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Topological Optimization of a Metal Extruded Doorhandle using nTopology

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Abstract

Entranceways are blocked with the use of doors. For these to be opened, door handles must be manipulated, making them one of the most used inventions in our lives. This article reviews the topological optimization of a door-handle design, its adaptation to being produced using Additive Manufacturing (AM), and the feasibility of Metal Extrusion as a part fabrication method. Two different door-handle designs were created and optimized with the introduction of lattices and generative design using nTopology software and later produced with Inconel 625 filament.

Author Keywords. Additive Manufacturing, Metal Extrusion, Design for AM, Door handle, Topological optimization, Inconel 625.

Type: Research Article

1. Introduction

Doors have always played a vital role in architecture. They act as barriers for opening and closing hall entrances, making them one of the most used human inventions, with many daily uses per person (Chang et al. 2007). This concept enhances the necessity of designing ergonomic door handles. A study by Demirbilek and Demirkan (2004) on the human/door interface theme explored the door factors considered necessary by a specific population: handle position, sharp edges on handles, door material, and door type. They also specified that the average applied force while opening a door range from 22 to 132 N.

Our work came to fruition with the idea of creating a topologically optimized design for a door handle. The goal was to eliminate the existence of sharp edges, reduce weight while maintaining mechanical properties and create an unconventional component design that attracts the user's attention, ultimately generating a new way to experience door handles. Classical approaches to manufacturing would be detrimental to the project’s feasibility, which led us to proceed with choosing Additive Manufacturing, given the possible complex geometry of the part.

Metal additive manufacturing (AM) has shown advantages from a programmatic and technical perspective over traditional manufacturing techniques for multiple applications. AM can provide significant cost savings and schedule reductions over subtractive manufacturing processes when appropriately applied. The main benefits of using this technology regarding component design are the possibility of weight reduction, integration of parts into a single assembly, enhanced complexity by building internal features, and use of traditionally challenging to manufacture materials (Gamon et al. 2021). The American Society for Testing and Materials (ASTM) defines AM as a fabrication process of joining materials to make components from 3D model data, layer upon layer, instead of subtractive manufacturing methodologies (I. ASTM 2012). AM facilitates the application of complex parts and dramatically enhances the freedom to design complex structures. The Design for AM (DfAM) framework relies on advanced design methods such as topology optimization and lattice structures (Li et al. 2021). Lattice structures are topologically ordered, three-dimensional (3D) open structures composed of one or more repeating unit cells. AM lattice structures have outperformed cellular structures produced by other manufacturing methods with equivalent porosity due to the AM process's greater geometric control and predictability (Maconachie et al. 2019).

Even though AM is a general term, the technologies themselves can be separated into different categories and processes, presented in **Table 1**, with the proper process choice for manufacturing a specific part being one of the most critical factors in the final quality of the product. The main things to consider in selecting a metal AM process are part complexity, process cost, build volume, process maturity, availability, post-processing operations (including heat treatment), and the final microstructure and properties (Gradl et al. 2019).

Categories	Technologies	Raw Materials
Material Extrusion	Fused Deposition Modeling (FDM) Contour Crafting	Thermoplastics, ceramics, and metal
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polyamides and polymers
	Direct Metal Laser Sintering (DLMS)	Metal and ceramic powder
	Selective Laser Melting (SLM)	
	Electron Beem Melting (EBM)	
Vat Photopolymerization	Stereolithography (SLA)	Photopolymer and ceramics
Material Jetting	Polyjet(Inkjet Printing	Photopolymer and wax
Binder Jetting	Indirect Inkjet Printing (Binder 3DP)	Polymer, metal, and ceramic powder
Sheet Lamination	Laminated Object Manufacturing (LOM)	Plastic film, metallic sheet, and ceramic tape
Direct Energy Deposition	Laser Engineered Net Shaping (LENS) Electronic Beam Welding (EBW)	Molten metal powder

Table 1: Information Available at ISO/ASTM52921 – 13 (2019), Standard Terminology for Additive Manufacturing (ASTM 2019)

