MULTI-MATERIAL FABRICATION OF STAINLESS STEEL TO NICKEL ALLOY PARTS USING DIRECT LASER METAL DEPOSITION: A REVIEW

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DOI: http://doi.org/ 10.57001/huih5804.2025.241

ABSTRACT

Direct Laser Metal Deposition (DLMD) employs additive manufacturing (AM) techniques for multi-material components, including stainless steel to nickel-based superalloys. It is applicable in aerospace, energy, and high-temperature applications because to its exceptional mechanical strength, corrosion resistance, and thermal stability. The article reviews the DLMD manufacturing method for multi-material parts, equipment schematics, and microstructural organization of stainless steel 316L in relation to Inconel 625 and Inconel 718, emphasizing hardness gradients, tensile strength, residual stress buildup, and thermal distortion. Despite its advantages, multi-material DLMD faces challenges such solidification cracking, porosity, phase segregation, and interfacial stress concentration, which may undermine structural integrity. Consequently, many strategies are suggested to improve quality and decrease defects, such as optimizing process parameters, applying real-time monitoring, and utilizing AI and Machine Learning in the design and manufacturing of multi-material components.

Keywords: *Multi-Material Additive Manufacturing, Functionally Graded Material, Direct Laser Metal Deposition, Stainless steel 316L, Inconel 625, inconel 718.*

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Received: 12/3/2025
Revised: 10/6/2025
Accepted: 25/7/2025

1. INTRODUCTION

Additive manufacturing has evolved modern production by allowing the layer-by-layer fabrication of complex, high-performance parts, consequently enhancing material efficiency and design adaptability [1]. In contrast to Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are constrained in multi-material applications [2], DLMD facilitates large-scale production with real-time modifications to inputs composition, hence enabling multi-material manufacturing [3, 4]. Multi-material additive manufacturing (MMAM) allows accurate deposition of many feedstock in just one produce, allowing for the production of functionally graded materials (FGMs) with regionally controlled materials and customized properties unattainable by traditional techniques [5]. Researchers utilize in-situ composition management to address issues like discrepancies in melting temperatures, variations in thermal expansion, and the production of brittle intermetallics [6]. Nonetheless, challenges in melt pool dynamics, residual stress, and interface design require further optimization of process parameters, including laser power, scanning travel speed, and post-deposition heat treatment [7].

Stainless steel 316L (SS316L), frequently utilized in maritime, biomedical, and chemical processing, offers superior corrosion resistance and ductility, mostly due to its molybdenum content [8]. In contrast, Inconel 625 (IN625) and Inconel 718 (IN718) are indispensable for high-temperature applications due to their superior oxidation resistance, fatigue performance, and creep resistance [9]. DLMD facilitates seamless transitions between Ni-based alloys and stainless or carbon steels in nuclear applications, improving corrosion resistance and mechanical integrity in pressure vessels [10]. However, integrating SS316L with IN625/IN718 presents considerable problems due to disparities in melting temperatures (SS316L ~1400°C, IN625~1350°C, IN718~1260 - 1336°C) and thermal expansion coefficients lead to solidification cracking, residual stress accumulation, and brittle intermetallic phase formation [11].

This study reviews metallic FGMs generated by DLMD, concentrating on the SS316-IN625 and SS316-IN718 systems. It analyzes the crystallographic and mechanical characteristics of FGMs and the influence of processing factors on interfacial bonding and residual stress. The paper also addresses defect creation, process optimization, and the uses of artificial intelligence and machine learning in multi-material directed laser metal deposition within advanced manufacturing.

2. EQUIPMENT AND FABRICATION METHODS

Equipment: The schematic diagram of the DLMD system uses a high-power laser to melt and deposit metal particles onto a substrate, as seen in Fig. 1. The system consists of a laser source, powder feeder, gas system, chiller, worktable, and control unit. Metal powders from two alloy sources are combined with shielding gas (inert gas). They are introduced into the laser-induced melt pool, where they solidify to create a metallurgical bond incrementally. The process is affected by critical factors like laser power, scanning velocity, powder feed rate, and the thermal history of each deposited layer [12]. An inert carrier gas guarantees accurate material delivery, while the chiller preserves system stability by averting overheating.

