Topological Optimization of Brake Pedal for Metal Additive Manufacturing: A Case Study

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Received: 19 May 2021, Revised: 9 June 2021, Accepted: 17 June 2021

Abstract: Additive Manufacturing (AM) has become popular for rapid prototyping and it is presently widely used in different branches of industry because of its advantages such as freedom of design, mass customization, waste minimization and the ability to manufacture complex shape. AM is the process of making 3D object from computer model data by depositing of material layer by layer. Topology optimization is iterative modifying the shape and optimizing material within a given designs space for load, boundary condition thus leading to weight reduction of components. Thus, to form lightweight components which have great advantage where energy consumption is minimal, topology optimization is used. Reducing weight and decreasing the material usage while keeping the product functions are the main challenges. Studies on the integration of the topology optimization and additive manufacturing, specifically mass reduction attract considerable attention. The topology optimization process is employed in this case study, to redesign a lightweight automotive brake pedal to show the potential of topology optimized design for additive manufacturing. As a result of this study 54.07% weight reduction was achieved in the total mass. The thermo- mechanical analysis for additive manufacturing showed that the part without topological optimization 108 MPa of stress and 1,099 mm of displacement were obtained and after optimization they were 196,1 MPa and 1,295 mm, respectively.

Keywords: Additive Manufacturing, Analysis, Light Weight, Topological Optimization

How to cite this paper: Batuhan Izgi, Meltem Eryildiz, and Mirigül Altan, "Topological Optimization of Brake Pedal for Metal Additive Manufacturing: A Case Study" , Int J of Advanced Design and Manufacturing Technology, Vol. 14/No. 2, 2021, pp. 123–130. DOI: 10.30495/admt.2021.1931105.1285

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1 INTRODUCTION

Recent advances in the fields of Computer-Aided Design (CAD) and Additive Manufacturing (AM) have given designers the tools to rapidly generate an initial prototype from a concept. Additive Manufacturing (AM) refers to the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. The differences between subtractive and additive manufacturing are displayed schematically in “Fig. 1”.

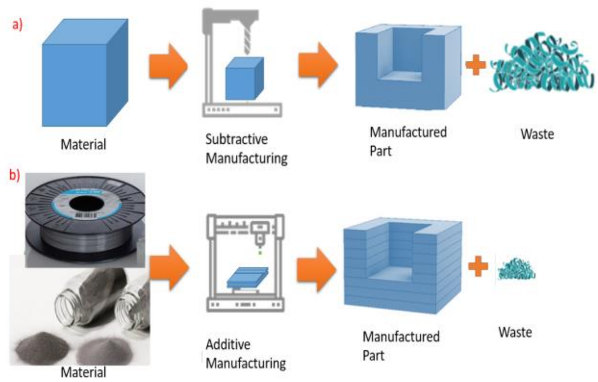

Fig. 1 Schematic illustration of a) subtractive manufacturing, b) additive manufacturing.

AM is categorized according to material state like solid based, powder based, and liquid based as shown in “Fig. 2”.

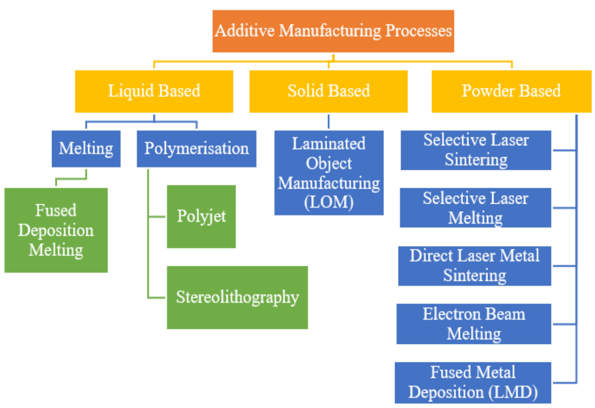

Fig. 2 Classification of additive manufacturing processes.

These techniques have its own unique set of competencies and limitations [1-4]. Regardless of the differences in material deposition mechanism, all AM technique adopts the same basic approach which has five steps in the process flow as shown in “Fig. 3”. A 3D-printing process starts with a digital model of the object to be printed. The virtual model can be achieved using a three-dimensional scanner (like CT), Computer-Aided Design (CAD) software, or by making use of photogrammetry technology which obtains the model through the combination of images of the object obtained by a photo scanning process performed from different positions. The 3D model needs to be converted into an STL file after creation. This STL file contains a list of coordinates of triangulated sections which store the information about the model’s surfaces. All 3D printer software can read STL files, and then slice the object to obtain a series of 2D cross section layers by a Z direction discrete approach. Finally, the desired 3D object is created using layer by layer printing [5].

