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Estudo das forças aplicadas em próteses de maxilar por meio do método de elementos finitos

Study of forces applied in maxillary prosthesis using finite element method

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Resumo: Este trabalho tem como objetivo simular e analisar a utilização de próteses personalizadas fabricadas por manufatura aditiva utilizando o método de fusão por feixe de elétrons (EBM). O Método dos Elementos Finitos (FEM) utiliza o estudo com resultados sobre a validação das propriedades mecânicas do processo de fabricação personalizado de próteses bucomaxilofaciais de Ti-6Al-4V através de testes de tração em simulações. Foram realizadas cinco simulações, variando as demandas de força na faixa de 200 a 500 N (forças típicas durante a mastigação) nas regiões cilíndricas frontal e posterior da prótese. A partir dos resultados analisados, pode-se observar que, na maioria dos casos, a tensão máxima permaneceu abaixo do limite de escoamento do material (827,34 MPa), com deformações restritas à zona elástica, o que implica em uma vida útil mais longa para a prótese. No entanto, nos casos em que os valores de tensão se aproximaram do ponto crítico, a tensão máxima pelo critério de Von Mises (869,86 MPa) excedeu o limite de resistência especificado.

Palavras-chave: ASTM F136. Elementos Finitos. Manufatura Aditiva. Método EBM. Liga Ti-6Al-4V.

Abstract: *This work aims to simulate and analyze the use of custom prostheses manufactured by additive manufacturing using the Electron Beam Melting (EBM) method. The Finite Element Method (FEM) uses the study with results on the validation of the mechanical properties of the custom fabrication process of Ti-6Al-4V oromaxillofacial prostheses through tensile tests in simulations. Five simulations were performed, varying the force demands in the range of 200 to 500 N (typical forces during chewing) in the prosthesis's frontal and posterior cylindrical regions. From the analyzed results, it can be observed that in most cases, the maximum stress remained below the material's yield strength limit (827.34 MPa), with deformations confined to the elastic zone, implying a longer lifespan for the prosthesis. However, in cases where stress values approached the critical point, the maximum stress according to the Von Mises criterion (869.86 MPa) exceeded the specified yield strength limit.*

Keywords: *ASTM F136. Finite Elements. Additive manufacturing. EBM method. Ti6Al4V alloy.*

I. INTRODUCTION

Current medicine faces a significant challenge in the replacement of human organs due to natural

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degradation, diseases, and traumas, among other factors (Wieja et al., 2022). In recent years, modular prostheses have been developed and widely utilized in surgeries (Radu, 2021).

In the medical field, the significance of creating 3D models arises from the ability to visualize an anatomical replica of the patient, enabling assessment and performance simulation before fabrication. It also allows the study of the model to comprehend and enhance its functionality, serving as a foundation for the development of personalized prosthetic implant designs (Shirganvi, 2023). Articulating prostheses subjected to cyclic loads imposed by patients' daily movements requires two considerations in their development. Implants must exhibit high fatigue resistance and low friction wear (Souza, 2022). Additionally, preventing mass loss is crucial as it can lead to implant failure (Jaegger, 2023).

In this study, Finite Element Method (FEM) software is used was utilized for analyses. This method has been widely adopted for optimizing parts manufactured through Additive Manufacturing (MA), making the parameter selection more straightforward and economical (Sabzi, 2019; Galati, 2019). Thus, this method enables the prediction of the mechanical behavior of the finished part and the simulation of physical reactions in the region during its fabrication (Bortoli, 2020). It is crucial to emphasize that there are few studies in the literature specifically involving the use of numerical simulations in the analysis of the mechanical behavior of parts produced in the industry. For oromaxillofacial prostheses, no references or regulations from the National Health Surveillance Agency (ANVISA) were found; therefore, a comparison of this work with other literature was not possible.

