Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 9, S. 464-471, 10, 2025

Araştırma Makalesi

IJANSER

https://as-proceeding.com/index.php/ijanser
ISSN:2980-0811

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 9, pp. 464-471, 10, 2025

Research Article

Structural Integrity Evaluation of SLM Ti-6Al-4V Components with Optimized Geometrical Features

Murat IŞIK*

[1]*Department of Automotive Engineering/Bursa Uludağ University, Türkiye*

(muratisik@uludag.edu.tr) Email of the corresponding author

(Received: 25 October 2025, Accepted: 26 October 2025)

(7th International Conference on Engineering and Applied Natural Sciences ICEANS 2025, October 25-26, 2025)

ATIF/REFERENCE: Işık, M. (2025). Structural Integrity Evaluation of SLM Ti-6Al-4V Components with Optimized Geometrical Features, *International Journal of Advanced Natural Sciences and Engineering Researches*, 9(10), 464-471.

Abstract – This study investigates the integration of topology optimization (TO) and additive manufacturing (AM) for lightweighting aerospace components, focusing on a structural bracket fabricated from Ti-6Al-4V (Ti64) via selective laser melting (SLM). The primary objective was to analyze the component's structural response under static loading and to evaluate the influence of load magnitude on topology optimization outcomes for 30% and 50% mass reduction targets. Finite element analysis (FEA) was conducted using assigned SLM Ti6Al4V material properties, applying static loads of 20 kN and 40 kN. The simulation results demonstrate that the bracket operates well within its linear elastic range, exhibiting a high factor of safety; the maximum observed elastic stress (approximately 81 MPa at 20 kN) remained significantly below the material's typical tensile strength (800-1200 MPa). Critically, the topology optimization algorithm produced nearly identical optimized geometries for both 30% and 50% mass reduction targets, irrespective of whether the 20 kN or 40 kN load was applied. This main finding indicates that for this linear system, the optimal material layout is conducted by the mass reduction target and initial geometry, not the load's magnitude. This conclusion supports the use of SLM Ti6Al4V and TO for creating strong, lightweight structures and suggests a potential to update the design process by reducing redundant optimization analyses within a linear loading range.

Keywords – Ti6Al4V Alloys, Mechanical Properties, Selective Laser Melting, Additive Manufacturing, Optimization.

I. INTRODUCTION

This introduction addresses the collaborative relationship between advanced structural optimization techniques, high-performance materials, and modern manufacturing processes, focusing specifically on applications in fields requiring lightweight design, such as the aerospace industry [1]. The foundational tool for achieving optimized structures is topology optimization (TO). TO is a structural optimization method that seeks to determine the optimum material distribution and voids within a predefined design space, subjected to specific loads and constraints, often aiming for a lightweight index [1–3]. It is highly effective for reducing weight while maintaining or improving mechanical properties. For instance, TO has been successfully used in the structural design of components such as engine bracket supports and satellite brackets [4,5]. Optimization studies have shown that TO can significantly decrease the mass of an engine bracket (e.g., nearly 20%) while increasing performance metrics, such as the first natural frequency (e.g., nearly 10%) [4]. The designs resulting from TO often feature complex, intricate geometries that are challenging to produce using conventional subtractive manufacturing methods.

This challenge promotes the adoption of additive manufacturing (AM), or 3D printing [6]. AM techniques, due to their increased geometrical freedom, are widely regarded as main enablers for the direct manufacture of complex end-use parts, particularly those resulting from optimization processes like TO. Among metal AM techniques, selective laser melting (SLM), classified as a powder bed fusion process [7]. SLM uses an infrared fiber laser to selectively melt and consolidate successive layers of loose metal powder to create solid, near fully dense components [8].

A highly desirable material in this domain, offering a crucial combination of strength, light weight, and performance, is the Ti-6Al-4V alloy (also known as Ti64) [9]. Ti-6Al-4V is extensively applied for load-bearing orthopedic implants due to its high corrosion resistance and excellent biocompatibility, and has been the most favorable titanium alloy since its introduction in the early 1950s [9]. SLM has been widely employed for manufacturing components from pre-alloyed Ti-6Al-4V powder feedstock [10]. The rapid melting and solidification characteristic of SLM processing often results in a unique microstructure in Ti-6Al-4V, typically dominated by the acicular α′ martensitic phase [10].

