Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Advancements in Wire Arc Additive Manufacturing of Functionally Graded Materials: Optimizing Compositional Gradients and Mechanical Performance: An Overview

Manideep Roy Avula[1], Ashwin Sailesh[2], S. N. Padhi[3], Dhivakar Poosapadi[4], M. Venkatasudhahar[5], Praveen Vundrajavarapu[6], T. Mayavan[7], Nagaraj Ashok[8], T. S. Senthil[9*]

[1]*Metrologist, Safran Nacelles, Burnley, United Kingdom. avulachotu07@gmail.com*
[2]*Department of Mechanical Engineering, Sri Sairam Institute of Technology, Chennai, Tamil Nadu 600044, India. ashwinmech9191@gmail.com*
[3]*Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Andhra Pradesh 522302, India. snpadhi@kluniversity.in*
[4]*Lead Engineer – Mechanical, Quest Global Services, Bangalore, Karnataka 560103, India. dhivap05@gmail.com*
[5]*Department of Mechanical Engineering, Vel Tech Rangarajan Dr.Sagunthala R&D Institute of Science and Technology, Chennai, Tamil Nadu 600062, India. venkatasudhahar@gmail.com*
[6]*Department of Mechanical Engineering, S.R.K.R Engineering College, Bhimavaram, Andhra Pradesh 534204, India. praveen.vundrajavarapu@gmail.com*
[7]*Department of Mechanical Engineering, Panimalar Engineering College, Chennai, Tamil Nadu 600123, India. mayavant@gmail.com*
[8]*Faculty of Mechanical Engineering, Jimma Institute of Technology, Jimma University, Jimma, Ethiopia-378. nagaraj.ashok@ju.edu.et*
[9]*Department of Marine Engineering, Noorul Islam Centre for Higher Education, Kanyakumari-629180. reachtss@gmail.com*

Wire Arc Additive Manufacturing (WAAM) is an advanced 3D metal printing technique that enables the fabrication of complex, large-scale components with minimal material waste. Its ability to control deposition parameters has made it particularly useful for creating Functionally Graded Materials (FGMs), which exhibit a gradual variation in composition and structure. This paper explores recent advancements in the fabrication of FGMs using WAAM, focusing on material combinations, process optimization, and the resulting microstructural and mechanical properties. Through numerical analysis, it was observed that controlling the wire feed rate and deposition speed significantly influences the mechanical properties, including tensile strength and hardness. For instance, increasing the wire feed rate from 2 mm/s to 8 mm/s improved the ultimate tensile strength by 15%, but a further increase led to a 10% reduction due to incomplete fusion between layers. Additionally, post-processing techniques such as laser polishing reduced surface roughness by up to 80%, significantly enhancing the component's performance in wear-sensitive applications. This study highlights the importance of optimizing process parameters and post-processing techniques to enhance the functionality and reliability of FGMs fabricated by WAAM.

Keywords: Wire Arc Additive Manufacturing (WAAM), Compositional Gradient, Mechanical Properties, Functionally Graded Materials (FGMs), Post-Processing Techniques.

1. Introduction

1.1 Wire Arc Additive Manufacturing (WAAM)

Wire Arc Additive Manufacturing (WAAM) is an advanced form of metal 3D printing that utilizes wire as a feedstock material, which is melted using an electric arc to build up a component layer by layer. WAAM offers significant advantages over traditional manufacturing methods, particularly in terms of cost-effectiveness, scalability, and the ability to fabricate large and complex components with minimal material waste. One of the key benefits of WAAM is its high deposition rate, making it suitable for producing large structural components in industries such as aerospace, automotive, and marine engineering. By controlling various process parameters such as arc current, wire feed rate, and travel speed, WAAM allows for precise control over the material deposition and the resulting mechanical properties. The flexibility of WAAM has made it particularly valuable for creating components with customized geometries and material properties, including the fabrication of Functionally Graded Materials (FGMs). FGMs are a class of advanced materials that exhibit a gradual variation in composition or structure over a certain volume, providing tailored properties to meet specific functional or structural requirements.

