

Research Article

Mechanical Performance of SLM-Manufactured Bolts Under Varying Torque Conditions for Aerospace Applications

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Abstract

This research study examines the mechanical performance of bolts fabricated using Selective Laser Melting (SLM), a Laser Powder Bed Fusion (LPBF) technique widely utilized in the aerospace and automotive industries for producing lightweight, high-performance components. To improve mechanical properties through SLM, building orientation plays a crucial role, particularly in enhancing fatigue strength. This study examines the bolts mechanical properties by using SLM optimal process parameters, including laser power of 225 W, scan speed of 500 mm/s, and hatching distance of 100 μ m. This study investigates the mechanical performance of M5, M6, and M8 hexagonal bolts with a focus on tensile strength, creep resistance and effects of torque tightening on fatigue life. Tensile testing demonstrated the bolts' high strength, achieving an ultimate tensile strength (UTS) of 1189.32 MPa and a yield strength (YS) of 967.61 MPa at room temperature with a crosshead speed of 1 mm/min. Fatigue testing, conducted under pre-load and torque-applied conditions, revealed that proper torque application significantly enhanced fatigue life, extending it from 21,000–25,000 cycles in pre-load conditions to 135,000 cycles under a torque of 12 N-mm. Additionally, creep testing confirmed the material's long-term stability, showing no deformation or failure when subjected to a sustained load of 660 MPa over a 24-hour period. These results emphasize the critical role of torque tightening in improving fatigue performance and highlight the reliability of the bolts under prolonged stress, making them suitable for high-performance applications in the automotive and aerospace industries.

Keywords

Additive Manufacturing (AM), Selective Laser Melting (SLM), Hexagonal Bolt, Torque Tightening, Mechanical Properties

1. Introduction

Rapid prototyping (RP), additive layer manufacturing, rapid manufacturing (RM), and additive manufacturing (AM) are terms used to describe the process of creating components layer by layer. Using selective laser melting (SLM), a layer-up-layer AM production method, metal powders may be formed into intricate, customer-specific structures [1, 2]. The four steps in the laser additive manufacturing (LAM) process

include wire feed, powder feed, powder bed, and other procedures [3, 4]. In the additive technique, the four technologies are layered. Slice files are used by each additive layer manufacturing (ALM) technique to create physical AM parts in the SLM process according to the given process parameter. Layer by layer, small layers of the 3D CAD (computer aided design) geometry are cut out [5, 6]. With a full dense sample of

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Received: 26 February 2025; **Accepted:** 14 March 2025; **Published:** 31 March 2025



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99.95%, powder bed fusion (PBF) production provides the highest geometrical freedom and precision among ALM process methods [7, 8]. A number of material characteristics, such as distribution, size, and morphology, affect the final AM part quality of an SLM printed sample [9]. Another significant aspect that limits the grade of powder particle consolidation defect form growth is the laser heat input, which can cause turbulence in the melt pool, potentially leading to a keyhole defect [10]. This is particularly important because stainless steel (SS) 316 alloys are used extensively in the space and automobile industries [11]. The aerospace, biomedical, and automotive industries are among the many industries that use SS 316 alloys for specialized purposes due to its low thermal expansion, robust mechanical properties, recycling potential, and light weight [12]. Manufacturer LPBF-SLM (ASTM/ISO 52900) produces parts composed of SS 316 alloy. Hex bolts are mechanical fasteners that are typically used in combination with nuts to secure two or more components [13]. Due to the ease of dismantling a bolted joint, bolts and screw fasteners are used more often than any other form of mechanical fastener, and their use has been crucial to the expansion of steel structures and mass-produced objects [14]. A head and a cylindrical body with screw threads running along part of its length make up the hexagonal bolt. The nut is the female component of the pair, and its internal threads match those of the bolts. Often, washers are employed to avoid crushing and loosening [15, 16]. Previous metallurgical and optimization studies have used high laser power in watts, scan speed in mm/s, and hatching distance in μm [17]. The build orientation and procedure characteristics affected the AM strength [18]. My earlier research examined process parameters that were optimized with a component that was completely dense and free of defects [19]. Using the ideal/optimal process parameter going to perform the tensile test, dynamic axial fatigue and creep behavior of the mechanical characteristics for SS 316 alloy under various testing parameters with different conditions were carried out [20]. According to ASTM and ISO standards, the SLM bolt printed samples showed extremely high mechanical performance, including tensile, axial fatigue, and creep behavior. Despite the widespread application of hexagonal bolts in critical industries such as aerospace and automotive, there remains a limited understanding of how torque tightening impacts their mechanical performance,

particularly fatigue life and creep resistance, under real-world loading conditions. Previous studies have primarily focused on static tensile properties or general fatigue behavior without considering the synergistic effects of torque application and material flaws at stress-critical regions, such as the shank-thread interface. Moreover, while SLM has shown promise in producing high-strength, lightweight fasteners, its influence on long-term mechanical properties, including fatigue life under torque and creep behavior, remains underexplored. This study addresses these gaps by investigating the mechanical performance of SLM-fabricated hexagonal bolts, optimizing process parameters, and evaluating their behavior under combined tensile, fatigue, and creep loading conditions. The findings aim to bridge the gap in understanding the relationship between torque tightening, SLM process optimization, and the long-term reliability of additively manufactured bolts in high-performance applications.

2. Material and Methods

2.1. Material

This material contained gas atomization-produced powdered stainless steel 316 spheres; Table 1 lists the chemical composition of SS 316. The powdered SS 316 alloy is supplied by SLM Solution Group AG in Germany. The powder particle size distribution, as shown in Figure 1a, was determined using a scanning electron microscope (SEM) and ranged from 20 to 63 μm . The powder weighted residual is 0.694%, the specific surface area is 0.154 m^2/g , the surface weighted mean is 38.8 μm , and the volume weighted mean is 43.505 μm . As seen in Figure 1b, round specimens measuring 8 mm in diameter and 50 mm in length were created for the bolts testing. A strong basis for the ensuing wear analysis and performance evaluation under various testing situations is provided by this thorough characterization of the SS 316 powder and the particular design of the test specimens. The long circular bar specimen was printed, and the bolt shape geometry prepared by wire electrical discharge machining (WEDM).

Table 1. Chemical composition of SS 316 alloy [21].

