International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XVII, No. 1 / 2025
https://doi.org/ 10.54684/ijmmt.2025.17.1.63

FINITE ELEMENT ANALYSIS AND TOPOLOGY OPTIMIZATION OF SLM ADDITIVE MANUFACTURED ORTHODONTIC BRACKETS

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Abstract: With rising standards of living globally, restorative dentistry has gained popularity and increase the demand for high performance dental tools, such as dental bracket, implants. etc. However, conventional orthodontic bracket designs are constrained by the limitations of traditional manufacturing techniques, and often fail to optimize their designs, resulting in bulkier, less comfortable and efficient orthodontic appliances. This work explores the integration of topology optimization with additive manufacturing to design orthodontic brackets for enhanced performance and reduced mass. Finite element analysis (FEA) was conducted on 3D models of brackets made from five materials: Aluminum Oxide (Al2O3), Ferritic Stainless Steel, AISI 316L Stainless Steel, Titanium Alloy (Ti-6Al-4V), and Co-Cr Alloy. The brackets were subjected to a torque of 0.0294 N-m applied by a 0.483 mm x 0.483 mm archwire. The FEA results showed that only Ti-6Al-4V and Co-Cr alloys met the minimum safety factor requirement (>1), with safety factors of 1.85 and 1.89, respectively. Topology optimization was applied to minimize mass while maintaining a safety factor above 1.25. The optimized Ti-6Al-4V and Co-Cr brackets achieved a 46% mass reduction. Despite increased maximum stress and a slight decrease in safety factor, the optimized designs demonstrated the potential to withstand required torque levels with reduced material usage. Topology optimization was performed using the SIMP (Solid Isotropic Material with Penalization) method, with the objective of minimizing mass while maintaining a safety factor above 1.25.

Keywords: Topology Optimization, Additive Manufacturing, Orthodontic Brackets, Finite Element Analysis (FEA), Material Performance

1. INTRODUCTION

The evolution of orthodontic treatment has seen significant advancements over the past few decades, with an increasing emphasis on improving the performance and comfort of orthodontic appliances. Orthodontic brackets are critical components in dental braces, responsible for transmitting forces to teeth and facilitating controlled tooth movement [1]. Traditional manufacturing methods for orthodontic brackets, such as casting and machining, often limit the complexity and optimization potential of bracket designs [2]. These methods typically produce components that are not fully optimized for strength-to-weight ratios, leading to heavier and potentially less comfortable orthodontic devices.

Recent advances in additive manufacturing (AM) and computational techniques like finite element analysis (FEA) and topology optimization have opened new avenues for the design and production of orthodontic components [3]. Additive manufacturing, particularly selective laser melting (SLM), allows for the creation of intricate geometries that are difficult or impossible to achieve with conventional manufacturing methods [4]. This capability is crucial for producing orthodontic brackets that are both lightweight and robust.

Topology optimization is a computational technique that optimizes the material layout within a given design space, subject to specific loading conditions and constraints. By identifying and retaining only the most critical material required for structural integrity, topology optimization can significantly reduce the weight of a component while maintaining or even enhancing its performance [5]. This study aims to leverage the synergies between topology optimization and additive manufacturing to design and produce orthodontic brackets that are optimized for mass reduction and enhanced mechanical performance.

Recent advancements in selective laser melting technology have further expanded its applications in biomedical and dental fields. Current research demonstrates that SLM techniques enable fabrication of biomedical devices