Although powder bed fusion processes (PBF) are the most used for metal AM (Herzog et al. 2016), they are complex and expensive to implement and maintain (Gibson et al. 2018), presenting difficulties in controlling the multiple inherent parameters. While alternative technologies are being created and studied, the Material Extrusion (MEX) process presents itself as a reliable alternative to PBF (DebRoy et al. 2018). To ensure proper flow behavior while extruding metals, it is common to use thermoplastics as flowing and binding agents (Taylor et al. 2018). Filaments used in this process combine the available viscosity of the thermoplastics (the typically loaded metal volume fraction <60%) with the metal's strength and other desirable properties. The main disadvantage of the process is that it requires subsequent polymer removal followed by sintering to achieve a dense metal part, which results in a lack of material systems with rheological behavior suitable for material extrusion (Gibson et al. 2018).

Metal-based MEX technology can be divided into four distinct steps: (1) filament production and characterization, (2) production of AM components by a filament extrusion process, (3) debinding, and (4) sintering. The production of the filaments is one of the most critical steps of this technology, as it directly influences the component's quality. Ideally, filament characterization should comprise particle size distribution (PSD), morphology, density, specific surface area, and interaction between particles (Costa et al. 2021). The extrusion process is represented in **Error! Reference source not found.**: the filament goes through the feeding system, reaching the extrusion head. It is heated to a viscous state and is deposited in the plate afterward by the nozzle. As said earlier, the operational mode of additive manufacturing consists of building up a component, layer by layer, from bottom to top, with the equipment moving on the X, Y, and Z-axis and drawing layers according to the coordinates given by the processing software. So, to know the exact plate position in which the nozzle must deposit material, the CAD model must be processed by a slicer, dividing the component into multiple layers and calculating the coordinates to be read by the software that works alongside the printing equipment. Material extrusion systems generally have a second nozzle that deposits support material that helps to produce surfaces with overhangs (Diegel et al. 2019).

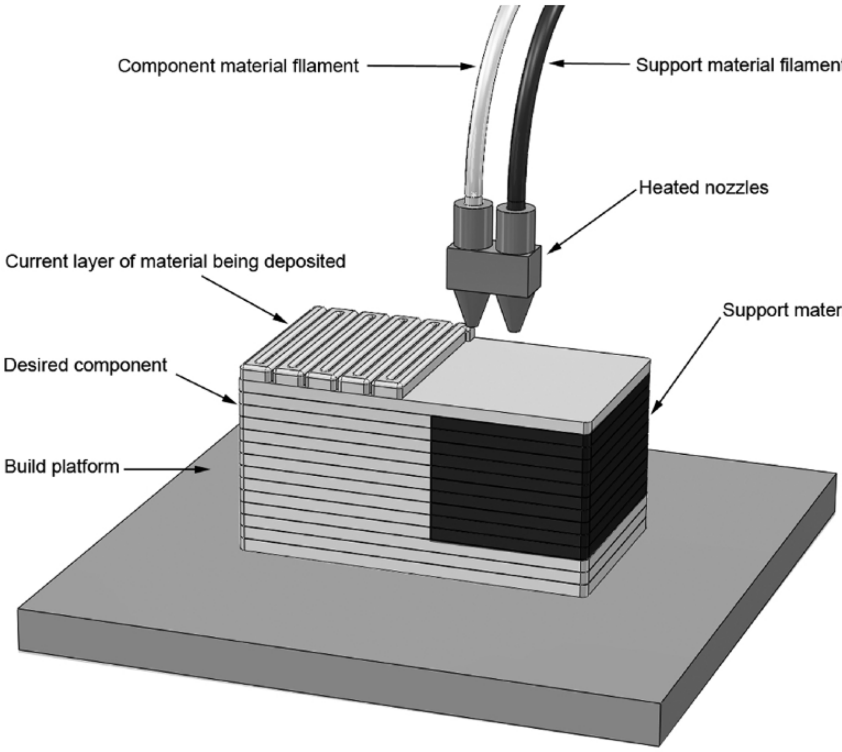

Figure 1: Schematical Representation of MEX AM Process

After step (2), the produced component is called Green Part. To remove the binder material without compromising the overall structure of the component, the debinding process is made gradually. Among the several used techniques, the most popular ones for the obtention of the brown part are thermal degradation, catalytic decomposition, and solvent extraction (Sequeiros et al. 2020).