II. THEORETICAL REFERENCE

In reconstructive surgeries, surgeons are tasked with restoring both function and aesthetics (Hadad, 2023). Autografts have been considered the standard for reconstruction for decades; however, they come with disadvantages such as donor site morbidity, prolonged healing time, and additional discomfort to the patient. These challenges have prompted the search for suitable alloplastic materials. Additive Manufacturing offers a solution to overcome these barriers and serves as an alternative to microvascular reconstruction (Das, 2023).

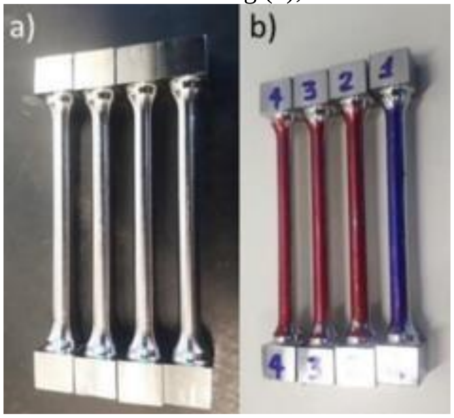
The Ti-6Al-4V alloy is the most widely used titanium alloy and is considered α+β type because its microstructure comprises these two phases at room temperature (Souza, 2022). This alloy also possesses other excellent properties, such as corrosion resistance, making it the ideal choice for the chemical and naval industries, and its biocompatibility makes it the best option for biomedical implants (Silva Junior, 2021). Various Additive Manufacturing methods enable the production of components in Ti-6Al-4V; among the diverse methods in Additive Manufacturing, the Electron Beam Melting (EBM) technique was chosen for this work (Qian, 2016). The study's interest in this technique stems from its high capability to control process parameters and the physical, chemical, and mechanical characteristics it imparts to the product compared to other manufacturing methods (Mommaerts, 2019).

This study will analyze the mechanical behavior of custom prostheses manufactured by Additive Manufacturing using the Electron Beam Melting (EBM) method, made with the Ti6Al4V alloy through finite element analysis. The aim is to validate quality indicators and predictions of the mechanical behavior of the studied prosthesis, given that this method is a relatively new manufacturing process in the market.

III. MATERIALS AND METHODS

To obtain input parameters for the Finite Element Method (FEM) simulation, tests were conducted on specimens made from the Ti-6Al-4V alloy using the Electron Beam Melting (EBM) Additive Manufacturing method. Tensile tests were performed on specimens with two different surface finishes: one with anodization and another without anodization, as depicted in Figure 1.

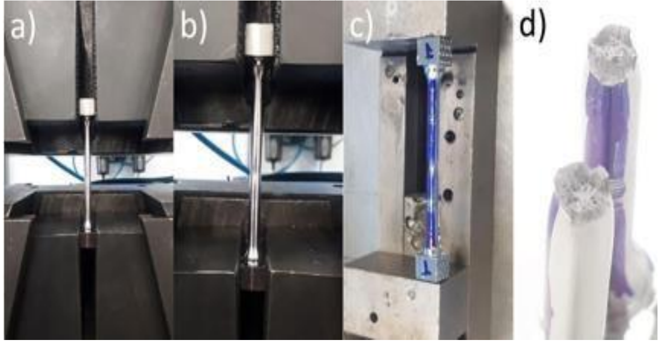
Figure 1 – Anodized Ti-6Al-4V samples (a); sample without anodizing (b);



Source: Author,2022.

The procedures for testing and the verification of results are illustrated in Figure 2. The outcomes are presented in Table 1.

Figure 2 – Start of CP 1 test (a); Neck formation (b); Measurement after neck formation (c); Fracture of the specimen (d).



Source: Author,2022.