C	Si	Mn	P	S	Cr	Ni	Mo	O	N	Fe
≤ 0.03	≤ 1.00	≤ 2.00	≤ 0.045	≤ 0.03	16.00-18.00	10.00-14.00	2.00-3.00	≤ 0.01	≤ 0.10	Rest

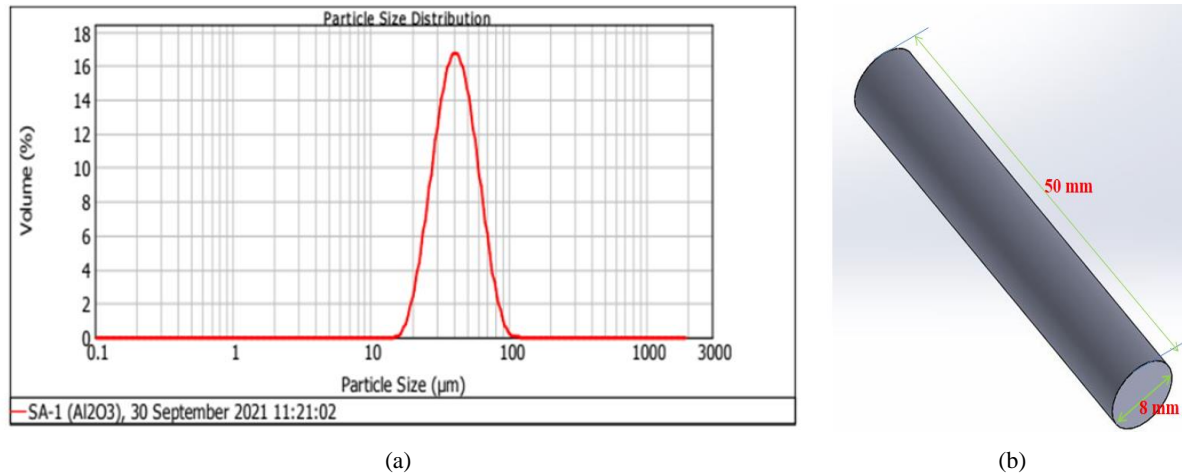
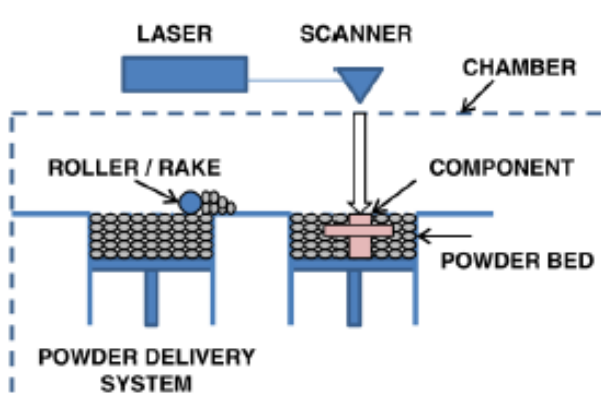


Figure 1. a) The SEM element examination for powder particle size supply in SLM chamber and b) CAD model geometry for SLM-AM printing.

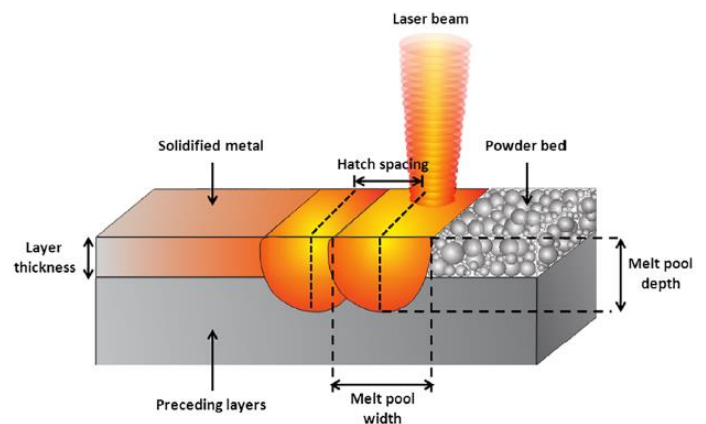
2.2. SLM Process

Among the new additive manufacturing methods that emerged in the late 1980s and early 1990s is SLM [22]. Through the interaction of a laser beam, successive layers of powder are selectively melted to produce a product during the SLM process. The powder substance gets heated during irradiation, melts, and creates a liquid pool if enough power is applied [23]. The consolidated material then begins to create the product as the molten pool rapidly cools and hardens. Following the scanning of a layer's cross-section, a fresh coating of powder is applied and the construction platform is lowered by the thickness of the layer [24]. Until the product is finished, this process is repeated. Even though this layer-by-layer approach was first used to create prototypes, direct manufacturing of components is gaining popularity because it

can net-shape complex structures from a CAD model and a range of materials without the need for expensive tooling and machining, which shortens the time between design and manufacture [25]. Figure 2 shows the SLM system (M280 2.0), which consists of an IPG fiber laser with a maximum power of about 400 W, a beam focus diameter of 80 to 115 μm, a scan speed of up to 10 m/s, an automatic powder spreading device, an inert argon gas protection system, and a computer system for process control. P = 225 W of laser power was employed, along with $v = 500$ mm/s for scanning, $h = 100$ μm for hatching spacing, $t = 30$ μm for layer thickness, 150 °C for build platform temperature, and a horizontal build wear test sample. $E = P/v \times h \times t$ was used to determine the laser energy volume, and the laser energy density came out to be 150 J/mm³. Figure 3 illustrates how a certain process parameter is used to make the SS 316 circular rod samples.



(a)



(b)

Figure 2. (a & b) SLM diagram and SLM-AM printing process [26].

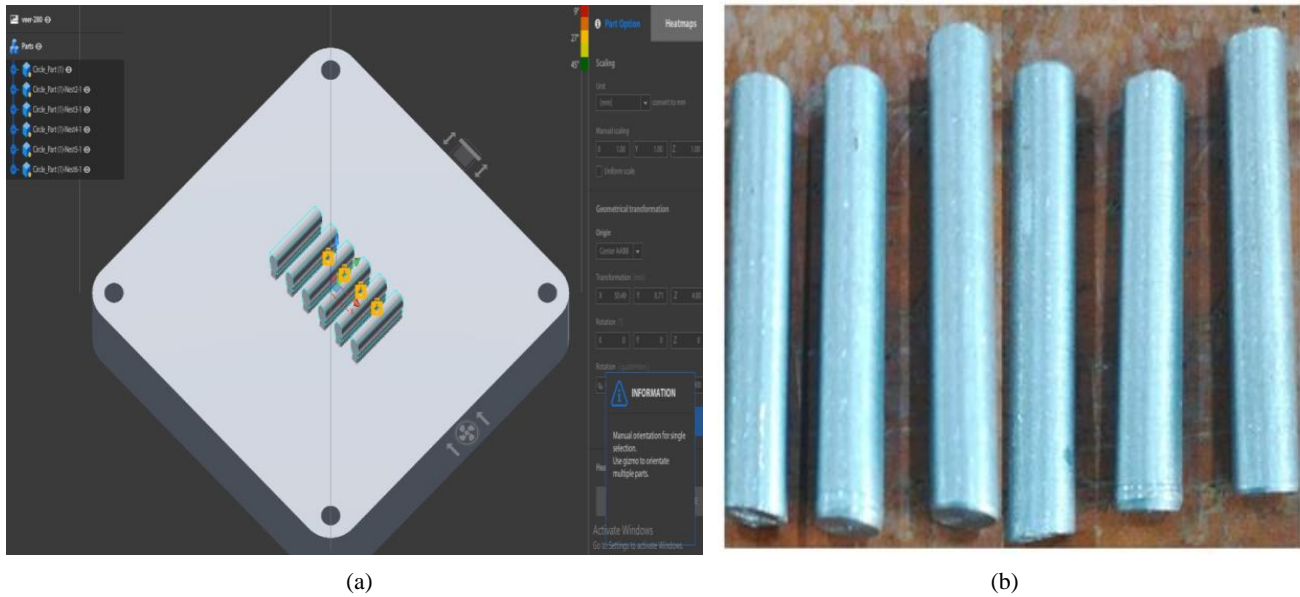


Figure 3. a) SLM build platform layout of specimen and b) After SLM-AM manufactured specimens.

