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Benefits of 3D printing technologies for aerospace lattice structures

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Abstract. The article makes a brief presentation of the latest 3D printing methods that are used for manufacturing aerospace lattice structures. Most 3D printing technologies are not fully deployed on the industrial scale of aerospace sector, but are rather used for rapid prototyping of components. One of the main potential applications is for them to offer a rapid solution for remote operations, where it is difficult to supply parts. Additive manufactured lattice structures are cellular structures based on biomimicry (inspired from nature lattice structures such as bones, metal crystallography, etc.), that possess many superior properties compared to solid materials and are ideal for fabricating aerospace structures mainly due to the mass reduction they introduce and the high strength-to-weight ratio. Their mechanical properties are defined by the infill percentage, the geometry of the cell structure and the material used in the manufacturing process.

1. Lattice structures

Lattice structures represent an innovative way of designing structures, by using repetitive arrays of unitary cells, in order to gain better performances such as reduced weight and higher resilience to applied loads. They are a part of a larger group of materials, called cellular materials, such as foams and honeycomb structures, but exhibit superior properties due to the specific development of their micro-architecture.

1.1. General facts

Lattice structure represent a viable alternative to classic cellular solids on account of their superior properties and have been widely used in various industrial fields. The development of additive manufacturing techniques such as 3D printing have allowed the evolution in complexity of the lattice structures design.

The main components of a strut-based lattice structure, as presented in figure 1, are as follows:

- the node - intersection point of the beams;
- the beams - that comprise the sides of the cells;
- the cells - which have different shapes and sizes depending on the beam's size and location.

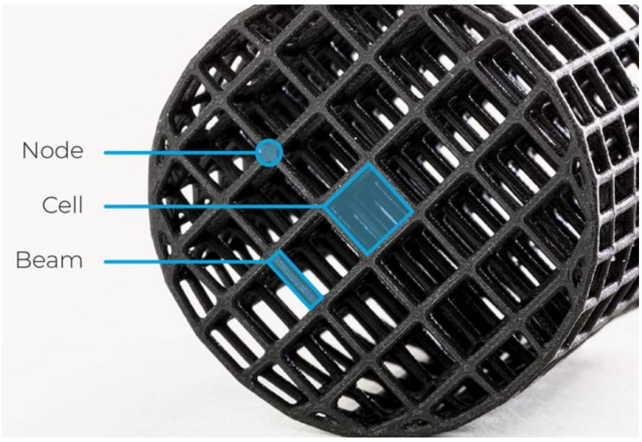

Figure 1. The main components of a strut-based lattice structure [1]

Some of the main characteristics to take into consideration when designing a lattice structure which will be manufactured thru additive manufacturing techniques are [2]:

- cell structure - there is a wide variety of cells available that have been developed to offer the desired structural response, such as high dampening or high strength-to-weight ratio;
- size and density of the cells - the size of the cell is defined by the thickness and the length of its components and the cell density determines how many unitary cells are repeated within the volume of the structure;
- material selection - the material properties are further transferred to the lattice structure, which in combination with the cell geometry and density, produce a structure with certain mechanical characteristics;
- cell orientation - represents the angle at which the cell is printed and is important because it establishes whether a support is necessary for the structure and where it should be placed.

1.2. Classification

According to the distribution and arrangement of the unit cells in the lattice structures, they can be classified in three categories [3], which can also be visualized in figure 2:

- random lattice structures - the unit cells are randomly distributed and have different shapes and sizes;
- periodic lattice structures - formed with cells of certain shape and sized, distributed in a periodic manner;
- conformal (pseudo-periodic) lattice structures - are similar with periodic lattice structures, but have cells of different sizes.