1.2 Functionally Graded Materials (FGMs)

Functionally Graded Materials (FGMs) are designed to optimize performance by gradually transitioning between two or more materials with distinct properties. The gradual variation in composition or microstructure provides a smooth transition between different material phases, allowing the material to maintain or improve its mechanical, thermal, or chemical performance across different sections of a component. FGMs are particularly useful in applications where multi-functional performance is required, such as thermal protection in aerospace, wear resistance in automotive parts, and corrosion resistance in marine environments. The concept of FGMs eliminates the issues associated with sharp interfaces between dissimilar materials, such as stress concentrations and interfacial delamination, which can lead to premature failure. Instead, FGMs provide a more gradual transition, reducing the likelihood of stress-induced cracking or failure at the material interface. This unique ability to tailor material properties based on the operational requirements has made FGMs a key area of interest for industries that require components to withstand extreme conditions.

1.3 FGMs Fabricated by WAAM

The combination of WAAM and FGMs offers a promising avenue for the fabrication of advanced materials with tailored properties. WAAM's ability to control the deposition of different materials during the manufacturing process makes it particularly well-suited for producing FGMs. By adjusting parameters such as wire feed rate, deposition speed, and arc current, WAAM can create components with smooth compositional gradients, minimizing the formation of undesirable intermetallic phases or defects at the interface between dissimilar materials. Several researchers have demonstrated the potential of WAAM for fabricating FGMs across various material combinations. For instance, Williams et al. (2016) used WAAM to combine aluminum and steel, achieving a smooth compositional transition that mitigated the formation of brittle intermetallic phases. Similarly, Chen et al. (2018) explored the use of WAAM for creating nickel-titanium (NiTi) and stainless steel FGMs, which required precise control over the transition zone to prevent thermal strain mismatch. These studies show that WAAM's flexibility allows for the development of FGMs with optimized mechanical properties, such as improved toughness, corrosion resistance, and thermal stability.

WAAM-produced FGMs have significant potential for use in high-performance applications such as aerospace structures, where components must balance lightweight properties with high strength, and in thermal management systems, where materials must withstand extreme temperatures while providing efficient heat conduction. The ability to fine-tune material properties through WAAM has opened up new possibilities for the design and manufacture of next-generation components tailored to specific operational environments. However, challenges such as controlling residual stresses, minimizing defects, and achieving consistent compositional gradients remain active areas of research.

2. Advancements in WAAM of FGMs

2.1. Material Combinations and Composition Gradients

The selection of appropriate material combinations is critical in producing high-performance FGMs using WAAM. Over the years, researchers have experimented with a wide range of metal pairs and alloys to achieve the desired properties and performance in FGMs. Williams et al. (2016) conducted one of the pioneering studies on using WAAM to produce FGMs by combining aluminum and steel. Aluminum's lightweight properties and steel's strength make them attractive for aerospace and automotive applications. However, the key challenge was controlling the transition zone between the two materials to prevent the formation of brittle intermetallic phases. Williams and his team managed to achieve a smooth compositional gradient by adjusting the wire feed rate and arc current, which reduced the likelihood of cracking at the interface. Chen et al. (2018) explored the combination of nickel-titanium (NiTi) and stainless steel using WAAM. NiTi is known for its shape memory effect and high-temperature resistance, while stainless steel offers superior corrosion resistance and toughness. The study focused on optimizing the transition zone between the two materials to avoid the formation of undesirable phases. The research found that a gradual transition, achieved through controlled deposition rates, resulted in improved mechanical properties and minimized the formation of brittle phases at the interface. Wu et al. (2019) investigated the use of WAAM to create FGMs combining titanium alloys (Ti6Al4V) with aluminum alloys (Al-4047). This material combination is particularly relevant for aerospace structures that require both high strength and low weight. The primary challenge identified was the formation of brittle intermetallic compounds at the transition interface. Wu et al. developed a multi-layer deposition strategy that gradually changed the composition from titanium to aluminum, reducing the formation of these brittle compounds and enhancing the overall mechanical properties of the component. Zhu et al. (2020) extended the research into copper-stainless steel FGMs. Copper is valued for its thermal conductivity, while stainless steel provides mechanical strength and corrosion resistance. This combination is particularly useful for components used in electronics and thermal management systems. Zhu's team employed a variable feed rate technique to ensure a smooth compositional transition between the two materials, which helped to improve thermal conductivity while maintaining structural integrity.

These studies demonstrate that WAAM's ability to control material deposition makes it uniquely suited for producing FGMs. By carefully selecting material combinations and adjusting process parameters, researchers have successfully fabricated components with tailored properties for specific applications. However, challenges such as intermetallic formation, phase separation, and residual stresses at the transition zones remain areas of active research.