3. Research Methodology

The selection of an optimal fastener material requires a comprehensive evaluation of multiple factors, including fatigue resistance, vibration tolerance, temperature stability, corrosion resistance, and overall strength. For most fastener applications, which are designed to support or transfer externally applied loads, strength is a critical consideration. Consequently, steel fasteners were chosen as the primary focus due to their superior strength characteristics and cost-effectiveness. However, recognizing the demands of specialized applications, such as those requiring high-temperature resistance or corrosion protection, non-ferrous materials were evaluated selectively. The study

employed a systematic approach, including tensile testing, fatigue testing, and creep testing, to assess the performance of M5, M6, and M8 hexagonal bolts fabricated using SLM-AM. The testing process examined the influence of key parameters such as torque tightening, material flaws, and SLM process settings (e.g., laser power, scan speed, and hatching distance) on the mechanical properties of the bolts. After printing, the SLM-AM sample was removed from the build chamber using WEDM and machined samples as per the standard for mechanical testing, as illustrated in Figure 4. By combining theoretical analysis with experimental testing under varying load and environmental conditions, the methodology provides a robust framework for understanding the behavior of fasteners in both conventional and specialized applications, especially in the automotive and aerospace industries.



Figure 4. (a) Hexagonal bolt 3D model for to prepare the specimen by WEDM and (b) Bolt specification [27].

Because of the detrimental aging brought on by corrosion or metal fatigue, engineers are extremely worried about the long service life of both military and commercial aircraft [28].

In reality, design concepts have changed recently, and fatigue life, durability, and damage tolerance rather than static strength and safe life are now key design elements. This has

significantly reduced the number of structural failures that occur in use [29, 30], in conjunction with improved materials, thorough testing processes, and sophisticated design analysis. Thorough documentation and knowledge regarding the behavior of bolts under cyclic stresses are still lacking [31]. How well a hexagonal bolt works over its fatigue life depends on a number of factors, including bolt size, quantity, and placement;

torque tightening or preload applied to the bolt; material plate thickness; and surface roughness [32]. These factors' full effects on a joint's fatigue life are complex and have not yet been thoroughly investigated [33]. As shown in Figure 5, the full experimental investigation was carried out on every bolt and fastener.

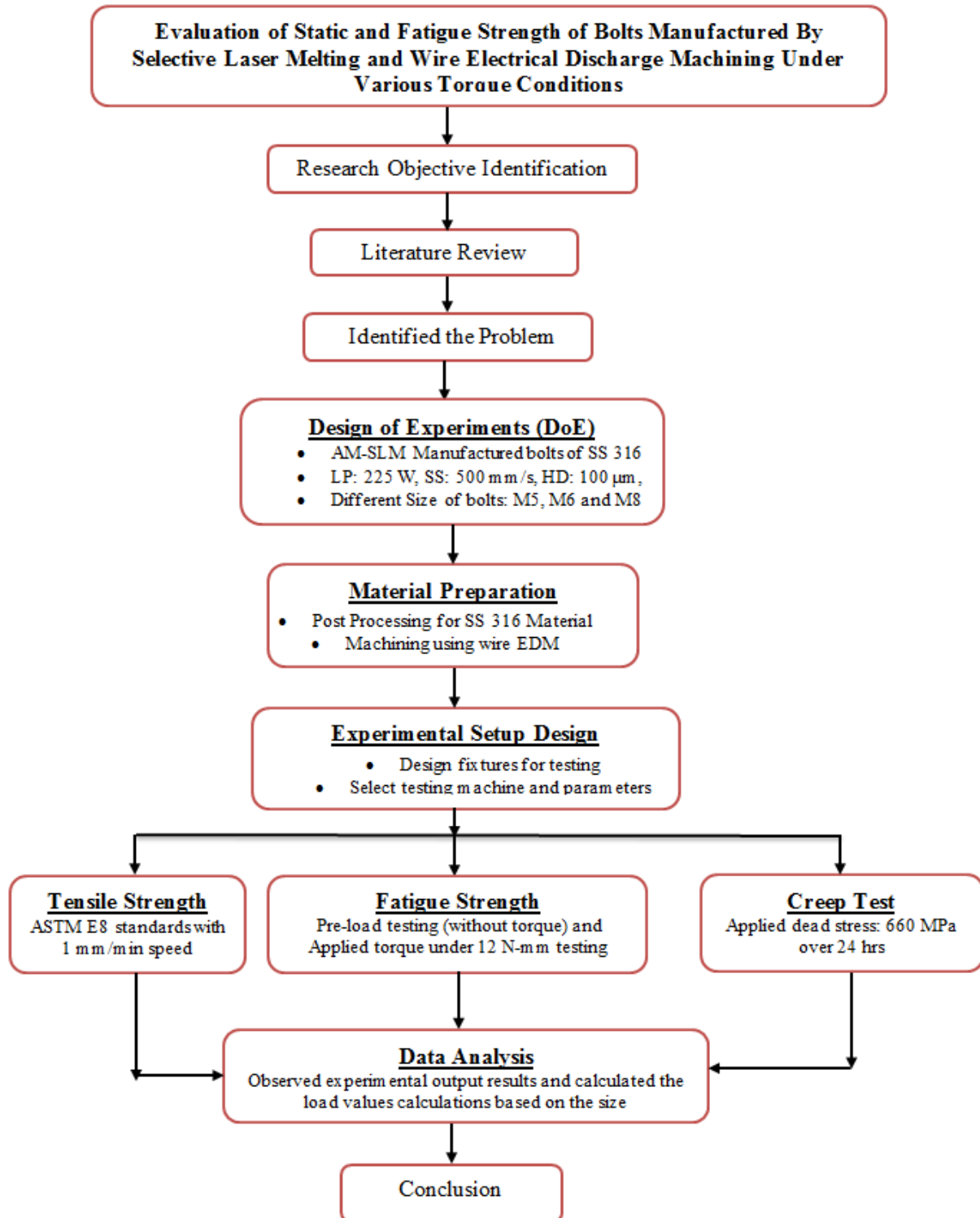


Figure 5. Research Work flow chart.

4. Results and Discussion

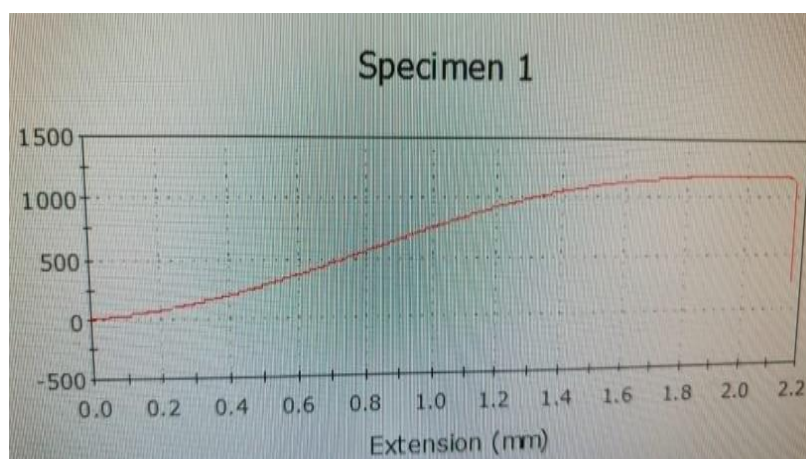
In the results and discussion section of this research paper, we aim to analyze the mechanical performance of hexagonal bolts fabricated using SLM. The discussion focuses on evaluating tensile strength, fatigue life under torque-tightening conditions, and creep behavior under prolonged loading. Compared performance of these additively manufactured bolts against traditional fasteners, highlighting the role of SLM process parameters such as laser power, scan speed, and hatching distance in optimizing material properties. Additionally, the results will demonstrate how torque application significantly enhances fatigue life, while the material's stable creep performance reinforces its reliability for aerospace and automotive applications.