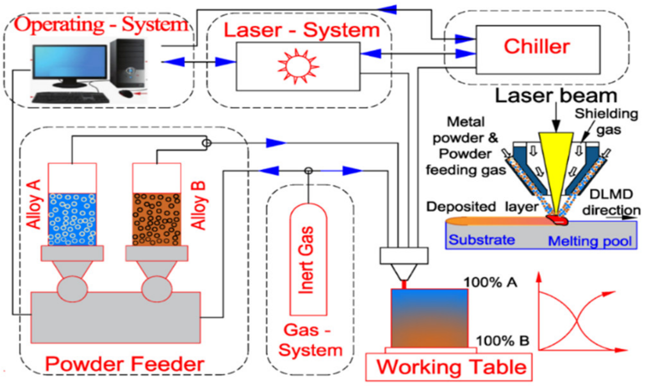

Fig. 1. Schematic of DLMD system

Design Methodologies: Fig. 2 illustrates various functionally graded materials that can be fabricated by powder-fed DLMD technology. Fig. 2(a) shows a steep gradient, wherein the composition transitions abruptly between two dissimilar alloys or elements, forming a distinct interface typically observed in bimetallic structures utilized for wear-resistant applications [13]. Fig. 2(b) depicts discontinuous (step-wise) gradient transitions, where the composition changes in discrete layers rather than gradually, a common approach in thermal barrier coatings to enhance heat resistance [6]. Fig. 2(c) demonstrates a smooth gradient, where the composition transitions progressively, depending upon the accuracy of the DLMD system, which is essential in biomedical implants since the gradual transition between titanium and hydroxyapatite improves osseointegration. Fig. 2(d) demonstrates multiple gradients, where repeated transitions improve material characteristics, particularly for aerospace components requiring customized mechanical strength and thermal expansion regulation. Fig. 2(e) displays gradients utilizing intermediate or filler materials, incorporating an intermediate composition between three distinct alloys to facilitate a regulated transition, especially when direct amalgamation is impractical due to phase incompatibility, as evidenced in Ni-Ti-Stainless Steel joints applied to structural applications. Fig. 2(f) demonstrates a metal-ceramic gradient, whereby an insoluble ceramic material is gradually incorporated into a metal matrix, resulting in a metal matrix composite utilized in high-performance cutting tools and aircraft heat shields [6]. These gradient structures provide excellent regulation of material characteristics, permitting customized mechanical, thermal, and functional performance across numerous applications in engineering.

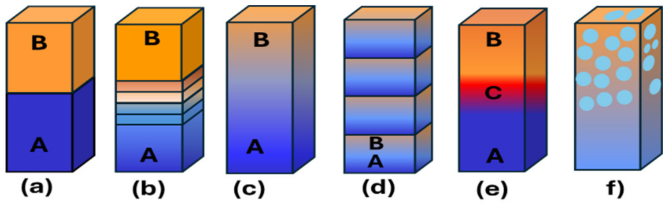

Fig. 2. FGMs fabrication methods; (a)-steep gradient; (b)- discontinuous (step-wise) gradient transitions; (c) - smooth gradient; (d) - multiple gradients; (e) - gradients utilizing intermediate; (f) - metal-ceramic gradient

Powder Feeding Methods: Fig. 3 demonstrates two prevalent powder feeding techniques employed in DLMD for fabrication FGMs: Independent Powder Feeding and Premixed Powder Feeding.

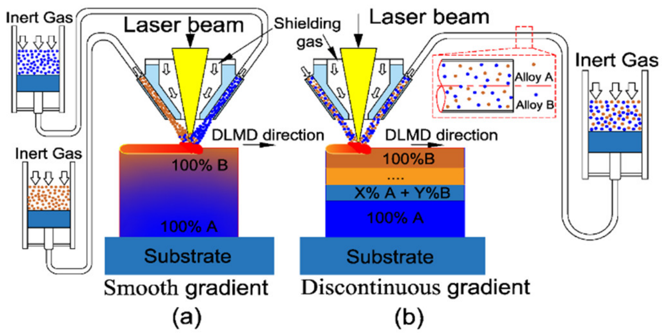

Fig. 3. Schematic of Powder Feeding Methods; (a) - Independent Powder Feeding Method; (b) - Premixed Powder Feeding Method

Independent Powder Feeding Method: This method utilizes many distinct powder feeders for various materials (Powder A, B, or C), enabling real-time adjustment of composition. The powders are fed into the laser beam's melt pool, allowing for a progressive adjustment of their ratio throughout the height of the deposited layers, resulting in either a continuous or discontinuous gradient transition. However, a significant issue of this approach is the "Poor Powder Mixing" defect, arising from the non-uniform dispersion of powder particles inside the melt pool. Factors including particle size, powder feed rate, and gas flow dynamics affect powder mixing prior to melting, leading to compositional inconsistencies in the deposited material. This problem is especially crucial for alloys with varying heat conductivities, potentially leading to phase separation and a decline in mechanical characteristics [14-16].

