A CASE STUDY ON DESIGN FOR ADDITIVE MANUFACTURING

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Table of Contents

List of Figures:

Abstract:

The past years in Additive Manufacturing has seen a wide range of research and focuses on the improvement of quality of the products, the various options of materials that can be used in the different additive manufacturing processes. The other perspective, where additive manufacturing process can improve is the design for additive manufacturing (DfAM). This case study presents an in-depth discussion on opportunities, hurdles, and economic considerations to be made for additive manufacturing from the design perspective with the help of literature survey, case studies, and industrial applications.

Introduction:

Additive Manufacturing (AM) is a manufacturing technology that has created a new door for manufacturing parts by adding layers to manufacture the part, just opposite to the subtractive manufacturing technique. It can also be simply called as layer by layer manufacturing process, and with the help of AM, it is possible to manufacture parts that are nearly impossible to manufacture with the help of other traditional manufacturing techniques. It is an expensive process and the user should know when not to use AM and use traditional manufacturing techniques considering the applications. For using AM to the fullest it is required to know the capabilities and the constraints that are posed by additive manufacturing.

Design for Additive Manufacturing [1]:

Additive manufacturing like any other manufacturing technique starts with a 3D CAD model and is converted into an STL file for manufacturing. Below is a process flow of how additive manufacturing works starting from the idea and ending up with the product manufacturing.

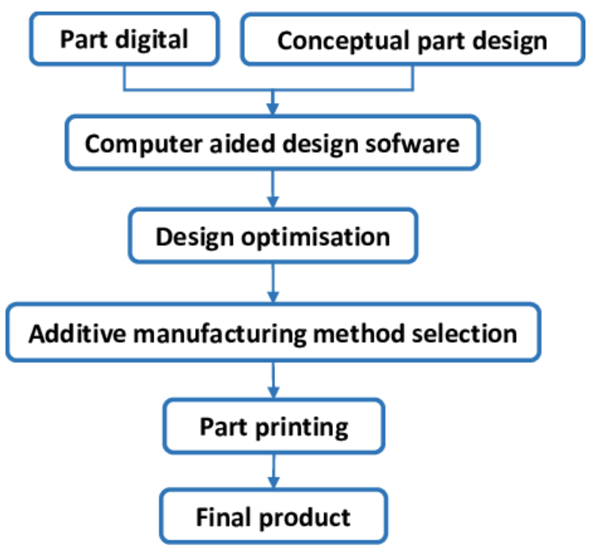

Figure 1: Additive Manufacturing Process Flow [2].

The process flow diagram shows that most of the steps involved in additive manufacturing lies in the design part of the process and it is important to have the best possible design before going into the manufacturing phase. As mentioned earlier it is an expensive process, most of the constraints posed by AM can be ruled out in the design stage of the product by having a proper set of guidelines and having the best possible product manufactured at the end.

Design for additive manufacturing can be seen from three levels, the macro-level where it deals with the part itself, the micro-level which involves the material, microstructure, etc. and the product level which is usually consolidating many functions into a single part.

Macro Level [1]:

Additive Manufacturing gives us a wide range of materials and it is possible to manufacture parts for having aesthetic values like jewelry, furniture, etc. which will have complex geometry and a wide range of customization is possible. With the help of additive manufacturing, it is possible to manufacture intricate internal free flow structures of a part which is not possible by other means of manufacturing. One such big area of work going on is the conformal cooling, by the help of additive manufacturing it is possible to have a complex die for injection molding with inbuilt conformal cooling systems within the die, which cools the die and gives a more efficient cooling process when the coolant flows through the dies instead of flowing around the dies of the mold.

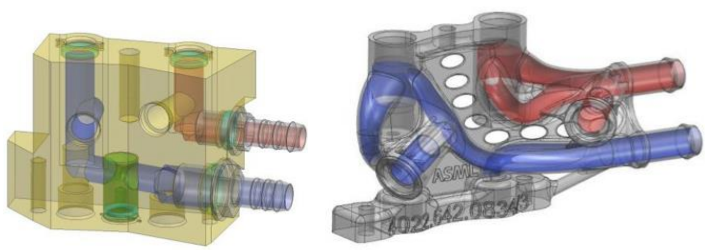

Figure 2: Internal Free Flow Geometry [1].

a) b)

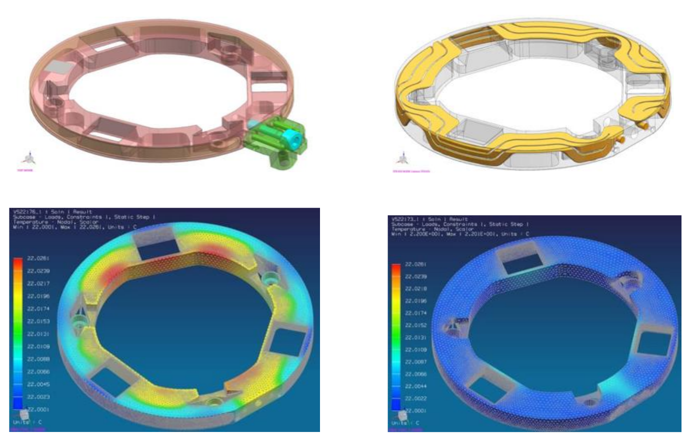

Figure 3: a) Thermal Conditioning ring with milled cooling channels

b) Additive Manufactured Ring with cooling channels[1].

The above figure of the thermal conditioning ring for a semiconductor industry manufactured by milling and additive manufacturing shows how additive manufacturing has helped in improving the thermal efficiency of the ring. The next big thing in the macro level is the topology optimization where additive manufacturing method stands out from other manufacturing techniques and it is discussed in the later section.

