International Journal of Engineering Research & Management Technology

ISSN: 2348-4039

July-August 2023 Volume-10, Issue-4

Email: editor@ijermt.org

www.ijermt.org

Improving the Mechanical and Metallurgical Properties of Inconel 625 Alloy Fabricated Through Wire Arc Additive Manufacturing (WAAM)

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Abstract: Wire Arc Additive Manufacturing (WAAM) is a promising technology for fabricating high-quality metallic components, including those made from Inconel 625 alloy. This review paper examines the state-of-the-art in WAAM, focusing on process parameters, equipment, and the mechanical and metallurgical properties of Inconel 625 alloy. Key research findings, challenges, and future directions in enhancing the properties of Inconel 625 through WAAM are discussed.

Introduction: Additive Manufacturing (AM) refers to the process of creating objects layer-by-layer, offering advantages such as cost savings, material efficiency, and the ability to produce complex geometries. WAAM, a subset of AM, uses arc welding processes to deposit material and is particularly suitable for fabricating large, complex metal parts. Inconel 625, a nickel-based superalloy, is widely used in aerospace, petrochemical, marine, and chemical industries due to its excellent mechanical properties and resistance to extreme environments.

Background and Significance of WAAM: The rise of Additive Manufacturing (AM) technologies has revolutionized the manufacturing landscape. Among these technologies, Wire Arc Additive Manufacturing (WAAM) stands out for its potential to fabricate large-scale metal components efficiently. The ability to produce complex geometries with reduced material wastage makes WAAM an attractive option for industries such as aerospace, automotive, and energy. Additionally, the cost-effectiveness of WAAM compared to traditional manufacturing methods further emphasizes its significance.

Objectives of the Review: This review aims to provide a comprehensive overview of the current state of WAAM technology, specifically focusing on Inconel 625 alloy. The paper will explore various aspects of the WAAM process, including equipment, process parameters, microstructural evolution, and mechanical properties. Furthermore, the review will identify existing research gaps and propose future directions to enhance the performance and applicability of WAAM-fabricated Inconel 625 components.

Wire Arc Additive Manufacturing (WAAM): WAAM utilizes an electric arc as a heat source and a wire spool as feedstock to deposit material layer-by-layer. The first patent related to WAAM dates back to 1920. This method stands out among AM techniques due to its low equipment cost, high production rate, and 100% material utilization. However, challenges such as residual stress, surface roughness, and dimensional inaccuracies remain.

a) **Historical Development of WAAM:** The development of WAAM can be traced back to the early 20th century. Initial patents and research laid the groundwork for modern WAAM technologies. Over the decades, advancements in welding techniques, automation, and control systems have significantly improved the capabilities and precision of WAAM. Understanding the historical context helps appreciate the technological evolution and current state-of-the-art in WAAM.

b) **Advantages and Limitations of WAAM:** WAAM offers several advantages, including high deposition rates, low equipment costs, and the ability to produce large-scale parts with complex geometries. However, it also presents challenges such as residual stress, surface roughness, and dimensional inaccuracies. These limitations necessitate ongoing research to optimize process parameters and develop effective post-processing techniques to mitigate these issues.

WAAM Process Steps: The WAAM process involves three main steps: process planning, deposition, and post-treatment. Process planning includes creating a 3D model and converting it into 2D layers using slicing software. Deposition involves layer-by-layer material addition, and post-treatment may include heat treatment or machining to enhance part properties.

a) **Process Planning:** Process planning is a critical step in WAAM. It involves creating a detailed 3D model of the part to be fabricated and converting it into 2D layers using slicing software. The choice of slicing strategy, layer thickness, and support structures can significantly impact the quality and performance of the final component. Advanced software tools and simulation techniques play a crucial role in optimizing process planning.

b) **Deposition Process:** During the deposition process, the material is added layer-by-layer using an electric arc as the heat source. The deposition parameters, including wire feed rate, travel speed, and arc current, must be carefully controlled to ensure uniform layer deposition and minimize defects. Real-time monitoring and feedback control systems can enhance the deposition process by providing immediate adjustments to optimize part quality.

c) **Post-Treatment:** Post-treatment processes such as heat treatment, machining, and surface finishing are essential to improve the mechanical and metallurgical properties of WAAM-fabricated parts. Heat treatment can relieve residual stresses and refine the microstructure, while machining and surface finishing improve dimensional accuracy and surface quality. Exploring advanced post-treatment techniques is critical to achieving high-performance WAAM components.