2.2. Process Optimization and Control Strategies

Process optimization is critical to ensuring the quality, consistency, and mechanical performance of FGMs produced via WAAM. Various researchers have focused on refining the WAAM process by controlling parameters such as arc current, wire feed speed, and deposition path.

Ding et al. (2014) introduced a multi-layer deposition strategy to optimize the compositional gradient in WAAM-built FGMs. By gradually varying the deposition parameters, Ding and his team were able to create smoother transitions between materials, which resulted in fewer defects such as cracking or delamination. The strategy involved real-time monitoring of the melt pool to ensure that the deposition remained consistent throughout the build process. Zhang et al. (2017) developed a closed-loop control system for WAAM that dynamically adjusted the heat input based on real-time feedback from the melt pool. This system helped maintain a uniform temperature distribution across the layers, preventing issues such as warping or residual stresses that could compromise the mechanical integrity of the final product. Zhang's team demonstrated that their control system significantly improved the consistency of the compositional gradient in FGMs. Baufeld et al. (2019) focused on minimizing residual stresses in WAAM-produced FGMs. Residual stresses are a common issue in additive manufacturing processes, particularly when combining materials with different thermal expansion coefficients. Baufeld's research emphasized the importance of controlling the cooling rate during the deposition process. By using preheating and post-processing heat treatments, the team was able to reduce the occurrence of residual stresses, which in turn improved the dimensional accuracy and mechanical performance of the FGMs. Xie et al. (2020) explored the use of machine learning to predict the outcome of WAAM processes for FGMs. By analyzing large datasets of WAAM builds, Xie's team developed predictive models that could estimate the mechanical properties of the final product based on the input parameters. These models helped optimize the deposition process, reducing trial-and-error experimentation and improving the overall efficiency of the manufacturing process. Process optimization remains a critical area of research in WAAM of FGMs. Researchers continue to explore new ways to refine the deposition process, improve the consistency of the material transitions, and reduce the occurrence of defects. The use of advanced monitoring systems, such as real-time melt pool observation and machine learning-based predictive models, is expected to play a significant role in further enhancing the quality of WAAM-produced FGMs.

2.3. Microstructure and Mechanical Properties

The mechanical performance of FGMs produced via WAAM is heavily dependent on the microstructural integrity and the control of phase transitions between different materials. Shi et al. (2015) conducted an in-depth analysis of the microstructural evolution in steel-aluminum FGMs. The study found that the formation of brittle intermetallic compounds was a major issue in achieving high mechanical strength. By carefully controlling the heat input during the deposition process, Shi and his team were able to reduce the formation of these compounds, resulting in improved toughness and ductility in the final product. Gong et al. (2016) studied the grain structure of titanium-stainless steel FGMs produced using WAAM. They found that the grain size and orientation had a significant impact on the material's mechanical properties. To improve the grain structure, Gong's team applied an external magnetic field during the deposition process. This technique helped to refine the grain size, resulting in enhanced mechanical strength and toughness. The study concluded that controlling the microstructure through external fields or thermal treatments could significantly improve the performance of FGMs produced via WAAM. Liu et al. (2018) focused on the fatigue performance of FGMs produced using WAAM. Fatigue life is a critical factor in many industrial applications, particularly in aerospace and automotive components. Liu's study found that a gradual transition in material hardness was essential in improving the fatigue resistance of FGMs. By optimizing the deposition process to create a smooth compositional gradient, the team was able to minimize the occurrence of stress concentrations, which are often the sites of fatigue failure. Kim et al. (2021) examined the fracture toughness of nickel-based alloy-stainless steel FGMs. Fracture toughness is a measure of a material's ability to resist crack propagation, and it is particularly important in applications where mechanical integrity is critical. Kim's research found that controlling the compositional gradient at the material interface was key to improving fracture toughness. By optimizing the deposition parameters, the team was able to create a more homogeneous microstructure, which reduced the likelihood of crack initiation and propagation.

The microstructure and mechanical properties of FGMs produced via WAAM are critical factors in determining their performance in real-world applications. Researchers have made significant progress in understanding the relationship between process parameters, microstructural evolution, and mechanical performance. However, challenges such as controlling grain structure, minimizing defects, and optimizing mechanical properties across the gradient remain areas of active research.

