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DESIGN OF CUSTOMIZED IMPLANT SLM MANUFACTURED

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Abstract: Additive manufacturing has the potential to change how customized implants are fabricated but challenges remain. The present work aimed to reduce the weight of a facial titanium implant and to fabricate it by selective laser melting (SLM) process. Finite element analyses (FEA) were used to determine the von Mises stress and total deformation, applying loads from 0.5 kN to 5 kN. The results show that loads over 1.5kN distributed high von Mises tensions beyond 1000 MPa, value which was considered the yield point of titanium alloy (Ti6Al4V). The proposed redesigned model was 10% lighter and the FEA simulations reveal that the von Mises stress and total deformation are similar in both models (initial vs. redesigned). The polished SLM surfaces significantly reduce the roughness. The Sa roughness parameter calculated on the unpolished areas was 27-35 µm and on polished areas between 3 to 5 µm. Additionally, a lightweight concept with integrated lattice structures is presented. Future work is required to develop and test (mechanical and biological), new design concepts for facial implants.

Key words: *facial implant, titanium alloy, von Mises stress, selective laser melting, surface roughness.*

1. INTRODUCTION

The manufacturing technologies are in constant growth and change, each of them evolving in their own way. One of the most significant developments is the groundbreaking emergence of Additive Manufacturing (AM) technologies, commonly known as 3D Printing. With its capacity for manufacturing intricate customizations and complex shapes, AM has influenced various industries and is particularly poised to reshape the medical field. This brief overview delves into the realm of medical engineering, an interdisciplinary field at the crossroads of engineering, biology, and medicine, where technological advancements converge to revolutionize healthcare solutions. AM technologies have the potential to transform patient care through precise models, instruments, and customized interventions, heralding a new era of healthcare innovation [1], [2].

A great influence in the medical field, especially when talking about customizable implants, is the evolution of the selective laser melting (SLM) technology. SLM is an AM process that enables production of complex and high-precision parts through the laser melting of metal powders, layer by layer. The melted alloy solidifies rapidly upon cooling, creating a solid layer. The build platform is then lowered, and a new layer of powder is applied on top of the previous layer. The process is repeated until the complete part is built [3], [4].

This technology is suitable for various applications such as:

- Patient-specific implants: SLM enables the production of patient-specific implants tailored to individual anatomical requirements. By using medical imaging data, such as Computer Tomography (CT) scans, SLM can fabricate implants with complex geometries that precisely fit a patient’s anatomy. This includes orthopedic applications like hip and knee replacements, cranial and facial reconstructions [5-7].
- Surgical instruments and guides: SLM can be used to manufacture customized surgical instruments and guides. Surgeons can benefit from tools that are specifically designed for a particular procedure. SLM enables the production of complex, lightweight, and ergonomic surgical

instruments that enhance surgical precision and efficiency [8].

- Bioresorbable implants: SLM allows for fabrication of bioresorbable implants, which gradually degrade and get absorbed by the body over time. Bioresorbable implants are particularly useful in applications such as bone fixation, where temporary support is needed during the healing process [9-11].
- Dental applications: SLM technology is employed in manufacturing dental prosthetics and orthotics. Prosthetic limbs and orthotic devices, such as braces and supports, can be designed, and produced to match unique needs and specifications of individual patients [1].
- Tissue engineering scaffolds: SLM is used in tissue engineering to create scaffolds that provide structural support for regeneration of tissue. SLM can produce intricate and porous structures with defined pore sizes, allowing cells to infiltrate and grow within the scaffold. These scaffolds can be used in applications like bone regeneration or cartilage repair [1], [5].

The use of SLM offers several advantages, including the ability to create complex and customized designs, achieve precise fit and functionality, and use biocompatible materials. These advancements contribute to improved patient outcomes, reduced surgical complications, and enhance quality of life for patients.

The purpose of this paper is to reduce the weight of a facial titanium implant and to fabricate it by SLM process. The design procedure involves CAD conversion of STL file and finite element analysis (FEA) focused to determine the von Mises stress and total deformation, where various forces were applied (between 0.5 kN to 5 kN). The surface quality of SLM implant was optically investigated.

