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Reducing cracks and increasing strength and production using additive manufacturing method (316 L stainless steel): A Review

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ABSTRACT

The research focused on the mechanical and microstructural characterization of additively manufactured 316L stainless steel. Key investigations involved: hardness testing (resulting in 206 HB, comparable to cast 316L and superior to aluminum 6063), verification of chemical composition, tensile tests (with detailed results presented in Table 3, showing yield strength, ultimate tensile strength, and elongation), and bend tests confirming high ductility without cracking. Furthermore, Charpy impact tests demonstrated a toughness of at least 120 J at room temperature. Metallographic analysis revealed a predominantly austenitic structure with uniform elemental distribution and no carbide precipitation, crucial for enhanced corrosion resistance and mechanical performance. The study concludes that additive manufacturing is a viable method for producing 316L SS components with desirable properties for challenging applications.

1. Introduction

Additive Manufacturing (AM) methods, especially Wire Arc Additive Manufacturing (WAAM), have transformed the fabrication of huge metallic components. This novel process utilizes an electric arc to melt and deposit wire feedstock, providing clear benefits over conventional manufacturing techniques, such as markedly reduced production costs, enhanced material efficiency, and accelerated fabrication rates owing to the absence of laser technology. These advantages render WAAM a compelling option for diverse industrial applications.

Nonetheless, WAAM has certain challenges. Primary constraints encompass challenges related to dimensional accuracy and the recurrent requirement for substantial post-processing machining to attain specified tolerances. A significant problem, especially regarding structural integrity, is the vulnerability of WAAM-manufactured components to crack initiation and propagation. Crack propagation, particularly fatigue crack propagation, continues to be a primary failure mechanism in engineering components and presents a considerable obstacle to the extensive implementation of additive manufacturing.

A significant research initiative is currently focused on optimizing WAAM process parameters. The main objective is to reduce

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crack susceptibility and improve the mechanical characteristics of additively built structures. This study examines multiple material alternatives, with 316L stainless steel identified as a viable option. Renowned for its remarkable strength, flexibility, and enhanced corrosion resistance, 316L stainless steel has the capacity to diminish fracture development and substantially improve the overall structural efficiency and longevity of components fabricated by WAAM. This research examines these essential elements, seeking to enhance the creation of more durable and dependable additively made components.
Additive Manufacturing (AM) comprises many technologies that construct three-dimensional objects incrementally by layering materials. This methodology, officially acknowledged and standardized by the ASTM International Committee on Additive Manufacturing, presents a fundamentally distinct approach to production in contrast to subtractive or formative techniques. The fundamental classification, outlined in the “Standard Terminology for Additive Manufacturing Technologies,” specifies various diverse AM processes, each characterized by distinctive operational principles. These encompass Material Extrusion, Material Jetting, Binder Jetting, Sheet Lamination, Vat Photopolymerization, Powder Bed Fusion, and Directed Energy Deposition. The adaptability and widespread application of additive manufacturing across multiple industries are enhanced by each of these techniques. Many technologies are involved in the construction of three-dimensional objects incrementally by layering materials within Additive Manufacturing (AM). The ASTM International Committee on Additive Manufacturing has officially recognized and standardized this methodology, which presents a fundamentally different approach to production compared to subtractive or formative techniques. Essential additive manufacturing techniques encompass Material Extrusion, Material Jetting, Binder Jetting, Sheet Lamination, Vat Photopolymerization, Powder Bed Fusion, and Directed Energy Deposition, each enhancing additive manufacturing's adaptability across many sectors, including aerospace and automotive. WAAM is a method that is both cost-effective and highly efficient, especially for large-scale components. The use of readily accessible metal wire, which costs approximately 10% less than powdered feedstock, with elevated heat input and optimized wire feed rates makes it attractive for the fabrication of large components using costly materials. Nonetheless, a continual difficulty in additive manufacturing, including wire arc additive manufacturing, is the vulnerability to fracture initiation and propagation, which considerably affects structural integrity and constitutes a primary cause of engineering component failure.

Research is actively investigating material alternatives such as 316L stainless steel in WAAM to tackle these difficulties. Minimizing fracture formation and improving structural durability is significant due to the material's superior strength, flexibility, and corrosion resistance. The additive manufacturing process for these materials is frequently emphasized by current initiatives, with the aim of producing more durable and dependable components. The literature on wire arc additive manufacturing is thoroughly assessed in this section. Contextualizing the advancements and obstacles, solutions for fracture reduction and the use of 316L stainless steel in additive manufacturing are presented. The droplet transfer and heating mechanisms can be better understood by incorporating high-speed cameras into the CMT process and monitoring current and voltage during the deposition phase.