To finalize the process of manufacturing a component by MEX, sintering is undertaken so the brown part can be turned into a sintered part - a thermal treatment is applied to transform the power into the bulk material, with temperature ranging between 70 and 90% of the melting point of the major metallic component (Costa et al. 2021). The temperature increase is responsible for reducing the surface energy, which ultimately results in the densification of the part by the formation of bonds between particles (Gonzalez-Gutierez et al. 2018). It is critical to understand that debinding and sintering conduct an approximate shrinkage of 20%

in the component, so special considerations need to be given to the part design (Diegel et al. 2019).

2. Materials and Methods

The handles used in most of the doors in our faculty’s department served as a term of comparison to our goal part, and their specific dimensions were used while modeling.

Figure 2: Door Handle Used as a Starting Point

The first step in our workflow was to analyze these dimensions and create new models; having been allowed to choose from different Computer-aided design software, we chose to work with nTopology. This software is particularly interesting for AM purposes. It was specifically created based on the DfAM framework, relying on advanced design methods such as topology optimization and lattice structures, giving the user more freedom to create new designs. It also has the significant advantage of creating reusable custom design workflows, automating repetitive tasks, and saving engineering time and money. Like other CADs in the market, this software enables simulation from the middle and late stage of the design process to the very front, allowing the user to make better decisions when creating. The development of the new door-handle models will be conducted ahead.

The as-designed model STL file was now transferred to Eiger, cloud-based software that works alongside the 3D-printing equipment later used, where multiple placements and orientations of the design in the printing plate were evaluated. This step is highly relevant in the process as it is directly connected with the amount of material and time needed to print the component and the overall success of the printing.

The subsequent steps of printing, debinding and sintering were performed using Markforged technology: printing was conducted in a Metal X Printer; Wash-1 was the solvent-based debinding system (with Opteon SF-79 being the solvent); sintering was directed in a tube furnace, Sinter-1. This technology can only be used for part fabrication using the following materials: Stainless steel (17-4 PH), Tool steel (H13, A2, D2), Inconel 625, and Copper. In this case, door handles were produced using a metallic filament of Inconel 625. This alloy is a nickel-chromium-based superalloy, highly resistant to corrosion and high temperatures. It is highly used to make functional prototypes to enable straightforward components manufacturing. The specific parameters inherent in each of the previous steps are chosen according to manufacturing requirements for each material but were not disclosed by Markforged.

Composition	Amount
Chromium	20-23%
Molybdenum	8-10%
Iron	5% max
Niobium	3.15-4.15%
Cobalt	1% max
Manganese	0.5% max
Silicon	0.5% max
Aluminum	0.4% max
Titanium	0.4% max
Carbon	0.1% max
Phosphorus	0.015% max
Sulfur	0.015% max
Nickel	bal

Table 2: Inconel 625 Composition

3. Development of the models

This section will focus on the successful modelation that eliminates errors and complications while improving the design of the door handle in its many aspects.

This project started by observing door handles and CAD models online. After some research and an introduction to the process, the CAD model presented in **Figure 3** - number 1 was chosen from GrabCAD. This first model was imported to nTopology, and a Voronoi lattice was introduced. However, this model brought some problems: incorrect dimensions and the existence of a very thin zone, apparently fragile. That said, nTopology was used to build a new door handle model from scratch, inspired by the previous one with the correct dimensions, Figure 3 - number 2. A Voronoi volume lattice with a gradient that would provide a better response when in service was introduced to the model. After this attempt, there were some complications with door handle 2, which led to modeling a new and similar door handle with Fusion 360 **Figure 3** - number 3. After importing it to nTopology, a gradient Voronoi volume lattice was introduced in the model. However, the product was not ergonomic and looked uncomfortable for a door-opening object. To increase ergonomy in part, the final template used in nTopology, number 4, was created using Fusion 360.