Premixed Powder Feeding Method: This approach employs a singular powder feeder, in contrast to the independent powder feeding method, wherein various powders are pre-mixed in a specified ratio prior to being supplied to the system. The powder mixture is conveyed by an inert gas into the nozzle and fused by the laser beam to create the deposited layer [16]. The premixed powder feeding method presents several advantages, significantly reducing the risk of "Poor powder mixing" by assuring uniform blending prior to delivery to the nozzle, hence ensuring consistent material composition, preventing phase segregation, and enhancing mechanical qualities. Moreover, it simplifies the powder deliver system, reduces operational costs, and enhances manufacturing efficiency due to a consistent powder feed rate [17]. However, this method lacks flexibility in real-time composition modifications, as the powder mixture ratio is predetermined before deposition.

3. METALLURGICAL AND MECHANICAL BEHAVIOR OF FGMS

3.1. SS316/Inconel 625 Functionally Graded Materials

Microstructural Evolution and Phase Formation: The microstructural evolution in SS316L-IN625 FGMs is governed by solidification kinetics, transitioning from equiaxed austenitic grains in SS316L to dendritic structures in IN625 due to thermal gradients [14, 15, 18, 19]. A gradual compositional gradient reduces interfacial stresses, while discrete layering increases Fe/Ni transitions and embrittlement [14, 20]. Nb and Mo segregation in the transition region forms brittle Laves phase (Ni_2Nb, Fe_2Nb), lowering ductility and fatigue resistance. These intermetallics create hardness inhomogeneity, making Laves-enriched areas prone to cracking. Post-deposition heat treatment (1100 - 1200°C) promotes diffusion-driven homogenization, reducing segregation and enhancing mechanical integrity [19].

Fig. 4 illustrates the microstructural evolution in the transition zone between SS316L and Inconel 625, emphasizing dendritic formation, porosity, and their influence on mechanical properties in additive manufacturing and material joining [15].

Hardness Gradient: Studies show a smooth hardness transition in graded builds, unlike the sharp changes in direct-joint deposits [14] . High cooling rates refine dendritic structures, increasing hardness. Mehrabi et al. found that increasing scan speed increased hardness due to higher solidification rates [15]. Conversely, Feenstra et al. observed that higher laser power led to grain growth, reducing hardness from 272 HV to 233 HV in IN625 layers [20]. They also noted that higher energy input increased distortion, highlighting the importance of controlled thermal gradients.

Mechanical Performance and Tensile Strength: Tensile testing showed that fractures occurred in the weaker SS316L region, confirming strong metallurgical bonding at the interface. FGM structures exhibit yield strengths ranging from 405MPa to 630MPa and UTS values from 605MPa to 1029MPa, depending on gradient optimization [14, 17]. Savitha et al. observed failure in the SS316 region without debonding at the interface [18]. Feenstra et al. reported only ~10 - 15% elongation due to microstructural inhomogeneity [20]. Bo Chen et al. linked premature fracture to Laves phase embrittlement, emphasizing the need to minimize brittle intermetallic phases [17].

Residual Stresses and Thermal Distortion: Wei Meng et al. successfully reduced thermal stresses using laser preheating, preventing cracks in transition layers [21]. They demonstrated that preheating reduced residual stresses and eliminated cracking in 90 - 70% 316L layers. Chen et al. [19] found that the printing sequence affected stress distribution, recommending IN625-on-316L for a gradual transition [19]. Mehrabi et al. found that high scan speeds improved uniformity and reduced distortion, highlighting that thermal distortion in SS316L-IN625 FGMs is significantly affected by heat input during laser metal deposition [15]. Meanwhile, Feenstra et al. observed that excessive deformation occurred at high laser power [20]. The mismatch in thermal expansion coefficients induces tensile residual stresses at the transition region, increasing susceptibility to hot cracking and delamination [19-21].