4.1. Tensile Test

The tensile testing procedure and mechanical performance evaluation of hexagonal bolts, conducted in accordance with ASTM E8 standards, are detailed in this study. Specimens were prepared using WEDM, and their precise dimensions were verified using a profile projector. The final sample had a diameter of 5.26 mm and a length of 25 mm. Tensile testing was performed at room temperature using an INSTRON 5500R machine with a 100 kN load capacity and a crosshead speed of 1 mm/min, as illustrated in Figure 6. The results revealed a yield strength (YS) of 967.61 MPa and an ultimate tensile strength (UTS) of 1189.32 MPa under an applied load of 25.825 kN. The experimental setup, combined with the resulting stress-strain behavior, provides valuable insights into the mechanical properties of the material, demonstrating its potential for applications in high-performance engineering environments.



(a)



(b)

Figure 6. (a) Tensile test equipment (MIC_MT Lab) used and (b) tensile test results [MIC lab, MICPL].

4.2. Fatigue Strength

Fixtures play a pivotal role in ensuring the accuracy and reliability of fatigue testing for critical fasteners like bolts, nuts, and rivets, especially in high-stakes applications such as aerospace. Fatigue testing evaluates the performance of fasteners under cyclic loading conditions that mimic real-world stresses experienced during various phases of an aircraft's operation, including takeoff, cruising, and landing. These fasteners are subject to cyclical loads with varying amplitude stresses, making it essential to replicate these conditions precisely in a laboratory setting. In this study, specially designed fixtures, as illustrated in Figure 7, were developed to securely hold hexagonal fastener specimens during axial fatigue testing.

These fixtures were tailored to accommodate cylindrical adapters, enabling a firm grip on the specimens and ensuring uniform load distribution during testing. Their robust design minimizes the risk of misalignment or slippage, which could otherwise compromise the validity of the test results. The use of these fixtures highlights the importance of accurate experimental configurations in replicating real-world loading scenarios. By ensuring the fasteners are subjected to the same types of stresses encountered in aerospace applications, the study achieves more reliable and representative data on the fatigue behavior of the fasteners. This approach underscores the critical role of well-designed fixtures in advancing the understanding of fatigue performance, ultimately contributing to improved safety and structural integrity in aerospace engineering.

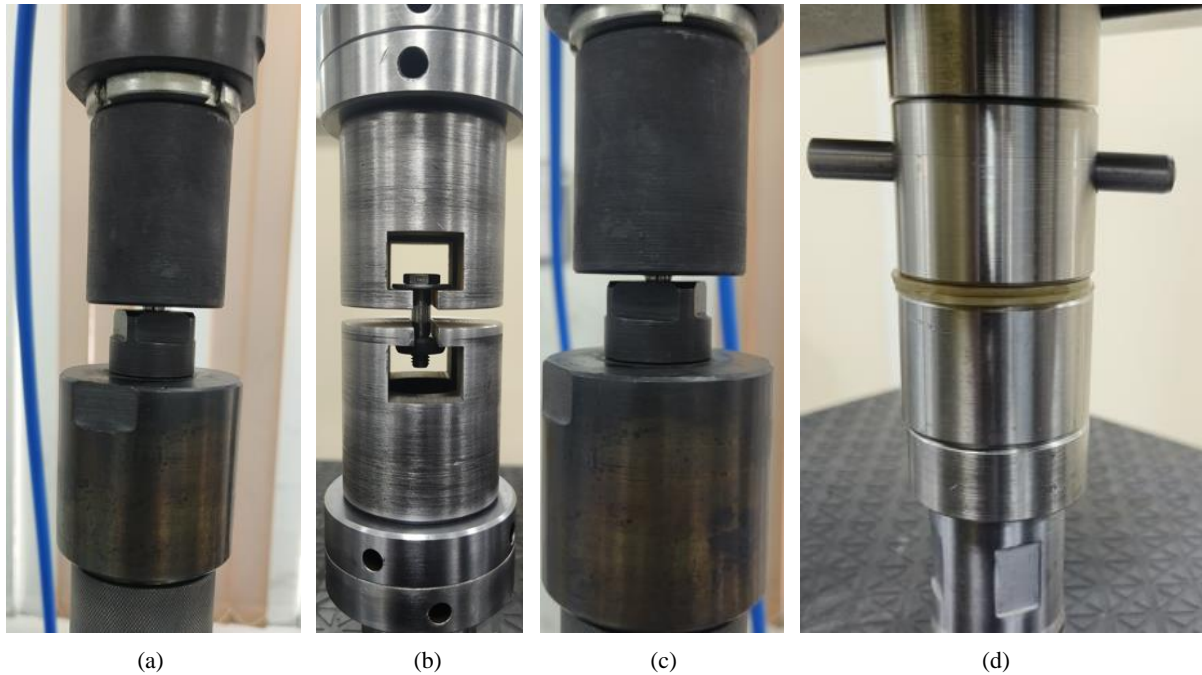


Figure 7. Different types of fixtures for fastener bolts testing [MIC labs, MICPL, Hyderabad, India].

The initial fixture configuration posed several challenges during early tests, including specimen slippage, inconsistent stress amplitudes (ranging from minimum to maximum), and unexpected buckling loads caused by fixture tolerances. These issues were systematically addressed to ensure accurate and reliable testing. Fatigue tests were conducted in two con-

figurations based on the application requirements: pre-load (without torque) and applied torque. Figure 8 illustrates the experimental setup and test configurations in detail, highlighting the modifications implemented to mitigate fixture-related irregularities and achieve precise loading conditions.

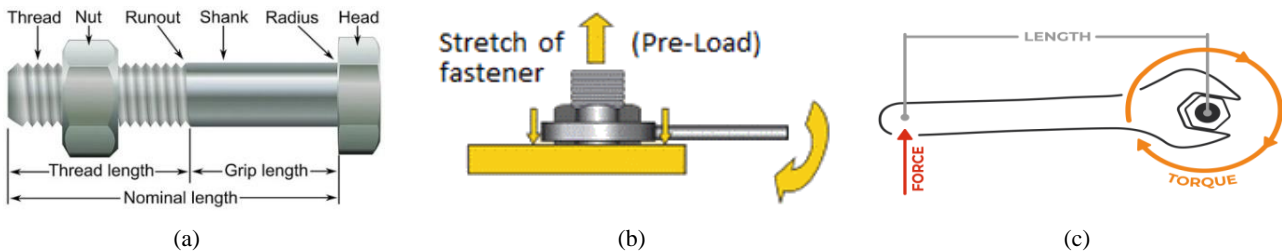


Figure 8. (a) Bolt specification, (b) pre-load on bolt before fatigue test and (c) Torque applied on bolt before fatigue test [24].