2. MATERIAL AND METHODS

2.1 Design steps

This paper describes the stages undertaken from design to manufacture and post-processing. The subject of this study is an implant that needs to be integrated in the anterolateral margin of the eye (Figure 1). This is an area where several bones of the skull converge to form a bony orbit. The bones involved in this region include the frontal bone, zygomatic bone, and greater wing of the sphenoid bone.

Initially the patient CT scan was processed to create an accurate 3D reconstruction of their bone structure. After processing the model, this was saved as an STL file. In the next phase, a meticulous CAD model of the implant was designed, focused on the affected area. The STL file was transformed into a solid model (CAD), for proper FEA simulations [2]. The design of the implant mirrors the healthy bone structure.

Fig. 1. Facial implant focused on this study.

Using Ansys SpaceClaims built-in automated commands was sufficient for this geometry conversion, as shown in Figure 2. The automated tools in SpaceClaim were effective, though it’s important to note that enhancing the conversion process requires a finer mesh and a preliminary skinwrap to increase accuracy.

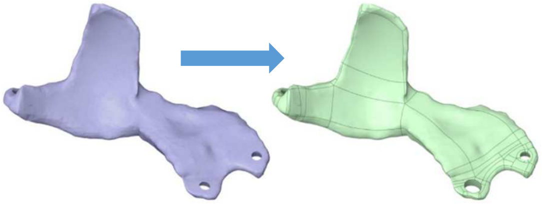


Fig. 2. Conversion from STL to CAD

Dealing with edges angled at 120° is important, as the software doesn't process them accurately and manual adjustments were needed. During the conversion, some faces might be lost, leading to gaps that need manual correction to fill properly [12]. Despite these efforts, there’s a possibility that certain parts of the model might not convert well.

2.2. FEM simulation

To reduce the weight of this facial titanium implant, FEA simulations were used. Once the STL model has been successfully converted into a conventional CAD file, the static study was conducted using ANSYS software [13]. The model was imported into the solver and re-meshed, which can be challenging due to the non-conventional geometry. The Patch Conforming Method, smaller element size (1.8 mm in this case), and Capture Curvature setting are recommended to ensure accurate meshing and geometric integrity (Figure 3).

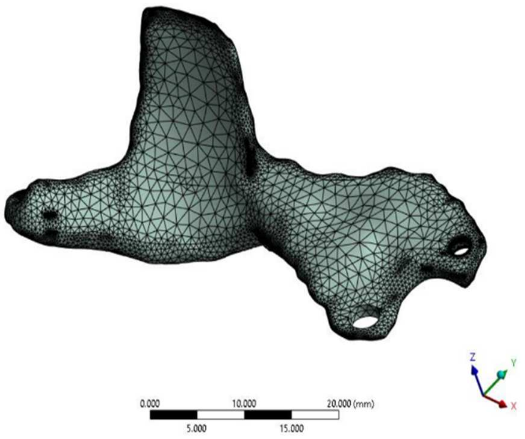


Fig. 3. Mesh overview

Boundary conditions are shown in Figure 4. Since the implant will be fixed with screws, fixed support is applied to the holes and its area. Material properties are assigned from the ANSYS Material Library, specifically Ti6Al4V, which belongs to the AM biomaterials (details in Table 1). Notably, this material differs from conventional ones, being more temperature dependent.

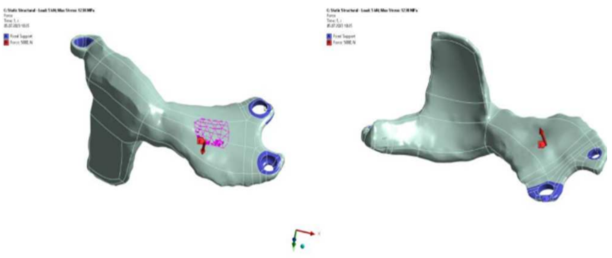


Fig. 4. Boundary conditions: Fixed area and load zone.

The simulations are carried out at an environmental temperature of 36°C to match the human body's average temperature. The maximum allowable equivalent stress is set at 1000 MPa as a safety criterion. This value corresponds to the yield strength of Ti6Al4V, indicating the limit of elastic behavior and the beginning of plastic one (see Table 1). To determine the von Mises stress and total deformation, loads between 0.5 kN to 5 kN were applied to explore the implant behavior under different conditions. Every force was applied constantly and uniformly, and the direction of it was perpendicular to marked area (see Figure 4 – purple area).