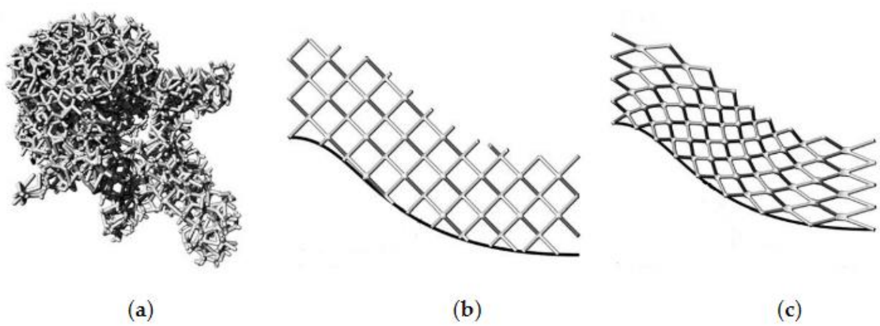

Figure 2. Classification of lattice structures by cell arrangement [3]

A special case of structures is represented by gradient lattice structures, characterized by cells of the same shape, with sizes that vary gradually. This allows a personalized density distribution by concentrating smaller cells in the zones more exposed to high strains.

Lattice structures can also be classified according to the unit cells they incorporate, into the following categories:

- strut-based cells - are composed of multiple beams which result in a 3D geometry with certain resistance characteristics such as the Kelvin, octet-truss and Gibson-Ashby cells presented in figure 3(a);
- skeletal-TPMS - are 3D geometries based on triply periodic minimal surfaces which exhibit certain symmetries such as IWP, diamond and gyroid cells presented in figure 3(b);
- sheet-TPMS - are based on the same geometrical characteristics as the previous category, with the difference that the walls are surfaces, such as the diamond, IWP, gyroid and primitive cells, represented in figure 3(c).

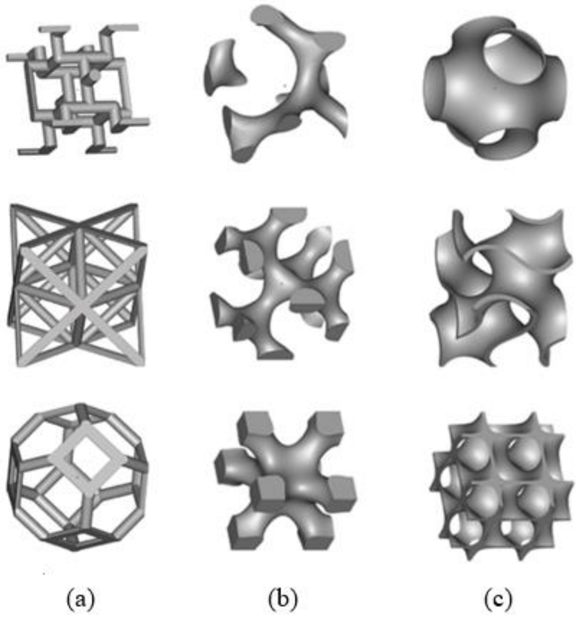

Figure 3. Classification of different cells for lattice structures - (a) strut-based cells, (b) skeletal-TPMS based cells, (c) sheet-TPMS based cell [4]

1.3. Main advantages

Lattice structures are generally used in manufacturing lightweight structures, where minimal material and energy loss is required.

There are numerous aspects of lattice structures which make them a more desirable constructive solution, compared to traditional structures. Some of which are worth mentioning are [3]:

- Good strength-to-weight ratio - is a result of the fact that the volume of a lattice structure is made predominantly out of air, depending on the infill grade attributed to the selected structure; latticing a structure has the downside of removing material even from critical areas of the part, but the mass reduction obtained can increase the overall strength-to-weight ratio;
- Good shock absorbing capabilities - when manufactured from materials which possess high strain capabilities, lattice structures offer very good impact protection, especially in the case of drops or collision, where they could be used to protect sensitive electronic equipment;
- Vibration and noise dampening - the manufacturer has the ability of eliminating the potentially harmful vibrations thanks to the low stiffness and high strain recovery ability of lattice structures, by refining the geometrical design;

- More complex geometry is achievable - 3D additive manufacturing techniques offer the possibility of fabricating very complex structures thanks to the layer-upon-layer approach of manufacturing.