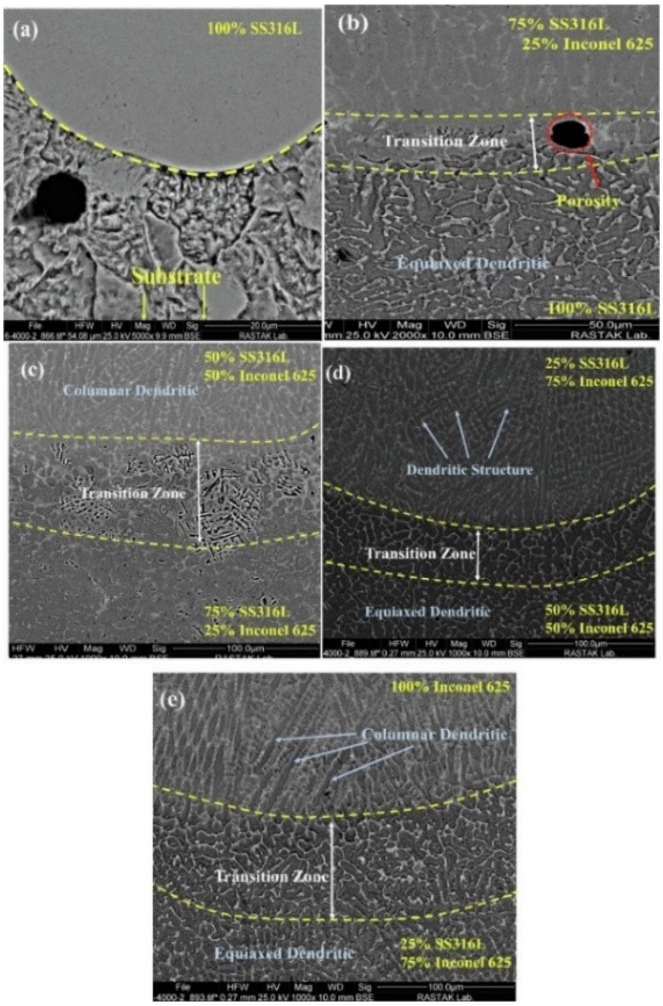

Fig. 4. Microstructural of SS316/IN625 [15]

3.2. SS316/Inconel 718 Functionally Graded Materials: The microstructure of SS316L-IN718 FGMs evolves with composition, transitioning from a coarse austenitic cellular (FCC) structure in SS316L to a dendritic γ-Ni structure in IN718. In the transition region (40 - 60% IN718), dendritic structures form alongside the precipitation of Laves and NbC phases, significantly affecting the mechanical properties. While the dendritic γ-Ni structure enhances strength, its inhomogeneous distribution can lead to mechanical instability. Brittle Laves and NbC phases reduce ductility and increase crack susceptibility. Additionally, the transition from cellular to dendritic structures impacts tensile strength and crack resistance [12, 22, 23].

Hardness Gradient and Residual Stress Accumulation: The microhardness distribution in SS316L-IN718 FGMs exhibits a significant variation, increasing from approximately 185-200 HV in SS316L to around 410-550 HV in IN718. However, the transition region (~40 - 60% IN718) shows a localized hardness dip due to microstructural instability, phase interactions, and the precipitation of Fe_2Nb and NbC compounds, which diminish ductility and load-bearing capabilities [22-25]. Although the overall hardness trend follows a nearly linear increase, regions with excessive Laves phase formation (~50 - 75% IN718) experience localized hardness reductions, adversely affecting fatigue life [12, 26].

Mechanical Properties and Tensile Testing: As-built SS316L-IN718 FGMs exhibit low tensile strength and poor ductility, with an ultimate tensile strength (UTS) of ~310MPa and elongation of only 7.8%, indicating a brittle nature and inadequate mechanical performance [22]. The formation of Laves phases at the interface contributes to premature failure, especially in discrete-interface samples with high stress concentration [12]. Post-deposition heat treatments, such as homogenization and aging, refine the microstructure by smoothing compositional gradients and promoting γ′ and γ″ strengthening phases, leading to better strength and ductility [22]. Despite these improvements, regions containing 50 - 75% IN718 remain prone to cracking due to excessive Laves and NbC phase formation, which reduces the material's load-bearing capacity under high-stress conditions [12, 27].

Residual Stresses and Thermal Distortion: The SS316L-IN718 interface in FGMs experiences the highest tensile residual stress, reaching approximately 475MPa, making it the most susceptible region to localized cracking and delamination due to thermal expansion mismatches between the two alloys [28]. Additionally, thermal distortion is a major concern during additive manufacturing, with the last-deposited layers experiencing strain up to 3.95×10^{-3}, leading to geometric inaccuracies and potential structural deformation [29]. To mitigate these issues, gradient transition designs and laser processing optimization have been employed, effectively reducing residual stress accumulation and improving structural stability [22, 30].