As shown in Figure 9, fatigue testing was conducted using a BISS Nano testing machine with a 25 kN load capacity, in compliance with ASTM F606/ISO 7961 standards. The equipment was compatible with various bolt types. The testing parameters included a frequency of 2 Hz, a maximum load of 11.9 kN, and a minimum load of 1.19 kN, with an expected fatigue life of 135,000 cycles. Tests were performed under two distinct conditions: pre-load (without torque) and applied torque. Fixtures, as shown in Figure 7(d), were utilized to securely hold the bolts in the fatigue testing apparatus during pre-load testing. Under pre-load conditions, bolt failures occurred between 21,000 and 25,000 cycles, indicating low-cycle fatigue, with fractures observed at the thread-shank interface. However, when torque was applied, fatigue life

improved significantly, with bolts achieving 135,000 cycles without any cracks during a 24-hour testing session. These findings highlight the critical influence of applied torque in enhancing the fatigue life of bolts and emphasize its importance in applications requiring extended durability under cyclic loading (i.e., if a material or fastener tested under ASTM F606/ISO 7961 conditions reaches 135,000 cycles without failure during fatigue testing, it generally indicates good performance. While ASTM F606 does not specify a universal "pass" threshold for fatigue life, achieving 135,000 cycles would be considered excellent for many applications, especially if the test conditions (stress levels and load cycles) are representative of real-world operating conditions. For critical applications like aerospace or automotive, manufac-

turers may define their own pass/fail criteria based on required safety factors and service life. If 135,000 cycles meet or exceed those criteria, then the material or component would likely be deemed acceptable for that application).

Mathematical calculations were utilized to determine the applied load during the fatigue tests, and the corresponding results are presented in Table 2. Additionally, fracture analysis,

as shown in Figure 10, revealed that failures commonly occurred at the radius just below the bolt head. These findings emphasize the significant role of applied torque in extending the fatigue life of the tested bolts and provide valuable insights into the failure mechanisms under varying loading conditions.

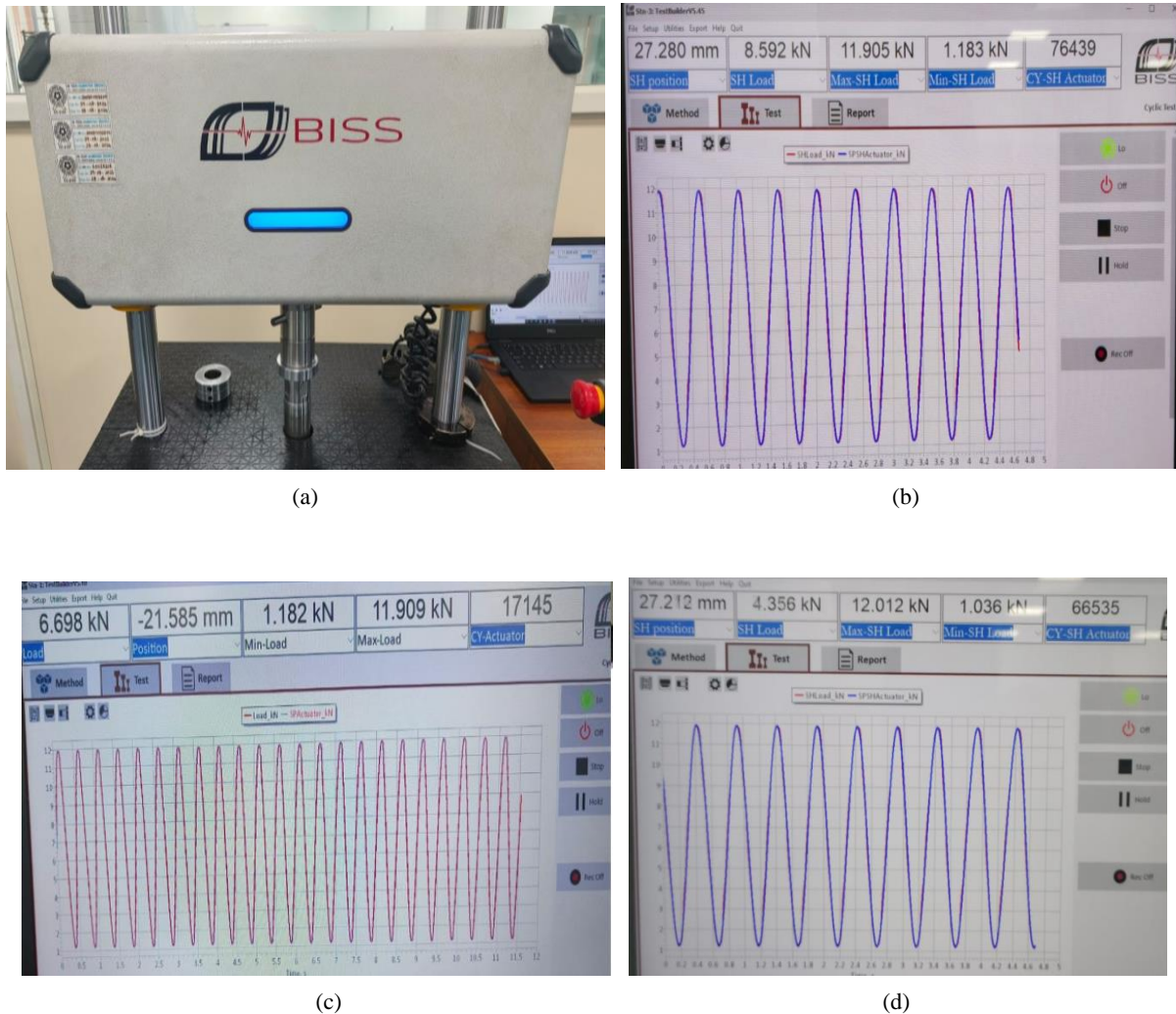


Figure 9. (a) Fatigue experimental set up (MIC_MT Lab) and (b, c&d) Experimental results.



Figure 10. (a&b) before and after experimental specimen (MIC Lab_ MICPL).

The calculated mathematical values for the different bolt sizes are presented as follows: Figure 11 displays a contrast

between the experimental results and the mathematical predictions.

The hexagonal bolt areas, obtained from standards of ASTM f606/ISO 3506 are given by:

1. $A (M5) = 15.3 \text{ mm}^2$
2. $A (M6) = 21.75 \text{ mm}^2$
3. $A (M8) = 41.7 \text{ mm}^2$

From the calculated areas, the corresponding bolt diameters are derived as follows:

1. $D (M5) = 2.50 \text{ mm}$
2. $D (M6) = 5.26 \text{ mm}$
3. $D (M8) = 7.28 \text{ mm}$

During the fatigue testing, the applied load conditions were as follows:

1. Minimum load = 1.19 kN

2. Maximum load = 11.9 kN

The calculated stress values under these loading conditions are:

1. $\sigma_{\max} (M5) = 777.78 \text{ MPa}$
2. $\sigma_{\min} (M5) = 77.77 \text{ MPa}$
3. $\sigma_{\max} (M6) = 547.12 \text{ MPa}$
4. $\sigma_{\min} (M6) = 54.71 \text{ MPa}$
5. $\sigma_{\max} (M8) = 285.37 \text{ MPa}$
6. $\sigma_{\min} (M8) = 28.53 \text{ MPa}$

These calculated values indicate the stress distribution across different bolt sizes under the applied fatigue load conditions. They are critical for understanding the mechanical performance and failure predictions of these bolts under varying load amplitudes as shown in the [Table 3](#).