In summary, the design process supporting topology optimization to achieve lightweight, high-performance designs, followed by the high-precision fabrication of these complex forms using selective laser melting with challenging, high strength materials like Ti6Al4V alloy, is critical for manufacturing sophisticated structural parts, such as aerospace brackets, for modern engineering applications [5,6,11].

II. MATERIALS AND METHOD

The material analyzed in this study was a Ti6Al4V alloy with properties corresponding to those produced by the selective laser melting (SLM) additive manufacturing process. The finite element analysis (FEA) was conducted using ANSYS software on a bracket model with an initial mass of 1.0493 kg. For the simulation, the material properties were assigned as follows: a density of 4420 kg/m³, an elastic modulus of 120 GPa, and a Poisson's ratio of 0.34. During the analysis, the model was subjected to a primary load of 20 kN and an additional load of 40 kN, while the holes were constrained with fixed supports. The primary objective of this study was to perform a topology optimization based on the low-stress distribution patterns to achieve a target mass reduction of 50%.

III. RESULTS

CAD model of the target model was presented in Figure 1a and mesh structure applied was represented in Figure 1b.

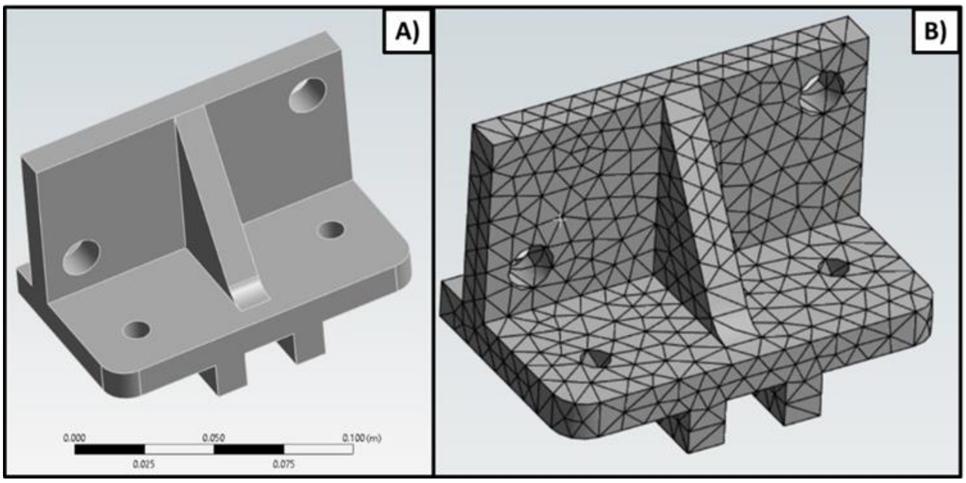

Figure 1. a) Computer-aided design (CAD) model of the bracket, with b) an introduction of the mesh applied to the model.

Figure 2 shows the total deformation distribution on bracket with different perspectives. The idea that geometry is the determining factor can also be supported by the characteristics of the applied forces. No significant change in distribution was observed under the conditions with 20 kN and 40 kN applied forces. The region of maximum deformation forms a V shaped pattern, with the peak deformation reaching approximately 0.033 mm in the case of applied load is 20 kN. However, the resulting deformation magnitude has been observed to change. In the 40 kN scenario, the maximum deformation is approximately 0.067 mm, which represents a near doubling of the deformation. The deformation increased in direct proportion to the applied force. When viewed from all three angles, where the deformation values gradually decrease in a step by step manner from the maximum at the top of the model toward the bottom. Deformation is minimal in the regions near the holes and gradually increases as the distance from the holes increases. Additionally, the deformation distributions near the holes extend in wave-like curves, creating a pattern that resembles undulating contours. It is evident that there is no symmetric distribution between the left and right sides.