4. DEFECTS AND QUALITY IMPROVEMENT METHODS

4.1. Common Defects in Multimaterial SS316/IN625 and SS316L/IN718

Figure 5 illustrates various defects in the fabrication of FGMs. The primary causes of process problems in the fabrication of multi material SS316/IN625 and SS316L/IN718 are solidification cracking, residual stress accumulation, phase segregation, poor bonding, porosity, and intermetallic phase formation. These defects are frequently attributed to non-ideal process parameters, including improper laser power, scanning velocities, powder feed rates, and variations in layer thickness. Furthermore, they arise from discrepancies in thermal expansion, poor powder mixing, variations in solidification behavior, and phase segregation.

Table 1. Common defects of SS316/Inconel 718 Functionally Graded Materials

Evaluation Criteria	**REASON**	
	SS316L-IN625	**SS316L-IN718**
Solidification Cracking	Laves phase formation due to Nb & Mo segregation, increasing crack susceptibility [15, 19, 20]	Interdendritic liquid film formation promotes segregation defects and embrittlement [22, 26]
Residual Stress	Higher CTE in SS316L causes tensile stress, leading to distortion and delamination [14, 19]	Wide solidification range and γ', γ'' precipitation cause severe stress accumulation [23, 26, 28]
CTE Mismatch	SS316 (~16.0 × $10^{-6}K^{-1}$) vs. IN625 (~13.0 × $10^{-6}K^{-1}$) = ~23% mismatch [20, 34]; CTE mismatch (~23%) causes residual stress accumulation and cracking at sharp transitions [19]	SS316 (~16.0 × $10^{-6}K^{-1}$) vs. IN718 (~12.8 × $10^{-6}K^{-1}$) = ~25% mismatch; Higher CTE mismatch (~25%) increases thermal stresses and crack risk [26, 28]
Porosity	Moderate porosity risk due to thermal conductivity mismatch, causing voids at interfaces [14, 15, 19]	Higher melt viscosity and reactivity cause keyhole instability and oxide inclusions [25, 28]
Crack Formation	Laves phase embrittlement leads to crack propagation and adhesion failure [19, 21]	A wider solidification range promotes hot cracking, increasing delamination risk [22, 26]
Melt Pool Instability	Thermal conductivity differences induce turbulence, keyhole porosity, and fusion defects [19, 20]	High viscosity and low thermal conductivity cause unstable melt pools and fusion defects [25, 30]
Intermetallic Formation	Laves phase & NbC formation reduces ductility, increasing failure risk [20, 21, 24]	Laves and Fe-Nb intermetallics form due to Nb segregation and degrading toughness [26, 27]
Thermo-dynamics & Kinetics	Rapid solidification leads to irregular grain growth and stress accumulation [19]	Rapid γ' and γ'' transformations induce grain coarsening and stress concentration [23]
Enthalpy Mixing Effects	High enthalpy differences cause uneven melting, segregation, and residual stress [15, 19, 20]	High melting point differences cause inconsistent solidification and thermal cracking [22, 29]
Grain Control Issues	Columnar grain structure causes anisotropy, weak interlayer bonding, and delamination [17, 19]	Dendritic growth promotes columnar structures, causing mechanical anisotropy [22, 25]
Poor Powder Mixing	Non-uniform powder flow results in segregation and weak bonding [14, 19]	High powder viscosity and density hinder uniform mixing, causing sharp transitions [26]
Over-Tempering	Laves phase precipitation embrittles microstructure, reducing ductility [20, 21]	δ-phase precipitation at grain boundaries weakens cohesion and reduces strength [23]

4.2. Improve Quality in FGM Manufacturing

Improving the quality of FGMs in AM requires tackling issues such as porosity, residual stress, and thermal distortion. AI-driven process optimization offers a breakthrough approach, utilizing machine learning (ML) algorithms to dynamically modify essential parameters laser power, scanning speed, and powder feed rate to ensure uniform deposition and reduce stress concentrations. Karimzadeh et al. reviewed the effect of machine learning in enhancing the production of FGMs, emphasizing parameter optimization and recognizing defects [31].