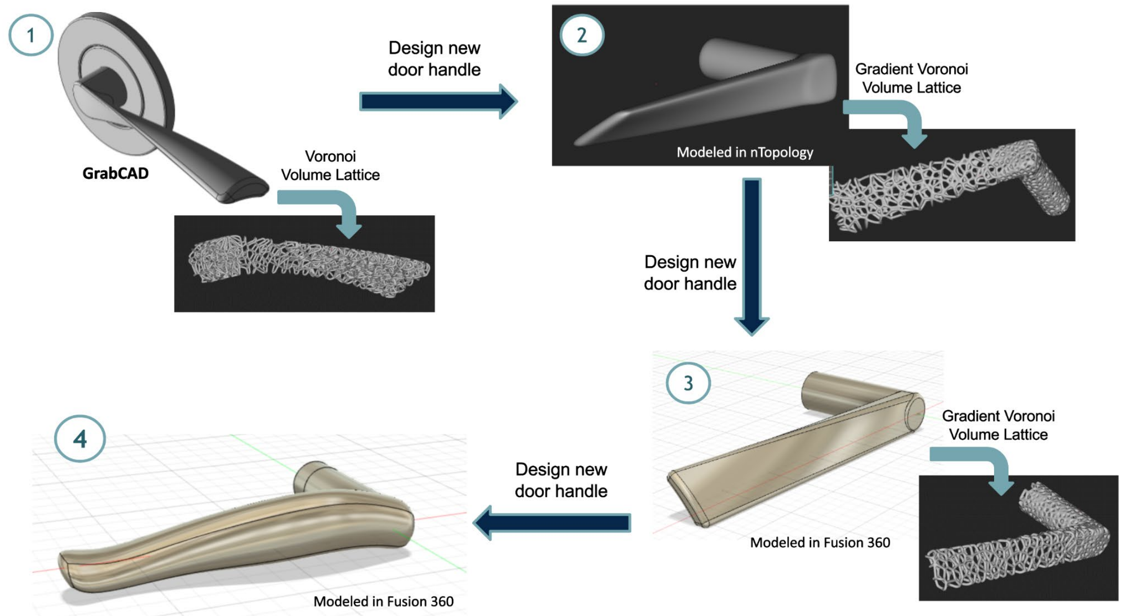

Figure 3: Scheme With the Successive Models and Optimizations in the Initial Stages

There were two approaches for optimizing the door handle 4: topology optimization and lattice introduction. The process began by simulating the forces applied to the door handle. The forces applied are shown in **Figure 4** with yellow being the force of 50N pointing down and red being the displacement restraints. The properties used in the simulation were 205GPa for Young's Modulus and 0,308 for Poisson's Ratio (Gao, Y. et al 2021). The results show, in **Figure 5**, that there is a von Mises stress concentration of 4,28 MPa between the connecting barrel and the handle. The von Mises Criteria indicates that a ductile material starts to yield when the von Mises stress becomes equal to or higher than the yield strength (Simscale, 2021). Since the yield strength for Inconel 625 is 460MPa (MatWeb, 2022), the part is not expected to yield.