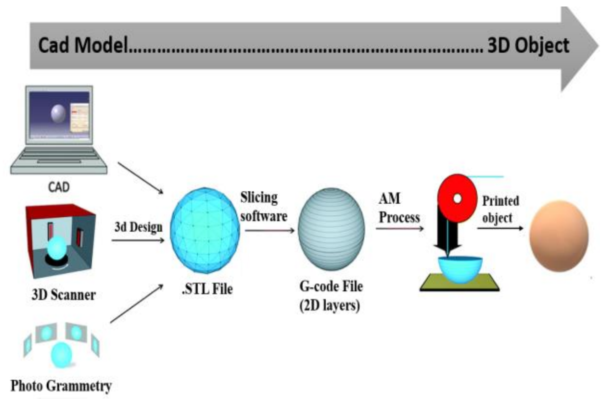

Fig. 3 Schematic illustration showing the AM process flow.

The metal 3D printing process can be used to manufacture complex, bespoke parts with geometries that traditional manufacture method is unable to produce. Metal 3D printing parts can be used for topology optimization to maximize their performance while minimizing their weight and the total number of components assembled. The extensive applications of the 3D metal printing technologies are most broadly utilized for aerospace, automotive industries as mentioned [4].
Topology Optimization (TO) is an advanced structural design method which can obtain the optimal structure configuration via reasonable material distribution satisfying specified load conditions, performance and constraints. Compared to sizing and shape optimization, topology optimization is independent of the initial configuration and has a broader design space (“Fig. 4”).

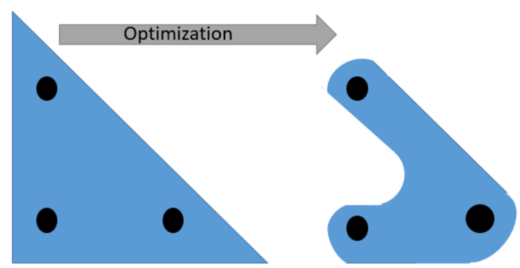

Fig. 4 Topology optimized AM parts suitable for light weight structures (before and after).

Most of the topology optimization techniques are carried out by collective use of Computer Aided Design (CAD) concept, Finite Element Analysis (FEA) concept and different optimization algorithms in consideration of different manufacturing techniques as shown on the topology optimization process on "Fig. 5". The use of CAD in topology optimization is to make a rough/initial model of the product to be optimized, whereas FEA is used to see the distribution of stresses and displacements throughout the product. The topology optimization is performed to remove the areas of the part that are not sufficiently supporting the applied loads and not undergoing significant deformation and thus not contributing to the overall performance of the part [4], [6].

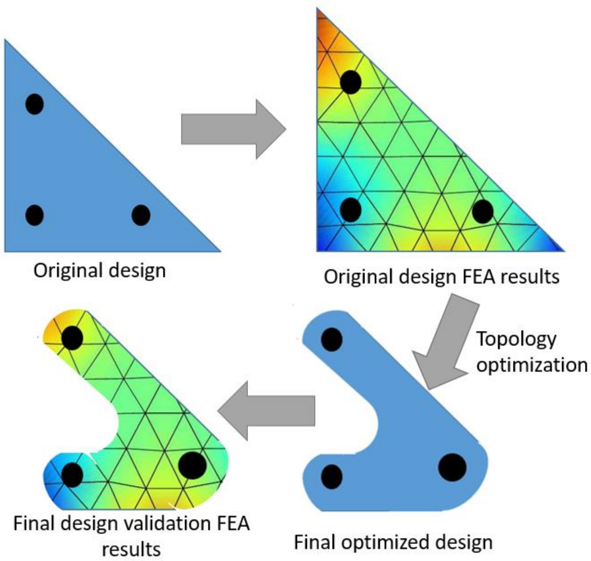

Fig. 5 Topology optimization process.

