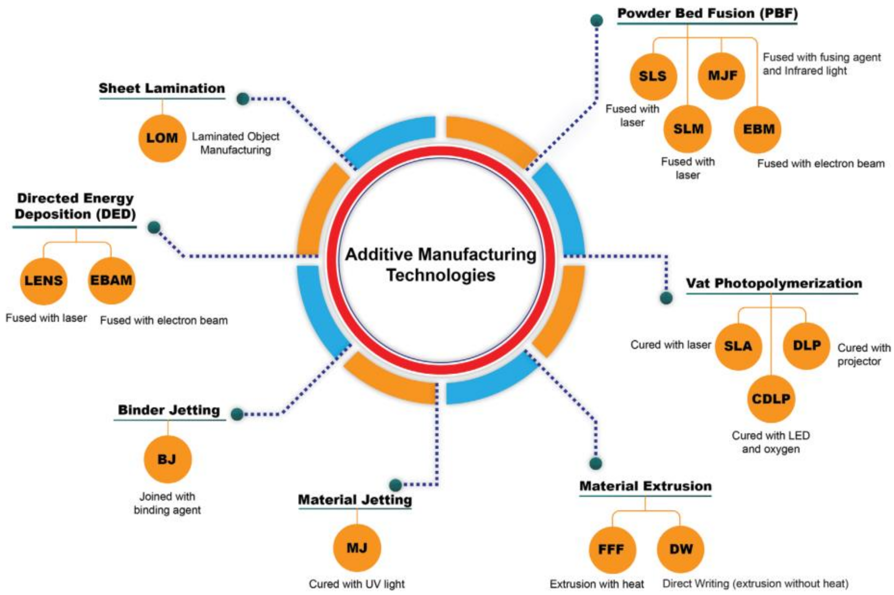


Figure 2: Classification of AM technologies [23]

1.5 Sustainability Consideration

The manufacturing sector plays a pivotal role in global sustainability, accounting for 25% of the world's energy demand, 40% of its material demand, and contributing to 20% of global CO_2 emissions in 2021. Increased awareness of climate change, global warming, eliminating natural resources, and the potential impacts of product usage, coupled with stringent governmental regulations, has compelled the industry to embrace sustainable production practices for future economic prosperity. The triple bottom line theory underscores the significance of economic, environmental, and social sustainability, which were addressed via three sustainability dimensions [24], in driving business success, leading to enhanced profitability, meeting stakeholder expectations, and preserving natural resources. Sustainable manufacturing necessitates continuous technological advancements, access to current manufacturing data, and the application of effective sustainability performance measurement methods [25].

Fortunately, AM is considered a resource-efficient technology and an environmentally friendly option that has been identified as having the potential to provide several sustainability advantages, which drive the manufacturing industry's transition from a linear to a circular economy [25], [26]. Among AM techniques, construction laser additive direct (CLAD), laser engineered net shaping (LENS), and direct metal deposition (DMD) have been shown in some cases to be more environmentally friendly than conventional manufacturing processes, with an impact reduction of approximately 70% [22]. Recently, new printing technologies are being developed that use less energy such as cold spray technology employs compressed air to deposit metal powder, eliminating the need for elevated temperatures or chemical binders [27].

Roughly, the implementation of a sustainable culture in AM is outlined in Figure 3. The process initiates with the assessment phases, incorporating life cycle assessments and focusing on characterizations related to sustainability aspects. Subsequently, the procedure addresses material considerations and their broader impacts on the environment, aiming to establish targeted sustainability within the AM culture. Following this, post-assessment steps are undertaken, and these are further refined through the execution of overall process improvements in AM [28].

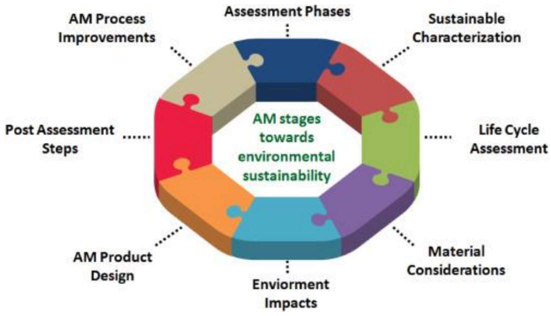


Figure 3: The flow of AM phases towards improving environmental sustainability [28].