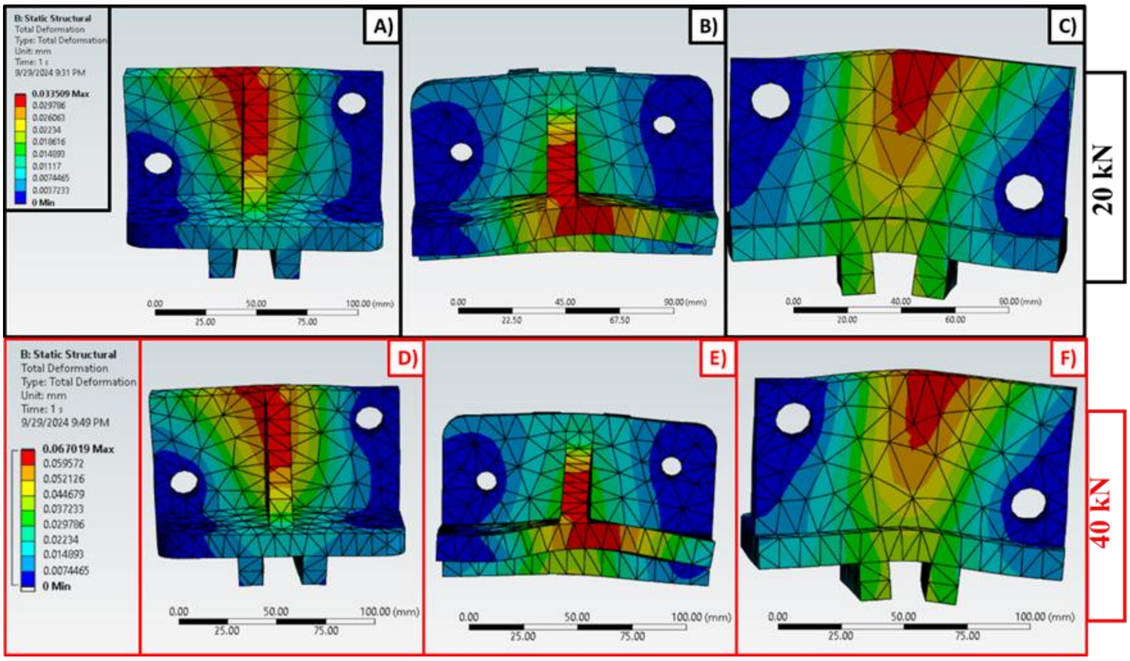

Figure 2. The distribution of total deformation for the SLM Ti6Al4V alloy during static structural analysis using finite element analysis (FEA) is presented under a) 20 kN load, with figures a), b), and c) corresponding to front, top, and back views, respectively, and d), e), and f) representing the same views under a 40 kN load.