Table 1

Physical-mechanical characteristics of Ti6Al4V alloy used in FEA simulation.

Young Modulus [MPa]	Poisson Ratio	Density [g/cm^3]	Yield tensile strength [MPa]
105	0.35	4.51	1000

2.3 SLM manufacturing and surface investigation

To manufacture the redesigned facial implant, a Realizer SLM 250 machine was used (Figure 5). Under layer-by-layer principle, this machine can produce directly complex custom implants made of bio-metallic powders. The present Ti alloy powder was purchased from MP4 company (Austria) and it was obtained by argon gas atomized process. The shape morphology of grains is spherical and is detailed in Figure 6. The melting point is 1670°C and the apparent density is 2.49 g/cm^3 (according to ISO 3923). The flow rate measured with a calibrated funnel was 29 seconds for 50 grams (according to ISO 4490). The particle size was analyzed by laser diffraction according to ISO 13322. The particle size distribution is described in percentiles: d10, d50 and d90. These d-values indicate that 10%, 50% and 90% of particles are finer than this diameter. The results are summarized in Table 2.

Table 2

Ti alloy particle size distribution.

Characteristic	Method /Standard	Result
d10	ISO 13322-2	19 µm
d50	ISO 13322-2	31 µm
d90	ISO 13322-2	43 µm

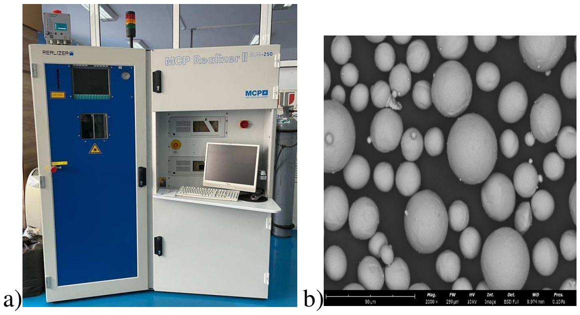


Fig. 5. a) Realizer SLM 250;
b) SEM image of Ti alloy powder

The following SLM parameters were configured to print the implant: 110 W laser power, 400 mm/s scanning speed (40 µm Point Distance and 100 µs Exposure Time), 50 µm layer thickness, and 0.10 mm hatch distance. These SLM parameters irradiated the Ti powder bed with 55 J/mm^3 density energy. The orientation of implant on SLM platform was carefully investigated to reduce the number of layers (see Figure 6). Moreover, the support structures were designed to be 4 mm in height. This distance allows us to use a wire-cut EDM machine for removing the implant from SLM platform.

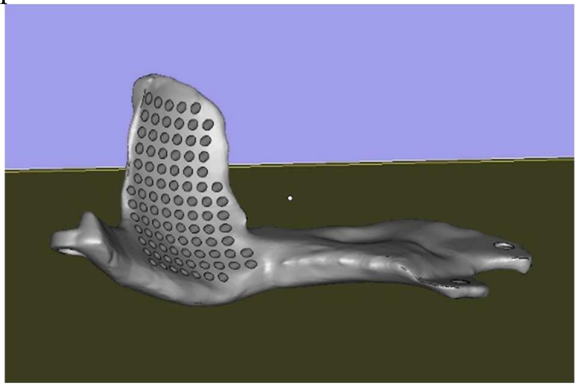


Fig. 6. Implant building orientation on SLM platform.

The surface investigation was performed using an Alicona G4 Infinite Focus (Alicona Imaging, Austria) microscope. This optical profilometry system uses Focus-Variation technology to extract the 3D morphology and depth information from curved surfaces [14], [15]. This investigation was performed on the redesigned model which was SLM-manufactured. Some areas of the SLM implant were polished using a pneumatic straight grinder with carborundum tools.

3. RESULTS AND DISCUSSION

3.1. FEA results of initial design

The applied load of 0.5 kN represents an extensive masticatory force and 5 kN can be a high collision impact. The von Mises stress and total deformation were determined in each scenario. The results of these simulations are summarized in Figure 7 and Table 3. More details are shown in Figure 8 where the distribution of von Mises stress is presented. These results assist us to illustrate the area where the maximum stress is being registered and the area where the stress is low, so actually the areas that can be optimized from a lightweight point of view.