Table 2. Hexagonal bolt fatigue test results.

Trial	Bolt size	Maximum Stress in MPa	Minimum Stress in MPa	Stress Ratio	Amplitude Ratio	Torque Applied	No. of Cycle	Fracture
1	M5	777.78	77.77	0.1	0.818	Pre-Load	21000	Fracture
2	M6	547.12	54.71			Pre-Load	25000	Fracture
3	M8	285.37	28.53			12 N-m	135000	No Fracture

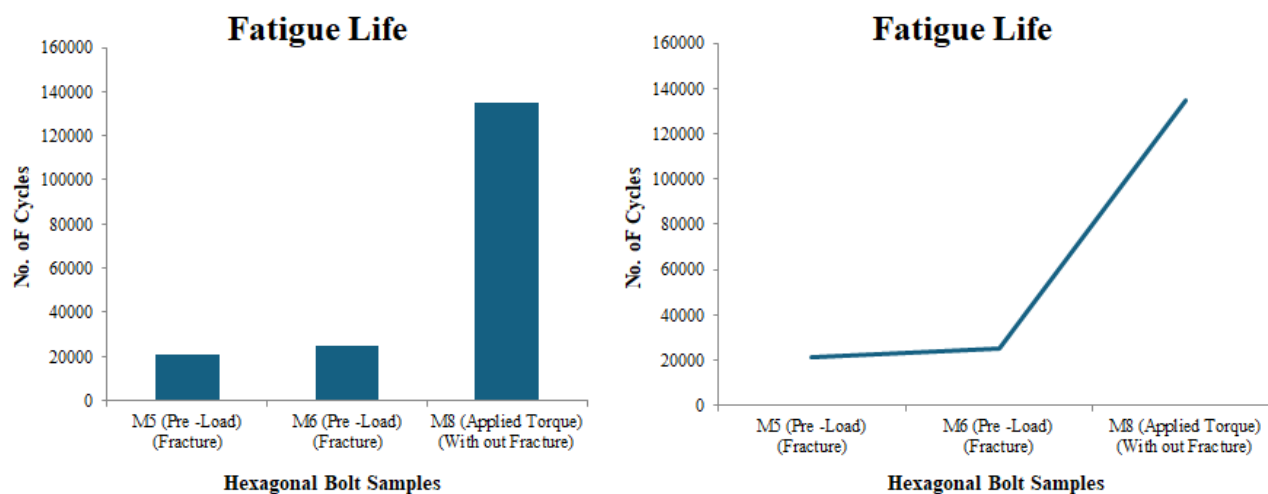


Figure 11. Experimental fatigue test results plotted by different bolts with torque conditions.

4.3. Creep Test

This study presents a comprehensive evaluation of a high-temperature testing apparatus specifically designed to assess material behavior under extreme thermal and mechanical conditions, with a focus on aerospace applications. The apparatus operates at a maximum temperature of 1200°C and a load capacity of 50 kN, utilizing advanced hot pull rods to securely grip the test specimen inside and outside the furnace, as illustrated in [Figure 12](#).

To simulate real-world service conditions, the pull rods were subjected to a sustained tensile load of 660 MPa at room temperature, demonstrating remarkable structural integrity and resistance to creep deformation over a continuous 24-hour period. Before mounting the specimen, the specified length was 25 mm. After successfully completing the test method, the final length was rechecked and remained 25 mm. As per DIN standards, a deviation of up to 0.2 mm is acceptable for the material to pass.

No signs of failure, fracture, or significant degradation were observed, underscoring the robustness of the pull rods in maintaining consistent load transfer and ensuring test accuracy. These findings are particularly critical for aerospace components, such as turbine blades and high-temperature structural elements, which must withstand prolonged exposure to extreme operational environments. Furthermore, this study provides a validated experimental framework for testing

next-generation materials, including 3D-printed alloys and advanced composites, under service-mimicking conditions. The insights gained from this research contribute to the broader understanding of high-temperature material performance, offering a reliable methodology for assessing durability, mechanical stability, and long-term reliability in aerospace and other high-performance engineering applications.



Figure 12. (a) Creep experimental set up (MIC_MT Lab) and (b) Mount the specimen.

5. Conclusion

This experimental study highlights the critical role of torque tightening in enhancing the mechanical performance and fatigue life of hexagonal bolts, particularly M5, M6, and M8 sizes, in demanding engineering applications.

Tensile testing revealed high material strength with an ultimate tensile strength (UTS) of 1189.32 MPa and a yield strength (YS) of 967.61 MPa, demonstrating the bolts' capacity to withstand significant static loads.

Fatigue testing showed a substantial improvement in bolt life when torque was applied, with a fatigue life of 135,000 cycles compared to 21,000–25,000 cycles in pre-load conditions, emphasizing the importance of proper torque application in mitigating failure at critical stress points like the shank-thread interface.

Creep testing further validated the material's durability under prolonged high-stress conditions, with stable performance observed at a load of 660 MPa over a 24-hour period. After successfully completing the test method, the final length was rechecked and remained 25 mm. As per DIN standards, a deviation of up to 0.2 mm is acceptable for the material to pass.

These findings underline the effectiveness of torque application in extending fatigue life and the reliability of the materials for long-term structural integrity. The study provides valuable insights for optimizing the design and appli-

cation of hexagonal bolts manufactured via SLM, offering significant potential for high-performance applications in the automotive and aerospace sectors where enhanced fatigue resistance and creep reliability are paramount.

Abbreviations

AM	Additive Manufacturing
SLM	Selective Laser Melting
LPBF	Laser Powder Bed Fusion
UTS	Ultimate Tensile Strength
YS	Yield Strength
ALM	Additive Layer Manufacturing
CAD	Computer Aided Design
PBF	Powder Bed Fusion
SS	Stainless Steel
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
DIN	German Institute for Standardization
SEM	Scanning Electron Microscope
WEDM	Wire Electron Discharge Machining
DoE	Design of Experiments

Acknowledgments

Sincere thanks are given by the author to the testing engi-

neers for their important support during the specimen testing procedure. I would especially like to thank Mr. K. Rajendra Prasad, Chief Executive Officer/Managing Director (CEO/MD) and K. Lavanya, Executive Director (ED) of Measure India Corporation Pvt. Ltd. (MICPL) in Hyderabad, for his diligent assistance and cooperation in making the mechanical testing possible. We also like to thank MIC Labs for lending their knowledge and cutting-edge testing facilities, which were invaluable in helping us accomplish the goals of this investigation. Their assistance was crucial in getting the research done successfully.

Author Contributions

Mudda Nirish: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing—original draft preparation, Writing—review and editing, Visualization

Koganti Rajendra Prasad: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data cura-

tion, Writing—original draft preparation, Writing—review and editing, Visualization, Supervision, Funding acquisition

Koganti Lavanya: Conceptualization, Formal analysis, Supervision, Funding acquisition

All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Data Availability Statement

Data will be made available on reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest/competing interests.