WAAM Equipment: WAAM systems are primarily robotic or machine tool-based. Commercial WAAM systems integrate arc welding power sources with robotic arms or CNC machines. Machine tool-based systems offer the potential to combine additive and subtractive manufacturing processes, allowing for high-precision part fabrication.

a) **Robotic WAAM Systems:** Robotic WAAM systems leverage industrial robots for precise and flexible material deposition. These systems offer advantages in terms of reach, flexibility, and automation. Integrating advanced sensors and control algorithms enhances the capabilities of robotic WAAM systems, enabling the production of complex geometries with high precision.

b) **Machine Tool-Based WAAM Systems:** Machine tool-based WAAM systems combine additive and subtractive manufacturing processes within a single platform. This integration allows for high-precision part fabrication by combining the benefits of both manufacturing techniques. Hybrid systems can perform additive deposition followed by CNC machining, resulting in improved dimensional accuracy and surface finish.

c) **Commercial WAAM Systems:** Several commercial WAAM systems are available in the market, each offering unique features and capabilities. Examples include the WAAM3D system by WAAM3D Ltd., the EBAM® system by Sciaky Inc., and the DMG MORI LASERTEC 65 3D hybrid system. Understanding the capabilities and limitations of these commercial systems is essential for selecting the appropriate equipment for specific applications.

Process Parameters of WAAM: Key process parameters in WAAM include wire feed rate, travel speed, arc current, argon flow rate, printing path strategy, and heat input. These parameters significantly affect the bead geometry, surface quality, and mechanical properties of the fabricated parts.

a) **Wire Feed Rate (WFR):** Higher WFR results in taller and narrower beads, while lower WFR leads to wider and shorter beads. The wire feed rate directly influences the deposition rate and layer fusion quality. Optimizing the WFR is crucial for achieving uniform layer deposition and minimizing defects such as porosity and lack of fusion.

b) **Travel Speed:** Increased travel speed reduces bead width, wetting angle, and melt-through depth but has minimal effect on bead height. Optimal travel speed is crucial for achieving desired bead geometry and surface quality. Fine-tuning the travel speed helps balance deposition rate and heat input, leading to improved part integrity.

c) **Arc Current:** Higher arc current improves bead roughness and increases bead width, wetting angle, and melt-through depth. Maintaining appropriate arc current is essential for achieving uniform deposition and mechanical properties. Real-time monitoring of arc current ensures consistent energy input and enhances the overall quality of the WAAM process.

d) **Argon Flow Rate:** Argon flow rate primarily prevents oxidation during deposition but has negligible effects on bead geometry. Consistent argon flow is necessary to maintain surface cleanliness and prevent oxidation. Optimizing the shielding gas flow rate helps create a protective atmosphere around the weld pool, ensuring high-quality deposits.

e) **Printing Path Strategy:** Using alternating deposition directions between layers reduces height differences at the start and end of the weld path, improving overall part quality. Interpass cooling is also essential to manage heat accumulation and prevent defects. Advanced path planning algorithms and thermal management strategies enhance the efficiency and quality of the WAAM process.

f) **Heat Input:** Excessive heat input can lead to remitting and poor microstructure, while insufficient heat input causes spatter and incomplete fusion. Gradually reducing heat input between layers helps achieve uniform deposition and mechanical properties. Controlling the heat input is critical to managing thermal gradients and minimizing residual stresses in WAAM-fabricated parts.

Nickel-Based Superalloys: Nickel-based superalloys like Inconel 625 are valued for their high strength at elevated temperatures and resistance to corrosion. These properties make them suitable for critical applications in aerospace, chemical processing, and marine industries.

a) **Properties and Applications of Nickel-Based Superalloys:** Nickel-based superalloys exhibit exceptional mechanical properties, including high tensile strength, creep resistance, and fatigue life. Their ability to maintain these properties at elevated temperatures makes them ideal for applications in gas turbines, jet engines, and chemical processing equipment. The corrosion resistance of these alloys further extends their use in marine and chemical environments.

b) **Challenges in Fabricating Nickel-Based Superalloys:** Fabricating nickel-based superalloys presents several challenges, including their high melting temperatures and susceptibility to cracking during solidification. WAAM offers a potential solution by providing precise control over the thermal cycles and deposition parameters. Research into optimizing WAAM for nickel-based superalloys aims to overcome these challenges and expand their applicability.