2. How are lattice structures influencing aerospace structures?

Every structure which offers a potential mass reduction and a similar (if not superior) resistance to mechanical loads, is of high interest to the aerospace industry.

Although lattice structures have been incorporated in the construction of aerospace structures for a few decades in the form of isogrids of different shapes and sizes, the modern concept of lattices fabricated with additive manufacturing techniques is gaining credibility.

2.1. Main benefits for the aerospace industry

In permanent search of means to reduce the overall mass in order to maximize the payload, the aerospace industry is one of the biggest domains interested in lattice structures integrability.

When used in combination with additive manufacturing, lattice structures provide the aerospace industry with a consistent energy and material waste reduction, due to the manufacturing process and the specific geometry.

The total mass can be varied according with the infill, geometry and density of the lattice. The final mass reduction can then be utilized to increase the total payload of the aircraft/spacecraft, which increases the profit of user the company, as figure 4 implies.

Figure 4. Benefits of lattice structures for the aerospace industry

In the competitive aerospace domain it all comes down to profitability, which is the central and final objective of any aerospace company that used lattices. One final aspect which is taken into account is durability, which for lattice structures is not an issue, since their properties can be tailored to a certain degree by assigning the suitable material and lattice topology to the structure.

2.2. Review of current implementation status

Lattices have been extensively used in aerospace structures under the form of isogrids, in the interstages of rocket spacecraft and other fairings, with the purpose stiffening and strengthening components, while maintaining a low weight.

Isogrid structures are manufactured from a single sheet of material, by machining triangular openings to obtain basically a skin reinforced with a lattice structure.

Orthogrids are the precursors of isogrids and imply the same characteristics, but by using square openings on the surface. Although both of these structures have been used in aerospace engineering, the isogrid offers superior resistance properties, while the orthogrid aerospace structures benefited from lower mass.

Due to their relative high cost, isogrids are mostly used in industries where safety and precision is critical. AMRO is an American company who provides components for the future rockets which will be used for space exploration. In figure 5(a), a photo of the Orion crew capsule is depicted, made almost entirely out of orthogrid panels, while in figure 5(c), a component of the Vulcan rocket equipment shelf is presented [5].

Aircraft engines also benefit from the advantages of lattice structures. In figure 5 (b), the EJ200 Turbofan engine which equips the Eurofighter Typhoon Military Aircraft has its gas chamber and compressor outer casing made out of a barrel type isogrid structure.

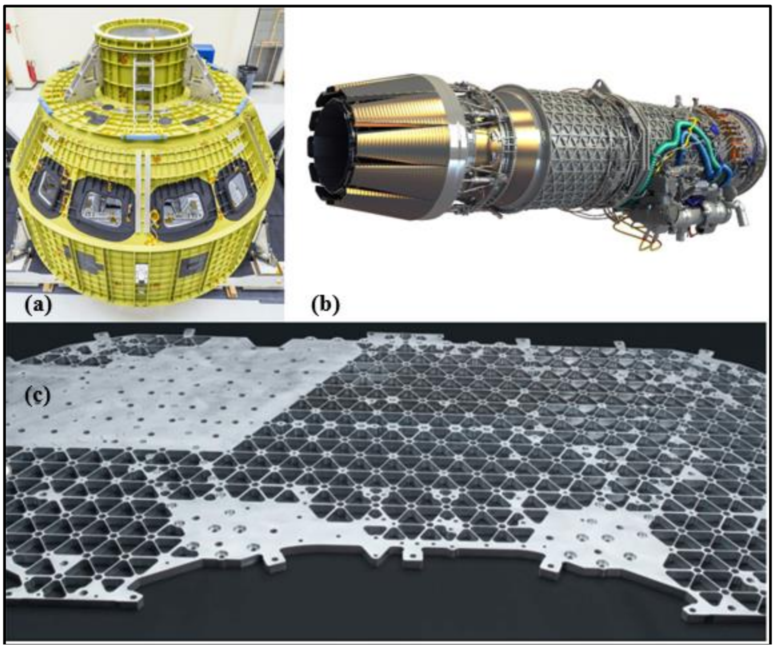

Figure 5. Current uses of lattice structures in aerospace applications - (a) Orion crew cabin; (b) EJ200 Turbofan Engine; (c) Vulcan equipment shelf