using high-quality materials such as titanium and cobalt-chrome with enhanced mechanical properties [6]. Modern SLM technologies make it possible to fabricate prosthetic restorations without material loss and to create prosthetic restorations with complex geometric shapes in a relatively simple way [7]. Studies have shown that SLM-processed Ti6Al4V lattices with graded porosities demonstrate excellent potential for dental applications [8], while additive manufacturing has gained significant attention in the production of customizable implants with complex shapes and superior mechanical properties [9]. Furthermore, titanium and cobalt-chromium-based alloys have been specifically investigated for implants, dental and orthodontic applications through SLM, with each material demonstrating excellent mechanical properties and biocompatibility for implantation [10].
This study introduces a novel integration of FEA and topology optimization to the workflow of design and manufacturing of orthodontic brackets, leveraging advanced AM technology to achieve lightweight, structurally optimized designs with enhanced performance. More specifically, in this study, the mechanical behavior of orthodontic brackets made from five different materials: Aluminum Oxide (Al_2O_3), Ferritic Stainless Steel, AISI Type 316L Stainless Steel, Titanium Alloy (Ti-6Al-4V), and Co-Cr (Cobalt-Chromium Alloy) was evaluated. Using FEA, the stress distribution and factor of safety of each material under orthodontic loading conditions were simulated. For the materials that meet the safety requirements, topology optimization was applied to minimize their mass while ensuring structural integrity. The optimized designs are subsequently manufactured using Selective Laser Melting (SLM) technology and evaluated for their performance. The optimization objective was to reduce mass while maintaining a minimum safety factor of 1.25 under orthodontic torque loading.

2. MATERIALS AND METHODS

2.1. Material Properties

The materials selected for this study are commonly used in orthodontic applications due to their favorable mechanical properties and biocompatibility. The mechanical properties of these materials are summarized in Table 1.

Table 1. Mechanical properties of materials evaluated [11-20]

	Alumina	Stainless Steel (Ferritic)	AISI Type 316L Stainless Steel	Titanium Alloy (Ti-6Al-4V)	Co-Cr
Elastic Modulus [MPa]	370000	200000	200000	104800	200000
Poisson's Ratio	0.22	0.28	0.265	0.31	0.33
Shear Modulus [MPa]	150000	77000	82000	44000	75188
Mass Density [kg/m^3]	3960	7800	8027	4428	8290
Tensile Strength [MPa]	200	485	513	1050	1060
Compressive Strength [MPa]	15400	300	300	970	900
Yield Strength [MPa]	200	170	172	827	839

Alumina Ceramic (Al_2O_3) is renowned for its excellent biocompatibility and aesthetic properties, offering high compressive strength and good wear resistance. However, its brittle nature and relatively low tensile strength can limit its application under high-stress conditions [11]. Ferritic Stainless Steel, known for good corrosion resistance and moderate mechanical properties, is often chosen for its cost-effectiveness, although its lower tensile and yield strengths can be disadvantageous [13]. AISI 316L Stainless Steel, austenitic stainless steel, provides excellent corrosion resistance and mechanical properties, making it popular in medical and dental applications due to its higher tensile and yield strengths [15]. Ti-6Al-4V (Titanium Alloy) is widely used in biomedical applications for its high strength-to-weight ratio, excellent biocompatibility, and corrosion resistance, making it particularly suitable for load-bearing orthodontic applications [17]. Co-Cr is noted for its high mechanical strength, wear resistance, and biocompatibility, making it ideal for applications requiring high durability and performance [19].
The orthodontic brackets used in this study were pre-adjusted edgewise brackets from GC Orthodontics (GC Orthodontics Europe GmbH, Breckerfeld, Germany), a well-known manufacturer of orthodontic appliances. These brackets were selected due to their compatibility with modern orthodontic techniques and their widespread

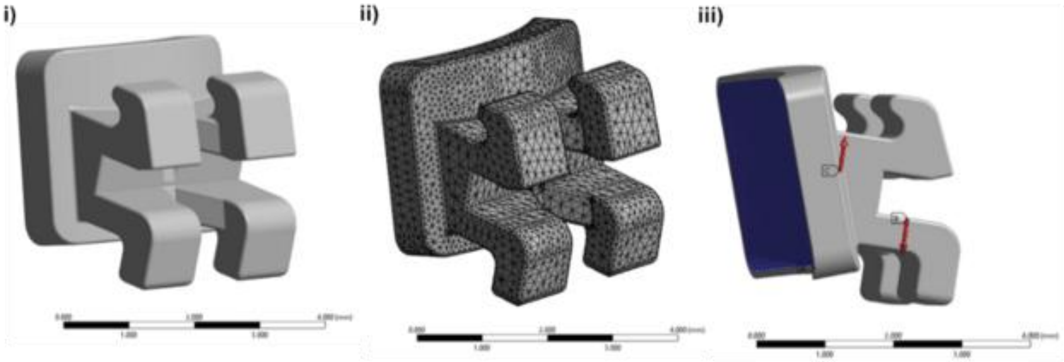
clinical use. The brackets feature a slot size of 0.559 mm, which is a standard dimension in orthodontic practice. These specifications were confirmed through direct measurement using high-precision calipers.