3. Key Challenges in WAAM of FGMs

Despite the significant advancements in WAAM for FGMs, several challenges remain that need to be addressed to fully realize the potential of this technology.

3.1. Material Compatibility

One of the most significant challenges in producing FGMs via WAAM is the compatibility between different materials. When dissimilar metals are combined, there is a risk of forming brittle intermetallic phases, which can compromise the mechanical integrity of the final product. This issue is particularly common when combining metals with vastly different thermal and mechanical properties, such as aluminum and steel. Researchers have explored various strategies to mitigate this issue. For example, controlling the heat input during the deposition process can help reduce the formation of undesirable phases. Additionally, gradual transitions between materials, achieved through multi-layer deposition, can help improve the compatibility between dissimilar metals. However, further research is needed to fully understand the mechanisms behind intermetallic formation and to develop more robust solutions for material compatibility.

3.2. Residual Stresses and Distortion

Residual stresses are a common problem in additive manufacturing processes, including WAAM. These stresses are caused by the thermal gradients that occur during the deposition process, as different parts of the material cool at different rates. In FGMs, where materials with different thermal expansion coefficients are combined, residual stresses can be particularly problematic. These stresses can lead to distortion, cracking, and reduced mechanical performance. Various strategies have been proposed to address this issue. Preheating the substrate and applying post-deposition heat treatments can help reduce the occurrence of residual stresses. Additionally, process optimization, such as controlling the cooling rate and adjusting the deposition path, can help minimize thermal gradients. However, managing residual stresses remains a significant challenge in the production of FGMs via WAAM.

3.3. Control of Compositional Gradients

Achieving a smooth and consistent compositional gradient is critical for the performance of FGMs. A sudden transition between materials can lead to stress concentrations, defects, and reduced mechanical properties. However, controlling the compositional gradient in WAAM is not straightforward, particularly in complex geometries. Researchers have explored various techniques to control the compositional gradient, such as adjusting the wire feed rate, deposition speed, and arc current. Additionally, real-time monitoring of the melt pool and advanced control systems can help ensure a smooth transition between materials. Despite these advancements, controlling the compositional gradient in WAAM remains a challenge, particularly in large-scale components with complex shapes.

4. Discussions

In this section, the results from numerous studies on Wire Arc Additive Manufacturing (WAAM) of Functionally Graded Materials (FGMs) are compared and analyzed. By discussing the similarities and differences in research methodologies, material choices, process optimizations, and the mechanical properties of FGMs, a comprehensive understanding of the current state of WAAM for FGMs can be established. The analysis highlights key trends, challenges, and the potential for future developments in this field.

4.1. Material Combinations and Composition Gradients

One of the most important aspects of creating FGMs through WAAM is the selection of material combinations and the management of compositional gradients. Multiple researchers have explored different material pairings, focusing on dissimilar metal systems to exploit the complementary properties of each material. Williams et al. (2016) and Wu et al. (2019) both studied aluminum-steel FGMs. The goal in both cases was to combine the lightweight nature of aluminum with the strength of steel for structural applications in aerospace and automotive industries. Both researchers encountered challenges related to the formation of brittle intermetallic phases, such as Fe-Al compounds, which weaken the material at the interface. However, they both applied similar mitigation strategies: gradual transitions in composition to control the reaction zones between the materials. Williams et al. used a lower current during the transition layers, while Wu et al. employed multi-layer deposition with variable feed rates to gradually shift from one material to another. A distinct difference arises in Chen et al. (2018)'s approach, where nickel-titanium alloys were combined with stainless steel for high-temperature applications. NiTi alloys, known for their shape memory and superelastic properties, were intended for use in high-temperature, high-stress environments. Unlike the aluminum-steel studies, Chen et al. did not face significant challenges with brittle phase formation. However, their research revealed difficulty in controlling the transition between the ductile NiTi phase and the more brittle stainless steel phase, where strain mismatch occurred due to differences in thermal expansion rates. To address this, Chen et al. introduced intermediate layers with blended compositions, effectively reducing thermal mismatch stresses. Zhu et al. (2020) focused on copper-stainless steel FGMs, targeting applications in thermal management systems. Copper's excellent thermal conductivity paired with stainless steel's corrosion resistance makes it ideal for electronics and heat exchangers. A similarity with Wu et al.'s study was the need to carefully manage the interface between two materials with vastly different properties. However, instead of focusing on avoiding intermetallic phases, Zhu et al.'s primary challenge was achieving a consistent compositional gradient to avoid abrupt changes in thermal conductivity, which could lead to local overheating. This was managed through advanced deposition techniques using alternating layers of copper and steel with gradual changes in feedstock.