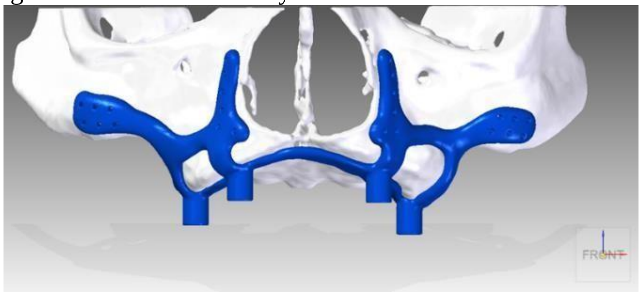
Table 1 – Dimensions of specimens

Proff Bodies	**Sample**	**Initial diameter (mm)**	**Final diameter (mm)**
Ti-Anodized 1	104	4.8	4.4
Ti-Anodized 2	105	4.8	3.02
Ti-Anodized 3	106	4.8	3.12
Ti-CP1	107	4.8	3.62
Ti-CP2	108	4.8	3.72
Ti-CP3	109	4.8	3.34
Ti-CP4	110	4.8	4.02

Source: Author,2022.

The prosthesis used in this study was based on the subperiosteal maxillary prosthesis technique, a surgical procedure in which the maxillary bone is exposed to allow for implant insertion. After recovery, the prosthesis is attached to its supports. This technique is recommended for patients who cannot use maxillary prostheses due to a lack of root-shaped bone density, resulting in an approximation to the floor of the maxillary sinus. Since this implant technique is not anchored in the bone, as shown in Figure 3, a critical analysis is necessary to ensure safety and effectiveness (Dogru, 2018).

Figure 3 – Bucco Maxillary Prosthesis embedded in the skull.



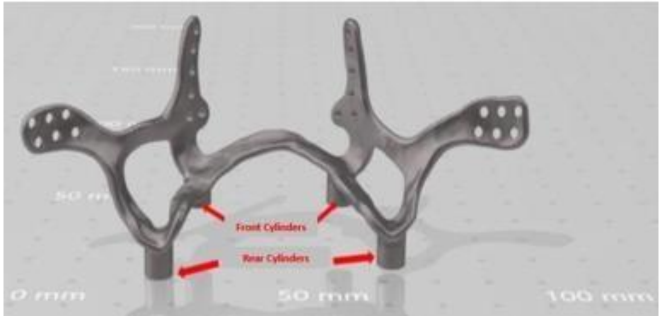
Source: Author, 2022.

In the application of FEM, obtaining the 3D model is crucial for the process, as its level of detail ensures a more accurate analysis. Along with this, the load properties must be realistic, as well as the types of joints and interactions between them. Another factor to be considered is the quality of the study mesh, which should be well-structured. Therefore, the reliability of the analysis results depends on the accuracy of the model properties, so that the fewer assumptions made, the more viable the simulation will be (Zafar, 2020).

The FEM technique for solving structural problems in prosthetics is widely used in the literature, as the analysis of prosthetic structures can be developed similarly to stress analyses in mechanical systems. Analyzing the entire structural assembly allows for observing stresses that occur in all components of the prosthesis. It is possible to analyze the distribution of stresses among each element of the prosthesis and the interaction between them. The prostheses were designed with a Dode-Medium (MSG) structure. These simulations were performed using static structural analysis. They were designed through Abaqus® software to check their critical points, effectiveness, and safety. In cases of dissatisfaction, it allows defining the path to optimize the parts and adapt them to their applications, such as dimensional increase or geometric changes in the region, without impacting the surgical technique, later re-evaluated by the surgeon. During the simulation, some properties of the Ti-6Al-4V alloy were used as parameters, such as yield strength, with a found value of 827.4 MPa, Young's modulus of 104.8 GPa, Poisson's ratio of 0.31, and a specific gravity of 4.43 g/cm^3.

For the simulations in this study, load values were defined and applied individually to each base of the four cylindrical regions of the prosthesis. The applied loads were 200 N, 300 N, and 500 N, as depicted in Figure 4.

Figure 4 – Prosthesis with indications of cylinder locations.



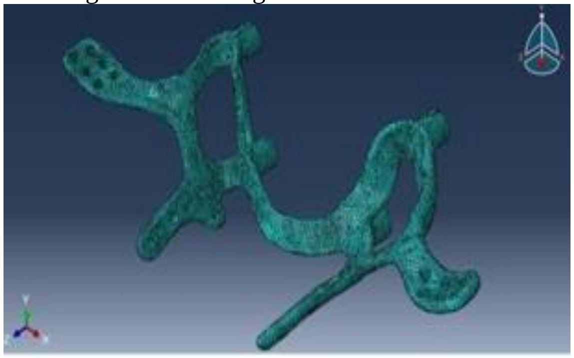
Source: Author, 2022.