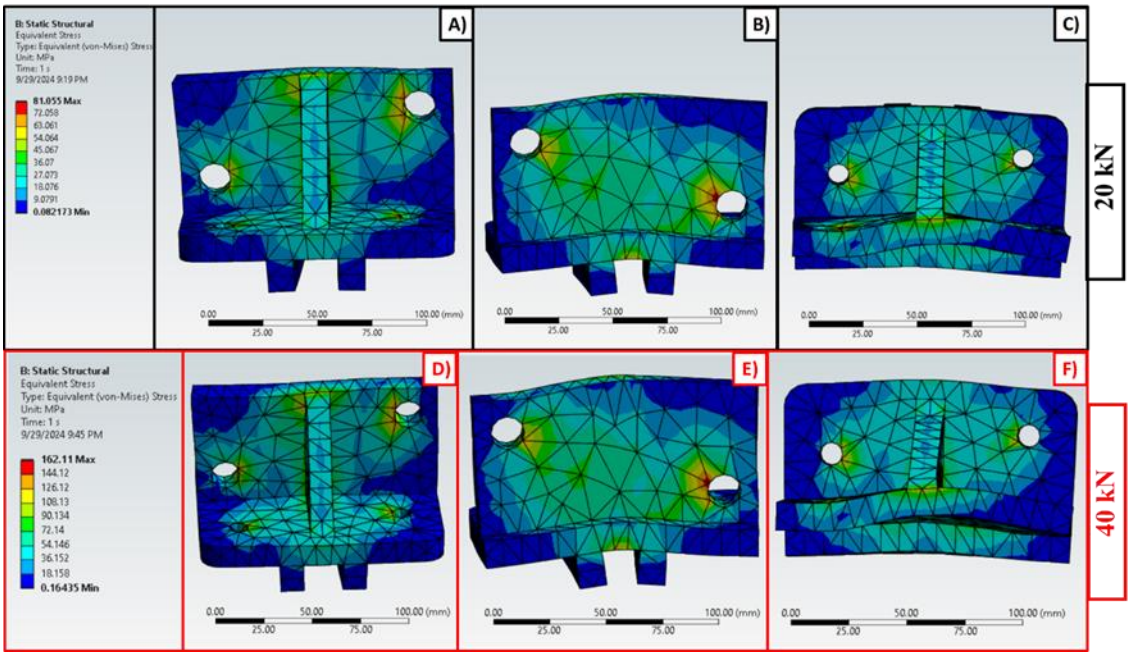

Figure 3. The distribution of equivalent stress for the SLM Ti6Al4V alloy during static structural analysis using finite element analysis (FEA) is represented under a) a 20 kN load, with figures a), b), and c) illustrating the front, back and top views, respectively, and d), e), and f) presenting the same perspectives under a 40 kN load.

Figure 3 shows the distribution of elastic strain for the SLM Ti6Al4V alloy during static structural analysis, with results presented under 20 kN and 40 kN loads using finite element analysis (FEA). By examining the distributions under 20 kN and 40 kN loads for the Ti alloy, it is clear that the distribution is not significantly affected by load changes. Instead, geometry appears to be the determining factor. Therefore, it can be concluded that a different geometry is required for a different distribution. However, it is true that a small change in the maximum stress values is observed. Under a 20 kN force, in the SLM Ti alloy, maximum stress is around 81 MPa. Similarly, a review study compiling results from multiple researchers indicated that the tensile strength of SLM Ti6Al4V alloy generally ranges between 800 MPa and 1200 MPa [12]. These values were obtained from various experimental studies conducted under different processing conditions, highlighting the variability in mechanical performance depending on parameters such as build orientation, porosity, and microstructure. In light of this information, the maximum stress values observed in our simulations, remaining significantly below these tensile strength limits, indicate that the SLM Ti6Al4V structure is operating well within safe mechanical boundaries under both 20 kN and 40 kN loading conditions. This further supports the structural reliability of the topologically optimized design. When compared to steel, SLM Ti6Al4V demonstrates significantly superior tensile strength, with values reaching up to three times higher. This inherent advantage allows for the design of lighter yet mechanically robust components, especially in applications where weight reduction is critical without compromising structural integrity. It has been recommended in previous studies that material choice with higher young modulus generally leads to better results [13], as it allows for more controlled load distribution and prevents plastic deformation. When examining Figures 3 b and e, it can be observed that the stress near the lower hole is slightly higher than in the other regions and holes. This is also the area that exhibits the highest stress in the part. At 20 kN, the majority of the stress values range between 45 and 9 MPa, while for 40 kN, they range between 90 and 18 MPa, indicating a proportional change consistent with the increase in the applied load.