Recently, AM is almost certainly green manufacturing because it resolves sustainability issues in different areas. Firstly, AM enables localized manufacturing, which leads to a decrease in transportation emissions and the carbon footprint related to shipping products across various locations over short distances. In addition, they aim to produce lightweight structures with superior mechanical properties, reduce material waste, and optimize topologies for a circular economy, as well as mimic nature, such as cellular lattice structures inspired by the circular patterns found in bamboo tree structures. Moreover, they have shadow effects due to producing many prototypes early, which prevent or at least reduce failures in the later product development stages, thus achieving excellent environmental impact. Additionally, its precision deposition can minimize waste, scrap, and material removal; even the waste can be recycled and reused again [22], [27]. According to these advantages, technological advancements, particularly in AM, when integrated with sustainability performance evaluations, hold the promise of attaining specified sustainable manufacturing objectives within various industrial applications.

2 SELECTIVE LASER MELTING

Selective Laser Melting (SLM) is also known as *Laser Metal Fusion (LMF), Laser Beam Melting (LBM), Laser Metal Fusion (LMF), Laser Powder Bed Fusion (LPBF), or Direct Metal Laser Sintering (DMLS)* [29], which offers incredible opportunities for directly producing 3D objects with flexible material and geometric options. It is considered one of the most significant branches of powder-bed laser AM techniques for metals [13]. M. Fockele and D. Schwarze, in collaboration with W. Meiners, K. Wissenbach, and G. Andres of Fraunhofer ILT, primarily invented this technique to convert metallic powder into metal components. The German Patent and Trademark Office received the initial application for this technology's patent in 1997, and it was published in 1998. Das and Beaman also filed a patent based on their groundbreaking work in direct selective laser sintering (SLS) in 2001 [29], [30].

2.1 General Principle

SLM is a technique that utilizes a high-powered laser to selectively melt and fuse layers of powdered material to create three-dimensional objects based on computer-aided design (CAD) data [31], [32]. The general principle of the SLM process is shown in Figure 4. The process starts with the 3D-CAD model that is sliced into layers with a thickness that mostly varies from 30 to 100 μm, and then transferred to the SLM machine. The process for building each layer consists of three repeating steps. Firstly, a thin layer of powder is applied to the base substrate with the help of a recoator device. In the second step, the powder is exposed to a focused laser beam to melt and fuse it, and the gas stream may be used to ensure the metal spatters and vapors are blown away from the melting zone. Finally, in the third step, the build base is lowered, and the recoater applies a new powder layer over the solidified layers, which form welding beads after solidification, creating a metallurgical bond. This process of iteration is continued until the whole part is constructed. After that, the component may be taken out of the machine [29], [33].

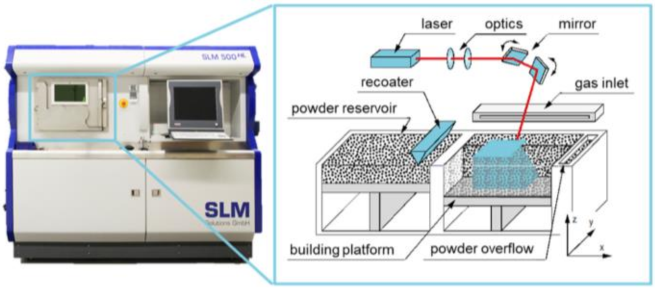


Figure 4: Illustration of an SLM processing chamber with main components [29]

2.2 Advantages and Challenges

SLM offers unparalleled advantages in the realm of advanced manufacturing. The process enables the fabrication of highly intricate structures, including complex internal features and fine lattice structures, providing opportunities for substantial weight savings and the integration of additional functionalities. Notably, SLM's tool-less manufacturing approach eliminates the need for specialized tooling, allowing direct creation from 3D CAD data and rendering part-specific investments obsolete. The technology excels in net-shape manufacturing, rapidly producing final part geometries with excellent mechanical properties. Additionally, SLM minimizes material waste, usually below 5%, as unused powder can be recycled. This, coupled with its suitability for Industry 4.0, makes SLM an ideal choice for highly flexible, integrated, and automated production processes, positioning it as a key player in the era of advanced manufacturing [29], [34].