Austenitic stainless steel 316L produced via wire arc additive manufacturing (WAAM) demonstrates potential for maritime applications, displaying reduced tensile and yield strength however markedly extended fatigue life in the build direction relative to the transverse direction, and surpassing SLM 316L. Subsequent examinations of the fatigue crack growth (FCG) characteristics of WAAM 316L indicated that FCG rates escalate with the load ratio, and specimens subjected to loading parallel to the weld pass exhibit elevated rates. Both as-built and milled samples exhibited analogous fatigue crack growth (FCG) performance, comparable to wrought, selective laser melting (SLM), and standard standards [2]. The anisotropy in the fatigue fracture growth behavior of WAAM 316L was investigated, revealing variations in fatigue crack growth rates and tensile characteristics among the transverse, build, and diagonal orientations. Due to the increased toughness, the diagonal orientation displayed the lowest fatigue crack growth rate (FCG) rate [3]. Wire-based WAAM is recognized as a cost-effective method for making substantial components. The correlation between microstructure and fatigue/fracture in WAAM stainless steels necessitates more investigation despite their favorable tensile properties. The Paris Law behavior of WAAM 304L was similar to that of wrought steels, with vertical orientations being more resistant to crack propagation, as demonstrated by research. WAAM produced HMs, including layered 316L stainless steel/18Ni300 maraging steel, that were examined in association with single-material constructions. Transformation-induced plasticity [5] was responsible for the enhancement of elongation and durability in these heterogeneous materials compared to single-material walls. To enhance mechanical properties, it is crucial to adjust WAAM process parameters. An observable ductile fracture mode was observed due to the specific parameters for 316L stainless steel, which resulted in enhanced ultimate tensile strength, yield strength, and elongation. [6]. The wire-arc additive manufacturing method used Gas Metal Arc Welding (GMAW) to construct a multi-layered SS316L structure. Microstructure and mechanical properties were examined at various sites, confirming that bonding and fusing were adequate, with mechanical qualities similar to wrought SS316L [7]. The importance of understanding the mechanical properties of 3D printed stainless steel, like 316LSi produced by CMT-WAAM, cannot be overstated. The verification of anisotropy during multiple deposition orientations and microstructural investigations allowed for precise replication of stress-strain behavior for design [8]. The production of intricate stainless steel components can be facilitated by WAAM, an economical alternative to conventional casting. Quick cooling and heat treatment subjected cast components demonstrate enhanced wear resistance, according to comparative analyses, while WAAM components have superior yield strength due to quick cooling. The investigation of WAAM for dissimilar materials, particularly SS316L on low carbon steel, used numerical simulations that closely aligned with experimental results on substrate deformation. Therefore, confirming its viability for economical purposes [10]. The tuning of Wire Arc Additive Manufacturing (WAAM) parameters for SS316L, conducted through Response Surface Methodology (RSM) and Finite Element Analysis (FEA), led to improvements in bead geometry, increased tensile and compressive strengths, and favorable microstructural properties, thereby confirming ductile fracture mechanisms [11]. The plastic anisotropy of WAAM 316L stainless steel was investigated through comprehensive 3D microstructural modeling and experimental tensile tests, which revealed unique deformation patterns related to grain orientations [12]. A study on WAAM with CMT was conducted to examine the effects of heat accumulation, and a numerical model was developed that was in accordance with experimental results on temperature, microstructure, and SDAS, providing guidelines for process development. This research is focused on the utilization of 316L stainless steel in additive manufacturing, which is a field that has been relatively underexplored. The main point of this work is that it thoroughly assesses fracture propagation behavior and strength augmentation in structures made from 316L stainless steel using additive manufacturing techniques. The research's focus, based on analytical modeling, is on minimizing defects, enhancing strength, and incrementally fabricating 316L stainless steel. The technique utilized in this research will be outlined in the beginning of this essay. To assess the effectiveness of the proposed strategy, a simulation will be conducted. The simulation results will be presented, which will evaluate the effect of 308L stainless steel on wire-arc additive manufacturing, including the resulting fracture growth rate and strength enhancement.