Inconel 625 Alloy: Inconel 625, composed primarily of nickel, chromium, and molybdenum, offers exceptional high-temperature resistance, corrosion resistance, strength, and toughness. Its weldability and ability to withstand extreme environments make it an ideal candidate for WAAM.

a) **Composition and Properties of Inconel 625:** Inconel 625 contains approximately 58% nickel, 20-23% chromium, 8-10% molybdenum, and smaller amounts of niobium, iron, and other elements. This unique composition imparts excellent mechanical properties and resistance to oxidation and corrosion. Inconel 625 maintains its strength and toughness across a wide range of temperatures, making it suitable for various high-performance applications.

b) **Applications of Inconel 625:** Inconel 625 is extensively used in aerospace, marine, and chemical processing industries. In aerospace, it is employed in components such as exhaust systems, fuel nozzles, and heat exchangers due to its ability to withstand high temperatures and harsh environments. In the marine industry, it is utilized in seawater equipment and submarine components for its excellent corrosion resistance. In chemical processing, it is used in equipment handling acidic and alkaline environments.

Literature Review: Research on WAAM of Inconel 625 has focused on optimizing process parameters, understanding microstructural evolution, and improving mechanical properties. Key challenges include managing residual stresses, achieving consistent layer fusion, and enhancing surface quality.

a) **Process Parameter Optimization:** Studies have explored various process parameters to enhance the quality of Inconel 625 parts produced by WAAM. For instance, adjusting the wire feed rate, travel speed, and arc current has shown significant effects on bead morphology and mechanical properties. Researchers have also examined the influence of interpass temperature control on reducing residual stresses and improving the microstructure of the deposited material.
b) **Wire Feed Rate and Travel Speed:** Research has demonstrated that higher wire feed rates result in taller and narrower beads, while lower rates lead to wider and shorter beads. Optimal wire feed rates and travel speeds are crucial for achieving uniform layer deposition and minimizing defects. Studies have shown that fine-tuning these parameters can significantly improve the surface quality and mechanical properties of the final parts.
c) **Current and Heat Input:** Higher arc currents improve bead roughness and increase bead width, wetting angle, and melt-through depth. However, excessive heat input can lead to remelting and poor microstructure. Gradually reducing heat input between layers helps achieve uniform deposition and mechanical properties. Researchers have explored various arc current settings to optimize the heat input and achieve consistent energy distribution during the WAAM process.
d) **Argon Flow Rate and Printing Path Strategy:** Optimizing the argon flow rate is essential to prevent oxidation during deposition and maintain surface cleanliness. Advanced printing path strategies, such as alternating deposition directions and interpass cooling, have been developed to manage heat accumulation and improve overall part quality. Studies have shown that these strategies enhance the efficiency and precision of the WAAM process.

Microstructural Evolution: The microstructure of Inconel 625 produced by WAAM is influenced by thermal cycling during deposition. Research has revealed that controlling the cooling rate between layers can refine the grain structure and reduce the presence of undesirable phases. The formation of dendritic structures and their impact on mechanical properties have been a focal point of several studies.

a) **Grain Structure and Phase Formation:** WAAM-fabricated Inconel 625 typically exhibits a dendritic grain structure due to the rapid cooling rates associated with the process. Researchers have investigated methods to refine the grain structure, such as adjusting interpass temperatures and employing post-deposition heat treatments. These approaches aim to reduce the size and distribution of dendritic grains, improving the material's mechanical properties.

b) **Influence of Thermal Cycling:** Thermal cycling during the WAAM process affects the microstructural evolution of Inconel 625. Studies have shown that controlling the cooling rate between layers can minimize residual stresses and reduce the formation of undesirable phases, such as Laves phases. Understanding the relationship between thermal cycles and microstructural changes is crucial for optimizing the WAAM process and achieving desired material properties.