Under a load of 1.5 kN, the model can be improved for lightweight, as the stress registered for this load is acceptable and it can be seen in Figure 8. There are large areas with a low stress level which allow us to redesign the model, lightweight being the priority. The weight of the initial model was 9.87 g.

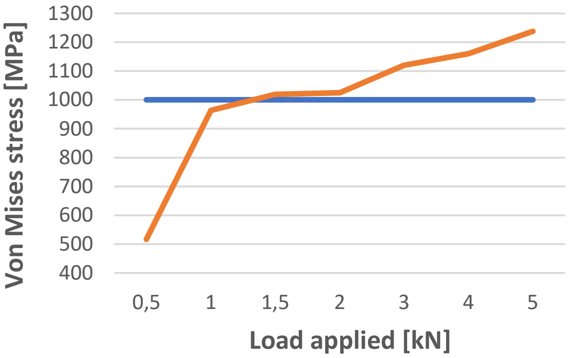


Fig. 7. Graphical representation of von Mises stress; Blue line indicates the yield strength of Ti6Al4V.

Table 3

Results of FEA static study on initial design

Applied load [kN]	Von Mises stress [MPa]	Total deformation [mm]
0.5	517	0.06
1	964	0.13
1.5	1019	0.19
2	1024	0.25
3	1120	0.39
4	1160	0.54
5	1238	0.72