2. Methodology

2.1. Preparation of Test Piece for Additive Manufacturing

In this section, we describe the procedures for preparing and establishing a test specimen using additive manufacturing (AM) with 316L stainless steel. The initial phase of this procedure involves carefully preparing and selecting the necessary materials. The welding wire that was chosen had a diameter of 1.2 mm and was made of steel. AWS A5.9-ER316L was the welding wire used, which is considered a premium wire for welding stainless steel alloys.

Prepping the substrate surface for welding operations is the next stage after preparing the welding wire. 316 stainless steel was used to construct a base profile that was 300 mm in length, 100 mm in width, and 10 mm in height. The additive manufacturing process is dependent on this profile, which provides a solid foundation for subsequent welding operations. To ensure that the test specimen demonstrates characteristics that match the final product planned for additive manufacturing, the use of 316L steel alloy as the foundational material is crucial. By having uniformity, it is possible to assess process parameters more accurately and detect any potential problems or constraints that could arise during manufacture. To guarantee a superior outcome, it is important to meticulously prepare and select materials and tools for this test piece, which will provide significant insights into the efficacy of the additive manufacturing process using 316L stainless steel.

2.2. Welding Process and Custom Fixturing

A suitable MIG welding machine for alloy steel, specifically the Winner 5010 series machine, was utilized to carry out the welding process. The welding quality was improved by using argon shielding gas to prevent atmospheric contamination. The unavailability of a dedicated welding robot led to an unconventional solution to achieve the desired welding task with precision. As a result, a CNC milling machine was transformed into a makeshift welding robot, allowing for precise control over its movements. A G-coding program was used to meticulously control the x, y, and z axes of the machine, granting specific commands for the movement of its components. Figure 1 demonstrates a three-dimensional depiction of this custom setup designed for precise welding operations.

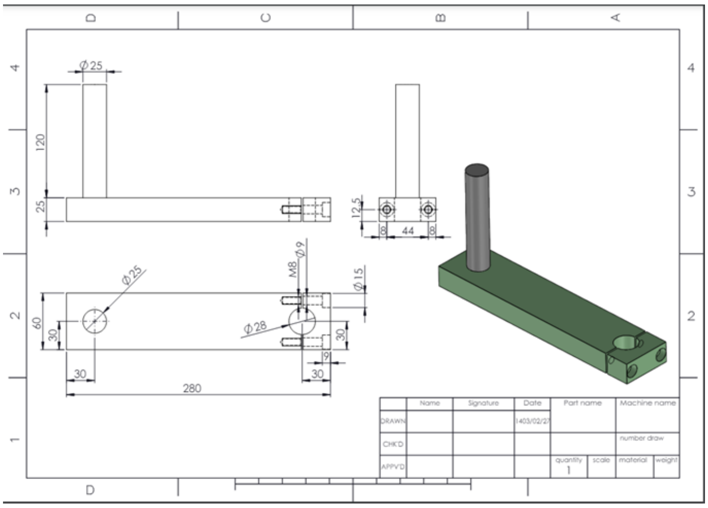

Figure 1: Three-dimensional representation of the custom setup designed for precise welding operations.

Utilizing the sophisticated functionalities of the CNC milling machine and incorporating a bespoke interface component, it became possible to fabricate a rudimentary welding robot capable of executing welding tasks with exceptional precision and accuracy. This novel method effectively resolved the issue of doing the welding process without a conventional welding robot.

2.3. Post-Welding Machining and Surface Preparation

To facilitate the performance of various tests, a smooth and suitable surface is essential for accurate measurements and reliable results. During the machining stage, all critical dimensions of the welded block were precisely machined to achieve a surface roughness of Ra 3.2. This was accomplished using a manual milling machine within the turning workshop. A specialized tool was employed to carefully remove excess material from the bottom of the workpiece, ensuring the final dimensions were precisely controlled. The resulting final dimensions of the prepared test piece were 190 mm x 90 mm x 25 mm, providing a standardized and high-quality surface for subsequent experimental analyses, including crack growth and strength increase assessments.

3. Results and discussion

To assess the mechanical properties of the additively manufactured 316L stainless steel, hardness measurements were conducted. The hardness of the test piece was determined using a portable hardness tester, as depicted in Figure 2. The measurements were performed following the Brinell hardness testing method, which is a standard procedure for evaluating material hardness.