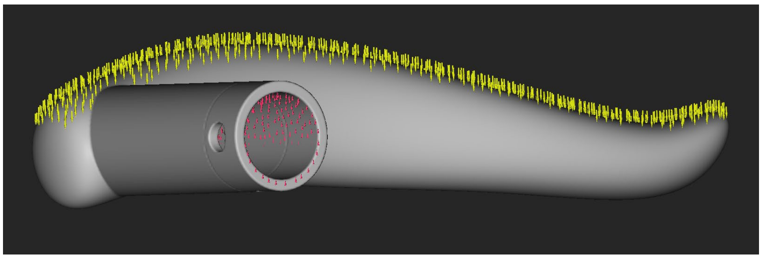

Figure 4: Forces Applied to the Door Handle

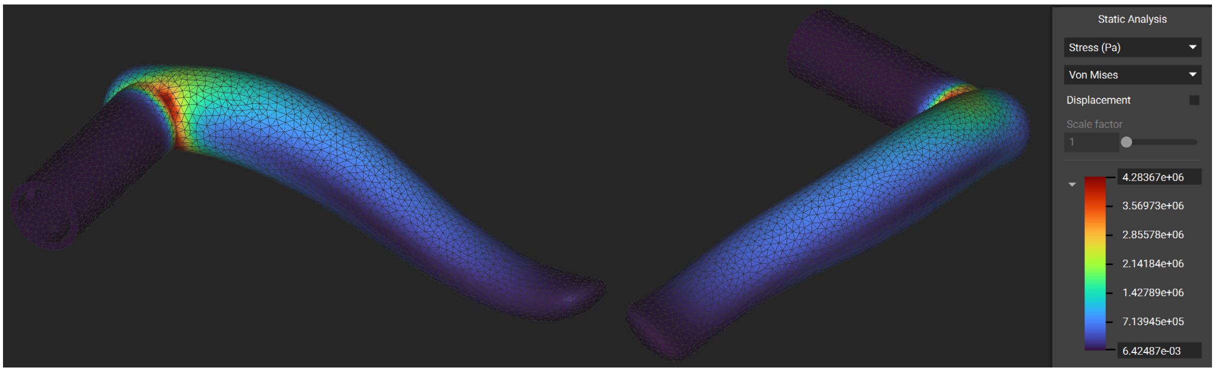

Figure 5: Results of the Simulation of the Door Handle 4

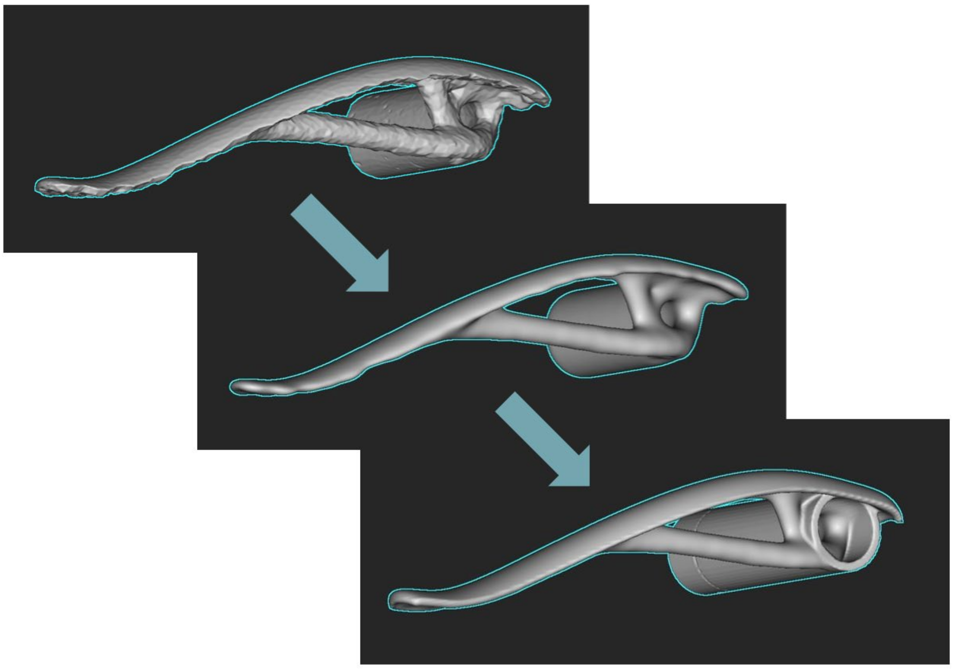

Figure 6: Steps in the Creation of a Door Handle With Topology Optimization

The first optimization approach was the generative design using the topology optimization block and the same force and restraints as the simulation. The first step was creating an optimized body from the topology optimization block and adjusting it with a threshold operation, with a chosen value of 0,25. Then, the body was smoothened, and optimal mass was obtained, but it lacked some parts and an excellent finish. To finalize the model, the Boolean union function was selected, which was conducted with the barrel (where the displacement restraints are applied) and the thickened surface (where the force is used) with the smoothen body, resulting in the model shown in **Figure 6**.

Then, the simulation was made with the same settings as the previous simulation **Figure 4** to ensure that the door handle could bear the tensions. The simulation results are shown in **Figure 7**, with a maximum von Mises stress concentration of 9,73 MPa.