3. Overview of available 3D printing technologies for manufacturing lattice structures

Additive manufacturing (also known as 3D printing) is defined as the process of binding materials with the purpose of realizing a 3D model, thru successive overlapping of material layers [6]. It offers users of all categories the possibility of designing complex geometries and rapidly prototyping their concepts. These methods are suitable for realizing functional parts as well as parts with high finishing quality.

The success of 3D printing techniques is the result of the numerous domains in which they can be implemented. As figure 6 depicts, according to the statistical analysis realized by Wohlers Associates [7], the aerospace industry is one of the leading domains.

In the aerospace industry, the main requirements for 3D manufacturing are that it produces parts of high thermal and mechanical strength and a mass as low as possible. Polymers as well as certain metals (titan and nickel alloy) are the main materials used for the current development of 3D printed aerospace parts.

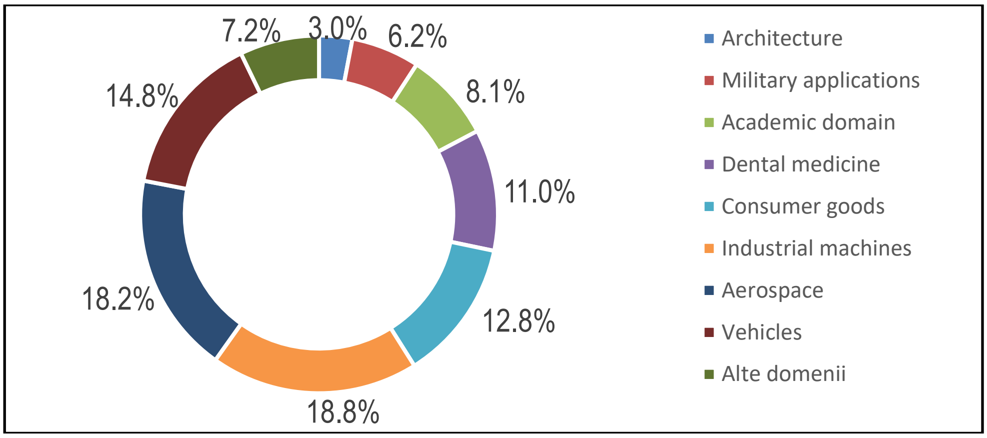

Figure 6. Distribution of 3D manufacturing technologies on domains of activity

According to the American Society for Testing and Materials (ASTM) [8], the main additive manufacturing technologies can be classified as presented in figure 7, with regard to the way the material is formed.