2.2. Topology Optimization and FEA

A linear elastic-static finite element analysis was conducted using ANSYS™ software (ANSYS, Inc., Canonsburg, PA, USA). A 3D CAD model of a pre-adjusted edgewise bracket (Figure 1.i) was created in SolidWorks (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA), featuring a slotted base and four tie-wings. The material properties listed in Table 1 were assigned to the corresponding models. The finite element mesh was generated using tetrahedral elements with an average element size of 0.1 mm, resulting in approximately 75,000 elements and 120,000 nodes. This meshing strategy ensured accurate stress distribution calculations while maintaining computational efficiency (Figure 1.ii). This mesh type and size were selected to accurately capture stress distributions and deformation patterns while balancing computational efficiency. The global mesh density was maintained consistently throughout the analysis. The bracket was subjected to a torque of 0.0294 N-m, applied by a 0.483 mm x 0.483 mm orthodontic archwire. This load simulates the forces experienced during orthodontic treatment [21]. The boundary conditions were set to simulate the attachment of the bracket to a tooth surface, with constraints applied to the base of the bracket to restrict movement (Figure 1.iii). The Von Mises stress and factor of safety distributions were calculated for each material under the applied load. A convergence test was performed by incrementally refining the mesh size until the changes in maximum stress values were below 5%. This confirmed the accuracy and stability of the finite element model.
Topology optimization was performed using SolidWorks (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA) with the Solid Isotropic Material with Penalization (SIMP) algorithm. This algorithm is widely used in topology optimization and works by iteratively redistributing material within the defined design space to achieve the desired objectives while adhering to specified constraints. The objective was to minimize the mass of the brackets while maintaining a minimum safety factor of 1.25. The optimization process involved defining the design space, loading conditions, and constraints (Figure 1.iv). The retained regions included the base for a secure fit, the slot for archwire functionality, and the tie-wing areas necessary for placing the elastic ties. A 10mm depth constraint was defined for these areas to ensure the necessary geometric dimensions were maintained. Non-critical material was systematically removed to achieve the optimal material layout (Figure 1.v). The optimized designs (Figure 1.vi) were then re-evaluated using FEA with the same mesh parameters (Figure 1.vii) to ensure that the reduced-mass brackets still met the required performance criteria (Figure 1.viii). The final optimized models were compared to the initial designs in terms of maximum stress, factor of safety, and mass reduction.

2.3. Additive Manufacturing

Additive manufacturing was performed using SLM technology, employing MetcoAdd 78A cobalt-chromium-based alloy powders sourced from Oerlikon Metco (Oerlikon Metco Inc., Westbury, NY, USA). This material is specifically formulated for the manufacture of medical or dental implants using SLM. The process was carried out on the ORLAS CREATOR metal 3D printer (Coherent Inc., Santa Clara, CA, USA). To ensure quality, SLM operations were conducted within an argon-purged build chamber to maintain oxygen levels below 100 ppm, thereby preventing oxidation. This advanced manufacturing method utilized a 1070 nm laser with a maximum power output of 250 W to selectively fuse metal powder layer by layer. Critical parameters, including layer height (0.025 mm), hatching distance (0.040 mm), laser power (120 W), and scan speed (700 mm/s), were meticulously optimized to achieve components with high density, minimal porosity, and exceptional mechanical properties suitable for demanding orthodontic applications. The criteria for topology optimization were to minimize mass while maintaining a minimum safety factor of 1.25 under applied torque loads.