Although SLM offers significant advantages, it encounters notable challenges. One major drawback is its low productivity and high part costs, with manufacturing times for large parts extending to several days, driven primarily by the machine-hour rate varying from 10 to 100 cm^3/h. The necessity of support structures poses an additional challenge, as they require manual removal in post-processing. Residual stresses induced by the local heat input of the laser beam necessitate careful design of support structures and subsequent heat treatment. SLM's limited surface quality, influenced by adherent or partially molten powder material, may require additional surface finishing to enhance mechanical properties. Reproducibility issues arise due to the complexity of the process and over 130 influencing parameters, leading to instabilities and the need for experienced operation. Quality assurance becomes crucial, often requiring post-build inspections. Despite its potential for automation, SLM faces a low degree of industrialization, hampered by non-standardized file formats and the need for manual intervention in machine preparation and part removal. These challenges underscore the importance of ongoing research and development to enhance SLM's efficiency and address its limitations [29], [34].

3 LATTICE STRUCTURES

AM's advanced capabilities have facilitated the creation of intricate designs, providing enhanced control and flexibility in the manufacturing process. This shift in focus has resulted in a concentrated exploration of architectured cellular structures, particularly lattice structures, known for their superior performance compared to stochastic cellular structures [35]. Cellular structures present distinctive functional attributes, providing design flexibility beyond what solid materials can offer. These features encompass high specific strength and stiffness, improved absorption of mechanical energy, control over heat transfer, thermal insulation, noise reduction, and lightweight characteristics, consequently, they have found extensive applications in various fields, including machinery, construction, automotive, aerospace, marine, military, medical, sports, and more [34], [36] [37].

3.1 *Types of Lattice Structures*

Lattice structures are composed of intersecting nodes and struts or shells, forming a lattice girder system with repeating unit cells at a mm or μm scale, distinguishing them from large-scale engineering structures [13]. Cell topology, cell number, geometric parameters such as strut diameter and cell size, material, manufacturing process variables, structural boundary, and loading conditions all influence the mechanical performance of lattice systems [34].

These structures can be classified based on different criteria, as shown in Figure 5. Firstly, they are designed through periodic or stochastic arrangements of open or closed cell types like foam structures, featuring either 2D cell patterns, such as honeycomb structures, or 3D polyhedral layouts, like hierarchical lattice structures [34]. Non-stochastic features offer superior controllability in architectural characteristics and exhibit desirable properties such as low elastic modulus, negative Poisson ratio, high stiffness-to-weight ratio, low thermal expansion coefficient, large surface area, and substantial internal pores [38]. Lattice structures can also be categorized based on morphology into strut-based and surface-based, known as triply periodic minimal surface (TPMS) structures, with different unit cells illustrated in Figure 6. Strut-based lattice structure, also known as beam-based lattice structure, is a simple design with a periodic arrangement of unit cells made up of struts and nodes while TPMS defines a periodic structure with zero average surface curvature and three coordinates. Finally, based on their mechanical response, lattice structures can be classified into stretch-dominated and bending-dominated, with bending-dominated structures being more ductile and deforming more consistently, while stretch-dominated structures are stiffer and stronger under axial loads [35].

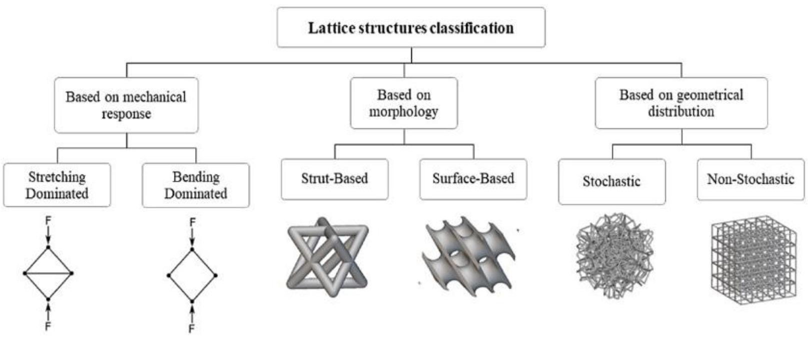


Figure 5: Modes of classification of lattice Structures [39].

