JMEPEG
https://doi.org/10.1007/s11665-025-11228-z

1059-9495/$19.00

ORIGINAL RESEARCH ARTICLE

Mechanical, Tribological, and Corrosion Properties of Selective Laser Melted 316L Stainless Steel

V. Ezhilmaran, P. Surya Prem Anand, S. Ashish Daniel, R. Harichandran, G. Kalusuraman, and S. Thirumalai Kumaran

Submitted: 19 October 2024 / Revised: 08 February 2025 / Accepted: 25 February 2025

This study endeavors to enhance the mechanical, tribological, and corrosion resistance attributes of 316L stainless steel fabricated by powder bed fusion process. A comprehensive understanding of the material's performance is achieved by investigating the impact of different scanning patterns and energy densities on tensile strength, compressive strength, hardness, porosity, roughness, and tribological behavior. Three distinct scanning patterns—line scanning, spiral scanning, and chessboard-type scanning—were examined, alongside a range of energy densities spanning from 30 to 95 J/mm^3. Results indicated that a notable improvement in tensile strength, with enhancements of 20.9, 22.6, and 31.1% observed for line, spiral, and chessboard-type scanning patterns, respectively, as the energy density of the laser increased from 30 to 95 J/mm^3. Remarkably, the chessboard-type pattern at 95 J/mm^3 yielded the highest tensile strength recorded at 736 MPa, surpassing commercially available 316L material by 41%. Moreover, the compressive strength experienced a slight increase of 1.3% (695 to 704 MPa), while hardness values exhibited a substantial 21% rise (228 to 275 HV) when utilizing the chessboard-type scanning pattern at 95 J/mm^3. Additionally, the lowest coefficient of friction, at 0.39, was observed in specimens manufactured with the chessboard-type pattern and at the highest energy density of 95 J/mm^3, indicating superior tribological performance. The corrosion rate decreases with increase in energy density (*E*) due to reduced porosity and improved bonding in the material, enhancing corrosion resistance. The chessboard scanning pattern showed the best performance, making it ideal for manufacturing 316L orthopedic implants.

Keywords 316L stainless steel, energy density, powder bed fusion, scanning patterns

1. Introduction

316L stainless steel emerges as a prime choice for biomedical applications, thanks to its robust corrosion resistance, exceptional ductility, absence of phase transformation, and stellar mechanical properties (Ref 1-3). The "*L*" designation in 316L denotes its low carbon content, less than 0.03%, significantly reducing the risk of carbide precipitation, thereby preserving its corrosion resistance and strength. Enriched with chromium, nickel, and molybdenum, it showcases remarkable corrosion resistance even under elevated temperatures. As a result, 316L finds widespread utility in fabricating machinery for chemical processing, medical apparatus, maritime hardware, and beyond (Ref 4). Notably, its resistance extends to crevice and pitting corrosion, prevalent in chloride-rich environments, further solidifying its status as a material of choice across diverse industries. The remarkable strength and biocompatibility of stainless steel have made it a mainstay in orthopedic surgery for decades. Its applications span a wide range of implants, both established and innovative (Ref 5, 6). Stainless steel 316L can be a suitable material for both orthopedic implants (Ref 7) and dental crowns (Ref 8, 9). A dental crown acts as an artificial cap fixed over a damaged or weakened tooth. It can restore the shape, size, and strength of the original teeth and also give a nice appearance. Dental crowns are usually made from metal (Ref 10), porcelain (Ref 10), or a combination of both (Ref 11). Numerous orthopedic implants, both old and new, have made substantial use of stainless steel. Some flexible nails, early prototypes of rigid intramedullary nails, orthopedic plates, screws, and sliding hip screws are typically made using it. Braided stainless steel wires are a typical material for constructing cerclage cables.

Today, casting, forging, or extrusion is used to make stainless steel items. However, manufacturing of complex-shaped 316L stainless steel especially for biomedical applications such as orthopedic plates limits the use of conventional manufacturing methods (Ref 12). In addition, conventional manufacturing methods are time-consuming processes for making complex shapes. The best alternative to overcome the negative effect of conventional manufacturing processes is the additive manufacturing (AM) process. Moreover, due to the possibility of recycling the feedstock, AM can be seen as a material-saving method and has gained significance in recent

V. Ezhilmaran, Department of Manufacturing Engineering, College of Engineering Guindy, Anna University, Chennai, Tamil Nadu 600025, India; **P. Surya Prem Anand** and **S. Ashish Daniel**, School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu 632014, India; and **R. Harichandran**, Department of Mechanical Engineering, National Engineering College, K.R.Nagar, Kovilpatti, TamilNadu 628503, India; **G. Kalusuraman**, Faculty of the Mechanical Engineering, Kalasalingam Academy of Research and Education, Krishnankoil, Tamil Nadu 626126, India; and **S. Thirumalai Kumaran**, Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore, Tamil Nadu 641062, India. Contact e-mails: ezhilmaran25@gmail.com and thirumalaikumaran@yahoo.com.