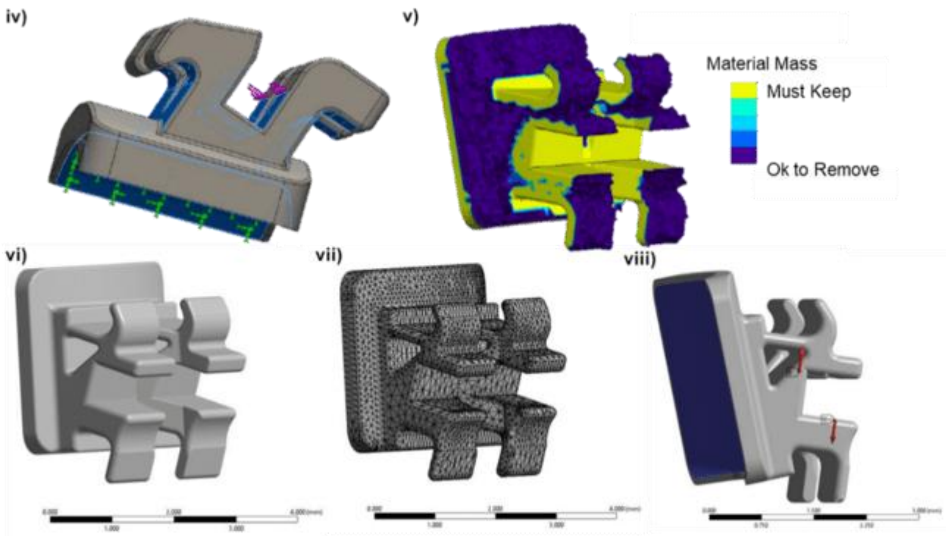


Fig. 1. i) The original CAD model of the orthodontic bracket, featuring the slotted base and tie-wings. ii) The tetrahedral mesh with a 0.1 mm element size applied to the initial bracket model for finite element analysis. iii) Application of a torque load (0.0294 N-m,) and boundary conditions in the finite element analysis of the initial bracket design. iv) The initial design space and loading conditions used for topology optimization. v) Visualization of material removal during the optimization process, highlighting changes made to reduce mass while maintaining structural integrity. vi) The CAD model of the bracket after topology optimization, showing the revised geometry. vii) Mesh configuration with a 0.1 mm element size for the optimized bracket model. viii) Application of a torque load (0.0294 N-m,) and boundary conditions in the finite element analysis of the optimized bracket design.

3. RESULTS AND DISCUSSION

Figure 2.i shows the CAD models of the initial and optimized orthodontic brackets, with the initial design on the left and the optimized design on the right. Figure 2.ii shows the additively manufactured initial and optimized orthodontic brackets. The initial FEA results for the standard bracket design showed varying performance across the different materials. The Von Mises stress and factors of safety distribution of the initial Co-Cr orthodontic bracket are shown in Figure 3.i,ii. The FEA results of each material are summarized in Figure 3.iii. Figure 3.iii shows the maximum Von Mises stress and safety factor for each bracket material. The performance comparison highlights why only Ti-6Al-4V and Co-Cr met the safety threshold for further optimization. Only the Ti-6Al-4V and Co-Cr brackets met the minimum safety factor requirement (>1) for the applied torque. The other materials exhibited either excessive stress or inadequate safety factors, making them unsuitable for further optimization. The topology optimization results for Ti-6Al-4V and Co-Cr brackets revealed significant mass reduction while maintaining acceptable performance levels. Specifically, the optimized Ti-6Al-4V bracket achieved a 46% reduction in mass, dropping from 47.53 mg to 25.56 mg. Similarly, the Co-Cr bracket saw a reduction from 98.89 mg to 53.96 mg. The optimized designs demonstrated the following metrics: Ti-6Al-4V bracket with a maximum stress of 594 MPa, a maximum displacement of 0.0073 mm, and a minimum safety factor of 1.4; and Co-Cr bracket with a maximum stress of 586 MPa, a maximum displacement of 0.0038 mm, and a minimum safety factor of 1.4. The Von Mises stress and factors of safety distribution of the optimized Co-Cr orthodontic bracket are shown in Figure 3.iv,v. The maximum stress and minimum safety factor values for the optimized brackets are summarized in Figure 3.vi. The optimized designs exhibited increased maximum stress and decreased safety factors compared to the initial designs. However, the values remained within acceptable limits, demonstrating the effectiveness of the optimization process. Figure 3.vi summarizes stress and safety factor of the optimized designs, and includes proper axis labeling for clarity.