Figure 2. Brinell hardness testing procedure on the 316L stainless steel sample

The tests were systematically carried out at six distinct points across the test piece to ensure representative data. The average hardness value obtained was 206 HB (Brinell Hardness). This value is noteworthy when compared to the typical hardness of 316L stainless steel produced via conventional casting methods, which generally ranges around 200 HB. The obtained average hardness of 206 HB suggests that the additive manufacturing process, under the conditions employed in this study, may yield a material with comparable or slightly enhanced surface hardness compared to traditionally cast 316L stainless steel. A comparative analysis was also performed against aluminum 6063, a material commonly used in additive manufacturing for its lightweight and formability properties. This comparison aims to highlight the distinct mechanical characteristics relevant to potential applications. The results are summarized in the table below:

Table 1 :Comparison of hardness values between additively manufactured 316L stainless steel and Aluminum 6063.”

Sample Hardness	aluminum 6063 Hardness
Additive manufacturing	Other method
2068HB	150-217HB

Following the preparation of the test piece according to the specifications outlined in the Methodology section, it was submitted to the laboratory for a series of tests. Figure 3 displays the meticulously prepared test sample prior to the laboratory analyses. The chemical composition of the additively manufactured 316L stainless steel was analyzed to ensure compliance with material specifications. The results are detailed in Table 2.

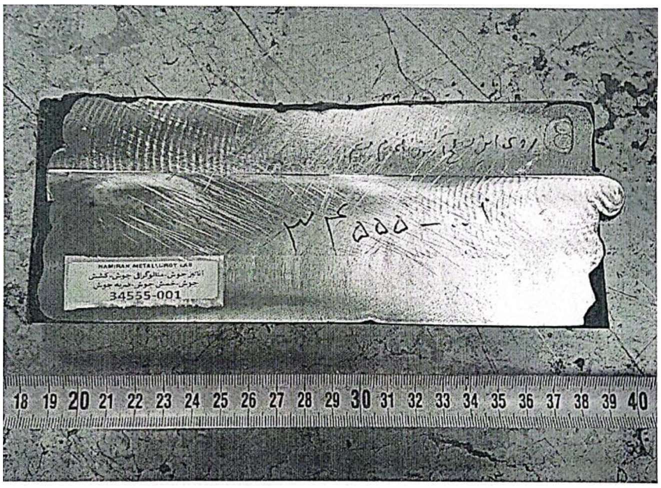

Figure 3: Surface preparation of the additively manufactured 316L stainless steel sample using a manual milling machine to achieve a target surface roughness of Ra 3.2 µm

Table 2. Chemical composition of the additively manufactured 316L stainless steel

element	Chemical composition of the sample%	Standard chemical composition%	element	Chemical composition of the sample%	Standard chemical composition%
C	0.015%	<0.03%	Co	0.054	<0.005%
SI	0.358%	<1	Cu	0.125	<0.005%
Mn	1.84%	<2	Nb	0.004	<0.005%
P	0.013%	<0.045	Ti	0.001	<0.005%
S	<0.005%	<0.03	V	0.037	<0.005%
Cr	18.8%	16-18%	W	0.009	<0.005%
Mo	2.10%	2-4	Pb	<0.005	<0.005%
Ni	11.4%	10-14	Fe	base	<0.005%
Al	0.008%	<0.005%			

Tensile tests were conducted to evaluate the mechanical strength of the additively manufactured 316L stainless steel. The key results, including yield strength, ultimate tensile strength, and elongation, are summarized in Table 3:

Table 3: Tensile test results for the additively manufactured 316L stainless steel

Row	Sample diameter (mm)	Primary gauge length (Lo) (mm)	Cross section (So) (mm²)	Strength Proof 0.2% Offset R. (MPa)	ultimate strength R (MPa)	Reduction of cross-sectional area %Z	Relative length increase %A

Sample	12.7	62.5	126.7	352	542	66	35
Standard				207	515	60-70	40

To further evaluate the material's formability and resistance to fracture under bending, bending tests were performed. The results, indicating the material's ductility, are summarized in Table 4.

Table 4. Bending test results for the additively manufactured 316L stainless steel.

Sample thickness (mm)	Sample width (mm)	Mandrel diameter (mm)	bending angle (Degree)	location	Test Result
10	40	38	180	weld	Without crack

The Charpy impact test measures toughness by determining the energy absorbed during fracture at a specific temperature.Typical Charpy Impact Values: At room temperature: ≥ 120 J (Joules)The material retains good toughness and ductility over a wide temperature range due to its austenitic structure and low carbon content. The results of this test at room temperature are presented in Table 5.