Published online: 22 April 2025

properties across all samples for line and spiral scanning patterns were inferior compared to the chessboard-type pattern. The spiral scanning pattern yielded samples with the lowest roughness, ranging from 4 to 3.3 μm as energy density varied from 30 to 95 J/mm^3. Relative density ranged from 88 to 90% at 30 J/mm^3 and reached 98% at 95 J/mm^3 for all samples additively manufactured with different scanning patterns. Friction and wear of additively manufactured samples decreased as energy density increased from 30 to 95 J/mm^3 for respective scanning patterns. The lowest coefficient of friction, 0.39, was observed in samples additively manufactured with a chessboard-type pattern at a energy density of 95 J/mm^3. Higher energy density induces elevated melting temperature, accelerated cooling rate, and increased local melting and solidification, thereby influencing the material's microstructure and subsequent mechanical properties. Higher energy density and chessboard scanning minimize porosity, enhancing corrosion resistance in additively manufactured 316L stainless steel.

Author Contributions

V.Ezhilmaran was involved in conceptualization, methodology, formal analysis, writing—original draft preparation. P.Surya Prem Anand helped in data curation, visualization, writing—review & editing. S.Ashish Daniel and R. Harichandran contributed to software, validation, writing—review & editing. G.Kalusuraman and S.Thirumalai Kumaran were involved in resources, project administration, writing—review & editing.

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article.

Conflict of interest

The authors declare no competing interests.

Ethics Approval

We comply with ethical standards. We provide our consent to take part.

Consent to Participate/Publication

The authors provide consent to participate/publication.