In the healthcare industry additive manufacturing is used as a customized tool for manufacturing where it is possible to manufacture custom prosthetics, custom made splints for writs ankles and even in the dental field.

Micro Level [1]:

There is a wide range of materials available for additive manufacturing and it is the only manufacturing process where material and geometry are formed at the same time. Because of this feature, it is possible to use custom made alloys by which parts with different mechanical property and even the thermal property from one point to other points can be achieved and this led to the development of multi-material part. It is also possible to get a custom surface finish based on the requirements of the application, as the surface finish totally depends on the material and the process parameters used for additive manufacturing.

The other big area in the micro-level additive manufacturing is the lattice structure. This is one of the best ways to improve strength in the desired direction by reducing the overall weight of the component.

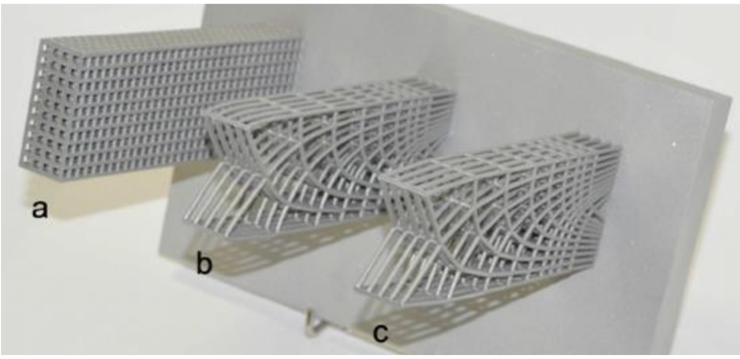

Figure 4: Beams with Lattice Structure Manufactured by AM[1].

Metamaterials are materials with properties that are not found naturally, and these metamaterials are can be classified into optical, electromagnetic, and mechanical metamaterials. The first two can be usually manufactured using microfabrication techniques, but the mechanical metamaterials can be manufactured only with the help of additive manufacturing. Many complex alloys like the soft magnetic composites (used in electric motor manufacturing) which are very hard to machine using the subtractive manufacturing process and can be easily used in additive manufacturing techniques. These are some of the design freedom at the micro-level that additive manufacturing offers, and other manufacturing techniques do not have this capacity.

Product Level [1]:

From the product standpoint of additive manufacturing offers a variety of options like parts consolidation – this is a technique of reducing the number of parts of the product and which in turn eliminates the assembly procedure or reduces the assembly process. It also offers the technique of embedding electronics or cores to add strength while the part is being manufactured.

Figure 5: Embedded Electronics by Additive Manufacturing[1].

And, also consolidating parts which have relative motion between each other is possible, but the designer should be sure about the clearance and the fit between the parts and also the behavior of the material during solidification in additive manufacturing such as shrinking, expansion, etc.

Topology Optimization for Additive Manufacturing:

Topology is a big area where additive manufacturing stands out from other manufacturing techniques. Topology Optimization is a numerical method that helps to identify where material should be present, and material should be removed over a design domain to provide the optimum material usage for the given loading and the boundary conditions. Usually, topology optimization often leads to a very complex structure, and manufacturing these complex structures using traditional manufacturing methods or even the with the subtractive manufacturing process is very difficult.

The numerical topology optimization is usually done using the SIMP method (Solid Isotropic Material with penalization) with either stress constraint optimization (SCO) or the compliance constraint optimization and this has two sub-categories: continuous (CCO) and discrete compliance (DCO). Considering additive manufacturing the thumb rule is to achieve a uniform relative density throughout the part to obtain the best strength and quality [3].

By, performing the topology optimization on cube using these three above mentioned processes and manufacturing the topology optimized shape using laser powder bed fusion process and it was found that the 98% relative density and also the mechanical properties found using the experimental results showed that the topology optimized parts performed well as indicated by the numerical values. The mode of failure observed in CCO and DCO was a shear failure while an axial failure mode was observed in SCO and this result can be useful to determine the topology optimization method to be used depending on the final application of the load. Meanwhile, the results showed that SCO gave best-optimized weight to strength ratio and the SCO method is time consuming computational method compared to the other two methods. The most important factor to be considered is that depending on the meshing quality the results obtained by the simulation methods will differ and it is important to decide on the mesh value based on the requirements [3].

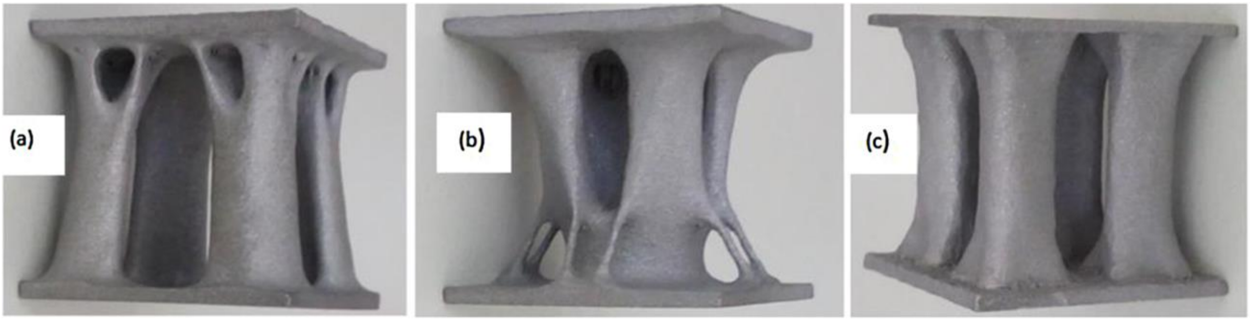

Figure 6: SLM-manufactured optimized structures: (a) Sample based on Abaqus DCO, (b) Sample based on Abaqus SCO, (c) Sample based on Opti struct CCO[3].

