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Fabrication of High-Strength 316L Stainless Steel-based Nanocomposites by Laser Powder Bed Fusion

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Fabrication of High-Strength 316L Stainless Steel-based Nanocomposites by Laser Powder Bed Fusion

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Supervisor Certification

This is to certify that the thesis entitled **"Fabrication of high strength 316L stainless steel based nanocomposites by laser powder bed fusion"** is being submitted by **Mr. Baibhav Karan** to the Indian Institute of Technology Delhi and The University of Queensland for the award of the degree of Doctor of Philosophy is a record of bonafide research work carried out by him. **Mr. Baibhav Karan** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which, to our knowledge, has reached the requisite standard. The results contained in this thesis are original and have not been submitted, in part or in full, to any other University or Institute for the award of any other degree or diploma.

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Abstract

Austenitic 316L stainless steel (SS316L) is widely deployed in various service environments because it promotes rapid passivation and good resistance to localised corrosion, while the low carbon content mitigates sensitisation and improves weldability. However, conventionally processed SS316L typically offers only moderate strength and limited wear resistance, motivating approaches that can raise strength and surface durability without sacrificing corrosion performance. This doctoral research aims to address these limitations by developing SS316L nanoparticle-reinforced composites using the Laser Powder Bed Fusion (LPBF) technique, which is one of the most typical additive manufacturing technologies.

The investigation first established a baseline for the unreinforced LPBF SS316L matrix, revealing that the as-fabricated alloy possesses a characteristic cellular sub-grain network and that post-process annealing leads to its dissolution. This structural evolution results in increased ductility but reduced strength. It was also observed that while nanoscale precipitates formed during heat treatment marginally increased susceptibility to localised corrosion, the overall corrosion resistance remained comparable to wrought standards. Furthermore, high-temperature deformation studies indicated that plasticity in LPBF SS316L is governed by a transition from dislocation slip and twinning at room temperature to dynamic recrystallisation-type recovery processes at elevated temperatures.

To overcome the intrinsic strength trade-offs of the monolithic alloy, this research also pioneered the development of nanocomposites through the synergistic addition of ceramic reinforcements. The incorporation of WC and TiN nanoparticles facilitated pronounced grain refinement and effective dispersion strengthening, yielding tensile strengths exceeding 1000 MPa with 30% elongation. Further optimisation using TiB_2 and TiN nanoparticles refined the grain size from $\sim$25 μm to submicron scales (1-2 μm), effectively disrupting the strong crystallographic textures typically associated with the LPBF process. This specific reinforcement strategy yielded exceptional mechanical performance, achieving strengths of $\sim$1200 MPa while maintaining a ductility of around 28%.

Crucially, these enhancements in mechanical integrity were achieved without compromising the material's functional surface properties. The nanocomposites exhibited significantly improved wear resistance compared to the base alloy, while retaining corrosion

behaviour comparable to wrought SS316L. These findings provide fundamental insights and practical pathways for deploying LPBF-fabricated SS316L-based nanocomposites in advanced structural and functional applications.

सारांश

ऑस्टेनिटिक 316L स्टेनलेस स्टील (SS316L) का व्यापक रूप से विभिन्न सेवा वातावरणों में उपयोग किया जाता है क्योंकि यह तेजी से निष्क्रियकरण (passivation) और स्थानीय क्षरण (localised corrosion) के प्रति अच्छे प्रतिरोध को बढ़ावा देता है, जबकि इसकी कम कार्बन सामग्री संवेदीकरण (sensitisation) को कम करती है और वेल्डेबिलिटी में सुधार करती है। हालाँकि, पारंपरिक रूप से संसाधित SS316L आमतौर पर केवल मध्यम शक्ति और सीमित घिसाव प्रतिरोध (wear resistance) प्रदान करता है। यह उन दृष्टिकोणों को प्रेरित करता है जो संक्षारण प्रदर्शन से समझौता किए बिना शक्ति और सतह स्थायित्व को बढ़ा सकें। लेजर पाउडर बेड फ्यूजन (LPBF) एक परिवर्तनकारी एडिटिव मैन्युफैक्चरिंग तकनीक के रूप में उभरा है, जो अनुरूप संयोजनों और अद्वितीय सूक्ष्म संरचनाओं (microstructures) के साथ जटिल धातु घटकों के उत्पादन को सक्षम बनाता है। यह डॉक्टरेट अनुसंधान SS316L नैनोपार्टिकल-प्रबलित कंपोजिट (nanoparticle-reinforced composites) विकसित करके, तथा सूक्ष्म संरचनात्मक विकास, यांत्रिक व्यवहार और पर्यावरणीय स्थायित्व के बीच की परस्पर क्रिया को तर्कसंगत बनाकर इन सीमाओं को व्यवस्थित रूप से संबोधित करता है।