Additively manufactured components need to be created with reliable and repeatable mechanical and material properties. Figure 6 shows topology optimized design process.

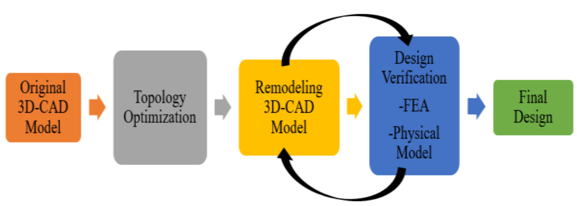

Fig. 6 Topology optimized design process flow.

First, the original CAD design is drawn in a 3D-CAD modelling software. The original design is then structurally analysed with the given loading conditions to see the stress and displacement distribution. Based on the stress and displacement distribution, the topology optimization removes material from areas that does not significantly contribute to carry the applied loads. Based on the topology optimization result the part is remodelled in a CAD software. The new CAD model is then verified with FEA to carry the loads and to satisfy the design requirements. If the model satisfies the verification physical model, verification is done using any of physical prototyping methods. If not, the remodelling is done again until verification is done. The final design is then prepared for the final additive manufacturing [6], [9]. After several years of intensive research, it has been developed as a mainstream structural design technique for high-performance, lightweight as well as multifunctional structures and been widely used in aerospace, automotive, architecture, etc. Topologically optimized structures are generally characterized with complex geometric configuration. Therefore, it is difficult to manufacture these innovate structures via conventional processes (e.g. machining, cast), thus additive manufacturing is a good potential of topology optimization [7]. Using CAD models enables one to optimize the design of elements to be further built by AM. Topological optimization allows shape adaptation taking into account only the functional properties (mechanical) without constraints related to the processing technology [8].

An important aspect of the topologically optimized design for Additive Manufacturing is to create self-supporting components, or when not possible, components with the minimal number of support structures [9]. However, topologically optimized designs are often not AM friendly because a topologically optimized design has 'props' that improve the structural rigidity but are overhanging. Overhangs cannot be printed in AM polymer processes because there is no supporting layer beneath them [10]. This problem is solved by creating support structures for the overhanging parts. These props will require additional support structures to prevent drooping' and 'burning'. It is beneficial to minimize the amount of support material. Less supports contribute to the faster printing time, less cleaning of the 3D model, and reduces the overall price of the object. The support structure not only wastes material and consumes printing time, but also increases the roughness of the surface which is in touch with support structure. Many researchers have focused on new topology optimization approaches that can automatically account for such overhang limitations. Bracket et al. [11] made several recommendations on integrating TO and AM in order to minimize support structures. Leary et al. [12] proposed a method that modifies the theoretically optimal topology into a support-free one. The topology optimisation process has also been applied successfully to minimize weight of components. It has been demonstrated that the use of topology optimisation for minimising the weight of aircraft or car parts reduce the fuel consumption and emission gasses, such as carbon dioxide and nitrogen oxide. Monaheng et al [13] used topology optimization and the optimized design and percentage of weight saving are presented in their study. Melissa et al. [9] demonstrated the value of topology optimization combined with AM for fabrication of light weight components. Topology optimization can be employed for new product design or redesigning of an already existing product so that lightweight product can be obtained while maintaining its functional requirements. Topology optimized lightweight design can be realized by using different materials internal structures: solid structures or cellular structures. Topology optimization with additive manufacturing is considered to redesign a bracket to reduce its weight from 70 gr to around 42 gr, which is about 40% reduction [6]. There is also another study conducted by Emmelmann et al. [14] about re-designing a bracket with more lightweight that was manufactured using laser additive manufacturing. These geometries are very difficult to manufacture using the traditional techniques but they can be realized with additive manufacturing. Studies on the integration of the TO and AM, specifically for mass and support minimizations are still ongoing. This study aims to discuss how topology optimization can be applied to optimize the design of a brake pedal for additive manufacturing process to produce automotive brake pedals with reduced material weight. Topology optimization was performed on the brake pedal to design a lightweight component for production in metal 3d printing. Each optimized design is subsequently analyzed with a separate Finite Element Modeling routine to simulate its performance under the prescribed loads for which it is designed. The topology optimization process is employed in this case study, to redesign a lightweight brake pedal to show the potential of topology optimized design for additive manufacturing.