Reference

1. M. Fellah, M. Labaïz, O. Assala, A. Iost and L. Dekhil, Tribological Behaviour of AISI 316L Stainless Steel for Biomedical Applications, *Tribology-Mater., Surf. Interfaces*, 2013, **7**(3), p 135–149.
2. B. AlMangour, D. Grzesiak, J. Cheng, and Y. Ertas, Thermal Behavior of the Molten Pool, Microstructural Evolution, and Tribological Performance During Selective Laser Melting of TiC/316L Stainless Steel Nanocomposites: Experimental and Simulation Methods, *J. Mater. Process. Technol.*, 2018, **257**, p 288–301.
3. Z. Zou, Z. Liu, L. Yang, Y. Tang, Y. Qiao, and D. Lu, Corrosion Behavior of Different Building Planes of Selective Laser Melting 316L Stainless Steel in 0.1 M HCl Solution, *J. Mater. Res. Technol.*, 2024, **28**, p 4738–4753.
4. K. Benarji, Y. Ravi Kumar, A. Jinoop, C. Paul, and K. Bindra, Effect of Heat-Treatment on the Microstructure, Mechanical Properties and Corrosion Behaviour of SS 316 Structures Built by Laser Directed Energy Deposition Based Additive Manufacturing, *Metals Mater. Int.*, 2021, **27**, p 488–499.
5. A. Esmaeili, S.A. Ghaffari, M. Nikkhah, F.M. Ghaini, F. Farzan, and S. Mohammadi, Biocompatibility Assessments of 316L Stainless Steel Substrates Coated by Fe-Based Bulk Metallic Glass Through Electro-Spark Deposition Method, *Colloids Surf., B*, 2021, **198**, 111469
6. Q. Chao, V. Cruz, S. Thomas, N. Birbilis, P. Collins, A. Taylor, P.D. Hodgson, and D. Fabijanic, On the Enhanced Corrosion Resistance of a Selective Laser Melted Austenitic Stainless Steel, *Scripta Mater.*, 2017, **141**, p 94–98.
7. H. Zhou and Q. Fan, 3D Reconstruction and SLM Survey for Dental Implants, *J. Mech. Med. Biol.*, 2017, **17**(03), p 1750084.
8. A. Threlfall, L. Pilkington, K. Milsom, A. Blinkhorn, and M. Tickle, General Dental Practitioners' Views on the Use of Stainless Steel Crowns to Restore Primary Molars, *Br. Dent. J.*, 2005, **199**(7), p 453–455.
9. N.S. Seale and R. Randall, The Use of Stainless Steel Crowns: a Systematic Literature Review, *Pediatr. Dent.*, 2015, **37**(2), p 145–160.
10. F.S. Ludovichetti, E. Stellini, A.G. Signoriello, A. Gracco, and S. Mazzoleni, Zirconia vs. Stainless Steel Pediatric Crowns: a Literature Review, *Minerva Dental Oral Sci.*, 2020, **70**(3), p 112–118.
11. J.G. Wall and D.L. Cipra, Alternative Crown Systems: Is the Metal-Ceramic Crown Always the Restoration of Choice?, *Dent. Clin. North Am.*, 1992, **36**(3), p 765–782.
12. M. Ziętala, T. Durejko, M. Polański, I. Kunce, T. Płociński, W. Zieliński, M. Łazińska, W. Stępniowski, T. Czujko, and K.J. Kurzydłowski, The Microstructure, Mechanical Properties and Corrosion Resistance of 316 L Stainless Steel Fabricated Using Laser Engineered Net Shaping, *Mater. Sci. Eng., A*, 2016, **677**, p 1–10.
13. A. Röttger, J. Boes, W. Theisen, M. Thiele, C. Esen, A. Edelmann, and R. Hellmann, Microstructure and Mechanical Properties of 316L Austenitic Stainless Steel Processed by Different SLM Devices, *Int. J. Adv. Manuf. Technol.*, 2020, **108**, p 769–783.
14. C.Y. Yap, C.K. Chua, Z.L. Dong, Z.H. Liu, D.Q. Zhang, L.E. Loh, and S.L. Sing, Review of Selective Laser Melting: Materials and Applications, *Appl. Phys. Rev.*, 2015, **2**(4), 041101
15. T. Larimian, M. Kannan, D. Grzesiak, B. AlMangour, and T. Borkar, Effect of Energy Density and Scanning Strategy on Densification, Microstructure and Mechanical Properties of 316L Stainless Steel Processed via Selective Laser Melting, *Mater. Sci. Eng., A*, 2020, **770**, 138455
16. T. Larimian, B. AlMangour, D. Grzesiak, G. Walunj, and T. Borkar, Effect of Laser Spot Size, Scanning Strategy, Scanning Speed, and Laser Power on Microstructure and Mechanical Behavior of 316L Stainless Steel Fabricated via Selective Laser Melting, *J. Mater. Eng. Performance*, 2021 https://doi.org/10.1007/s11665-021-06387-8
17. B. Şener, O. Çavuşoğlu, and C. Yuce, Effects of Process Parameters on Surface Quality and Mechanical Performance of 316L Stainless Steel Produced by Selective Laser Melting, *Optik*, 2023, **287**, 171050
18. L. Hao, W. Wang, J. Zeng, M. Song, S. Chang, and C. Zhu, Effect of Scanning Speed and Laser Power on Formability, Microstructure, and Quality of 316L Stainless Steel prepared by Selective Laser Melting, *J. Market. Res.*, 2023, **25**, p 3189–3199.
19. A. Adeyemi, E.T. Akinlabi, and R.M. Mahamood, Powder Bed Based Laser Additive Manufacturing Process of Stainless Steel: A Review, *Mater. Today: Proc.*, 2018, **5**(9), p 18510–18517.
20. H. Jia, H. Sun, H. Wang, Y. Wu, and H. Wang, Scanning Strategy in Selective Laser Melting (SLM): a Review, *Int. J. Adv. Manuf. Technol.*, 2021, **113**, p 2413–2435.
21. M. Amirjan and H. Sakiani, Effect of Scanning Strategy and Speed on the Microstructure and Mechanical Properties of Selective Laser Melted IN718 Nickel-Based Superalloy, *Int. J. Adv. Manuf. Technol.*, 2019, **103**, p 1769–1780.
22. K. Davidson and S. Singamneni, Selective Laser Melting of Duplex Stainless Steel Powders: an Investigation, *Mater. Manuf. Processes*, 2016, **31**(12), p 1543–1555.
23. K.P. Davidson, G. Littlefair, and S. Singamneni, On the Machinability of Selective Laser Melted Duplex Stainless Steels, *Mater. Manuf. Processes*, 2022, **37**(12), p 1446–1462.
24. J.M. Jeon, J.M. Park, J.-H. Yu, J.G. Kim, Y. Seong, S.H. Park, and H.S. Kim, Effects of Microstructure and Internal Defects on Mechanical Anisotropy and Asymmetry of Selective Laser-Melted 316L Austenitic Stainless Steel, *Mater. Sci. Eng., A*, 2019, **763**, 138152