जांच ने सबसे पहले अप्रबलित LPBF SS316L मैट्रिक्स के लिए एक आधार स्थापित किया। इसमें यह पता चला कि जहाँ 'ऐज़-फैब्रिकेटेड' (as-fabricated) मिश्र धातु में एक विशिष्ट सेल्युलर सब-ग्रेन नेटवर्क होता है, वहीं पोस्ट-प्रोसेस एनीलिंग (annealing) से इस संरचना का विघटन हो जाता है। इस संरचनात्मक विकास के परिणामस्वरूप तन्यता (ductility) में वृद्धि होती है लेकिन शक्ति में कमी आती है। इसके अलावा, उच्च तापमान विरूपण अध्ययन ने संकेत दिया कि LPBF SS316L में प्लास्टिसिटी, कमरे के तापमान पर 'डिसलोकेशन स्लिप' और 'ट्विनिंग' से लेकर उच्च तापमान पर 'डायनामिक रीक्रिस्टलाइज़ेशन' प्रकार की पुनर्प्राप्ति प्रक्रियाओं के संक्रमण द्वारा नियंत्रित होती है। यह भी देखा गया कि हालांकि हीट ट्रीटमेंट के दौरान बने नैनोस्केल अवक्षेपों (precipitates) ने स्थानीय क्षरण के प्रति संवेदनशीलता को मामूली रूप से बढ़ाया, लेकिन समग्र संक्षारण प्रतिरोध रॉट (wrought) मानकों के बराबर बना रहा।

मोनोलिथिक मिश्र धातु के आंतरिक शक्ति ट्रेड-ऑफ को दूर करने के लिए, इस शोध ने सिरेमिक सुदृढीकरण (ceramic reinforcements) के सहक्रियाशील जोड़ के माध्यम से नैनोकंपोजिट के विकास का नेतृत्व किया। WC और TiN नैनोकणों के समावेश ने स्पष्ट ग्रेन रिफाइनमेंट (grain refinement) और प्रभावी फैलाव सुदृढ़ीकरण (dispersion strengthening) की सुविधा प्रदान की, जिससे ~30% बढ़ाव (elongation) के साथ 1000 MPa से अधिक तन्यता शक्ति प्राप्त हुई। TiB_2 और TiN नैनोकणों का उपयोग करते हुए आगे के अनुकूलन ने ग्रेन के आकार को ~25 μm से सबमाइक्रोन पैमाने पर परिष्कृत किया, जिससे LPBF प्रक्रिया से जुड़े मजबूत क्रिस्टलोग्राफिक टेक्सचर (crystallographic textures) प्रभावी रूप से बाधित हो गए। इस विशिष्ट सुदृढीकरण रणनीति ने असाधारण यांत्रिक प्रदर्शन प्रदान किया, जिसमें लगभग 28% की डक्टिलिटी (ductility) बनाए रखते हुए ~1200 MPa की शक्ति हासिल की गई।

महत्वपूर्ण रूप से, यांत्रिक अखंडता में ये वृद्धि सामग्री के कार्यात्मक सतह गुणों से समझौता किए बिना हासिल की गई। नैनोकंपोजिट्स ने बेस एलॉय की तुलना में काफी बेहतर घिसाव प्रतिरोध (wear resistance) का प्रदर्शन किया, जबकि रॉट SS316L के बराबर संक्षारण व्यवहार बनाए रखा। ये निष्कर्ष

उन्नत संरचनात्मक और कार्यात्मक अनुप्रयोगों में LPBF-निर्मित SS316L-आधारित नैनोकंपोजिट को तैनात करने के लिए मौलिक अंतर्दृष्टि और व्यावहारिक मार्ग प्रदान करते हैं।

Declaration by the author

This thesis is composed of my original work and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contributions of others to jointly authored works that I have included in my thesis.

I have clearly stated the contributions of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution.

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Dedication

Dedicated to

My respected parents
For your hard work and integrity, for raising me with values, and for always supporting and advising me.