2 EXPERIMENTAL PROCEDURE

2.1. Initial Design of Brake Pedal

There are many components that control the movement and dynamics of a vehicle. However, there are not many components that are in direct contact with the driver and one of these key components is a brake pedal. A brake pedal acts as a switch for the driver to stop the vehicle and it is a critical part of the vehicle. During the emergency braking, a huge force from the driver is transferred into the brake system within the least time, making the pedal brake to provide great mechanical strength and resistance to hold the force. Current automotive brake pedal uses conventional manufacturing method such as metal press and CO2 welding processes, which are known to be heavy, costly and demand higher quality control.

Figure 7 shows the technical drawing of the initial brake pedal. The brake pedal material used in this study was AISI 316L. The material properties are given in “Table 1” . [15] The CAD model of the initial brake pedal is shown in “Fig. 8”. The initial brake pedal consists of 4 parts like foot rest, arm, link and sleeve. The force was applied from foot rest. Supports and pins were applied to sleeve part. The function of link is to maintain the arm brake pedal location during the non-braking event, thus this part is ignored in this study since it is not involved during the braking event. The arm part was optimized in this study. The total mass of the initial design, excluding the mass of the link, was 1.1598 kg.

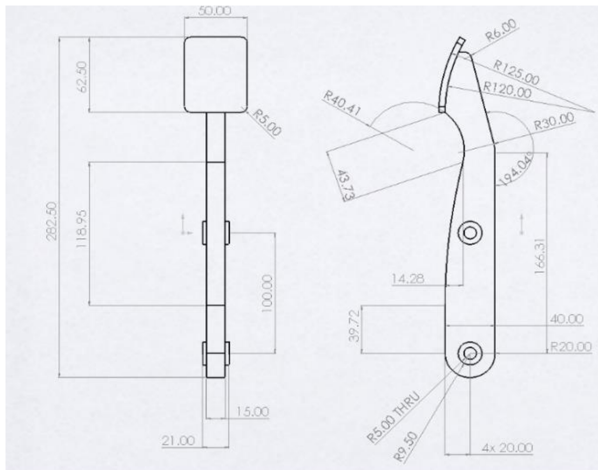

Fig. 7 Technical drawing of the initial brake pedal.

Table 1 The properties of AISI 316L

Properties	AISI 316L
Yield Point, MPa	205
Ultimate Tensile Strength, MPa	515
Modulus of Elasticity, GPa	193
Izod impact, J	150
Hardness, Brinell	149
Elongation at Break, %	60
Density g/cc	8
Melting Temperature,℃	1375-1400
Specific Heat Capacity J/g-℃	0.5

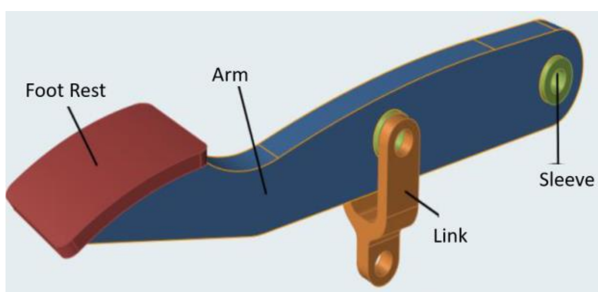

Fig. 8 3D design of the initial brake pedal.

2.2. Boundary Conditions

In order to test the performance of the lever brake pedal, the brake force requirement was determined based on the work of Limpert [16]. In this study, it has been suggested that the maximum force applied with the right foot is 823 N for men and 445 N for women. For maximum performance evaluation, a maximum force of 823 N was used in this study. This force was applied to the footrest in the -Z direction. Three pins were used and supports were applied to both of them to rotate. The load case to be used in this study is shown in “Fig. 9”.

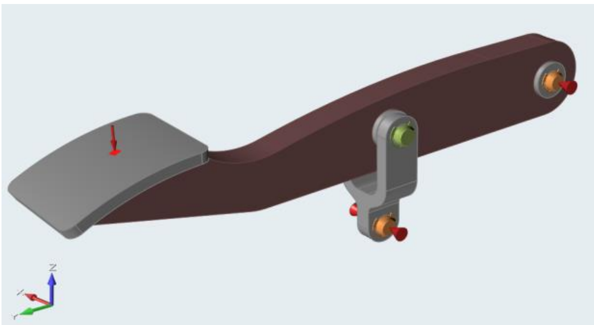

Fig. 9 The load case.