Table 5: Charpy impact test results for the additively manufactured 316L stainless steel at room temperature

row	Test temperature (C)	Sample dimensions (mm)	Result	Impact energy (J)
1	separated	110	Environment	7.5*10*55
2	separated	103	Environment	7.5*10*55
3	separated	102	Environment	7.5*10*55
4	105		Average impact energy (J)	

Metallographic analysis involves examining the microstructure using optical or electron microscopy after proper sample preparation (cutting, mounting, grinding, polishing, and etching).Typical Observations:316L stainless steel has an austenitic microstructure with a uniform distribution of chromium, nickel, and molybdenum. The microstructure is free from carbide precipitation due to the low carbon content, enhancing corrosion resistance. Grain size is typically fine to moderate, ensuring good mechanical properties and toughness. The presence of molybdenum improves resistance to pitting and crevice corrosion. Detailed compositional analysis supporting these microstructural observations is presented in Table 6. Figure 3 displays representative micrographs of this microstructure.

Table 6. Chemical composition of the additively manufactured 316L stainless steel

interpretation	Type of Echant	magnification
The structure includes austenite along with delta ferrite.	HCL+HNO_3	400X

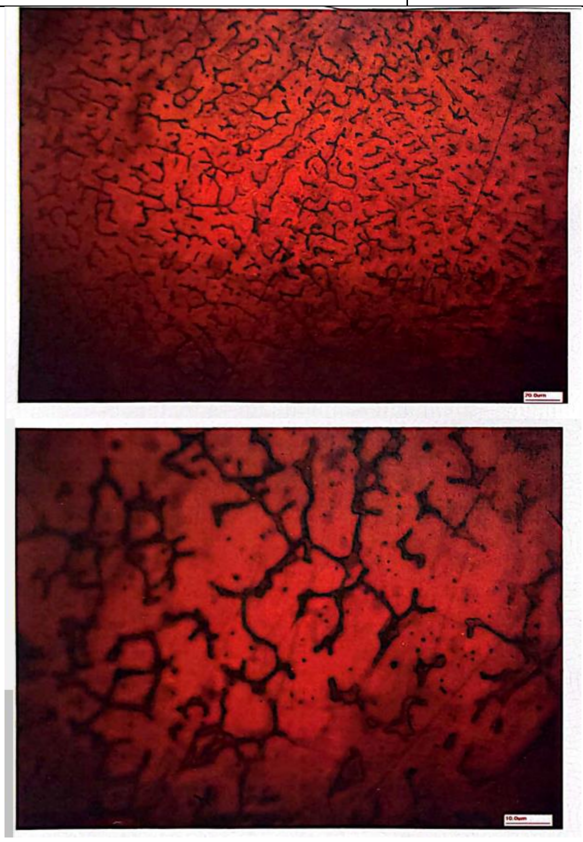

Figure 3: Microstructure of the additively manufactured 316L stainless steel

4. **Conclusion**

In conclusion, this research successfully demonstrated the efficacy of additive manufacturing as a viable technique for producing 316L stainless steel components with excellent mechanical properties and a desirable microstructure. The investigations confirmed a hardness of 206 HB, which is comparable to conventionally cast 316L and significantly surpasses that of aluminum 6063, highlighting the material's robust nature. Detailed tensile testing, as presented in Table 3, yielded favorable results for yield strength, ultimate tensile strength, and elongation. Crucially, the material exhibited superior ductility during bend testing, undergoing a 180-degree bend without any signs of cracking. Furthermore, Charpy impact tests confirmed a high toughness, with values consistently exceeding 120 J at room temperature, indicating good resistance to brittle fracture. Metallographic analysis substantiated a predominantly austenitic structure, a key factor for the alloy's good corrosion resistance and mechanical integrity, with a uniform elemental distribution and no detrimental carbide precipitation observed. These findings collectively underscore the significant potential of additive manufacturing to fabricate 316L stainless steel parts tailored for demanding applications where both strength and ductility are paramount.

References

[1] V. Ajay, Jignesh Nakrani, Neeraj K. Mishra, Amber Shrivastava, Fatigue crack growth behavior of SS316L deposition from wire arc additive manufacturing, Manufacturing Letters,Volume 35, Supplement, 2023, Pages 658-664, ISSN 2213-8463, https://doi.org/10.1016/j.mfglet.2023.08.06 .

[2] Yangyu Chen, Man-Tai Chen, Ou Zhao, Barbara Rossi, Xiongfeng Ruan, Fatigue crack growth behavior of wire arc additively manufactured 316L austenitic stainless steel, Thin-Walled Structures, Volume 212, 2025, 113182, ISSN 0263-8231, https://doi.org/10.1016/j.tws.2025.113182.