The combination of the topology and additive manufacturing can be widely used in the field of aerospace and automotive as these are the major field that aims to reduce the weight without any compromise to the performance of the parts. The following is one such case study of topology optimization of a connector, lever used in airplanes.

The main function of the connector is to provide support for an electrical connector, and the original connector was produced by assembling four individual parts using rivets. The major constraint to be taken into consideration for this part is the dynamic vibration and mechanical loading the part must withstand. As this connector is an assembly of four parts a major redesign consideration was made to make it a single piece before topology optimization and the two redesign models are shown in the figures. After this, the topology optimization was carried out using the SIMP method by defining the design and the non-design space, the non-design spaces are the area where the shape will not be changed as it might affect the intended function of the part. The final topology optimized part of the two different orientations which was obtained, and the red areas show where the part should have high relative density [4].

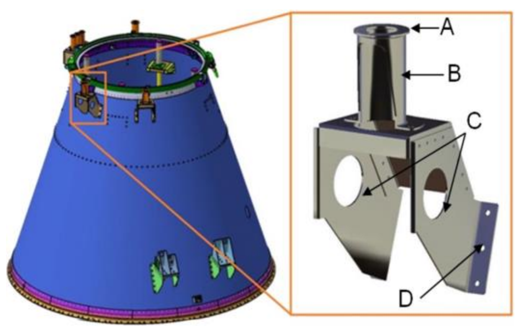

Figure 7: Actual Existing Connector[4].

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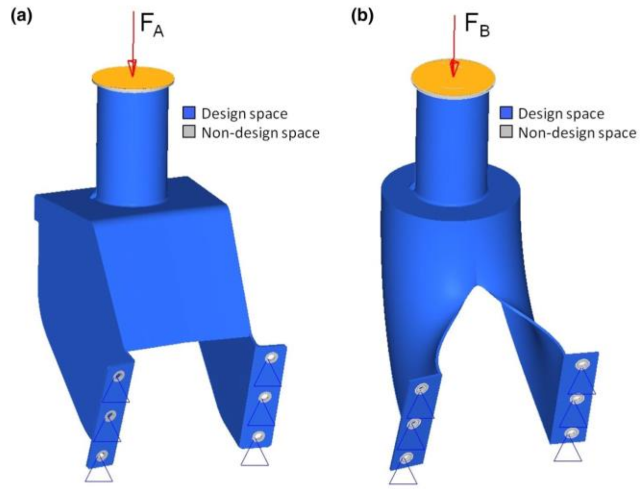

Figure 8: Loading Conditions & Redesigned Connector[4].

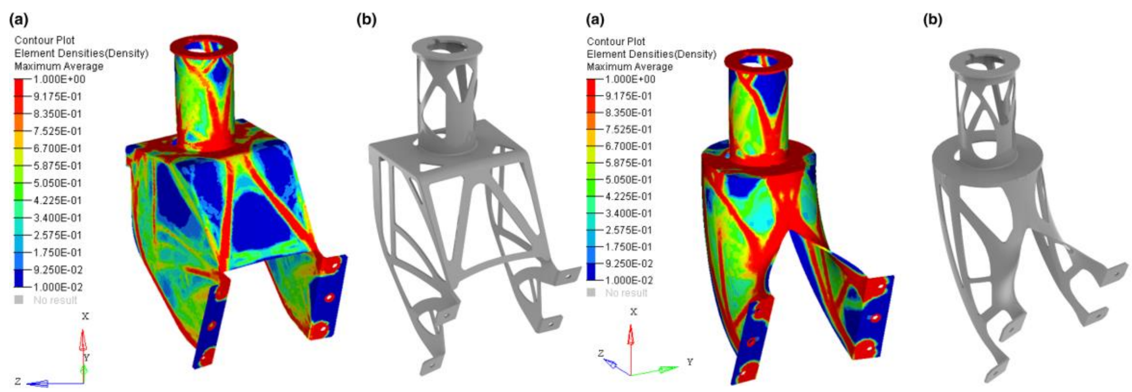

Figure 9: Topology Optimized Connector[4].

The topology optimized parts are then manufactured using the powder bed fusion process. Choosing the orientation is a very important step to move further in the process as the orientation will affect the relative density of the manufactured part which in turn will affect the quality of the product. The desired orientation is shown below in fig. Support structures are given in between the circular cut out area and this is to avoid any shape during the melting and the solidification of the part during the additive manufacturing process. The support structures are provided on between the build plate and the part instead of building it directly on the build plate, this will facilitate easy removal of the part without any damage to the part [4]. Even lattice structures are used in the part to reduce the weight even more, without losing the strength and this will be discussed in the later section of the report.

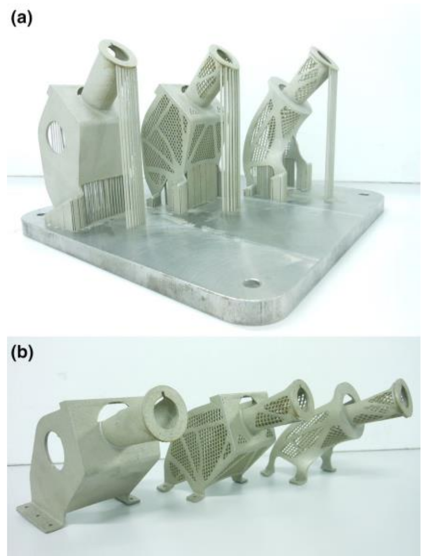

Figure 10: Build Orientation & Additively Manufactured Connector

[4].

The next part is the door lever of the airplane, and like the connector all the loading conditions were taken into consideration and the lever was subjected to topology optimization.