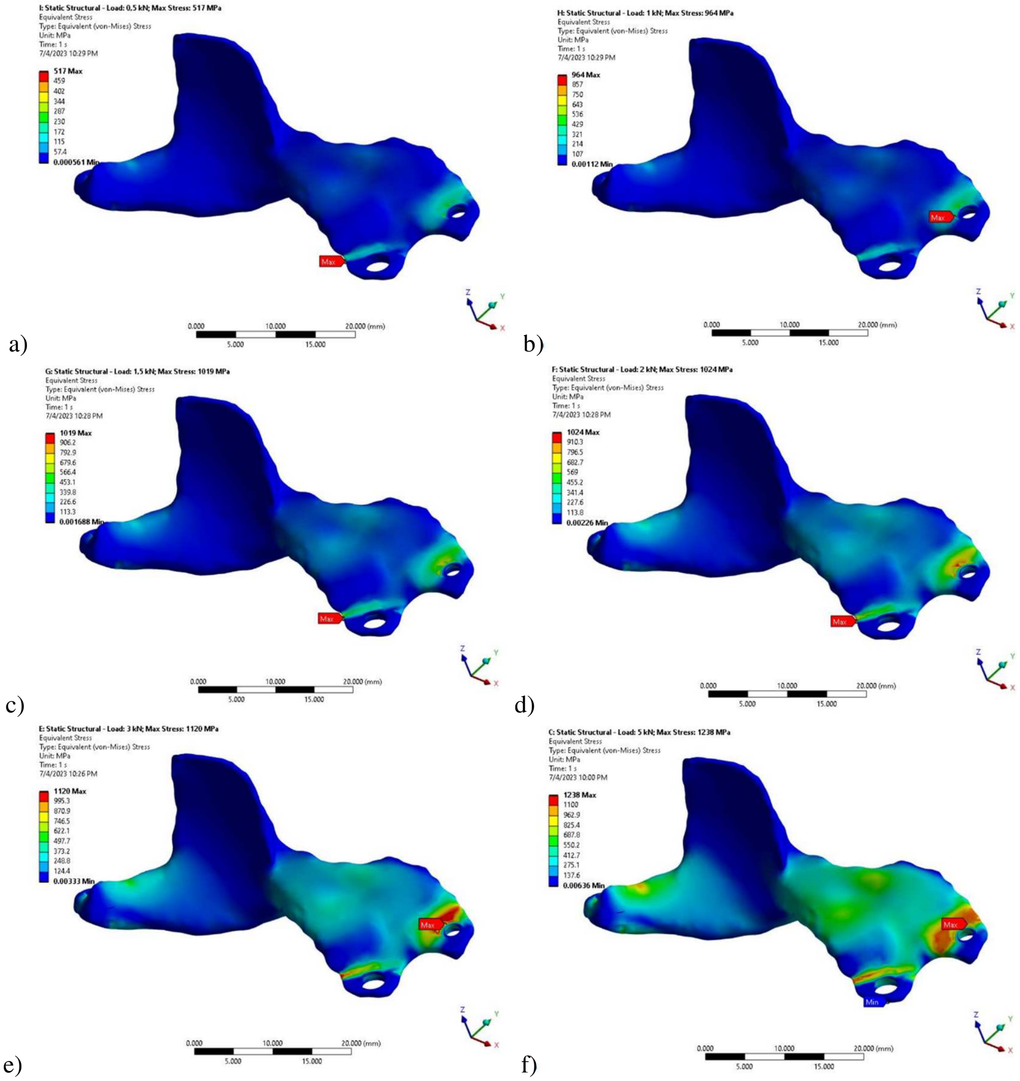


Fig. 8. Von Mises stress distribution in facial implant after it were applied various loads: a) 0.5 kN; b) 1 kN; c) 1.5 kN; d) 2 kN; e) 3 kN; f) 5 kN.

FEA results of redesigned model

Based on the initial static simulations, some areas possess reduced stress level, even when we applied high loads (Figure 8). Consequently, this area represents a promising target for optimization with the aim of achieving a lightweight design capable of withstanding similar loads. To attain lightweight, there are several strategies that can be explored:

- *Material Reduction*: In certain cases, if specific features of the implant serve non-critical purposes or can be fulfilled differently while supported by FEA, designers might consider removing sections of material to enhance overall weight reduction.

- *Lattice Structures:* This solution used unit cells which are typically geometric shapes such as cubes, spheres, or prisms. The lattice structure is characterized by its periodicity and symmetrical arrangement of the unit cells, providing an effective means of reducing weight while maintaining mechanical integrity.

- *Topology Optimization*: is a growing trend in mechanical design that aligns well with advancements in AM technologies. This method is used to optimize material distribution within a given design space to achieve optimal structural performance. Topology optimization is frequently employed in engineering and design to enhance the efficiency and functionality of structures and systems.

While some of these strategies can be readily applied to the model, others may introduce complications.

Material changes, for example, could pose challenges in manufacturing the implant or raise concerns regarding biocompatibility. Lattice structures and topology optimization are potent tools suited for SLM manufacturing but may pose challenges in verifying reliability, as both methods require a conversion from STL to CAD that can be more complex than the initial conversion. The decision was made to incorporate small holes into the low-stress area, each with a 1 mm diameter. This approach removes some material, contributing to weight optimization without significantly altering the geometry. This solution is advantageous because it maintains simplicity in terms of design, manufacturing, and simulation. The results obtained from analyzing this modification could serve as a valuable steppingstone for future investigations and research. The lightweight design is presented in Figure 9, and this alteration resulted in a weight reduction of 10%.

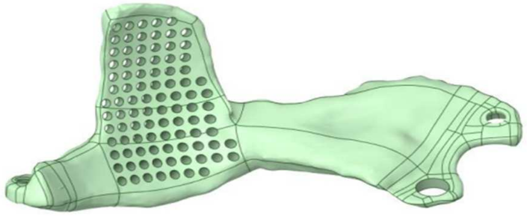
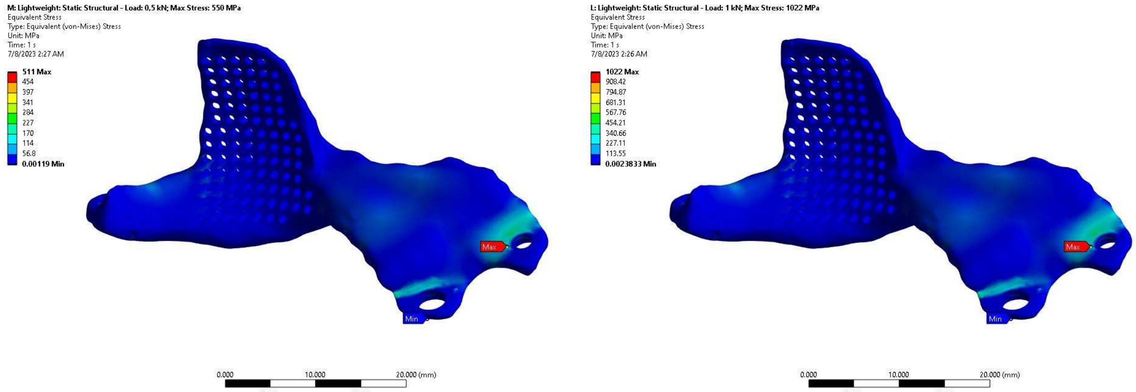


Fig. 9. Redesigned model with 10% weight reduction.