Inconsistencies in powder composition and flow rates may result in heterogeneous material distribution and porosity defects. AI-driven powder flow monitoring systems control powder density, particle size, and feed rate, enhancing compositional accuracy. Ciccone et al. emphasized the importance of integrating AI-based predictive models to improve AM process control [32].

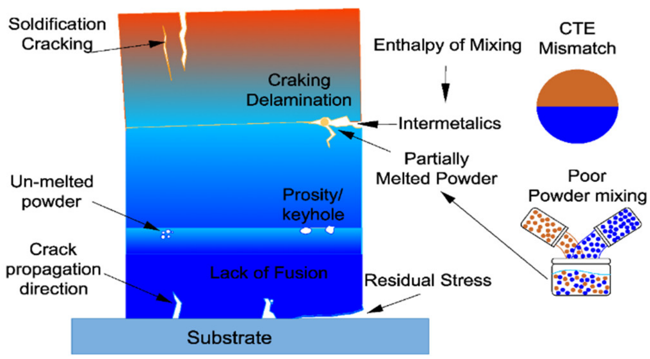

Fig. 5. Schematic of common defects in multimaterial SS316/IN625 and SS316L/IN718

Defect detection is critical for maintaining the structural integrity of FGM. AI-driven multi-sensor fusion methodologies provide real-time defect detection through the integration of thermal imaging, optical coherence tomography, and acoustic emission sensors. Herzog et al. explored ML applications in laser-based AM, demonstrating improvements in defect identification using picture analysis [33].

AI-assisted computational modeling accelerates the development of FGMs by predicting optimal compositions, microstructural changes, and phase transitions, resulting in customized characteristics. Karimzadeh et al. highlighted the significance of ML in optimizing fabrication parameters and real-time monitoring [31].

Residual stress influences the integrity, fatigue resistance, and dimensional stability of FGMs. AI-driven prediction and control utilize ML models trained on thermal-fluid interactions, mechanical deformation, and phase transitions to enhance stress distribution optimization. Ciccone et al. emphasized the potential of AI in AM for real-time quality control and stress management [32].

In summary, AI-driven advancements in process optimization, powder feeding, defect management, material innovation, and residual stress reduction revolutionize FGM manufacturing. Through the integration of real-time monitoring, computational modeling, and intelligent automation, AI improves accuracy, minimizes waste, and accelerates material creation. As artificial intelligence advances, MMAM is set to emerge as a more economical, sustainable, and high-performance alternative for aerospace, medicinal, and energy sectors.

5. CONCLUSION

Directed Laser Metal Deposition has emerged as a key additive manufacturing technology for fabricating multi-material components, solving the demand for specific mechanical and thermal characteristics in heterogeneous metal structures. This paper evaluates the microstructural development and mechanical properties of stainless steel-nickel alloy components manufactured using DLMD, emphasizing flaws such solidification cracking, porosity, deformation, residual stress, and delamination in SS316, IN625, and IN718. Despite the limitations caused by intermetallic phase formation, powder mixing, and process stability, advancements in powder delivery, real-time process control, and multi-physics modeling are crucial for the commercial applications of DLMD. The integration of AI and machine learning for in-situ monitoring and adaptive parameter optimization presents interesting options for improving production accuracy, efficiency, and material performance. These innovations will be essential for the development of next-generation FGMs, guaranteeing enduring structural integrity and industrial feasibility.

REFERENCES

[1]. A. Bandyopadhyay, S. Bose, *Additive manufacturing*. CRC Press, 2015. doi: https://doi.org/10.1201/b18893.

[2]. C. Wang, et al., "Additive manufacturing of NiTi shape memory alloys using pre-mixed powders," *J Mater Process Technol*, 271, 152-161, 2019. doi: 10.1016/j.jmatprotec.2019.03.025.

[3]. A. Bandyopadhyay, B. V. Krishna, W. Xue, S. Bose, "Application of Laser Engineered Net Shaping (LENS) to manufacture porous and functionally graded structures for load bearing implants," *Journal of Materials Science: Materials in Medicine*, 2009. doi: 10.1007/s10856-008-3478-2.

[4]. D. Han, H. Lee, "Recent advances in multi-material additive manufacturing: methods and applications," *Current Opinion in Chemical Engineering*, 28, 158-166, 2020. doi: 10.1016/j.coche.2020.03.004.