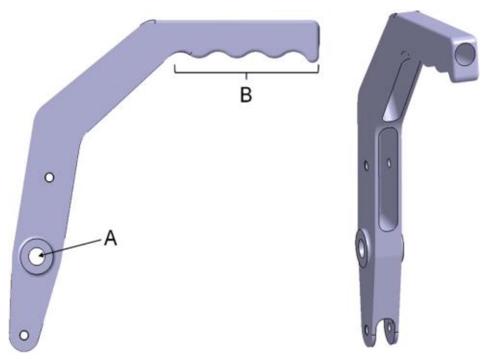

Figure 11: Actual Door Lever [4].

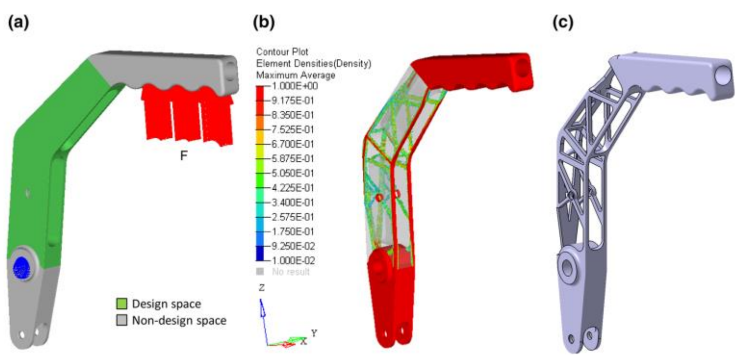

Figure 12:Loading Conditions & Topology Optimized Connector [4].

The build orientation of the part is vertical because the horizontal orientation the part will have a larger cross-sectional area and this might cause wrapping and in the vertical orientation the part is a self-supported structure as most of the overhanging structure is more than 45° angle and since its too tall only two support structure would be sufficient and even the topology optimized trusses act as supports [4].

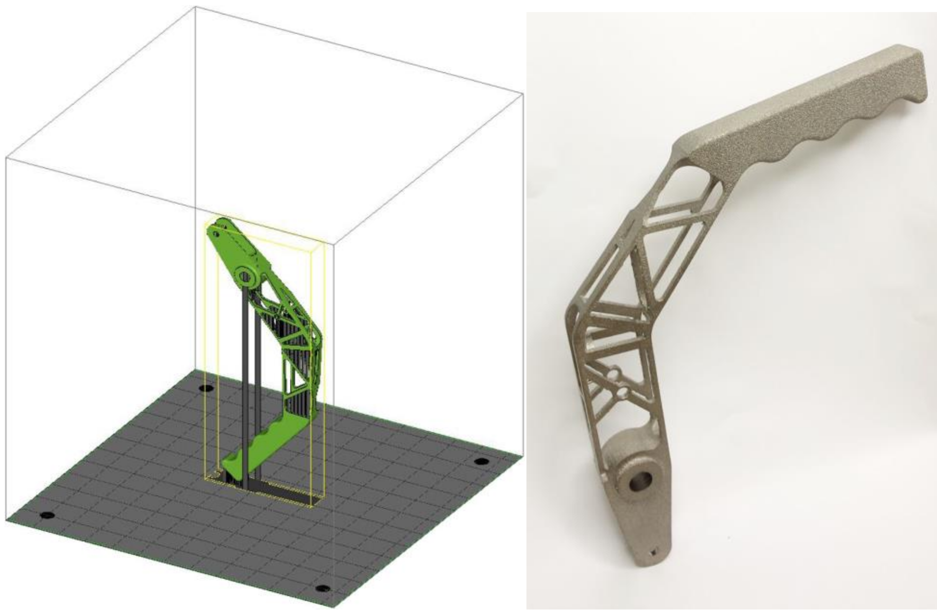

Figure 13: Build Orientation and Additive Manufactured Lever [4].

The topology optimized parts were found to be reduced around 60% and 30% in weight compared to the original weight of the connector and the lever respectively without any compromise to the actual function. These weight reductions will add a great value to the aero industry and similarly, many other parts can be topology optimized [4].

Lattice Structure [5]:

The main reason for additive manufacturing to stand out from other manufacturing techniques is the ability to manufacture complex structures with ease. The lattice structure is one such complex structure that has excellent and unique properties when compared to the solid structure. The lattice structure can be simply defined as an array of 2D or 3D cells arranged repeatedly in a space frame to form a structure. By using these complex structures, it possible to reduce the weight and have unique mechanical and thermal properties compares to the same part produced from a solid structure.

Even though there are seven types of standard AM process, the process should be selected based on the constraints posed by the individual AM process and the requirement of the product. For e.g. the strut size identifies the smallest shape, feature, and constrains the minimal unit cell of the given lattice structure. If we consider a powder bed fusion process this strut size is determined by the process parameters employed, the powder size employed during the manufacturing process. Since the lattice structure is thin and complex there might be a need for support structure and the post-processing removal of these support structures (which are not a part of the design) should be taken into consideration. For instance, if a fused deposition modeling is used the support structures can be by using chemical solvents which will dissolve the support structure, and in the case of the powder bed fusion process the powder itself will act as support structures. And by most other methods it is very difficult to remove the support structure as the lattice architect itself is a complex structure.

The design of the lattice structure starts by defining the unit cell which forms the entire structure and there are three major methods 1) primitive based method – in which the unit cell is defined as a particular geometric shape 2) implicit surface-based – in this method the unit cell shape is governed by a mathematical equation 3) topology optimization – in this method the shape is governed by optimized calculations. For the additive manufacturing process the major factor that governs the quality is the relative density of the part and to achieve the uniform relative density the best method to identify the shape of the unit cell is the topology optimization method as it uses a mathematical calculation to identify the optimal material distribution.