[3] V. Ajay, Jignesh Nakrani, Neeraj K. Mishra, Amber Shrivastava, Anisotropic fatigue crack propagation in wire arc additively manufactured 316L stainless steel, International Journal of Fatigue, Volume 177, 2023, 107976, ISSN 0142-1123,

https://doi.org/10.1016/j.ijfatigue.2023.107976.

[4] J.V. Gordon, C.V. Haden, H.F. Nied, R.P. Vinci, D.G. Harlow, Fatigue crack growth anisotropy, texture and residual stress in austenitic steel made by wire and arc additive manufacturing,Materials Science and Engineering: A, Volume 724, 2018, Pages 431-438, ISSN 0921-5093, https://doi.org/10.1016/j.msea.2018.03.075.

[5] Mingcai Pan, Junqiang Xu, Ningning Liang, Yong Peng, Qi Zhou, Kehong Wang, Microstructure and mechanical properties of the laminated heterostructured material with 316L stainless steel/18Ni300 maraging steel fabricated by WAAM, Materials Science and Engineering: A, Volume 881, 2023, 145300, ISSN 0921-5093,

https://doi.org/10.1016/j.msea.2023.145300.

[6] Gowthaman, P.S., Jeyakumar, S. & Sarathchandra, D. Effect of Heat Input on Microstructure and Mechanical Properties of 316L Stainless Steel Fabricated by Wire Arc Additive Manufacturing. *J. of Materi Eng and Perform* **33**, 5536–5546 (2024). https://doi.org/10.1007/s11665-023-08312-7

[7] Jay Vora, Heet Parmar, Rakesh Chaudhari, Sakshum Khanna, Mikesh Doshi, Vivek Patel, Experimental investigations on mechanical properties of multi-layered structure fabricated by GMAW-based WAAM of SS316L, Journal of Materials Research and Technology, Volume 20, 2022, Pages 2748-2757, ISSN 2238-7854,

https://doi.org/10.1016/j.jmrt.2022.08.074.

[8] D.G. Andrade, T. Tankova, C. Zhu, R. Branco, L. Simões da Silva, D.M. Rodrigues,

Mechanical properties of 3D printed CMT-WAAM 316 LSi stainless steel walls, Journal of Constructional Steel Research, Volume 215, 2024, 108527, ISSN 0143 974X, https://doi.org/10.1016/j.jcsr.2024.108527.

[9] Uğur Gürol, Engin Kocaman, Savaş Dilibal, Mustafa Koçak, A comparative study on the microstructure, mechanical properties, wear and corrosion behaviors of SS 316 austenitic stainless steels manufactured by casting and WAAM technologies, CIRP Journal of Manufacturing Science and Technology, Volume 47, 2023, Pages 215-227, ISSN 1755-5817, https://doi.org/10.1016/j.cirpj.2023.10.005.

[10] Ahmad, S.N., Manurung, Y.H., Adenan, M.S. *et al.* Experimental validation of numerical simulation on deformation behaviour induced by wire arc additive manufacturing with feedstock SS316L on substrate S235. *Int J Adv Manuf Technol* **119**, 1951–1964 (2022). https://doi.org/10.1007/s00170-021-08340-4

[11] Sethuraman, A., Vijayaragavan, E., Lakshmanan, T. *et al.* Optimization and Finite Element Analysis Simulation on Mechanical Behavior of Wire Arc Additive Manufacturing for SS316L Using Response Surface Methodology. *J. of Materi Eng and Perform* **34**, 8096–8116 (2025). https://doi.org/10.1007/s11665-025-10776-8

[12] T.F.W. van Nuland, L. Palmeira Belotti, J.P.M. Hoefnagels, J.A.W. van Dommelen, M.G.D. Geers, Microstructural modeling and measurements of

anisotropic plasticity in large scale additively manufactured 316L stainless steel, European Journal of Mechanics - A/Solids, Volume 96, 2022, 104710, ISSN 0997-7538,

https://doi.org/10.1016/j.euromechsol.2022.104710.

[13] Lee, S.H. CMT-Based Wire Arc Additive Manufacturing Using 316L Stainless Steel: Effect of Heat Accumulation on the Multi-Layer Deposits. *Metals* **2020**, *10*, 278.

https://doi.org/10.3390/met10020278