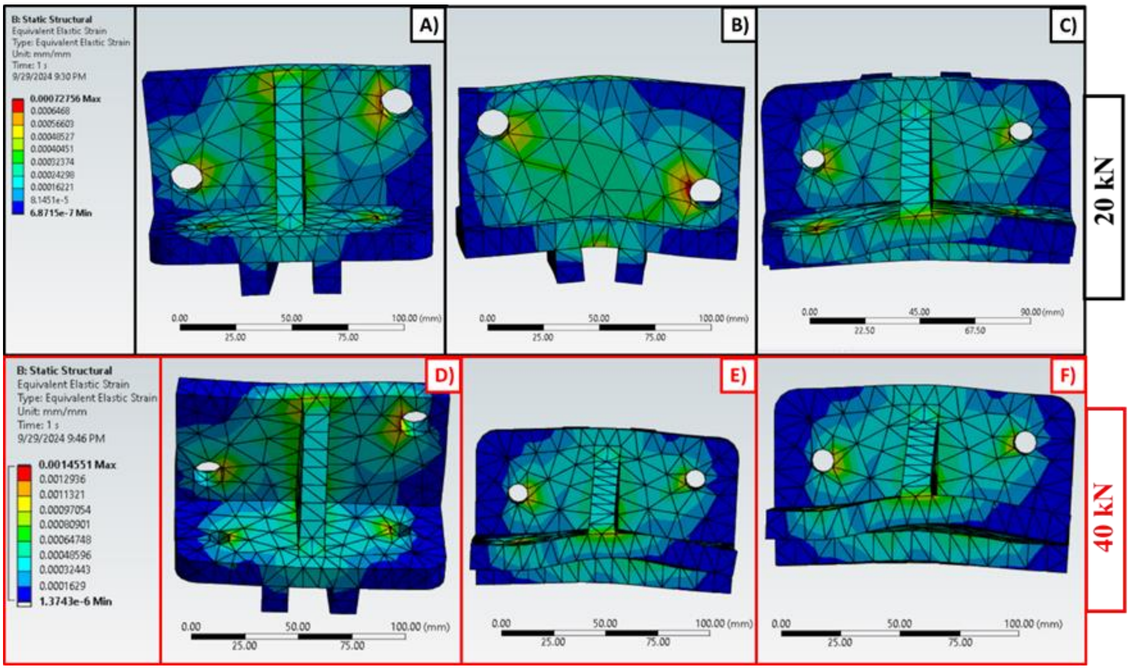

Figure 4. The distribution of equivalent strain for the SLM Ti6Al4V alloy during static structural analysis using finite element analysis (FEA) is illustrated under a) a 20 kN load, with figures a), b), and c) showing the front, top, and back views, respectively, and d), e), and f) displaying the same views under a 40 kN load.

Figure 4 displays the distribution of equivalent strain for the SLM Ti6Al4V alloy during static structural analysis under 20 kN and 40 kN loads, using FEA. The models subjected to 20 kN and 40 kN loads produced nearly identical results. The maximum deformation values are approximately 7×10^{-4} and 14×10^{-4}, respectively. The regions of maximum strain are located near the holes. On the back side of the bracket, the lower hole shows the highest strain, while on the front side, higher strain values are observed at the upper hole.