25. N.S. Seale, The Use of Stainless Steel Crowns, *Pediatr. Dent.*, 2002, **24**(5), p 501–505.
26. B. Zhou, P. Xu, W. Li, Y. Liang, and Y. Liang, Microstructure and Anisotropy of the Mechanical Properties of 316L Stainless Steel Fabricated by Selective Laser Melting, *Metals*, 2021, **11**(5), p 775.
27. S. Liu, H. Li, C. Qin, R. Zong, and X. Fang, The Effect of Energy Density on Texture and Mechanical Anisotropy in Selective Laser Melted Inconel 718, *Mater. Des.*, 2020, **191**, 108642
28. S. Wang, L. Wang, J. Liu, R. Yang, J. Li, and G. Wang, Effects of Laser Energy Density on Morphology Features and Microstructures of the Single Molten Track in Selective Laser Melting, *Front. Mater.*, 2023, **10**, p 1110844.
29. J. Liu, Y. Song, C. Chen, X. Wang, H. Li, J. Wang, K. Guo, and J. Sun, Effect of Scanning Speed on the Microstructure and Mechanical Behavior of 316L Stainless Steel Fabricated by Selective Laser Melting, *Mater. Des.*, 2020, **186**, 108355
30. Y. Li, Y. Ge, J. Lei, and W. Bai, Mechanical Properties and Constitutive Model of Selective Laser Melting 316L Stainless Steel at Different Scanning Speeds, *Adv. Mater. Sci. Eng.*, 2022, **2022**, p 1–13. https://doi.org/10.1155/2022/2905843
31. S. Greco, K. Gutzeit, H. Hotz, B. Kirsch, and J.C. Aurich, Selective Laser Melting (SLM) of AISI 316L—Impact of Laser Power, Layer Thickness, and Hatch Spacing on Roughness, Density, and Microhardness at Constant Input Energy Density, *Int. J. Adv. Manuf. Technol*, 2020, **108**, p 1551–1562.
32. M. Pant, L. Nagdeve, G. Moona, H. Kumar, and A. Sharma, Tribological Behavior Investigation of 316L Stainless Steel Samples Processed by Selective Laser Melting, *Proc. Instit. Mech. Eng., Part J: J. Eng. Tribol*, 2023, **237**(4), p 718–731.
33. J. Jhabvala, E. Boillat, T. Antignac, and R. Glardon, On the Effect of Scanning Strategies in the Selective Laser Melting Process, *Virtual Phys. Prototyping*, 2010, **5**(2), p 99–109.
34. X. Miao, X. Liu, P. Lu, J. Han, W. Duan, and M. Wu, Influence of Scanning Strategy on the Performances of GO-reinforced Ti6Al4V Nanocomposites Manufactured by SLM, *Metals*, 2020, **10**(10), p 1379.
35. J. Guan and Q. Wang, The Effect of a Remelting Treatment Scanning Strategy on the Surface Morphology, Defect Reduction Mechanism, and Mechanical Properties of a Selective Laser-Melted Al-Based Alloy, *J. Mater. Sci.*, 2022, **57**(21), p 9807–9817.
36. H. Wan, Z. Zhou, C. Li, G. Chen, and G. Zhang, Effect of Scanning Strategy on Mechanical Properties of Selective Laser Melted Inconel 718, *Mater. Sci. Eng., A*, 2019, **753**, p 42–48.
37. H. Ali, H. Ghadbeigi, and K. Mumtaz, Effect of Scanning Strategies on Residual Stress and Mechanical Properties of Selective Laser Melted Ti6Al4V, *Mater. Sci. Eng., A*, 2018, **712**, p 175–187.
38. L. MatWeb, AISI Type 316L Stainless Steel, Annealed Sheet, ed., 2014
39. Y. Wang, L. Lei, L. Shi, H. Wan, F. Liang, and G. Zhang, Scanning Strategy Dependent Tensile Properties of Selective Laser Melted GH4169, *Mater. Sci. Eng., A*, 2020, **788**, 139616
40. H.G. Coe and S. Pasebani, Use of Bimodal Particle Size Distribution in Selective Laser Melting of 316L Stainless Steel, *J. Manuf. Mater. Proc.*, 2020, **4**(1), p 8.
41. Y. Parikh and M. Kuttolamadom, Property-Graded Stainless Steel 316L by Selective Laser Melting: Characterization & Design, *J. Manuf. Sci. Eng.*, 2023, **145**(6), 061008