A structural analysis was conducted to evaluate the performance of the initial brake pedal design. The element size of the analysis was 4.131 mm. The results of displacement and the Von Misses stress are shown in “Figs.10 and 11”, respectively.

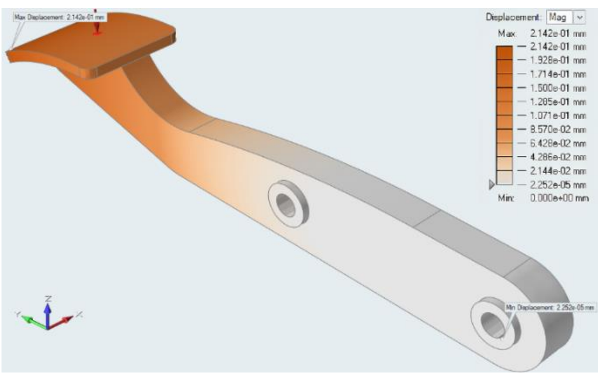

Fig. 10 Displacement on the initial design.

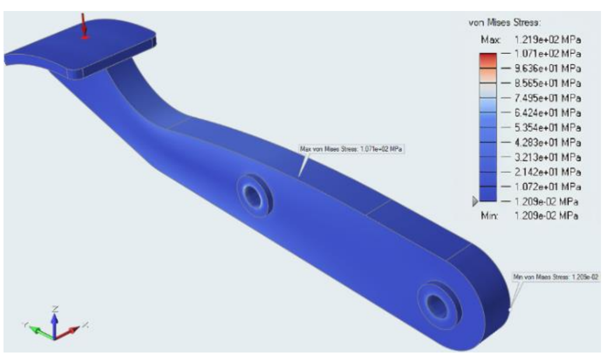

Fig. 11 Von Misses stresses on the initial design.

According to the results of the structural analysis, the maximum displacement that can occur on the initial design was 0.2142 mm and the maximum von Misses stress was 121.9 MPa. These results showed that the initial design can withstand the applied load case.

2.3. Topology Optimization Approach

Altair Inspire software was used for topology optimization of the brake pedal. It is processed to generate a topologically optimized model, eliminating the non-necessary mass in the part, hence reducing the mass of the brake pedal without affecting its structural integrity. The factor of safety and the minimum thickness constraint have been taken as 1.2 and 12.806 mm, respectively. The topology optimized design is shown in “Fig. 12”.

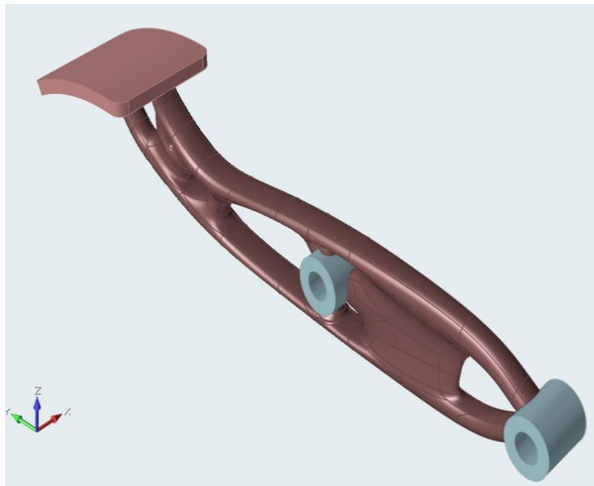

Fig. 12 Topology optimized design.

Another structural analysis was performed to ensure that the topology optimized design can withstand the applied load case. The analysis results of the optimized design of safety factor, displacement and the Von Misses stress are shown in “Figs. 13, 14 and 15”, respectively.

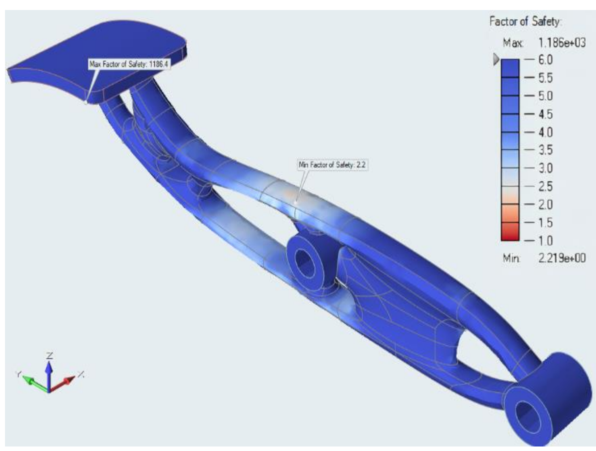

Fig. 13 Factor of safety on the optimized design.