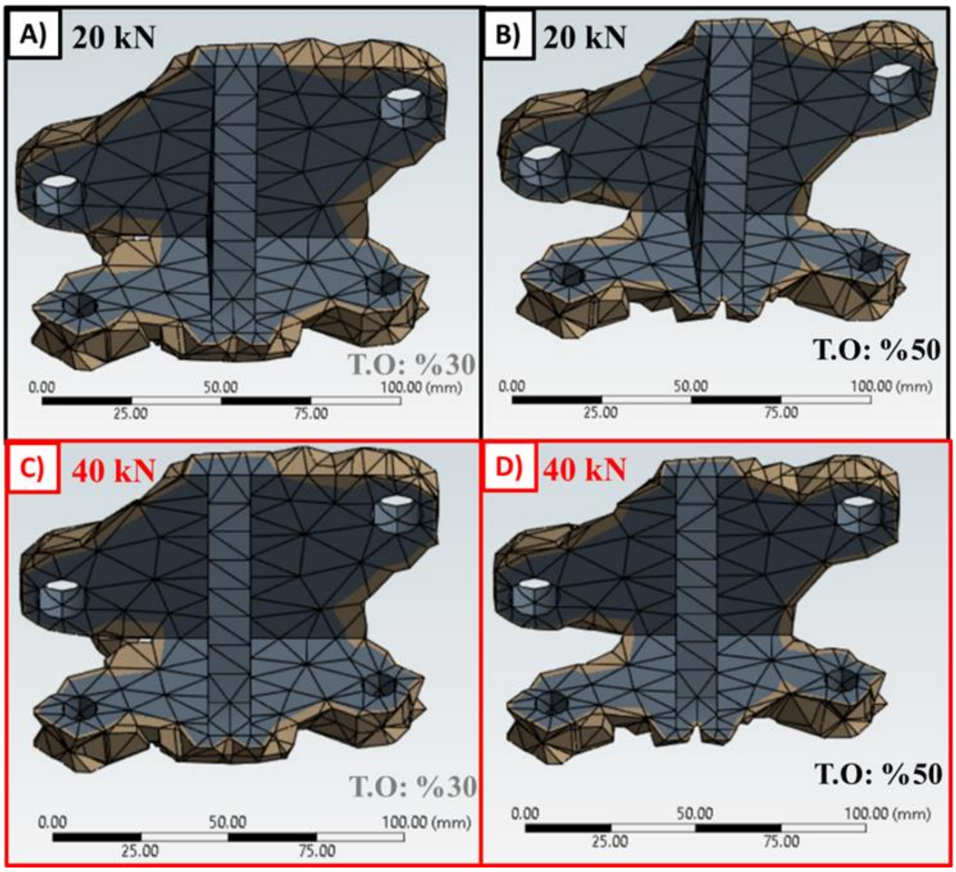

Figure 5. Topologically optimized SLM Ti6Al4V bracket achieving a 30% mass reduction a) under 20 kN load and c) under 40 kN load, and a 50% mass reduction b) under 20 kN load and d) under 40 kN load, based on static structural test results.

Figure 5 shows the topologically optimized SLM Ti6Al4V bracket, which achieves 30% and 50% mass reduction under 20 kN and 40 kN loads, respectively. It is clearly observable from the figure that as the topology optimization percentage increases, more material is removed from the part. Approximately the same topology optimized model is obtained under both 20 kN and 40 kN loads. In the case of 50% TO, the analysis results suggest that the change in applied force has little to no significant effect on the optimized geometry. A similar observation can also be made for the case with 30% topology optimization, where the change in applied force does not lead to a notable difference in the resulting optimized geometry. Considering this, it is understood that the topology optimization percentage and geometry play the crucial role in determining the final result.

IV. DISCUSSION

The findings of this study provide key insights into the structural behavior of the SLM Ti6Al4V bracket under static loading and its implications for topology optimization (TO). The most prominent observation across all analyses (total deformation, elastic strain, and equivalent strain) is the dominance of geometry over load magnitude in determining the distribution of mechanical responses. The analyses presented in Figures 2, 3, and 4 compellingly demonstrate that the component operates well within its linear elastic range. While the distribution patterns for deformation and strain remained virtually identical under both 20 kN and 40 kN loads, the magnitudes of these responses scaled in direct proportion to the applied force. For instance, the total deformation (Figure 2) and equivalent strain (Figure 4) almost perfectly doubled when the load was increased from 20 kN to 40 kN . This predictable, linear relationship confirms that the bracket's design is stable and does not undergo plastic deformation or unexpected geometric stiffening under the tested conditions. This finding reinforces the thesis that the inherent geometric features of the bracket, such as the V shaped region of maximum deformation and the stress concentrations near the holes, are the primary factors dictating the load path and stress distribution. The elastic strain analysis (Figure 3) confirms the structural integrity and high safety factor of the design. The maximum observed stress at 20 kN (approximately 81 MPa) is exceptionally low relative to the known tensile strength of SLM Ti6Al4V, which literature [12] places between 800 MPa and 1200 MPa. Even assuming a linear increase for the 40 kN load (implying a maximum stress of approximately 162 MPa), the stress levels remain comfortably within safe operational limits. The superior strength-to-weight ratio of Ti6Al4V compared to steel, combined with its high tensile strength, allows for a lightweight design (achieved via TO) that does not compromise mechanical robustness. The identification of the lower hole as the area of highest stress (Figure 3) is a critical finding for fatigue assessment under cyclic loading. Perhaps the most significant finding of this study relates to the topology optimization process (Figure 5). The fact that nearly identical optimized geometries were obtained for both 30% and 50% mass reduction targets, regardless of whether the simulation was run with a 20 kN or 40 kN load, carries important design implications. This suggests that for this component's specific boundary conditions and linear elastic behavior, the optimal load path is independent of the load's magnitude. The TO algorithm identifies the most efficient material placement to sustain the applied forces, and this structural layout remains the same. The primary driver for the final optimized shape is not the force value itself, but rather the target mass reduction percentage and the initial design space geometry. This finding could potentially reorganize the design process, suggesting that a single TO run (within a range of expected linear loads) may be sufficient, saving significant computational time and resources. While these FEA results are insightful, they are only computational. As noted by [12], the mechanical properties of additively manufactured parts, particularly SLM Ti6Al4V, are known to be variable and dependent on process parameters, build orientation, and post processing. Therefore, experimental validation is a crucial next step. Manufacturing the 30% and 50% topologically optimized brackets and subjecting them to physical tensile testing would be necessary to confirm the accuracy of the simulated deformation and stress values. Furthermore, this study was limited to static structural analysis. Future work should investigate the bracket's performance under dynamic or cyclic loading (fatigue analysis), especially given the identified stress concentration near the lower hole, which could be a critical point of failure over time.