The pattern design is the next factor for consideration as it identifies the pattern in which the unit cell must be placed over the domain to achieve the best structure. The patter design usually has three methods 1) direct pattering – the unit cell in this method will place in a transitionally repeated method 2) conformal pattering – the unit cell placed according to a desired shape 3) topology optimization – this method can not only be used to define the unit cell design but also how the unit cell should be arranged in the given domain. The topology optimization as we already know using the SIMP method gives the best possible optimized design for the given loading and other constraint conditions. By integrating this topology optimization method with a lattice structure, it is possible to get the best possible optimal design without any compromise to the performance.

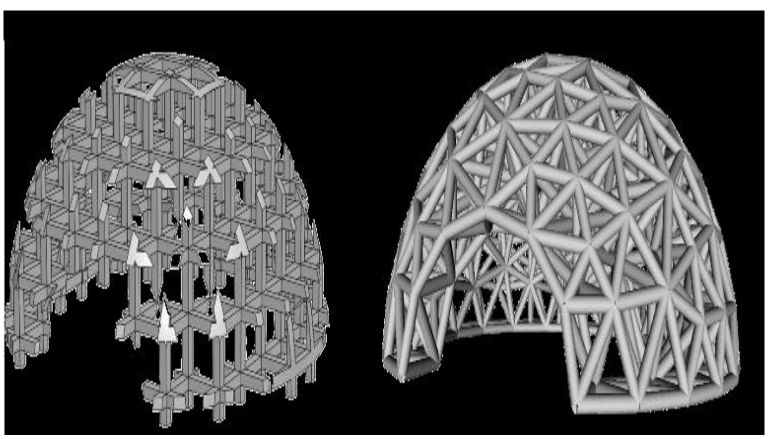

Figure 14: Conformal Pattern [5].

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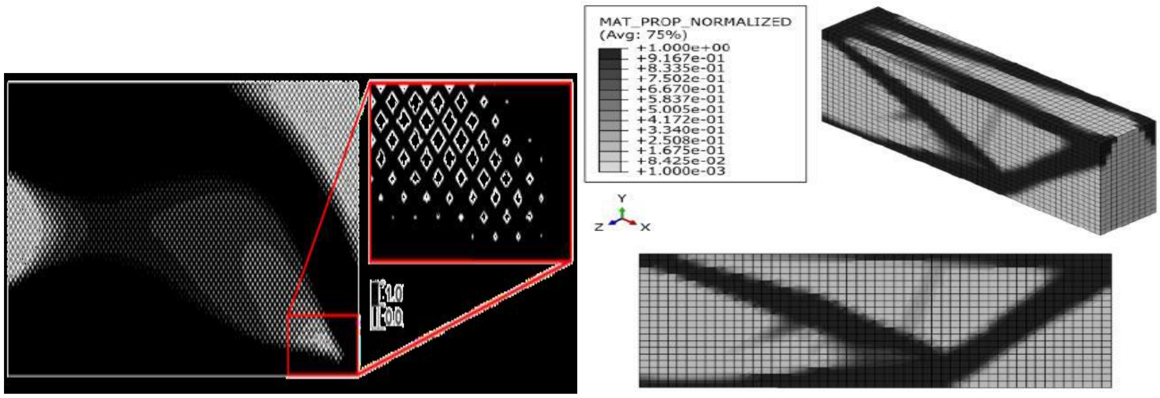

Figure 15: Topology Optimized Pattern[5].

The lattice structure properties depend on the material and the pattern of unit cell distribution and the porosity. The material is the baseline for determining the mechanical properties and since additive manufacturing is used the process parameter of the manufacturing process also governs the lattice properties. When a solid material is replaced by a lattice structure it is possible to get additional properties by using the correct lattice architecture, and the stability of the lattice structure can be determined by Maxwell stability criteria equation which is: $M = b-3j+6$, where b is the number of struts and j is the number of joints. When $M < 0$ the space is unstable or it can be said that the pattern will behave as a mechanism (this will bend under external loading in a the practical situation) and when $M \geq 0$ the space frame is fully constrained and acts as a rigid structure (this will carry a compression or tensile loading). In other words, these are called bending and stretch dominated the architecture respectively.

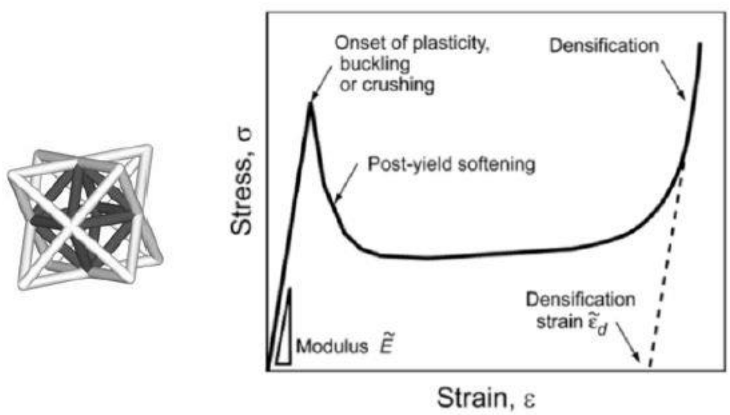

Figure 16: Stress Strain Relationship of Stretch Dominated Lattice Structure [5].