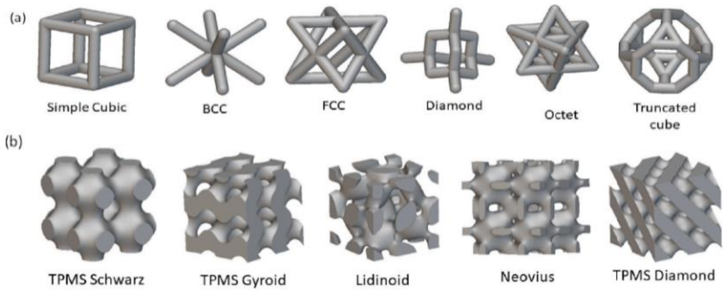


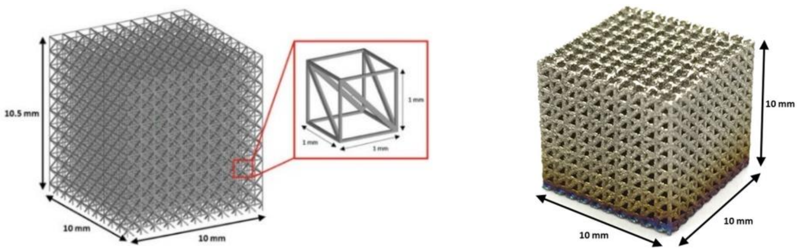
Figure 6: Different lattice architectures (a) strut-based (b) surface-based lattice structures [39].

3.2 Manufacturing of metal lattice structures

The conventional fabrication methods of lattice structures primarily involve the use of metal including investment casting, stamping forming, stretched mesh folding, extrusion wire cutting, lap assembly, powder metallurgy, and wire weaving. However, these methods face limitations in creating complex lattice structures and often necessitate combining single-order structures through welding, leading to potential joint failure, and reduced mechanical properties. In contrast, 3D-printed metal lattice structures offer the advantage of producing intricate designs without the need for complex assembly. Moreover, traditional methods have drawbacks, including stochastic structure creation and limited architectural possibilities. Stochastic structures have unstable performances due to imprecisely uncontrolled pores and wall thicknesses, while non-stochastic structures require further assembly or bonding steps, complicating the manufacturing process, and limiting the availability of types of architectures [38], [40].

Fortunately, AM technologies have revolutionized lattice structure production by eliminating constraints and allowing for the creation of components with more complex geometries. AM processes, with their precision and efficiency, enable the fabrication of multi-scale lattice structures with unprecedented geometries, resulting in enhanced performance. This is due to the larger surface area and open pores for active sites [38], [40]. In a study, 3D printed foam of AlSi10Mg with a cellular structure and 86.5% porosity had a 60% greater heat transfer coefficient than traditional metal foams with stochastic architectures because active sites have a larger surface area and open pores[41].

SLM is a popular AM process for fabricating lattice structures for many applications. Several investigations have shown that SLM-fabricated lattice structures exhibit superior characteristics under specified processing parameters [42], [43]. This method has successfully used alloys such as Ti6Al4V, AlSi10Mg, and 316LSS to produce dense, durable components [44]. As discussed pervious, the SLM process builds these structures layer by layer, starting with CAD design through achieving the solid part as shown in Figure 7. The most descriptors of lattice structure unit cell are the strut diameter (D), the strut length (L), and the strut orientation angle (θ) [45].



(a) (b)

Figure 7: (a) Cell structure CAD design and (b) Lattice structure manufactured by SLM [46]

3.3 Applications of Additively- -Manufactured Lattice Structures in Marine Applications

Unique characteristics of lattice structures, including high strength/stiffness to weigh ratio, corrosion resistance, material efficiency, and flexibility, make them excellent candidates for many applications. The aerospace industry comes first since it shares around 15% of the global AM market [44], [47]. This includes aircraft, engine, and satellite components[38]. In addition, such cellular materials are used in biomedical and healthcare fields such as medical implants, models, devices, and tools [48],[49]. Moreover, they can be used in other disciplines such as automotive, nuclear, toolmaking, sports, and marine applications [47], [48].

Despite not embracing AM as swiftly as the aerospace or automotive sectors, the marine transportation business is gaining traction in the AM industry as well as the utilization of lattice structures. The industry is investigating the advantages of early AM technologies that are shown in Figure 8, such as lightweight parts, as well as possible uses for this technology. The marine transport sector provides interesting prospects for AM, with a global fleet value of $950 billion and an average annual capital allocation of $88.7 billion for new vessels [47].

Because of their lightweight properties, lattice structures are critical for improving fuel consumption and lowering carbon emissions in automobiles, ships, and airplanes. These structures can be used by engineers in small and medium-sized surface and underwater vehicles as shown in Figure 9(a), such as ship load-bearing structures and thin shells, shafting, impeller, and propeller wheel hubs. For ship load-bearing structures, large-scale single-layer or low-density lattice structures can be employed, however, for small and medium-sized ocean surface and underwater structures, a lattice structure design approach that combines topology optimization and homogenization can be used. For example, the lightweight design of a compressor impeller using the central symmetric lattice structure is shown in Figure 9(b) [50], [51]. In addition, shipbuilding, yacht, and offshore structures can use this lattice structure to gain the advantages of lightweight along with improved mechanical properties [52].