[5]. D. R. Feenstra, R. Banerjee, H. L. Fraser, A. Huang, A. Molotnikov, N. Birbilis, "Critical review of the state of the art in multi-material fabrication via directed energy deposition," *Curr Opin Solid State Mater Sci,* 25, 4, 2021. doi: 10.1016/j.cossms.2021.100924.

[6]. M. Ansari, E. Jabari, E. Toyserkani, "Opportunities and challenges in additive manufacturing of functionally graded metallic materials via powder-fed laser directed energy deposition: A review," *Journal of Materials Processing Technology,* 294, 117117, 2021. doi: 10.1016/j.jmatprotec.2021.117117.

[7]. X. Tian, Z. Zhao, H. Wang, X. Liu, X. Song, "Progresses on the additive manufacturing of functionally graded metallic materials," *J Alloys Compd*, 960, 170687, 2023. doi: https://doi.org/10.1016/j.jallcom.2023.170687.

[8]. M. Ziętala, et al., "The microstructure, mechanical properties and corrosion resistance of 316 L stainless steel fabricated using laser engineered net shaping," *Materials Science and Engineering: A,* 677, 1–10, 2016. doi: 10.1016/j.msea.2016.09.028.

[9]. S. Pratheesh Kumar, S. Elangovan, R. Mohanraj, J. R. Ramakrishna, "A review on properties of Inconel 625 and Inconel 718 fabricated using direct energy deposition," in *Materials Today: Proceedings,* 7892-7906, 2021. doi: 10.1016/j.matpr.2021.02.566.

[10]. T. DebRoy, et al., "Additive manufacturing of metallic components - Process, structure and properties," *Progress in Materials Science*, 92, 112-224, 2018. doi: 10.1016/j.pmatsci.2017.10.001.

[11]. F. Khodabakhshi, M. H. Farshidianfar, S. Bakhshivash, A. P. Gerlich, A. Khajepour, "Dissimilar metals deposition by directed energy based on

powder-fed laser additive manufacturing," *J Manuf Process,* 43, 83-97, 2019. doi: 10.1016/j.jmapro.2019.05.018.

[12]. Y. Su, B. Chen, C. Tan, X. Song, J. Feng, "Influence of composition gradient variation on the microstructure and mechanical properties of 316 L/Inconel718 functionally graded material fabricated by laser additive manufacturing," *J Mater Process Technol*, 283, 2020. doi: 10.1016/j.jmatprotec.2020.116702.

[13]. S. Tyagi, S. K. Balla, M. Manjaiah, C. Aranas, "Microstructure and mechanical properties of stainless steel 316L-Inconel 625 bimetallic structure fabricated by laser wire direct energy deposition," *Journal of Materials Research and Technology*, 33, 8361-8371, 2024. doi: 10.1016/j.jmrt.2024.11.130.

[14]. X. Zhang, Y. Chen, F. Liou, "Fabrication of SS316L-IN625 functionally graded materials by powder-fed directed energy deposition," *Science and Technology of Welding and Joining*, 24, 5, 504-516, 2019. doi: 10.1080/13621718.2019.1589086.

[15]. O. Mehrabi, S. M. Hossein Seyedkashi, M. Moradi, "Experimental and response surface study on additive manufacturing of functionally graded steel-inconel wall using direct laser metal deposition," *Opt Laser Technol*, 167, 109707, 2023. doi: 10.1016/j.optlastec.2023.109707.

[16]. M. Mohammadi, M. Rajabi, M. Ghadiri, *Functionally graded materials (FGMs): A review of classifications, fabrication methods and their applications*. University of Novi Sad, Faculty of Technology, 2021. doi: 10.2298/PAC2104319M.

[17]. B. Chen, Y. Su, Z. Xie, C. Tan, J. Feng, "Development and characterization of 316L/Inconel625 functionally graded material fabricated by laser direct metal deposition," *Opt Laser Technol,* 123, 2020. doi: 10.1016/j.optlastec.2019.105916.

[18]. U. Savitha, G. Jagan Reddy, A. Venkataramana, A. Sambasiva Rao, A. A. Gokhale, M. Sundararaman, "Chemical analysis, structure and mechanical properties of discrete and compositionally graded SS316-IN625 dual materials," *Materials Science and Engineering A*, 647, 344-352, 2015. doi: 10.1016/j.msea.2015.09.001.

[19]. N. Chen, et al., "Microstructural characteristics and crack formation in additively manufactured bimetal material of 316L stainless steel and Inconel 625," *Addit Manuf,* 32, 2020. doi: 10.1016/j.addma.2020.101037.