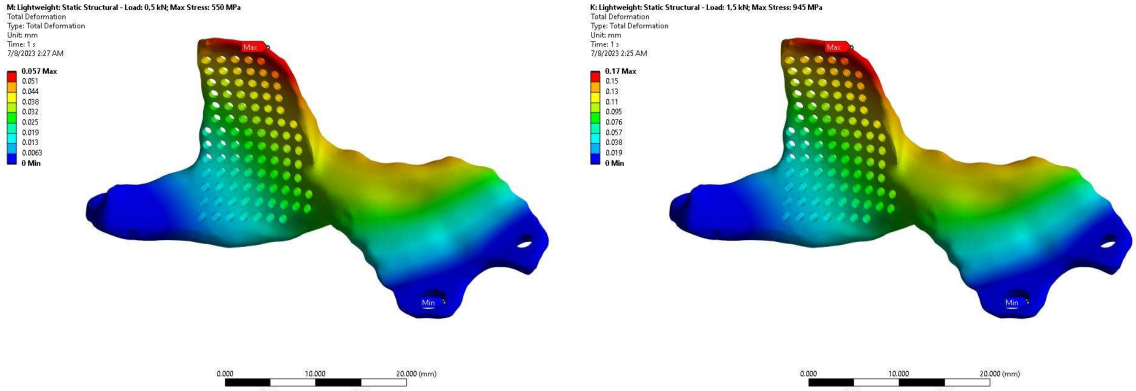
The FEA simulations were developed using the same configuration as previously discussed. The only adjustment made is that we performed the simulations applying loads between 0.5 kN to 1.5 kN. The initial study demonstrates that loads over 1.5 kN conduct tensions that are above the yield strength of Ti6Al4V (1000MPa). FEA results are shown in Figure 10.

Figure 11 illustrates the total deformation of the redesigned implant. Increasing the applied force from 0.5 to 1.5 kN, raised the total



a) b)

Fig. 10. Von Mises stress distribution in the redesigned implant; Applied loads: a) 0.5 kN; b) 1.5 kN.



a) b)

Fig. 11. Total deformation of the redesigned implant; Applied loads: a) 0.5 kN; b) 1.5 kN.

deformation from 0.06 mm to 0.17 mm. The outcomes of the second study indicate that stress values closely approach the acceptable limit, reassuring us that the implemented modifications do not compromise the structural integrity of the model (Figure 10). Furthermore, substantial portions of the structure maintain low stress levels. This observation suggests that further optimization efforts show promise, as there is potential to enhance the design by further reducing weight through the exploration of additional lightweight techniques. These results underscore the feasibility of achieving an optimized solution that strikes a balance between structural integrity and the potential for weight reduction or improved performance.

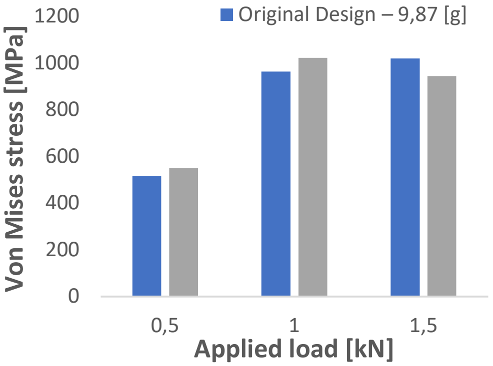


Fig. 12. Stress comparison between the initial design vs. lightweight model.

Figure 12 compares the FEA results of the initial model and the redesigned one. This graph shows that the stress distribution is similar in these models.

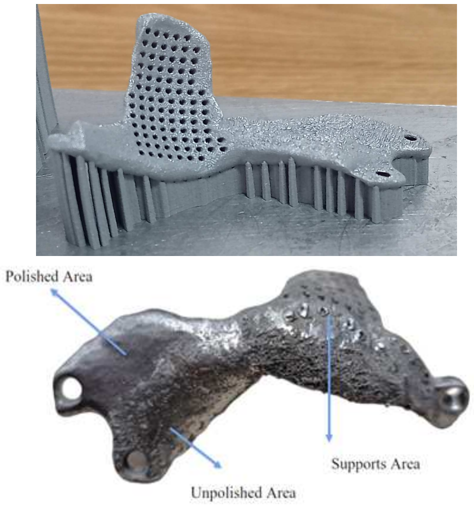


Fig. 13. Redesigned implant SLM-manufactured.