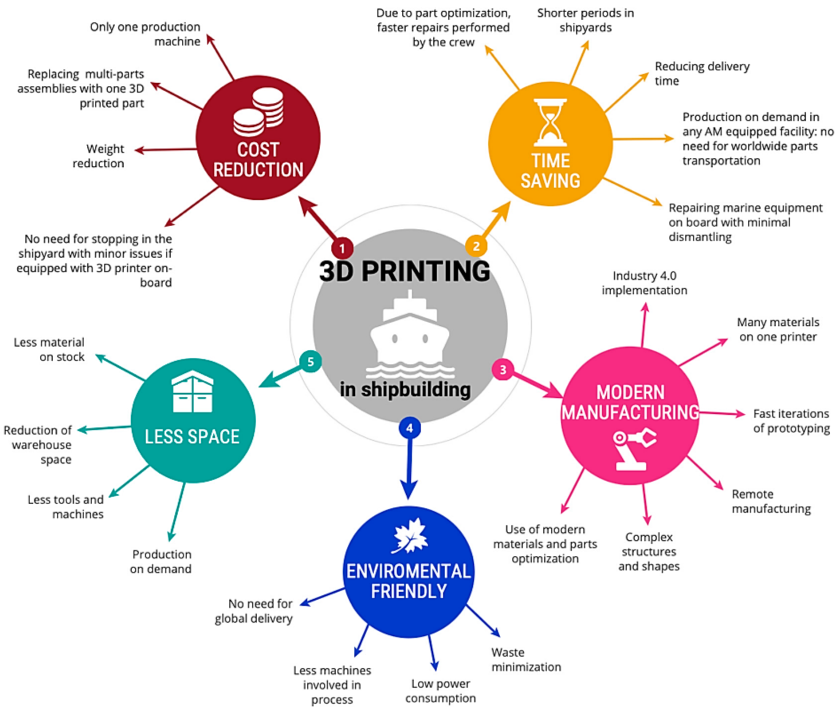


Figure 8: The benefits of using AM in shipbuilding [53].

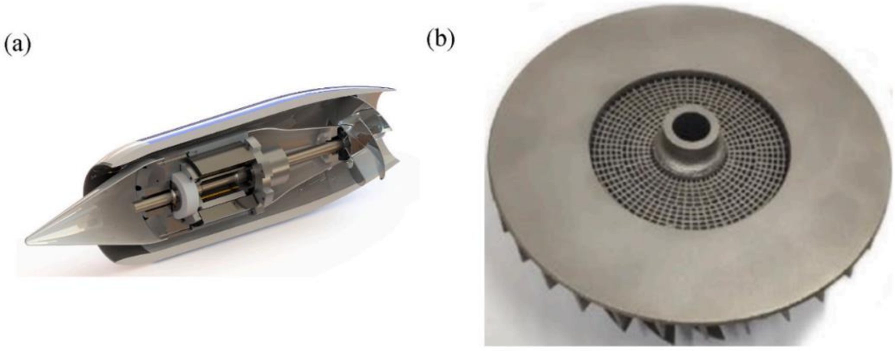


Figure 9: (a) Small underwater vehicle and (b) lattice compressor impeller for small vehicle [50]

4 CONCLUSION

SLM paves the way for resolving enormous challenges for designing and printing of complex geometries, which is ideal for fabricating lattice structures. Using this technology, lattice structures with highly tuned geometries and topologies can be fabricated to produce a wide variety of properties unachievable by their bulk materials. This technique was proven as a green and sustainable manufacturing process due to its material and energy saving as well as the elimination of CO_2 emission. Therefore SLM-fabricated lattice structures have found application in several sectors, especially aerospace and marine fields. In this paper, the development of additive manufacturing and its process chain were discussed. The effect on improving economic, environmental, and social sustainability was demonstrated. In addition, an overview of the SLM process was accomplished that highlights its working principle, advantages, and limitations. Furthermore, the concept of lattice structures was explained. Their classification, properties, and manufacturing techniques were presented, and their applications in marine and ocean technologies were introduced.

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