[20]. D. R. Feenstra, A. Molotnikov, N. Birbilis, "Effect of energy density on the interface evolution of stainless steel 316L deposited upon INC 625 via directed energy deposition," *J Mater Sci*, 55, 27, 13314-13328, 2020. doi: 10.1007/s10853-020-04913-y.

[21]. W. Meng, W. Zhang, W. Zhang, X. Yin, B. Cui, "Fabrication of steel-Inconel functionally graded materials by laser melting deposition integrating with laser synchronous preheating," *Opt Laser Technol*, 131, 2020. doi: 10.1016/j.optlastec.2020.106451.

[22]. Z. Liu, M. Tang, "Control of microstructure, defects and mechanical properties in direct energy deposited SS316L/Inconel 718 functionally graded material via mechanical vibration," *Mater Des,* 242, 113010, 2024. doi: 10.1016/j.matdes.2024.113010.

[23]. C. Ji, K. Li, J. Zhan, S. Bai, B. Jiang, L. E. Murr, "The effects and utility of homogenization and thermodynamic modeling on microstructure and mechanical properties of SS316/IN718 functionally graded materials fabricated by laser-based directed energy deposition," *J Mater Process Technol*, 319, 118084, 2023. doi: 10.1016/j.jmatprotec.2023.118084.

[24]. K. Shah, I. ul Haq, A. Khan, S. A. Shah, M. Khan, A. J. Pinkerton, "Parametric study of development of Inconel-steel functionally graded materials by laser direct metal deposition," *Mater Des,* 54, 531-538, 2014. doi: 10.1016/j.matdes.2013.08.079.

[25]. F. Kermani, M. R. Borhani, R. ShojaRazavi, "Assessment of structural defects and mechanical characteristics of IN718/St6 functionally graded material produced by direct laser deposition," *Journal of Materials Research and Technology*, 31, 1557-1570, 2024. doi: 10.1016/j.jmrt.2024.06.194.

[26]. S. W. Yang, J. Yoon, H. Lee, D. S. Shim, "Defect of functionally graded material of inconel 718 and STS 316L fabricated by directed energy deposition and its effect on mechanical properties," *Journal of Materials Research and Technology*, 17, 478-497, 2022. doi: 10.1016/j.jmrt.2022.01.029.

[27]. Y. Wu, et al., "Corrosion behavior of laser directed energy deposited SS316L/Inconel718 functionally graded materials," *Mater Today Commun*, 40, 110038, 2024. doi: 10.1016/j.mtcomm.2024.110038.

[28]. R. Ghanavati, H. Naffakh-Moosavy, M. Moradi, E. Gadalińska, A. Saboori, "Residual stresses and distortion in additively-manufactured SS316L-IN718 multi-material by laser-directed energy deposition: A validated numerical-statistical approach," *J Manuf Process,* 108, 292-309, 2023. doi: 10.1016/j.jmapro.2023.11.018.

[29]. R. Ghanavati, H. Naffakh-Moosavy, M. Moradi, M. Eshraghi, "Printability and microstructure of directed energy deposited SS316l-IN718 multi-material: numerical modeling and experimental analysis," *Sci Rep,* 12, 1, 2022. doi: 10.1038/s41598-022-21077-8.

[30]. W. Li, et al., "Comprehensive studies of SS316L/IN718 functionally gradient material fabricated with directed energy deposition: Multi-physics & multi-materials modelling and experimental validation," *Addit Manuf,* 61, 103358, 2023. doi: 10.1016/j.addma.2022.103358.

[31]. M. Karimzadeh, D. Basvoju, A. Vakanski, I. Charit, F. Xu, X. Zhang, "Review of Machine Learning Methods for Additive Manufacturing of Functionally Graded Materials," *arXiv:2309.16571*. https://doi.org/10.48550/arXiv.2309.16571

[32]. F. Ciccone, A. Bacciaglia, A. Ceruti, "Optimization with artificial intelligence in additive manufacturing: a systematic review," *J Braz. Soc. Mech. Sci. Eng.,* 45, 303, 2023. doi: 10.1007/s40430-023-04200-2.

[33]. T. Herzog, M. Brandt, A. Trinchi, A. Sola, A. Molotnikov, "Process monitoring and machine learning for defect detection in laser-based metal additive manufacturing," *J Intell Manuf,* 35, 1407-1437, 2024. doi: 10.1007/s10845-023-02119-y.