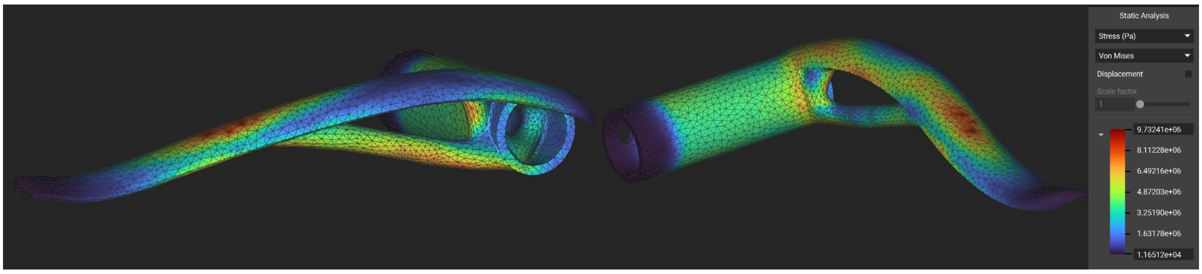

Figure 7: Results of the Simulation of the Door Handle With Topology Optimization

After 3D printing with PLA, it was possible to identify a sharp edge, and it was necessary to add some material to the model. Using successive operations of adding primitives and the Boolean operation functions, some material blended well with the optimized door handle was added to the model, as shown in **Figure 8**.

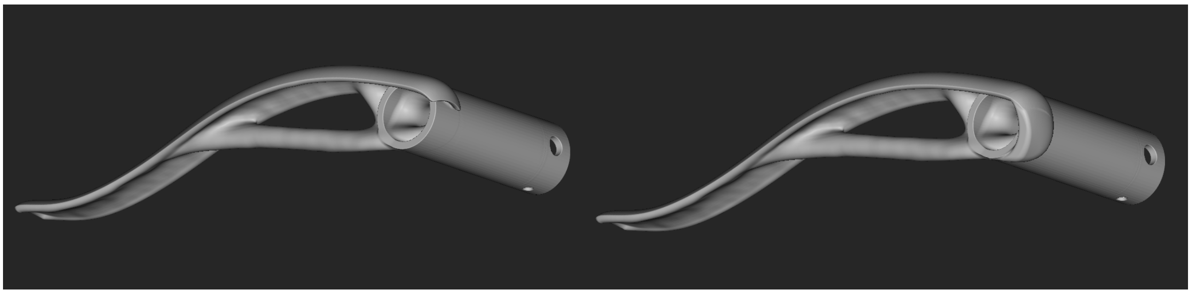

Figure 8: Before and After the Addition of Material to the Model

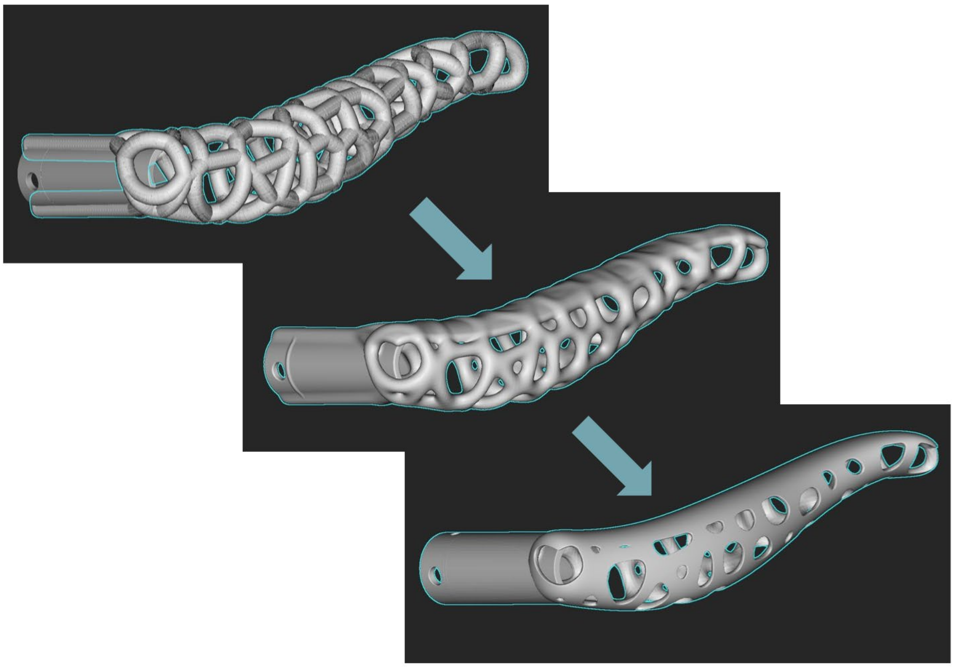

Figure 9: Results of the Simulation of the Door Handle With Voronoi Boundary Lattice