To determine the appropriate application of these values on the prosthesis, the simulation was divided into five cases for subsequent result analysis:

- Case 1: A single force of 200 N was applied to the base of the prosthesis.
- Case 2: A single point load of 300 N was distributed on the surface.
- Case 3: Two forces were applied, one of 200 N at the bases of the front cylinders and another of 200 N at the bases of the rear cylinders.
- Case 4: Two forces were applied, one of 300 N at the bases of the front cylinders and a second force of 300 N at the bases of the rear cylinders.
- Case 5: Two forces were applied, one of 300 N at the bases of the front cylinders and another of 500 N at the bases of the rear cylinders.

With the tensile test parameters, the simulation was initiated, generating a mesh, as shown in Figure 5, consisting of 306,224 and 200,537 elements. These elements are of type C3D10.

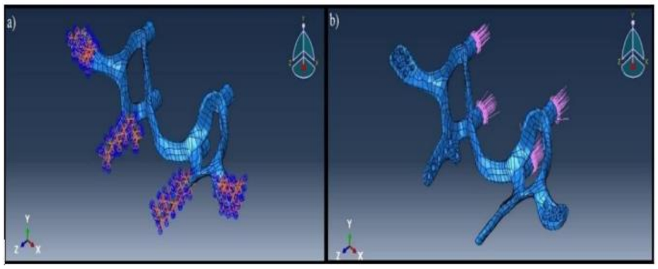
Figure 5 – Mesh generated for the model.



Source: Author, 2022.

To conduct the simulation, the holes were fixed in contact with the bucomaxillary bone, as illustrated in Figure 6, and the load was applied to the external faces of the cylinders where screws would be placed to secure the prosthesis.

Figure 6 – Indication of the fixed support of the prosthesis (a) indication of loads on the prosthesis (b).

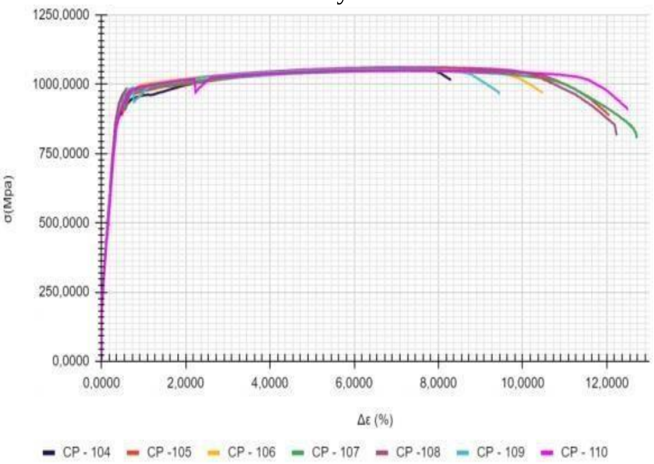


Source: Author, 2022.

IV. RESULTS AND DISCUSSIONS

Tensile tests were conducted following the ABNT NBR ISO 6892-1:2013 standard. Samples manufactured through additive manufacturing were subjected to tensile forces until failure to determine mechanical properties (elongation, deformation, tensile strength, among other parameters) that were used as input parameters in the FEM simulation. Figure 7 presents the stress-strain curve of the tested specimens made from the Ti-6Al-4V alloy.

Figure 7 – Stress x Average deformation chart of Ti-6Al-4V alloy.



Source: Author, 2022.

The obtained results are presented in Table 2, and they meet the minimum indicators of the ASTM F136 standard. Therefore, the mechanical behavior exhibited falls within the values indicated by the literature.