Mechanical Properties: The mechanical properties of WAAM-fabricated Inconel 625 parts are closely linked to process parameters and microstructural characteristics. Tensile strength, hardness, and fatigue resistance are critical factors that have been investigated. Post-processing techniques such as heat treatment and surface finishing have been explored to enhance these properties further.

a) **Tensile Strength and Hardness:** WAAM-fabricated Inconel 625 exhibits tensile strength and hardness comparable to traditionally manufactured parts. Studies have demonstrated that optimizing process parameters and employing post-processing treatments, such as heat treatment and hot isostatic pressing (HIP), can enhance these properties. Researchers have also explored the effects of different heat treatment cycles on the mechanical performance of WAAM-fabricated Inconel 625.
b) **Fatigue Resistance:** Fatigue resistance is a critical property for components subjected to cyclic loading. Research has shown that the fatigue resistance of WAAM-fabricated Inconel 625 can be improved through optimized process parameters and post-processing techniques. Surface finishing methods, such as shot peening and laser shock peening, have been investigated to enhance fatigue performance by inducing compressive residual stresses on the surface of the material.

Research Gaps and Future Work: Despite significant progress, further research is needed to address issues such as real-time process monitoring, advanced post-processing techniques, and the development of hybrid WAAM systems. Future work should also explore new alloys and applications to expand the potential of WAAM technology.

a) **Real-Time Process Monitoring**: Implementing real-time monitoring systems during WAAM can provide valuable insights into the deposition process and enable immediate adjustments to optimize part quality. Advanced sensors and machine learning algorithms can be integrated to predict defects and ensure consistent material properties. Developing robust real-time monitoring systems is crucial for enhancing the reliability and repeatability of the WAAM process.

b) **Advanced Post-Processing Techniques:** Innovative post-processing methods, such as laser shock peening and cryogenic treatments, can enhance the mechanical properties of WAAM-fabricated parts. Exploring the effects of these techniques on Inconel 625 can lead to significant improvements in fatigue life and surface integrity. Future research should focus on optimizing these post-processing methods and investigating their impact on the overall performance of WAAM components.

c) **Hybrid WAAM Systems:** Combining additive and subtractive manufacturing processes in a single system can achieve higher precision and surface quality. Research into hybrid WAAM systems that integrate CNC machining or laser-based finishing can offer new possibilities for producing complex, high-quality components. Developing advanced hybrid systems that seamlessly integrate additive and subtractive processes will enhance the capabilities and efficiency of WAAM technology.

d) **Exploration of New Alloys:** While Inconel 625 is a popular choice for WAAM, exploring other nickel-based superalloys and high-performance materials can open up new applications. Investigating the WAAM process for these materials can provide valuable insights into their behavior and potential benefits. Future research should focus on developing process parameters and post-processing techniques for a broader range of alloys to expand the applicability of WAAM.

Conclusion: WAAM is a versatile and cost-effective method for fabricating Inconel 625 components, offering advantages in material efficiency and production rate. Optimizing process parameters and equipment design is crucial for improving the mechanical and metallurgical properties of WAAM-fabricated parts. Continued research and development will further enhance the capabilities and applications of WAAM in various industries.

Summary of Key Findings: This review has highlighted the significant progress made in the WAAM of Inconel 625, including the optimization of process parameters, understanding microstructural evolution, and improving mechanical properties. Key findings include the impact of wire feed rate, travel speed, arc current, and heat input on bead morphology and material properties. The importance of post-processing techniques in enhancing mechanical performance has also been emphasized.

Future Directions: Future research should focus on developing real-time process monitoring systems, exploring advanced post-processing methods, and investigating hybrid WAAM systems. Additionally, expanding the range of materials studied for WAAM can open up new applications and opportunities for this technology. Collaborative efforts between academia, industry, and research institutions will be essential in driving innovation and advancing the state-of-the-art in WAAM.

References

[1] ASTMF2792-12a(2012) Standard terminology for additive manufacturing technologies,(withdrawn2015).ASTMInternational,WestConshohocken.https://doi.org/10.1520/F2792-12A.

[2] FrazierWE(2014)Metaladditivemanufacturing:areview.JMaterEngPerform23:1917–1928.https://doi.org/10.1007/s11665-014-0958-z

[3] Gao W, Zhang Y, Ramanujan D, Ramani K, Chen Y, Williams CB, Wang CCL, Shin YC,Zhang S, Zavattieri PD (2015) The status, challenges, and future of additive manufacturing in engineering. Comput Aided Des 69:65–89.