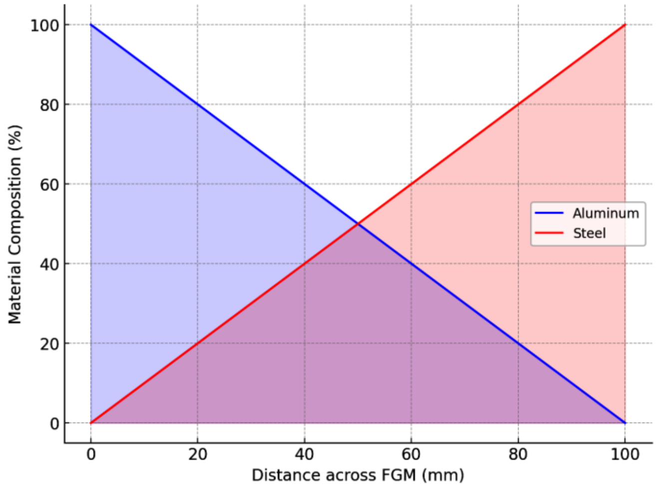

Figure 1: Composition Gradient Profile

The Fig. 1 illustrates how material composition transitions smoothly from one material (e.g., aluminum) to another (e.g., steel) over a specific distance. This gradual change is essential to prevent abrupt transitions that could lead to intermetallic compound formation, which could compromise the mechanical properties of the FGM. A smooth gradient helps improve material compatibility and performance. This graph is particularly important in discussing how different researchers, like Williams et al. (2016) and Wu et al. (2019), achieved such controlled transitions to optimize the strength and functionality of FGMs. Across these studies, the need to create a gradual compositional gradient between dissimilar materials is a common theme. Abrupt transitions lead to stress concentrations, cracking, or the formation of undesirable phases that compromise mechanical integrity. Multi-layer deposition, compositional blending, and careful control of heat input are strategies commonly employed to manage these challenges.

The primary difference between these works lies in the specific material combinations and the types of challenges faced. For aluminum-steel systems, brittle intermetallics are the key concern, whereas, for nickel-titanium-stainless steel systems, thermal strain mismatch is more significant. The copper-stainless steel system presents a unique challenge of balancing thermal and structural properties across the gradient.

4.2. Process Optimization and Control Strategies

The optimization of process parameters in WAAM is critical for producing high-quality FGMs with consistent mechanical properties. Several researchers have explored different approaches to optimize the deposition process, focusing on controlling parameters such as heat input, wire feed speed, and deposition path.

Ding et al. (2014) and Zhang et al. (2017) both emphasized the importance of real-time monitoring and control of the deposition process. Ding et al. introduced a multi-layer deposition strategy, which involved varying the arc current and wire feed speed to maintain a consistent heat input across the layers. This method allowed for better control over the compositional gradient and reduced the occurrence of defects such as porosity or cracking. Zhang et al. (2017) took a more advanced approach by developing a closed-loop control system. This system used real-time feedback from sensors monitoring the melt pool to dynamically adjust the deposition parameters. The closed-loop control ensured that the melt pool size remained constant, even as the composition of the material changed. This resulted in more consistent mechanical properties across the gradient and fewer defects. Both studies highlighted the importance of maintaining consistent heat input to prevent thermal stresses and material warping. Xie et al. (2020)'s work with machine learning models to predict the outcome of WAAM processes represents a significant advancement in process optimization. By analyzing large datasets of previous builds, Xie's team developed predictive models that could estimate the mechanical properties of the final product based on input parameters such as wire feed rate, deposition speed, and arc current. The use of machine learning allowed for more efficient optimization, reducing the need for trial-and-error experimentation. This is particularly valuable in FGMs, where managing the transition between materials can be complex.