The combination of topology optimization and additive manufacturing offers a transformative approach to the design and production of orthodontic components. The optimized Ti-6Al-4V and Co-Cr brackets not only met the required mechanical performance criteria but also achieved significant mass reduction. This reduction in material usage can lead to lighter orthodontic appliances, improving patient comfort and treatment efficiency. The results of this study highlight the potential of advanced computational techniques and manufacturing technologies to revolutionize orthodontic component design. The optimized brackets demonstrated improved performance compared to their traditionally manufactured counterparts, suggesting that further innovations in this field could lead to even greater advancements in orthodontic treatment.

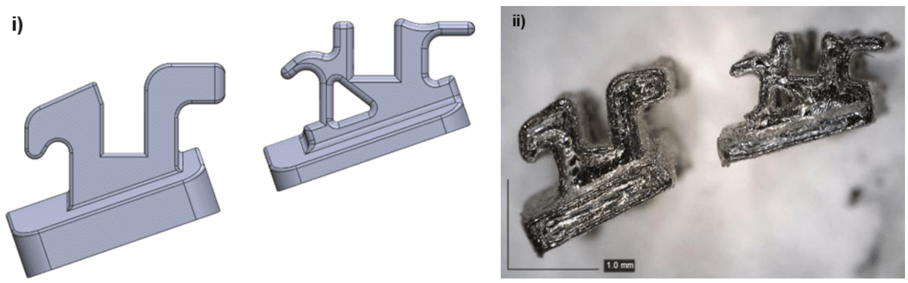


Fig. 2. i) High-detail 3D CAD models of the initial and optimized orthodontic brackets. ii) Additively manufactured initial and optimized orthodontic brackets.