The lattice optimization approach was made using the Voronoi Boundary Lattice block as a starting point, which enables the creation of lattice only on the model's surface. The distance between points was 10 mm, and the lattice thickness was 5mm, with the lattice body being smoothened. Following the Boolean union software function with the barrel and the thickened surface, the body had more outwards volume than what is necessary to use the Boolean intersect operation with the original door handle, resulting in the model shown in **Figure 9**.

After creating this new model, a simulation with the same settings as the previous was made **Figure 4**. The results are shown in **Figure 10**, with a maximum von Mises stress concentration of 25,5 MPa.

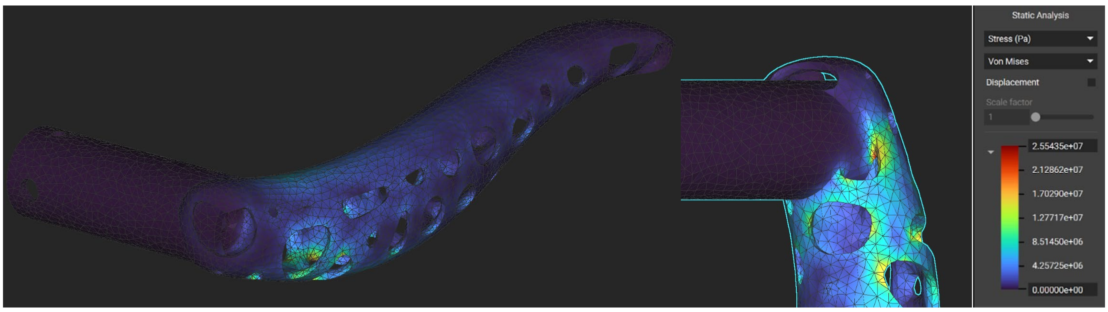

Figure 10: Results of the Simulation of the Door Handle With Voronoi Boundary Lattice

The model was converted to an STL file imported to the online platform eiger.io to slice the models for the printing process. The models were positioned to minimize the supports and their removal, as shown in (1), **Figure 11**. The supports are in purple, and the release material (ceramic), usually placed in the interface between the component and the supports, can be identified in orange. Since the lattice-optimized door handle has a complex shape for 3D printing, there is difficulty in extracting supporting material, which led to the introduction of layers of release material in between to facilitate the removal. After the slicing process, the two-door handle models were printed (2), debinded (3), and sintered (4).