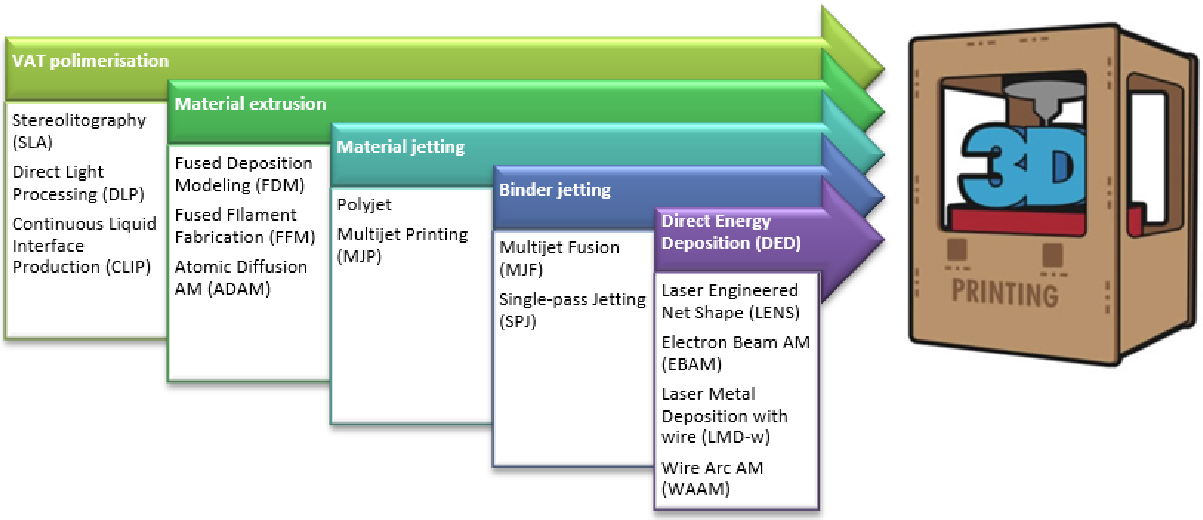

Figure 7. ASTM classification of additive manufacturing technologies, adapted from [8]

Out of all the previously presented method, thermoplastic extrusion (or F.D.M.) represents the most accessible choice, both financially and commercially. It was implemented in 1980 by Stratasys Ltd. but has developed significantly in the decade. The thermoplastic filament is extruded, whilst being heated until the melting temperature is reached and the model is formed by successively overlapping the layers of material based on a previously designed 3D model.

Currently, there are 3D printed parts being used in most of the passenger commercial airplanes. Diehl Aviation produces windshield curtain components from fiber glass for Qatar Airways [9], whilst Materialise has signed a partnership with Airbus to produce various interior finishing parts, thru thermoplastic extrusion [10].

When choosing the proper additive manufacturing method, the following aspects must be taken into consideration:

- Equipment acquisition (if necessary);
- Level of finishing needed (physical appearance);
- Material choice;
- Manufactured part's mechanical resistance;

- Printing speed;
- Printing temperature.

The additive manufacturing process is characterized by multiple stages, with certain specificities depending on the method utilized. Before the printing has started, the part must be designed in a finite element software in order to split the part in overlapping layers. The length of the manufacturing process depends on the size and the complexity of the part. The general steps to follow are presented in figure 8.

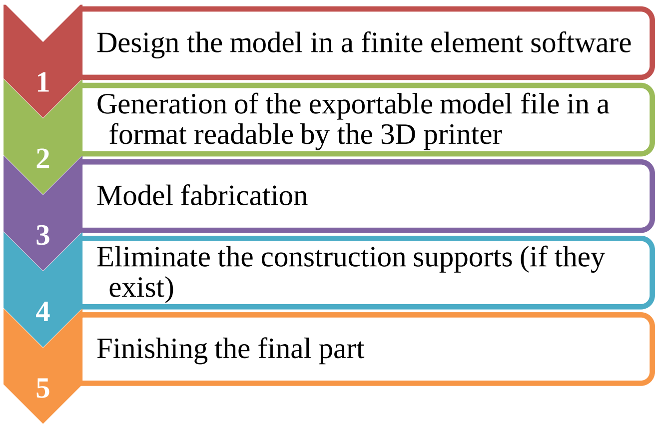

Figure 8. Main steps in 3D printing a structure

An important aspect of 3D printed parts to take into account is their anisotropy. The physical properties of the printed part depend on the part orientation at the moment of manufacture. This effect is especially visible at parts realized thru F.D.M., when the printing head moves to an upper layer, the inferior layer has already partially hardened. This results in weaker interlaminar strengths between upper and lower layers than between adjacent layers on the same level.

Lattice structures developed thru the use of additive manufacturing methods are not in practical use in the aerospace industry, but as 3D printing technologies will evolve to offer better products, it is only a matter of time until the benefits of lattice structures will be acknowledged.

4. Integration of lattice structures on certain aerospace components

One of the main components of an aircraft which could benefit from lattice integration is the engine. Take for example de compressor disk of a turboshaft engine. The disks are usually made from metal alloys with high resistance to the thermal and aerodynamic loads which occur in this area. With the proper material and manufacturing choice, the disk could be made with a hollow interior which significantly reduces the overall weight and also contributes in the uniform dissipation of heat across the part, as can be seen in figure 9.