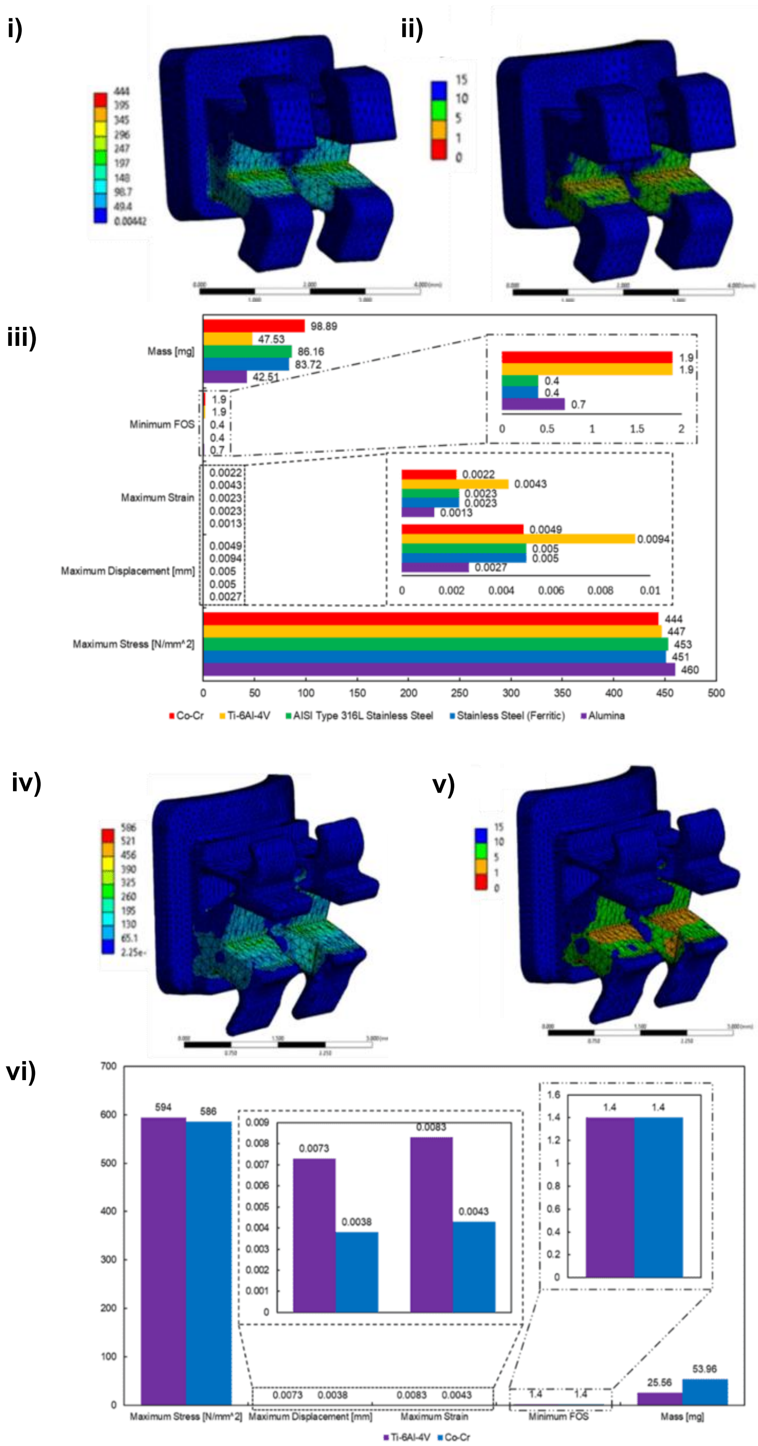


Fig. 3. i) Von Mises stress distribution of initial Co-Cr orthodontic bracket. ii) Factor of safety distribution of initial Co-Cr orthodontic bracket. iii) FEA results of initial orthodontic brackets. iv) Von Mises stress distribution of optimized Co-Cr orthodontic bracket design. v) Factor of safety distribution of optimized Co-Cr orthodontic bracket design. vi) FEA results of optimized orthodontic brackets

4. CONCLUSION

This study demonstrates the effectiveness of combining topology optimization and additive manufacturing for the design of orthodontic brackets. The optimized Ti-6Al-4V and Co-Cr brackets achieved notable improvements in performance. Specifically, the Ti-6Al-4V brackets showed a remarkable 46% reduction in mass, from 47.53 mg to 25.56 mg, while maintaining a minimum safety factor of 1.4 and a maximum stress of 594 MPa. Similarly, the Co-Cr brackets achieved a mass reduction from 98.89 mg to 53.96 mg, with a minimum safety factor of 1.4 and a maximum stress of 586 MPa. These results highlight the potential of optimized designs to significantly enhance the efficiency and comfort of orthodontic treatments. Additive manufacturing enabled the production of complex, optimized geometries that are not feasible with traditional methods. The findings of this study suggest that topology-optimized brackets can improve treatment efficiency and patient comfort in orthodontic applications. The integration of advanced computational techniques and manufacturing technologies holds great promise for the future of orthodontic component design, paving the way for more innovative and efficient treatment solutions. Future research could focus on exploring additional advanced materials and composites for orthodontic bracket design, aiming to enhance mechanical properties and further reduce mass. Additionally, long-term durability studies are needed to evaluate the performance and wear of topology-optimized and additively manufactured brackets in real-world conditions, ensuring their reliability and effectiveness throughout extended orthodontic treatments.

Author contributions: Conceptualization: T. Profitiliotis; Data curation: T. Profitiliotis; Formal analysis: T. Profitiliotis; Investigation: T. Profitiliotis, N. Kladovasilakis; Methodology: T. Profitiliotis, N. Kladovasilakis, D. Tzetzis; Project administration: D. Tzetzis; Resources: E.M. Pechlivani; Software: T. Profitiliotis; Supervision: D. Tzetzis; Validation: T. Profitiliotis, N. Kladovasilakis, D. Tzetzis; Visualization: T. Profitiliotis; Writing – original draft preparation: T. Profitiliotis; Writing – review and editing: N. Kladovasilakis, D. Tzetzis; Funding acquisition: E.M. Pechlivani
Funding source: This research was supported partially by the Horizon Europe CircSyst project under the GA no. 101135505 and "En3DSyst" (Project code: KMP6–0232019) under the framework of the Action "Investment Plans of Innovation" of the Operational Program "Central Macedonia 2021–2027", which is co-funded by the European Regional Development Fund (ERDF) of the European Union and Greece.
Conflicts of interest: There is no conflict of interest.
Acknowledgements: Not applicable.

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Received: January 10th, 2025 / Accepted: June 15th, 2025 / Paper available online: June 20th, 2025