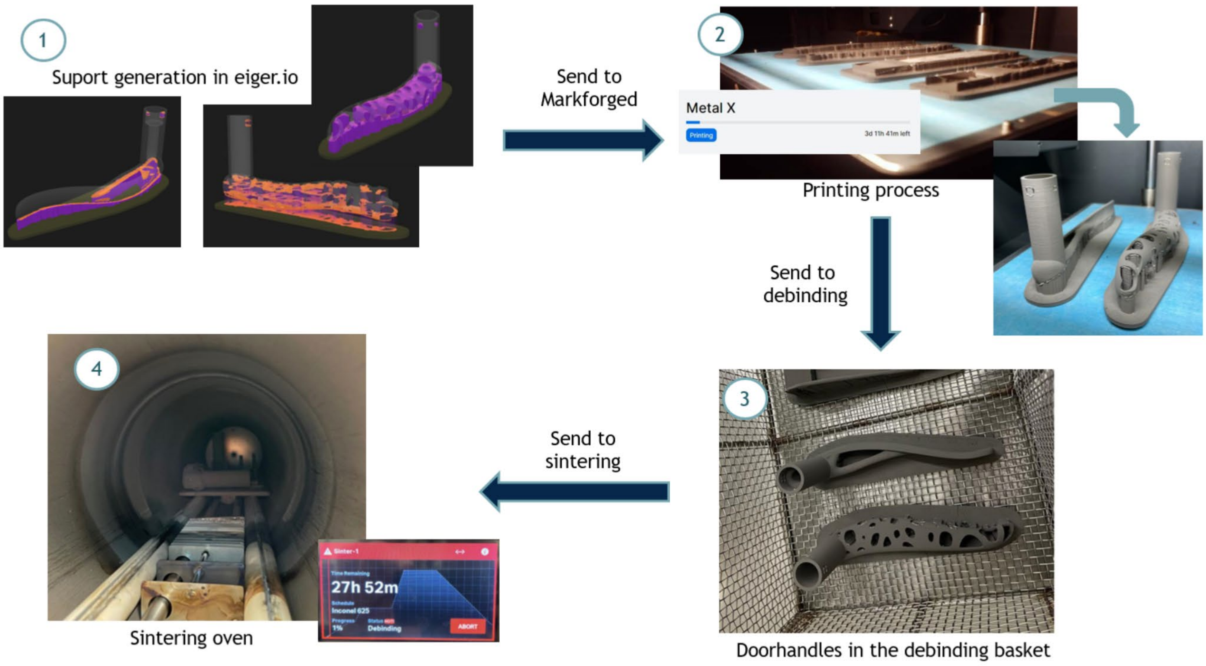

Figure 11: Scheme of the Successive Steps of the Printing, Debinding, and Sintering Process

4. Results and discussion

One of the models showed an error in a specific area of the base during the printing process, **Figure 12**. This unusual phenomenon, displayed in an orange/brown color, was probably caused by external factors, such as humidity on the paper base that might cause oxidation, since printing parameters are internally established according to the printing metallic filament Markforged and cannot be changed.

Figure 12: Material Loss During Printing and Subsequent Interference in Debinding Step

This phenomenon brought some problems in the following steps: the material in the bottom of the part ensures stability for the overall printing piece in the subsequent processes. After debinding, as we can see on the right side of **Figure 12**, the base of that door handle model lost even more material. The position of the components on the sintering plate directly influences the results and is shown in **Figure 13**. The placement of the part sideways is a means to combat the lack of material in the part's base and ensure sintering. This caused some issues on the component after the sintering process since the supports no longer played their role in the model, which led to hot temperature and gravity changing the door handle design. The effects of this in the model are shown on the right of **Figure 13**, as it is possible to see warping along the deposition lines on the top side; the cylinder part that connects to the door is deformed and missing material, endangering the application and function of the door handle.

Figure 13: Influence of Component Positioning in the Sintering Plate:
Lattice Optimized Door Handle

The position of the topology optimized door handle was kept intact, as shown in **Figure 14**. However, there was some warping effect on the model caused by the heat in the sintering furnace, collapsing the building supports. These no longer supported that part, becoming deformed and changing the original design. Nonetheless, this part can still be used since its function and ergonomic design wasn't changed.

Figure 14: Door Handle After Sintering and the Effect of Support Collapse

The nature of the process creates a surface with rugosity because of the deposited layers. After removing the supports, there is even more roughness at the interface between the supports and the door handle, as shown in **Figure 15**.

Figure 15: Roughness at the Interface Between Supports and Component

The follow-up of this study is to implement ways to increase the surface quality of the obtained parts. One possible option is to use sand/shot blasting technology to decrease surface roughness. Once the finishing steps are over, part sizing and subsequent door-handling implementation in their respective door mechanisms will be conducted.

Later, these same parts will be fabricated by Laser Powder Bed Fusion technology, and a direct comparison between MEX and LPBF will be undertaken.

5. Conclusions

The software selected for component design and topology optimization, nTopology, performed according to expectations regarding design for AM and showed to be a disruptive technology regarding lattice creation, generative design, properties simulation, and overall topology optimization.

Concerning fabrication methods, although the tested geometries were not feasible using traditional subtractive manufacturing methods, MEX exhibited under expected results. These were snubbed by a certain degree of material loss in one of the component's bases, leading to residual stresses and structural material loss during the debinding step and, consequently, causing post-sintering deformation. This combined made us believe that this technology still has a long path to walk when metallic parts fabrication is due. Nevertheless, the fact of obtaining such a complex geometry certainly shows the potential that this technology has for the future.

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