3.2 Surface roughness of SLM implant

Figure 13 shows the implant SLM-manufactured, highlighting some areas which were investigated (unpolished and polished). The unpolished areas are in as-built state, and they have the Sa surface roughness between 27 to 35 µm. Depends on surface geometry and complexity, the polished areas have a significant lower roughness (Sa from 3 µm to 5 µm).

Besides roughness measurements, 3D images of the surface topography were collected using height-based coloring. The depth information from curved surfaces was recorded and the height maps visualization are shown in Figures 14 and 15. Typical topography for stairs step effect is illustrated in Figure 14. The initial unpolished SLM surface is presented in Figure 15a, where the peaks and valleys are from -200µm to +150 µm. In limited areas, they were out of this scale. As can be seen in 3D surface texture, the polishing method reduced the height of peaks, uniformizing the surfaces (Figure 15b). Compared with as built surfaces, the polished areas significantly improve the quality of anatomical shapes, reducing the Sa surface roughness from 35 µm to 3 µm.

4. FUTURE PERSPECTIVE

Lattice structures present viable options worth exploring. These approaches offer the potential for significant weight reduction while preserving structural integrity [16]. Nevertheless, constructing models using these methods typically entails working with STL files and facet-based geometry. Transforming these intricate designs into CAD format may present challenges. Overcoming these difficulties and effectively implementing lattice structures or topology optimization in the design process necessitates careful consideration and specialized expertise.

Figure 16 illustrates a lightweight design concept constructed using lattice structures within Siemens NX. It should be noted that this model posed significant challenges during the conversion process back to CAD and when conducting FEA. Nonetheless, it serves as a compelling example of the possibilities achievable from a design perspective using today's CAD solvers.

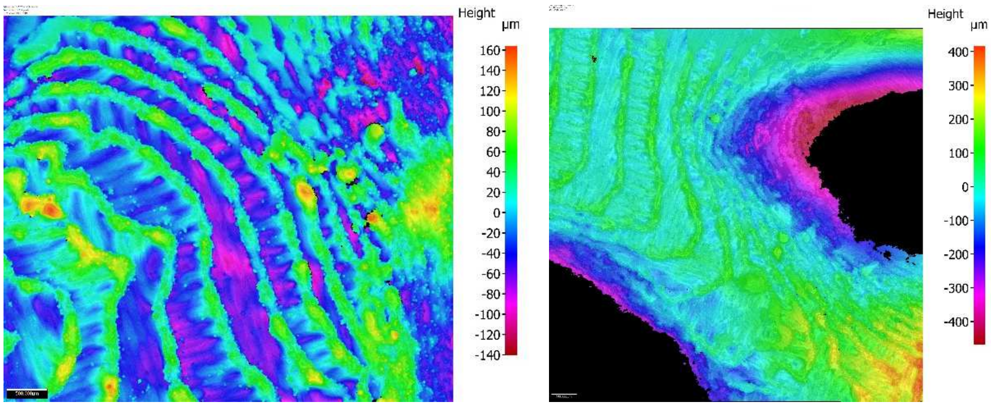


Fig. 14. Height map visualization of “stairs step effect” (Unpolished area).

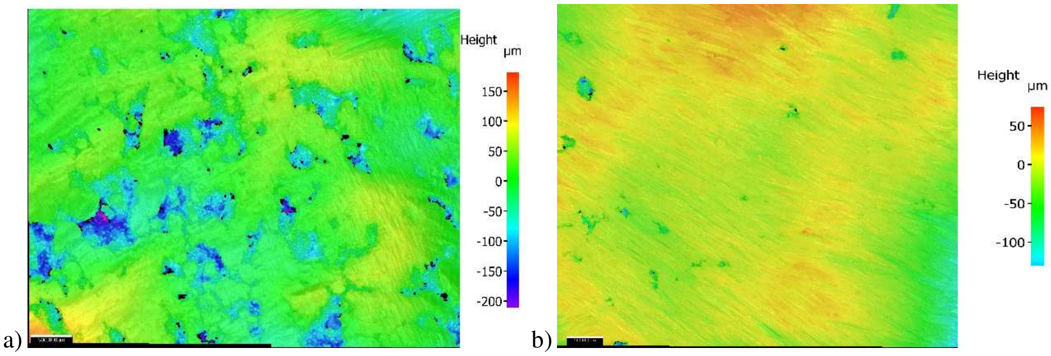


Fig. 15. Height map visualization of surface topography: a) Unpolished area; b) Polished.