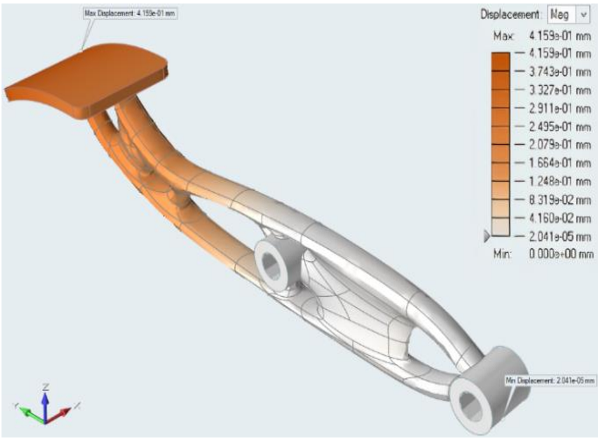

Fig. 14 Displacement on the optimized design.

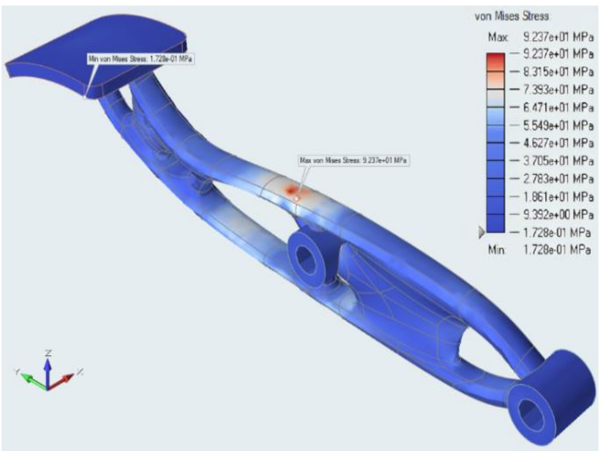

Fig. 15 Von Misses stresses on the optimized design.

According to “Fig. 13”, the minimum safety factor of 2.2 is obtained for the optimized design. It is seen in Fig. 14 that the maximum displacement is 0.4159 mm and as shown in Fig. 15, the maximum Von Mises stress becomes 92.37 MPa. The total mass of the optimized design, excluding the mass of the link, is 0.533 kg. The optimized design can withstand the applied load case.

2.4. Additive Manufacturing of the Initial Design and The Topologically Optimized Design

All possible orientations were determined to minimize the total area of undercut surfaces and hence minimize the support required for additive manufacturing by using the options of the software. Minimum distance between print bed and the part is selected as 5mm. The oriented initial design and the oriented optimized design and their supports are shown in “Fig. 16”. Square profile is selected for the supports. The total mass of the oriented initial and the optimized design with supports is 1.164 kg and 0.6 kg, respectively.

Thermo-mechanical analysis was performed for the additive manufacturing. 600 W laser power, 1200 mm/s laser speed, 0.03 mm layer thickness were used for the thermo-mechanical analysis.