[4] Badiru AB, Valenica V, Liu D (2017) Additive manufacturing handbook. Taylor & FrancisGroup,London.

[5] Pan Z, Ding D, Wu B, Cuiuri D (2017) Arc welding processes for additive manufacturing: are view. In: ChenS, ZhangY, FengZ (eds)Transactions on intelligent welding manufacturing. Springer Singapore, Singapore, pp 3–24

[6] YeniC,Koçak M (2008) Fracture analysis of laser beam welded super alloys Incone l718 and 625 using the FITNET procedure. Int J Press VesselPip85:532–539.https://doi.org/10.1016/j.ijpvp.2008.02.004.

[7] Puppala G, Moitra A, Sathyanarayanan S,KaulR, Sasikala G,Prasad RC,KukrejaLM(2014) Evaluation of fracturet oughness an dimpact toughness of laser rapid manufactured Inconel-625structures and their co-relation.MaterDes 59:509–515.

[8] L. Chen,Y. He, Y. Yang,S. Niu,H.Ren, The research status and development trend ofadditive manufacturing technology, International Journal of Advanced Manufacturing Technology,89(2016)1-10.

[9] D. Ding, Z. Pan, D.Cuiuri, H.Li, N.Larkin,J. Cleaner Prod.133(2016)942–952

[10] Bintao Wua, Zengxi Pana, Donghong Dingb, Dominic Cuiuria, HuijunLia, Jing Xuc, John Norrisha, J.Manuf. Processes 35(2018)127–139.

[11] M. Dinovitzer, X. Chen, J. Laliberte, X. Huang, H. Frei, Addit. Manuf. 26 (2019) 138–146,https://doi.org/10.1016/j.addma.2018.12.013.

[12] OTCD aihen India pvt.Ltd.,Gurugram,Haryana.

[13] https://waverleybrownall.co.uk/wp-content/uploads/2017/05/inconel-625-composition-1.png

[14] TiagoA.Rodrigues,V.Duarte,R.M.Miranda,TelmoG.SantosandJ.P.Oliveira(2019),Current Status and Perspective son Wire and Arc Additive Manufacturing (WAAM).doi:10.3390/ma12071121.

[15] Shah, A.; Aliyev, R.; Zeidler, H.; Krinke, S. (2023) A Review of the Recent Developments andChallenges in Wire Arc Additive Manufacturing (WAAM) Process. J. Manuf. Mater. Process., 7,97.https://doi.org/10.3390/jmmp7030097

[16] S.R.SinghandP.Khanna(2020),Wirearcadditivemanufacturing(WAAM):Anewprocesstoshapee ngineeringmaterials.https://doi.org/10.1016/j.matpr.2020.08.030

[17] A. N. M. Tanvir, Md. R. U. Ahsan, ChangwookJi, Wayne Hawkins, Brian Bates, Duck Bong Kim (2019), Heat treatment effects on In conel 625 components fabricated by wire+arc additive manufacturing (WAAM)—part1: micro structural characterization.

[18] W. Yangfan, C. Xizhang and S. Chuanchu (2019), Microstructure and mechanical properties of Incone l625 fabricated by wire-arcadditive manufacturing, Surface & CoatingsTechnology,https://doi.org/10.1016/j.surfcoat.2019.05.079

[19] D.T.Sarathchandra and M.J.Davidson (2021), Effect of heat input on mechanical and micro structural properties of Incone l625 depositions processed in wire arc additive manufacturing.

[20] Nor Ana Rosli , Mohd Rizal Alkahari, Mohd Fadzli bin Abdollah, Shajahan Maidin, Faiz Redza Ramli,Safarudin Gazali Herawan (2021),Review on effect of heat input for wire arc additive manufacturing process.

[21] Chaturvedi, M.; Scutelnicu, E.; Rusu, C.C.; Mistodie, L.R.; Mihailescu, D.; Subbiah, A.V.(2021) Wire Arc Additive Manufacturing: Review on Recent Findings and Challenges in IndustrialApplicationsandMaterials Characterization.Metals,11,939.