Appendix

Appendix I: Graphical Abstract

1. SLM Manufacturing and Testing Methods: The graphical abstract illustrates the Selective Laser Melting (SLM) process for fabricating hexagonal bolts, followed by mechanical testing methods, including tensile, fatigue, and creep tests, to evaluate their performance under various loading conditions.
2. Key Findings and Applications: The results highlight enhanced fatigue life (135,000 cycles), creep resistance, and high tensile strength (UTS: 1189.32 MPa, YS: 967.61 MPa), demonstrating the suitability of SLM-manufactured bolts for critical aerospace and automotive applications.

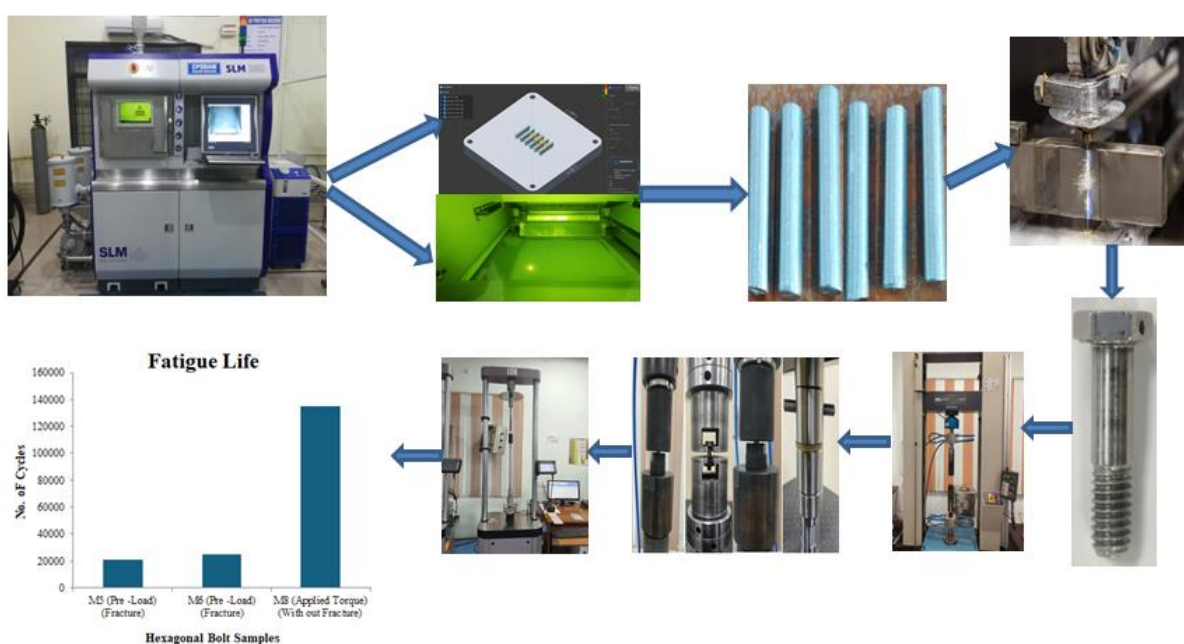


Figure 13. SLM Manufacturing and Testing Methods.

Appendix II: Highlights

1. The tensile testing of M5, M6, and M8 hexagonal bolts revealed high strength, with a UTS of 1189.32 MPa and YS of 967.61 MPa.
2. Fatigue life improved significantly with torque tightening, increasing from 21,000, 25,000 cycles (pre-load) to 135,000 cycles under 12 N-mm torque.
3. Creep testing confirmed excellent material stability under a sustained load of 660 MPa over 24 hours without deformation or failure.
4. Torque tightening proved critical in extending fatigue life and preventing failure at critical stress points, such as the shank-thread interface.
5. The study demonstrates the effectiveness of SLM in manufacturing hexagonal bolts, with the additive manufacturing (AM) process enabling the production of high-performance materials suitable for demanding structural applications.
6. The results validate the use of SLM-based additive manufacturing for producing bolts with enhanced mechanical properties, offering significant potential in automotive and aerospace industries.

<https://doi.org/10.1016/j.phpro.2012.10.059>

References

- [1] Cao Y, Lin X, Wang QZ, Shi SQ, Ma L, Kang N, Huang WD, "Microstructure evolution and mechanical properties at high temperature of selective laser melted AlSi10Mg", *Journal of Materials Science & Technology*, vol. 62, pp. 162-72, 2021. <https://doi.org/10.1016/j.jmst.2020.04.066>
- [2] Nirish M and Rajendra R, "Suitability of metal additive manufacturing processes for part topology optimization—A comparative study", *Materials Today: Proceedings*, vol 27, pp. 1601-7, 2020. <https://doi.org/10.1016/j.matpr.2020.03.275>
- [3] Xiong ZH, Liu SL, Li SF, Shi Y, Yang YF, Misra RD, "Role of melt pool boundary condition in determining the mechanical properties of selective laser melting AlSi10Mg alloy", *Materials Science and Engineering: A*, vol.740, pp.148-56, 2019. <https://doi.org/10.1016/j.msea.2018.10.083>
- [4] Wang P, Lei H, Zhu X, Chen H, Fang D, "Influence of manufacturing geometric defects on the mechanical properties of AlSi10Mg alloy fabricated by selective laser melting", *Journal of Alloys and Compounds*. Vol. 789, pp. 852-9, 2019. <https://doi.org/10.1016/j.jallcom.2019.03.135>
- [5] Li R, Chen H, Zhu H, Wang M, Chen C, Yuan T, "Effect of aging treatment on the microstructure and mechanical properties of Al-3.02 Mg-0.2 Sc-0.1 Zr alloy printed by selective laser melting", *Materials & Design*, vol. 168, pp. 107668, 2019. <https://doi.org/10.1016/j.matdes.2019.107668>
- [6] Aboulkhair NT, Maskery I, Tuck C, Ashcroft I, Everitt NM, "The microstructure and mechanical properties of selectively laser melted AlSi10Mg: The effect of a conventional T6-like heat treatment", *Materials Science and Engineering: A*, vol. 667, pp. 139-46, 2016. <https://doi.org/10.1016/j.msea.2016.04.092>
- [7] Read N, Wang W, Essa K, Attallah MM, "Selective laser melting of AlSi10Mg alloy: Process optimisation and mechanical properties development", *Materials & Design*, vol. 65, pp. 417-24, 2015. <https://doi.org/10.1016/j.matdes.2014.09.044>
- [8] Kempen K, Thijs L, Van Humbeeck J, Kruth JP, "Mechanical properties of AlSi10Mg produced by selective laser melting", *Physics Procedia*, vol. 39, pp. 439-46, 2012. <https://doi.org/10.1016/j.phpro.2012.10.059>
- [9] Li X, Ni J, Zhu Q, Su H, Cui J, Zhang Y, Li J, "Structure and mechanical properties of the AlSi10Mg alloy samples manufactured by selective laser melting", *In IOP Conference Series: Materials Science and Engineering*, vol. 269, no. 1, pp. 012081, 2017. <https://doi.org/10.1088/1757-899X/269/1/012081>
- [10] Han Q, Setchi R, Lacan F, Gu D, Evans SL. Selective laser melting of advanced Al-Al₂O₃ nanocomposites: simulation, microstructure and mechanical properties. *Materials Science and Engineering: A*. 2017 Jun 20; 698: 162-73. <https://doi.org/10.1016/j.msea.2017.05.061>
- [11] Ch SR, Raja A, Jayaganthan R, Vasa NJ, Raghunandan M, "Study on the fatigue behaviour of selective laser melted AlSi10Mg alloy", *Materials Science and Engineering: A*, vol. 781, pp. 139180, 2020. <https://doi.org/10.1016/j.msea.2020.139180>
- [12] Bai P, Huo P, Kang T, Zhao Z, Du W, Liang M, Li Y, Liao H, Liu Y, "Failure Analysis of the Tree Column Structures Type AlSi10Mg Alloy Branches Manufactured by Selective Laser Melting", *Materials*, vol. 13, no. 18, pp. 3969, 2020. <https://doi.org/10.3390/ma13183969>
- [13] Giannopoulos IK, Doroni-Dawes D, Kourousis KI, Yasaei M. Effects of bolt torque tightening on the strength and fatigue life of airframe FRP laminate bolted joints. *Composites Part B: Engineering*. 2017 Sep 15; 125: 19-26. <https://doi.org/10.1016/j.compositesb.2017.05.059>
- [14] Chakherlou TN, Mirzajanzadeh M, Vogwell J, Abazadeh B. Investigation of the fatigue life and crack growth in torque tightened bolted joints. *Aerospace Science and Technology*. 2011 Jun 1; 15(4): 304-13. <https://doi.org/10.1016/j.ast.2010.08.003>
- [15] Esmaeili F, Zehsaz M, Chakherlou TN, Hasanifard S. Experimental and numerical study of the fatigue strength of double lap bolted joints and the effect of torque tightening on the fatigue life of jointed plates. *Transactions of the Indian Institute of Metals*. 2014 Aug; 67: 581-8. <https://doi.org/10.1007/s12666-014-0385-8>
- [16] Abazadeh B, Maleki HR. Effect of bolt tightening on the fatigue behavior of GLARE double shear lap joints. *Journal of Composite Materials*. 2021 Sep; 55(21): 2911-20. <https://doi.org/abs/10.1177/00219983211003315>