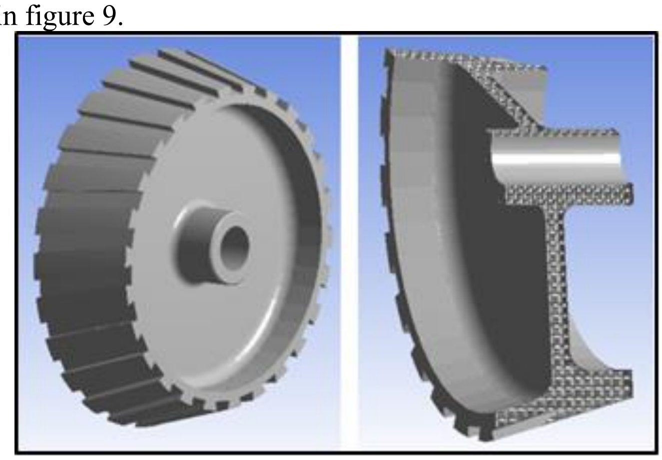

Figure 9. View of a section of the compressor disk with interior lattice

The tail rotor blade seen in figure 10 is also a desirable structure in which lattice cells could be integrated. This component is subjected to very high pressures, aiding the Tumansky R-11F-300 engine of the MIG 21 military aircraft in achieving a compression ratio of 8.9:1.

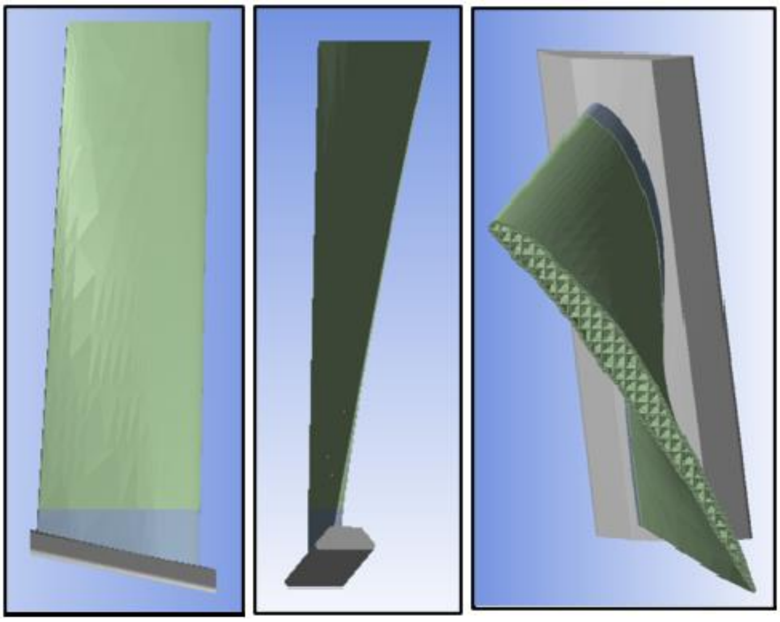

Figure 10. Compressor rotor blade - section view from above of the lattice structure

The section of the blade can be observed in the right side of the picture, from above. Such blades could benefit from the use of lattice structures due to the high thermal loads they are subjected to. Some of them are equipped with internal space that reduce their temperature, but with the use of an internal lattice structure, the cooling air could circulate freely inside the blade, assuring a proper heat distribution and a longer service life.

5. Conclusions

Nowadays, additive manufacturing and lattice structures are concepts that are almost always implemented together. The 3D printing of structures has brought about a new method of realizing complex designs, which traditional manufacturing methods were unable to achieve.

Lattice structures are indispensable for the future of aerospace structures, because they are defined by the very goals of this engineering industry: low mass, high resistance to loads and good thermal stress distribution.

Once the means of manufacture are perfected and the materials are realized so that they can be used under filament form, additively manufactured lattice structures will surely be a part of most aerospace structures and components.

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