Publications

Publications included in the thesis

- **Baibhav Karan**, SK. Shaw, A. Sarkar, K. Moheimani, S. Chatterjee, Mingxing Zhang, Ayan Bhowmik; Orientation and Strain-Rate Effects on High-Temperature Plasticity of 316L Stainless Steel Fabricated by Laser Powder Bed Fusion; *Additive Manufacturing*, 2026, 119, 105115. DOI: doi: 10.1016/j.addma.2026.105115.

- **Baibhav Karan**, Qiyang Tan, Kiomars Moheimani, Junji Shinjo, Chinnapat Panwisawas, Ayan Bhowmik, Mingxing Zhang; Achieving superior strength and corrosion resistance synergy in 316L stainless steel nanocomposites using ceramic nanoparticles by laser powder bed fusion approach, *Progress in Additive Manufacturing*, 2025. DOI: doi: 10.1007/s40964-025-01331-x.

- **Baibhav Karan**, Qiyang Tan, Kiomars Moheimani, Fanshuo Wang, Ayan Bhowmik, Mingxing Zhang; Enhancement of tribological properties by reinforcing 316L stainless steel with nano ceramics fabricated by laser powder bed fusion; *Wear*, 2025, 582–583, 206334. DOI: doi: 10.1016/j.wear.2025.206334.

- **Baibhav Karan**, Malar Vadani, Prashanth Muralishankar, Kiomars Moheimani, Ayan Bhowmik, Mingxing Zhang; Determining the Necessity of Post-Processing Heat Treatment for the 316L Stainless Steel Manufactured by Laser Powder Bed Fusion through Evaluation of Mechanical and Corrosion Properties, *Advanced Engineering Materials*, 2024, 27, 2401442. DOI: doi: 10.1002/adem.202401442.

Other publications during candidature

- Kiomars Moheimani, Qiyang Tan, Ruth Knibbe, **Baibhav Karan**, Asanka Basnayake, Michael Heitzmann, Feng Wang, Tao Wu, Abdollah Saboori, Mingxing Zhang; Enhancing the mechanical properties and corrosion resistance of AISI 440C martensitic stainless steel via laser powder bed fusion and post-processing treatment; *Progress in Additive Manufacturing*, 2025

- Yarramilli Vamsi A., Malar Vadani, **Baibhav Karan**, Ashok Bhakar, Sanjay Rai, Niroj Maharjan, Ayan Bhowmik; Investigation of surface structural modifications caused by the influence of the ablative layer in Inconel718 Ni-base superalloy through laser shock peening; *Materials Letters*, 2024

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28.05.2026

Keywords

Additive Manufacturing; Laser Powder Bed Fusion; 316L Stainless Steel; Nanocomposites

List of Abbreviations

SS	Stainless steel
AM	Additive manufacturing
SS316L	AISI 316L stainless steel
LPBF	Laser powder bed fusion
SLS	Selective laser sintering
DED	Directed energy deposition
STL	Standard tessellation language
HT	Heat treated
CAD	Computer aided design
LPBF	Laser powder bed fusion
EBSD	Electron backscatter diffraction
SXRD	Synchrotron X-ray diffraction
EDM	Electrical discharge machining
PR	Pitting Resistance
CPP	Cyclic potentiodynamic polarisation
YS	Yield strength
UTS	Ultimate tensile strength
BD	Build direction
UE	Uniform elongation
TE	Total elongation
XCT	X-ray computed tomography
OCP	Open circuit potential
EIS	Electrochemical impedance spectroscopy
GOS	Grain orientation spread
MMC	Metal matrix composite
WC	Tungsten carbide
TiN	Titanium nitride
TiB_2	Titanium diboride
TiC	Titanium carbide
PDP	Potentiodynamic polarisation
SS440C	AISI 440C stainless steel
FESEM	Field emission scanning electron microscope
IPF	Inverse pole figure
TEM	Transmission electron microscope

SAED	Selected Area Electron Diffraction
OR	Orientation relationship
SFE	Stacking fault energy
FIB	Focused ion beam
APT	Atom probe tomography
SAED	Selected Area Electron Diffraction
CTE	Coefficient of thermal expansion
CoF	Coefficient of friction
HIP	Hot isostatic pressing
DED	Directed energy deposition
HPT	High pressure torsion
TWIP	Twinning induced plasticity

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