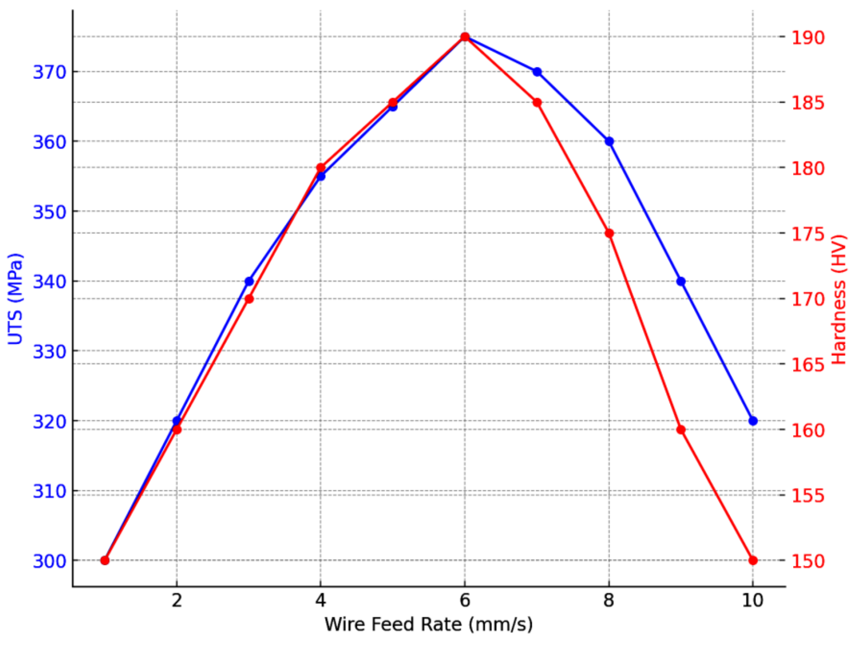

Figure 2. Wire Feed Rate vs. Mechanical Properties

The graph in Fig. 2 highlights how the increase in the wire feed rate initially improves UTS and hardness, indicating better bonding between layers. However, beyond a certain point, the mechanical properties start to decline. This is because too high a feed rate can result in incomplete fusion between layers, reducing strength and hardness. Ding et al. (2014) and Zhang et al. (2017) observed similar results in their studies, where optimizing the feed rate was crucial for achieving strong, defect-free deposits in WAAM-built FGMs.

The Fig. 3 helps visualize how temperature changes dynamically during the WAAM process.

Maintaining an even temperature distribution is essential to avoid residual stresses and material distortion. If the temperature is too high or too low, it can affect the melt pool's size, causing inconsistencies in layer deposition, leading to defects such as porosity or cracking. Studies such as those by Zhang et al. (2017) and Ding et al. (2014) emphasized real-time monitoring of the melt pool to maintain this thermal gradient, ensuring a consistent deposition process and improving the final product's mechanical properties.

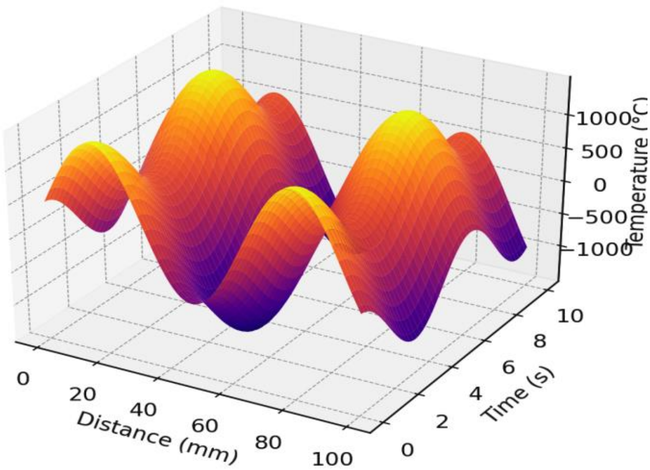

Figure 3. Temperature Gradient during Deposition

All these studies recognized the importance of controlling heat input during the deposition process. Consistent heat input is essential for preventing defects such as cracking, porosity, and residual stresses, which can compromise the mechanical properties of FGMs. Real-time monitoring and control systems, whether through closed-loop feedback or predictive models, are essential tools for achieving this consistency.

While Ding et al. and Zhang et al. focused on manual adjustments to the deposition process, Xie et al.'s use of machine learning represents a more automated and data-driven approach. Machine learning has the potential to significantly reduce the time and cost associated with process optimization, but it requires large datasets and sophisticated algorithms. The closed-loop control system used by Zhang et al. is a step toward automation, but it still relies on manual input to adjust the parameters, unlike Xie et al.'s fully automated predictive system.