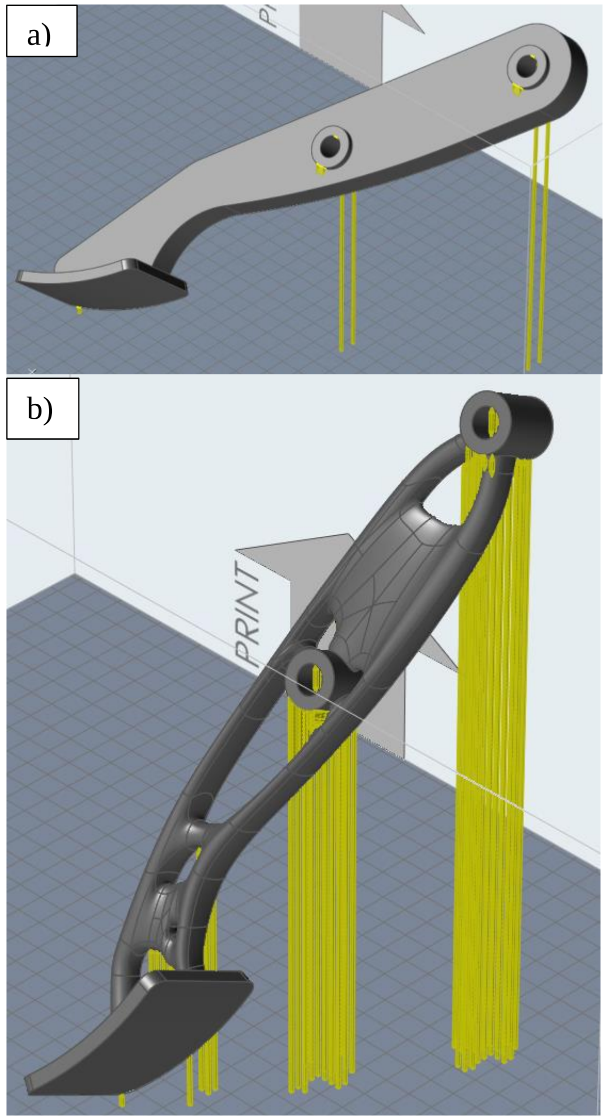

Fig. 16 Generated supports and orientation for a) the initial design, b) optimized design.

3 RESULTS AND DISCUSSION

Comparison between the initial design and the optimized design is given in “Table 2” . According to the results, mass reduction was achieved in the total mass but the total support volume was increased for the optimized design. Also, printing time increases as a result of the increased support volume.

Table 2 Transitions selected for thermometry

	Printing time, s	Support volume, m^3	Total mass with supports, kg
Initial Design	18862.25	15000	1.1644
Optimized Design	30714.42	124000	0.6

The initial design acts as a support itself, as there are not many holes or gaps in the design part. Therefore, support is less in the design. The displacement on the initial design is shown in “Fig.17”.

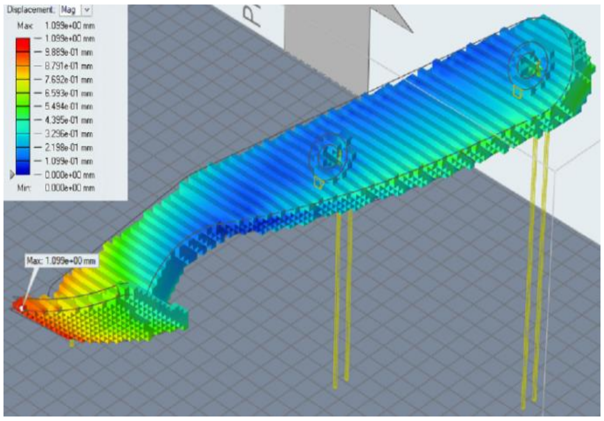

Fig. 17 Displacement on the initial design during AM.

As shown in “Fig. 17”, the maximum displacement on the initial design during additive manufacturing is 1,099 mm and the maximum displacement position is around the end of the footrest of the pedal. The Von Misses stress on the initial design is shown in “Fig.18” and the highest stress is obtained as 108.9 MPa.

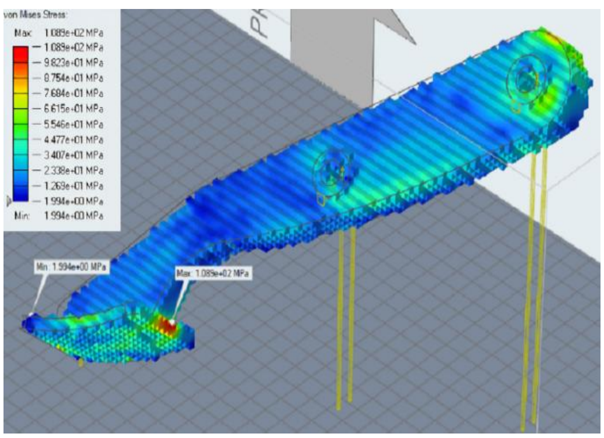

Fig. 18 Von Misses stresses on the initial design during AM.