Table 2 – Traction test result

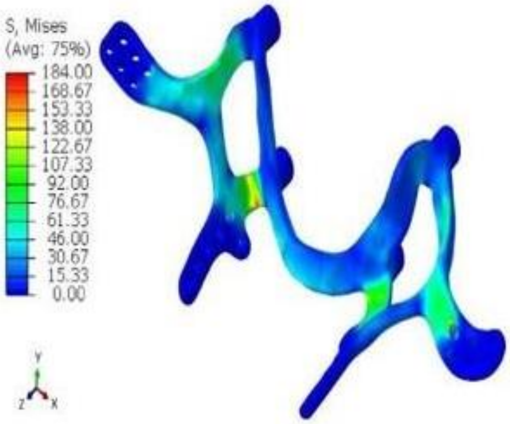
Sample	**Yield strength (MPa)**	**Tensile strength limit (MPa)**
104	954.55	1054.02
105	947.30	1042.73
106	985.24	1068.15
107	943.12	1038.37
108	987.07	1073.68
109	989.46	1057.23
110	977.27	1033.56
Average	969.15	1052.54

Source: Author, 2022.

Analyzing the results, it is possible to note that the specimens have mechanical strength within the parameters recommended by the ASTM F136 standard, and the values obtained are suitable for use in prosthesis projects

With the acquisition of the input parameters, they were inserted into the software, and meshes were generated, initiating the simulation process. The simulation for Case 1 is shown in Figure 8, and it can be observed that no significant critical points were detected in the simulation.

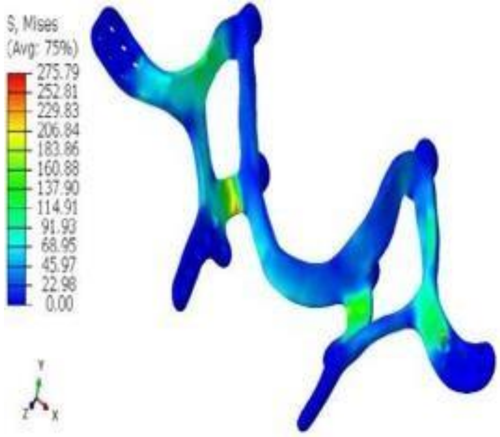
Figure 8 – Simulation Case 1.



Source: Author, 2022.

In the second case, an increase in points with average stresses was observed, with no significant critical issues presented, as shown in Figure 9, reaching a maximum Von Mises stress of 275.79 MPa in the simulation.

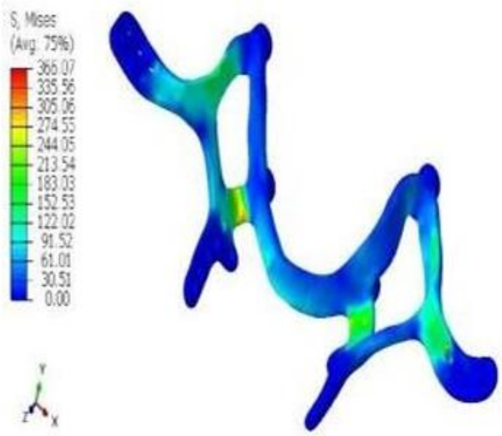
Figure 9 – Simulation Case 2.



Source: Author, 2022.

In Case 3, there was an increase in the maximum stress, according to the Von Mises criterion, to 366.07 MPa. However, the critical points obtained show a similar result to Case 2, as can be observed in Figure 10.

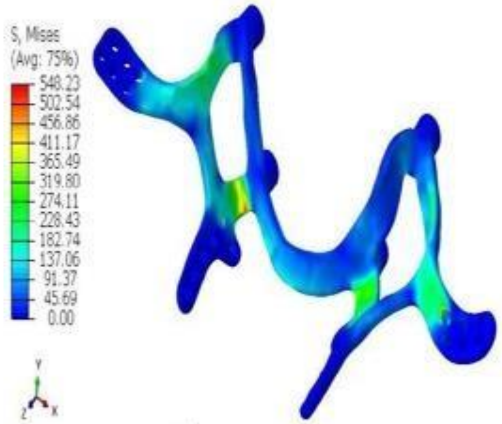
Figure 10 – Simulation Case 3.