- [17] Esmaeili F, Chakherlou TN, Zehsaz M. Prediction of fatigue life in aircraft double lap bolted joints using several multiaxial fatigue criteria. *Materials & Design*. 2014 Jul 1; 59: 430-8. <https://doi.org/10.1016/j.matdes.2014.03.019>
- [18] Noda NA, Chen X, Sano Y, Wahab MA, Maruyama H, Fujisawa R, Takase Y. Effect of pitch difference between the bolt-nut connections upon the anti-loosening performance and fatigue life. *Materials & Design*. 2016 Apr 15; 96: 476-89. <https://doi.org/10.1016/j.matdes.2016.01.128>
- [19] Gajera H, Shah D, Pancholi N. Effect of SLM process parameters on hardness and microstructure of stainless steel 316 material. *Materials Today: Proceedings*. 2022 Jan 1; 50: 1653-9. <https://doi.org/10.1016/j.matpr.2021.09.144>
- [20] Benhaddou T, Chirol C, Daidie A, Guillot J, Stephan P, Tuery JB. Pre-tensioning effect on fatigue life of bolted shear joints. *Aerospace Science and Technology*. 2014 Jul 1; 36: 36-43. <https://doi.org/10.1016/j.ast.2014.03.003>
- [21] Qian G, Jian Z, Qian Y, Pan X, Ma X, Hong Y, "Very-high-cycle fatigue behavior of AlSi10Mg manufactured by selective laser melting: Effect of build orientation and mean stress", *International Journal of Fatigue*, vol. 138, pp. 105696, 2020. <https://doi.org/10.1016/j.ijfatigue.2020.105696>
- [22] Aboulkhair NT, Tuck C, Ashcroft I, Maskery I, Everitt NM, "On the precipitation hardening of selective laser melted AlSi10Mg", *Metallurgical and Materials Transactions A*, vol. 46, no. 8, pp. 3337-41, 2015. <https://doi.org/10.1007/s11661-015-2980-7>
- [23] Kong Z, Wang X, Hu N, Jin Y, Tao Q, Xia W, Lin XM, Vasdravellis G. Mechanical properties of SLM 316L stainless steel plate before and after exposure to elevated temperature. *Construction and Building Materials*. 2024 Sep 20; 444: 137786. <https://doi.org/10.1016/j.conbuildmat.2024.137786>
- [24] Wang P, Gammer C, Brenne F, Prashanth KG, Mendes RG, Rummeli MH, Gemming T, Eckert J, Scudino S, "Microstructure and mechanical properties of a heat-treatable Al-3.5 Cu-1.5 Mg-1Si alloy produced by selective laser melting", *Materials Science and Engineering: A*, vol. 711, pp. 562-70, 2018. <https://doi.org/10.1016/j.msea.2017.11.063>
- [25] Iturrioz A, Gil E, Petite MM, Garciandia F, Mancisidor AM, San Sebastian M, "Selective laser melting of AlSi10Mg alloy: influence of heat treatment condition on mechanical properties and microstructure", *Welding in the World*, vol. 62, no. 4, pp. 885-92, 2018. <https://doi.org/10.1007/s40194-018-0592-8>
- [26] Larrosa NO, Wang W, Read N, Loretto MH, Evans C, Carr J, Tradowsky U, Attallah MM, Withers PJ, "Linking microstructure and processing defects to mechanical properties of selectively laser melted AlSi10Mg alloy", *Theoretical and Applied Fracture Mechanics*, vol. 98, pp. 123-33, 2018. <https://doi.org/10.1016/j.tafmec.2018.09.011>
- [27] Susan D, Kilgo A, McKenzie B. Fatigue failures of fasteners: Optical metallography and SEM fractography. *Microscopy and Microanalysis*. 2006 Aug; 12(S02): 192-3. <https://doi.org/10.1017/S1431927606067274>
- [28] Yapici O, Theofanous M, Yuan H, Afshan S, Skalomenos K. Comparative study on fracture characteristics of carbon and stainless steel bolt material. *Journal of Constructional Steel Research*. 2023 Nov 1; 210: 108102. <https://doi.org/10.1016/j.jcsr.2023.108102>
- [29] Song Y, Wang J, Uy B, Li D. Experimental behaviour and fracture prediction of austenitic stainless steel bolts under combined tension and shear. *Journal of Constructional Steel Research*. 2020 Mar 1; 166: 105916. <https://doi.org/10.1016/j.jcsr.2019.105916>
- [30] Wang J, Uy B, Li D, Song Y. Fatigue behaviour of stainless steel bolts in tension and shear under constant-amplitude loading. *International Journal of Fatigue*. 2020 Apr 1; 133: 105401. <https://doi.org/10.1016/j.ijfatigue.2019.105401>
- [31] Akiyama E. Evaluation of delayed fracture property of high strength bolt steels. *ISIJ international*. 2012; 52(2): 307-15. <https://doi.org/10.2355/isijinternational.52.307>
- [32] Boucha ř A, Averseng J, Abidelah A. Analysis of the behaviour of stainless steel bolted connections. *Journal of Constructional Steel Research*. 2008 Nov 1; 64(11): 1264-74. <https://doi.org/10.1016/j.jcsr.2008.07.009>
- [33] Chowdhury T, Sathianarayanan D, Dharani G, Ramadass GA. Failure analysis of fasteners in a remotely operated vehicle (ROV) system. *Journal of Failure Analysis and Prevention*. 2015 Dec; 15: 915-23. <https://doi.org/10.1007/s11668-015-0034-5>