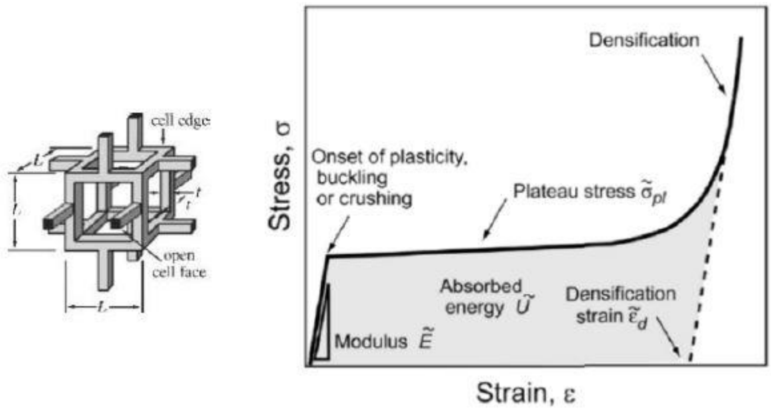

Figure 17: Stress Strain Relationship of Bending Dominated Lattice Structure [5].

From the figure, we can see that stretch dominated architecture the unit cell shape is usually triangular ad the latter one is square-shaped. And from the stress-strain graph, we can also infer that the two layouts have a vast difference in the mechanical properties. The stretch dominated structure is usually used when lightweight parts with high stiffness and strength are required and the bending dominated structure is usually for high energy absorption application with good bending strength.

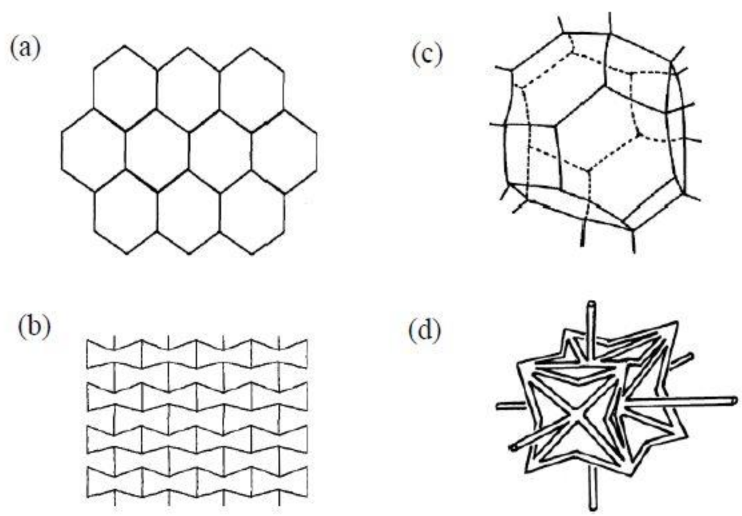

Figure 18: Auxetic Lattice Structure [5].

In between the two above mentioned lattice structure, the stretch and the bending constraint there exist one lattice structure called the auxetic structure. The unique nature of the auxetic structure is the Poisson ratio is usually seen as a negative value. The structure with positive Poisson ratio when subject to a uniaxial loading the structure shrinks transversely under tension condition and expands outwards in compression state, but in the auxetic structure either if the loading is compression or tension this structure deforms laterally.

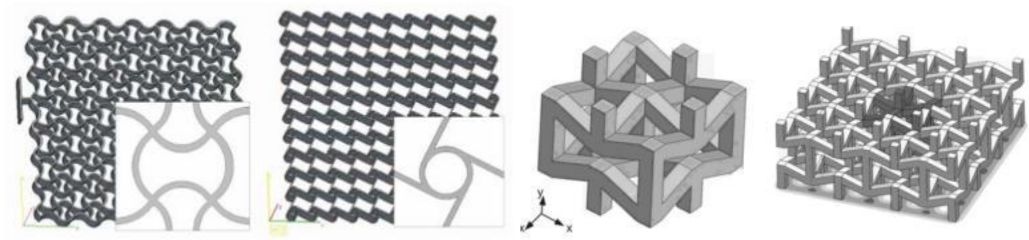

Figure 19: Additively Manufactured Auxetic Lattice Structure [5].

The auxetic structure-property solely depends on the lattice structure and by carefully choosing the lattice structure it possible to auxetic structure with exhibits superior qualities like toughness, tear resistance, traverse shear resistance.

The most crucial factor to be understood during the design of lattice the structure is to know the mode or how the failure of this structure will take place. If the structure is overloaded more than the actual loading it could withstand than the failure mode will by the failure of the struts, which is influenced by factors like plastic yielding, elastic buckling or permanent break and these are again interrelated to material and architecture configuration.

Due to the humongous amount of advantages the lattice structure poses it finds ways in a variety of applications, and most of their usage in aerospace and automotive industries where weight reduction is a major factor. One such application was discussed in the previous section on topology optimization of connector for airplane and the lattice-like structure were used to reduce weight and improve strength. For e.g. FIT West Corp used the powder bed fusion process and manufactured a cylinder head with an internal lattice structure and was able to achieve 66% and the lattice structure surface area helps to improve the cooling efficiency. Due to the mesh-like structure of the lattice, they are also used in air filters. The lattice structure application is also used in healthcare industries. The successful surgery was reported by implanting 3D printed lattice structure ribs into a human body with the electron beam powder bed fusion.

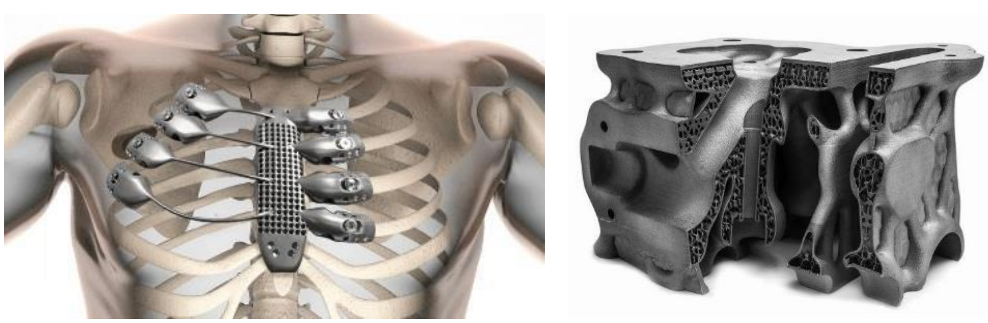

Figure 20: Application of Lattice Structure in Human Ribcage (on the left) and Automobile Cylinder Head (on the right) [5].