Source: Author, 2022.

Case 4 exhibited some points of medium and critical criticality similar to the other cases analyzed. Figure 11 shows that the maximum stress obtained was 548.23 MPa.

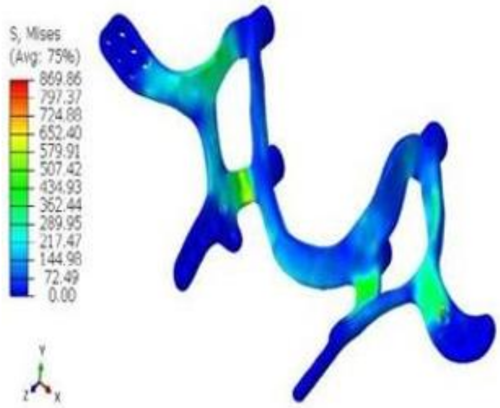
Figure 11 – Simulation Case 4.



Source: Author, 2022.

Case 5 exhibited critical points near the nodes, and the maximum stress obtained was 869.86 MPa, a result higher than the other cases, as shown in Figure 12. In this case, with the application of forces of 300 N distributed on the bases of the front cylinders and 500 N on the bases of the rear cylinders, extreme conditions were observed.

Figure 12 – Simulation Case 5.



Source: Author, 2022.

Analyzing the results obtained in the simulations, it is evident that the parts of the prosthesis experiencing the most significant impact are the nodes that connect the base to the upper part of the fixation on the skull and the lower fixation holes, which was expected since these nodes are regions with less material compared to others. In the case of the holes, they are crucial for fixing the prostheses to the skull. For a better understanding of the maximum stress values found, these are presented in Table 3.

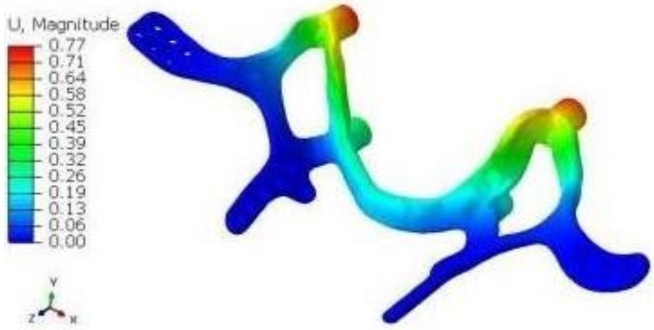
Table 3 – Maximum voltage of Von Mises per case.

Cases	**Máx Von Mises Voltage (MPa)**
1	184.00
2	275.79
3	366.07
4	548.23
5	869.86

Source: Author, 2022.

Therefore, to prevent the prosthesis from breaking, it will be necessary to add material to the critical stress points. The finite element simulations indicate that there will be bone loss due to the concentration of stresses localized in the bones and prosthetic components. Knowing that the higher the peak, the greater the risk of loosening and fractures of the structures, this compromises the aesthetic, structural, and longevity results of bucomaxillofacial prosthetic restorations. The critical stress points can be seen in Figure 13; the red color represents these regions.

Figure 13 – Critical stress points.



Source: Author, 2022.

V. CONCLUSIONS

As this is an unprecedented work, it was not possible to compare it with other literature due to the lack of standardization by the National Health Surveillance Agency (ANVISA) for custom prostheses. Computational tools were employed to assess critical stresses in custom prostheses. As observed in the majority of the studied cases, in addition to the critical point, the Von Mises stresses are below the yield limit used for the Ti-6Al-4V alloy. The deformations found are within the range of the elastic zone and below the plastic deformation range. The mesh generation in a trabecular structure emerged as one of the key elements in this study, given that bones consist of porous trabecular structures, promoting osseointegration and prosthesis biocompatibility.

VI. ACKNOWLEDGMENTS

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