Continuous advancements in technologies significantly influence these domains and are poised to usher in further improvements. As technologies evolve, they frequently introduce new opportunities, enhanced capabilities, and inventive solutions applicable across various sectors [17-20]. In the context of the specific technologies being explored, such as lightweight design optimization and lattice structures, the progress made in CAD software, simulation tools, and manufacturing processes will be of paramount importance [21-24].

Enhancements in CAD software can lead to more user-friendly and efficient design workflows, empowering designers to create and modify lattice structures with increased ease and precision. Additionally, the development of increasingly sophisticated simulation tools will enable more precise predictions of lattice structure performance, aiding engineers in optimizing their designs to meet specific requirements. These advancements may encompass improved material modeling, enhanced analysis algorithms, and greater computational power, all of which contribute to more dependable and efficient simulations.

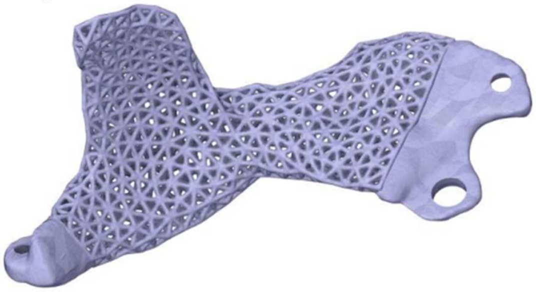


Fig. 16. Future perspective: lightweight concept integrating lattice structures.

As exploration and innovation in medical engineering continue to unfold, a promising future lies ahead, where groundbreaking technologies have the potential to significantly enhance healthcare outcomes and positively transform lives.

5. CONCLUSIONS

In the author's knowledge, at the time, there are limited solutions for converting .STL files to conventional CAD, none of them that could universally be applied to complex models. Such a tool would be immensely helpful in the industry.

Based on the findings of this study, the following conclusions were drawn:

1. Loads over 1.5 kN distributed von Mises stress over 1000 MPa, value which was considered the yield point of Ti6Al4V.
2. FEA results show that the von Mises stress and total deformation are similar in both models (initial vs. redesigned). The redesigned model developed is 10% lighter.
3. The polished SLM surfaces significantly reduce the roughness. The Sa roughness parameter calculated on the unpolished areas was 27-35 µm and on polished areas between 3 to 5 µm.
4. Future work is required to develop and test (mechanical and biological), new design concepts for facial implants.

6. ACKNOWLEDGEMENT

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PROIECTAREA UNUI IMPLANT PERSONALIZAT FABRICAT PRIN TEHNLOGIA SLM

Rezumat: Tehnologia de fabricație aditivă are potențialul de a schimba modul în care sunt fabricate implanturile personalizate. Această lucrare și-a propus să prezinte modalitatea de-a reduce greutatea unui implant facial din titan, fabricat prin procesul SLM. Analizele cu elemente finite (FEA) au fost utilizate pentru a determina distribuția tensiunilor von Mises și deformația totală, aplicând forțe între 0,5 și 5 kN. S-a observat că sarcinile de peste 1,5 kN au distribuit tensiuni von Mises ridicate de peste 1000 MPa, valoare care a fost considerată limita de curgere a aliajului de titan (Ti6Al4V). Modelul reproiectat dezvoltat a fost cu 10% mai ușor, iar simulările FEA au arătat că tensiunile von Mises și deformația totală sunt similare în ambele modele (inițial vs. reproiectat). Suprafețele SLM lustruite reduc semnificativ rugozitatea. Parametrul de rugozitate Sa calculat pe suprafețele nelustruite a fost de 27-35 µm și pe zonele lustruite între 3 și 5 µm. În plus, s-a prezentat un concept ușor cu structuri lattice (macro-poroase) integrate. Sunt necesare lucrări viitoare pentru a dezvolta și testa (mecanic și biologic) noi concepte de design pentru implanturi faciale.

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