V. CONCLUSION

This simulation study successfully demonstrates that the analyzed SLM Ti6Al4V bracket design is structurally good, with a high safety factor under static loads up to 40 kN. The component's behavior is dominated by its geometry and remains predictably linear within this loading range. Critically, the topology optimization results indicate that for this linear system, the optimized material layout is conducted by the mass reduction target and initial geometry, not the specific magnitude of the applied force. These findings support the use of TO and SLM Ti6Al4V for developing lightweight, reliable, and predictable structural components.

REFERENCES

[1] M.U. Erdaş, M. Kopar, B.S. Yildiz, A.R. Yildiz, Optimum design of a seat bracket using artificial neural networks and dandelion optimization algorithm, Mater. Test. 65 (2023) 1767–1775. https://doi.org/10.1515/mt-2023-0201.

[2] O. Sigmund, K. Maute, Topology optimization approaches, Struct. Multidiscip. Optim. 48 (2013) 1031–1055. https://doi.org/10.1007/s00158-013-0978-6.

[3] Z. Xiao, Y. Yang, D. Wang, C. Song, Y. Bai, Structural optimization design for antenna bracket manufactured by selective laser melting, Rapid Prototyp. J. 24 (2018) 539–547. https://doi.org/10.1108/RPJ-05-2017-0084.

[4] E. Armentani, V. Giannella, A. Parente, M. Pirelli, Design for NVH: Topology optimization of an engine bracket support, Procedia Struct. Integr. 26 (2020) 211–218. https://doi.org/10.1016/j.prostr.2020.06.024.

[5] İ. Gökdağ, O. İzgü, A. Dağkolu, A.A. Tanrıkulu, E. Acar, Design optimization and validation for additive manufacturing: a satellite bracket application, Struct. Multidiscip. Optim. 65 (2022). https://doi.org/10.1007/s00158-022-03345-3.

[6] Y. Chen, Q. Wang, C. Wang, P. Gong, Y. Shi, Y. Yu, Z. Liu, Topology optimization design and experimental research of a 3d-printed metal aerospace bracket considering fatigue performance, Appl. Sci. 11 (2021). https://doi.org/10.3390/app11156671.

[7] Z. Chen, X. Wu, D. Tomus, C.H.J. Davies, Surface roughness of Selective Laser Melted Ti-6Al-4V alloy components,

Addit. Manuf. 21 (2018) 91–103. https://doi.org/10.1016/j.addma.2018.02.009.
[8] M. Simonelli, Y.Y. Tse, C. Tuck, On the texture formation of selective laser melted Ti-6Al-4V, Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 45 (2014) 2863–2872. https://doi.org/10.1007/s11661-014-2218-0.
[9] B. Song, S. Dong, B. Zhang, H. Liao, C. Coddet, Effects of processing parameters on microstructure and mechanical property of selective laser melted Ti6Al4V, Mater. Des. 35 (2012) 120–125. https://doi.org/10.1016/j.matdes.2011.09.051.
[10] N. Dai, L.C. Zhang, J. Zhang, X. Zhang, Q. Ni, Y. Chen, M. Wu, C. Yang, Distinction in corrosion resistance of selective laser melted Ti-6Al-4V alloy on different planes, Corros. Sci. 111 (2016) 703–710. https://doi.org/10.1016/j.corsci.2016.06.009.
[11] O. Okorie, A. Perveen, D. Talamona, K. Kostas, Topology Optimization of an Aerospace Bracket: Numerical and Experimental Investigation, Appl. Sci. 13 (2023). https://doi.org/10.3390/app132413218.
[12] D. Agius, K.I. Kourousis, C. Wallbrink, A review of the as-built SLM Ti-6Al-4V mechanical properties towards achieving fatigue resistant designs, Metals (Basel). 8 (2018). https://doi.org/10.3390/met8010075.
[13] J. Achleitner, E. Wehrle, On material selection for topology optimized compliant mechanisms, Mech. Mach. Theory 167 (2022) 1–22. https://doi.org/10.1016/j.mechmachtheory.2021.104474.