Hybrid Manufacturing:

Hybrid Manufacturing is a new age technology where additive manufacturing technology can be combined with other traditional manufacturing techniques. Various techniques like additive manufacturing coupled with machining techniques like milling to have a good surface finish, additive manufacturing coupled with re-melting to improve the surface hardness. Additive Manufacturing process like DED (Direct Energy Deposition) can be coupled with a regular 5-axis CNC machine where it can be used just another tool, and this application can be used for repair of products and even for manufacturing for new components like turbines and other complexes structure, and even functionally graded materials are manufactured with this hybrid additive manufacturing techniques. So, when the initial idea of the component is decided the designer should take into consideration these advantages and design part accordingly.

Application of Design for Additive Manufacturing:

A real-time application of applying the design for additive manufacturing is discussed in detail below, this project is additive manufacturing of portable laptop cooling pad using material extrusion of polymer (PLA as the material) (The design is actually not suitable for additive manufacturing but the parts had to be made by 3d printing techniques so I have improved the design to use the advantage of additive manufacturing). The major parts are the arms which should withstand the weight of the laptop and the bottom case and the top case acts as a housing for the motor and the fan.

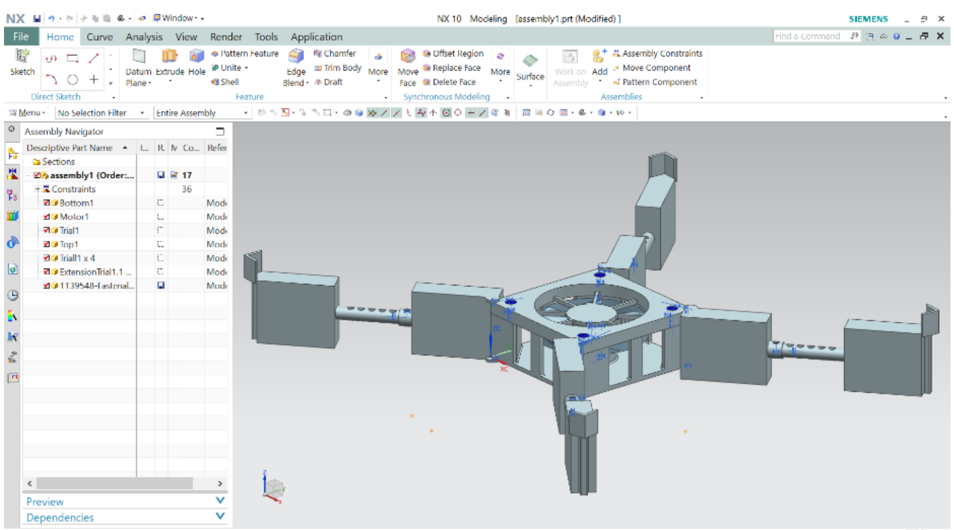

Figure 21: Laptop Cooling Pad.

The original design of the arm was a solid material block and when subject to static stress analysis, the factor of safety turned out to be very high and turned out to be over-engineered, so there is an option to reduce the factor of safety and to do this we can optimize the shape by using topology optimization or we can use lattice structure instead of solid, and manufacturing of the lattice structure is an easy process with additive manufacturing.

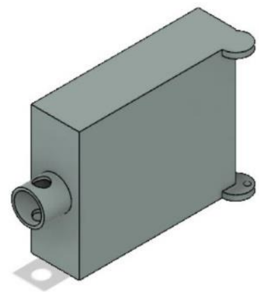

Figure 22: Actual Solid Block Arm

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The Topology optimization of the arm is done with the help of Autodesk Fusion 360 with giving appropriate loading and boundary condition, and the regions whose shape changes would affect the intended function of the part was preserved so that its shape does not change during topology optimization. By using this method, it was possible to reduce the weight by around 50% of the original weight.

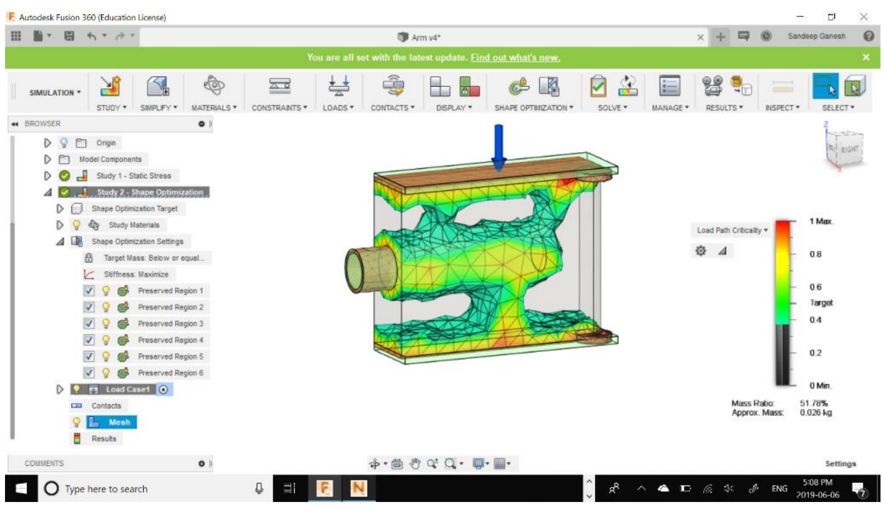

Figure 23: Topology Optimized Arm.