The displacement and the Von Misses stress on the optimized design during additive manufacturing are shown in “Figs. 19 and 20”. As shown in “Fig. 19”, the maximum displacement in the optimized design is 1.295 mm and the maximum displacement position is around the end of the footrest of the pedal. The Von Misses stress on the oriented design is shown in “Fig. 20”, the highest stress is 196.1 MPa.

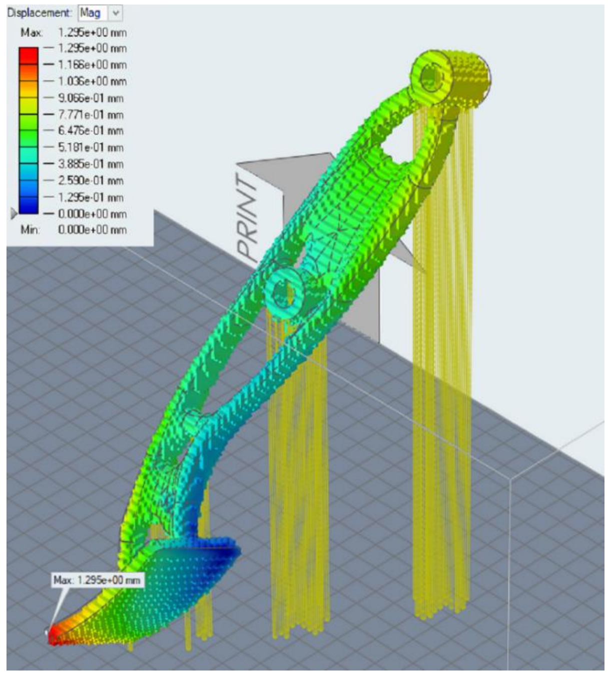

Fig. 19 Displacement on the optimized design during AM.

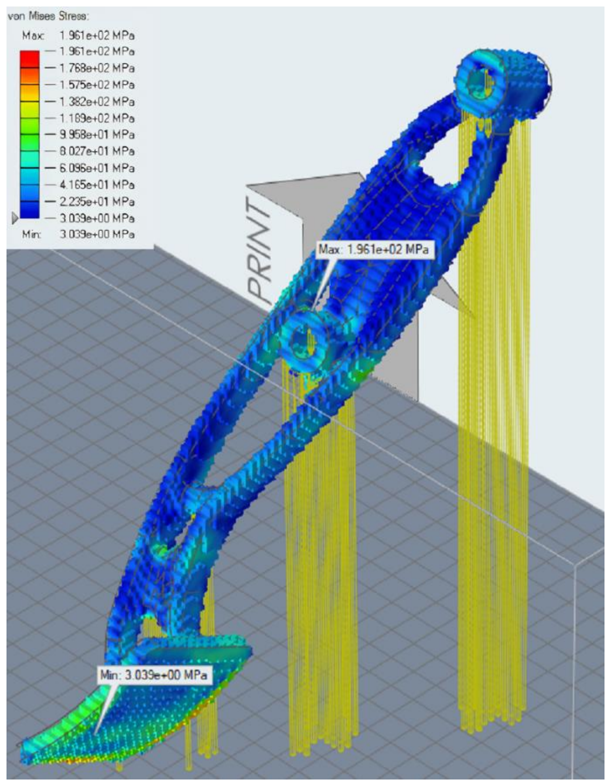

Fig. 20 Von Misses stresses on the final design during AM.

This step in the holistic process is included to simulate the design concept to understand the behaviour of the structure and to insure that the new design is suitable for the use in which it was intended. If the simulation and modal analysis results indicate that the optimized design is not sufficiently robust (e.g., the margin of safety is too low), the previous topology optimization step is revisited to create a more robust solution, which is then verified with FEM. The feedback loop continues until the topology optimized part has been verified to possess a desired margin of safety through numerical simulations [17].

5 CONCLUSION

The aim of this paper is to propose a topology optimization that leads to designs with reduced mass and support structures. For the design of a brake pedal, structural topology optimization and additive manufacturing are proposed; As a result of this study 54.07% weight reduction was achieved in the total mass but the total support volume was increased. Also, printing time increases as a result of the increased support volume. The part without topological optimization gave 108 MPa of stress and 1,099 mm of displacement and after optimization they were 196,1 MPa and 1,295 mm, respectively.

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