The next method of optimization is by using the lattice structure inside arm instead of having a solid fill and we can define the pattern and shape of lattice structure according to the needs. For this application triangular unit cells for the structure have been used, because this is the best possible way to have a light structure with high stiffness and strength. The lattice structure was developed using Autodesk Netfabb. By using this lattice structure, the volume and weight were greatly reduced without changing the external appearance of the part.

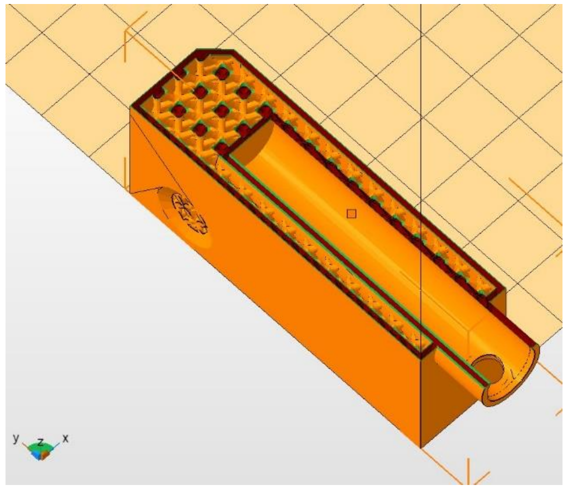

Figure 24: Topology Optimized Arm.

The next part chosen for shape optimization is the bottom case of the part as this part was also a solid part. The only function of the case was to house the motor and the fan and, and it does not require more strength as almost the entire weight of the laptop is taken up by the arm. The case should facilitate airflow to reduce the heat the generation and increase the cooling efficiency of the motor and as discussed earlier the lattice structure can be used in place of airflow requirements like in an air filter etc.

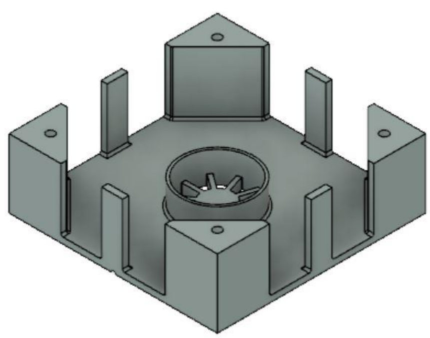

Figure 25: Bottom Case

Using the Autodesk Netfabb, it was able to achieve a complete lattice structure of the bottom case and by using this the airflow inside the casing will improve and increase the cooling efficiency. Figure shows the lattice structure bottom case. This is optimization is done as additive manufacturing has the advantage of manufacturing these complex structures very easily compared to the other manufacturing techniques.

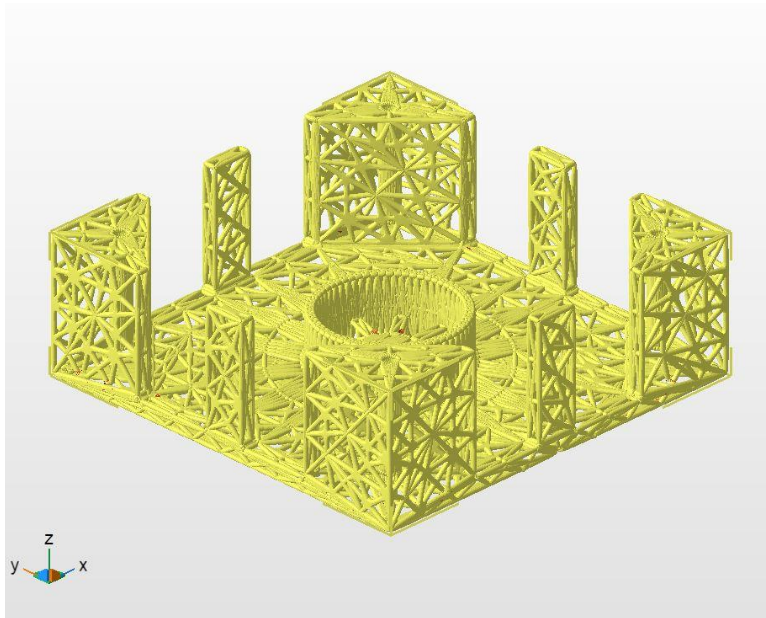

Figure 26: Lattice Structure Bottom Case.

The main requirement of the portable laptop cooling pad is, it should as light as possible and by using the shape optimization techniques as shown in the above figures it possible to reduce the entire weight of the cooling pad and also the usage of material can also be reduced drastically without losing the strength of the part.

Constraints related to Additive Manufacturing [1]:

To summarise, AM poses many constraints even though it gives a lot of opportunities. For instance, the orientation of a part can affect the quality and surface finish. A part with complex shapes and many faces can have a difference in the surface finish in a particular face due to the orientation of the part. The process parameters of the AM process can also affect the quality of the part, as the current AM machine has only the capacity to monitor the process parameters, so if the future AM machines have the capacity to monitor and control the process parameter in real-time during the manufacturing process can have a major impact to produce good quality parts and can also eliminate the need for post-processing. The other major constraint is the use of support structures in additive manufacturing because this is nonvalue added and the more support structure the need for post-processing increases. So, designing the part to have so that it should have minimum support structures would be an ideal design. Apart from these, there are many other constraints posed by AM like when consolidating a part (to have a smaller number of parts), it can lead to difficulty in post-maintenance, service.

Conclusion:

From the above discussion and the case studies presented, it shows that additive manufacturing has a wide range of opportunities in the area of topology optimization, lattice structure. There can be many more advancement in the field of additive manufacturing by using a proper set of guidelines in design for additive manufacturing as this most part the process relies purely on the design of the part.

Future advancements in CAD software will be very much needed with the focus of design options for additive manufacturing.

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