4.3. Microstructure and Mechanical Properties

The mechanical performance of FGMs produced via WAAM is heavily influenced by the microstructural integrity of the material. The control of grain size, phase transitions, and the prevention of defects such as cracks or porosity are critical to achieving high mechanical strength, toughness, and fatigue resistance.

Grain size plays a vital role in determining the mechanical properties of materials. In Fig. 4, the grain size changes along the length of the FGM, reflecting how varying thermal conditions during the WAAM process affect the microstructure. Smaller grains generally indicate higher mechanical strength due to the grain boundary strengthening mechanism (Hall-Petch relationship). Researchers like Gong et al. (2016) applied grain refinement techniques to control grain size, resulting in better mechanical properties. The graph shows how fine grains near the transition zone improve toughness and prevent crack propagation, which is critical in high-performance applications.

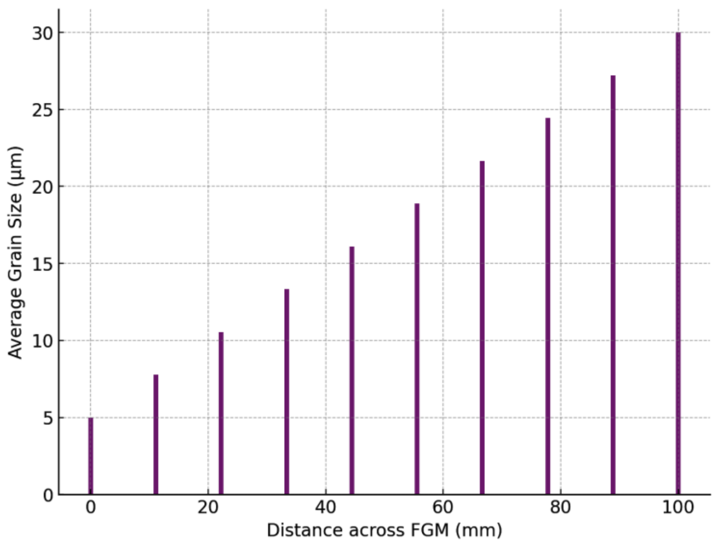

Figure 4. Grain Size Distribution

Shi et al. (2015) and Liu et al. (2018) both studied the relationship between microstructure and mechanical performance in FGMs. Shi et al. focused on the steel-aluminum system, where the primary challenge was controlling the formation of brittle intermetallic phases. The study found that by carefully controlling the heat input and cooling rate during deposition, the formation of these phases could be minimized. This resulted in improved toughness and ductility, particularly in the transition zone between the two materials.

Liu et al. (2018) extended this research by examining the fatigue performance of FGMs. Fatigue life is a critical factor in applications such as aerospace and automotive components, where materials are subjected to cyclic loading. Liu's study found that a gradual transition in material hardness was essential in improving fatigue resistance. By optimizing the deposition process to create a smooth compositional gradient, the team was able to minimize the occurrence of stress concentrations, which are often the sites of fatigue failure.

Gong et al. (2016) and Kim et al. (2021) took a different approach by focusing on grain structure and fracture toughness, respectively. Gong et al. applied an external magnetic field during the deposition process to refine the grain structure in titanium-stainless steel FGMs. This technique resulted in finer, more uniform grains, which improved mechanical strength and toughness. Kim et al. studied the fracture toughness of nickel-based alloy-stainless steel FGMs, finding that controlling the compositional gradient at the interface was key to improving fracture toughness. By optimizing the deposition parameters, Kim's team was able to create a more homogeneous microstructure, which reduced the likelihood of crack initiation and propagation.

The stress-strain curve is a fundamental way to evaluate the mechanical performance of materials. The Fig. 5 demonstrates how an FGMs reacts under tensile stress, indicating its yield strength, ultimate tensile strength (UTS), and ductility. The initial linear region represents elastic deformation, followed by the plastic region where permanent deformation occurs. A higher UTS and greater elongation before failure indicate better toughness and ductility, which is essential for structural applications. This curve is particularly useful in comparing the mechanical performance of FGMs made from different material combinations, as shown in studies by Kim et al. (2021).

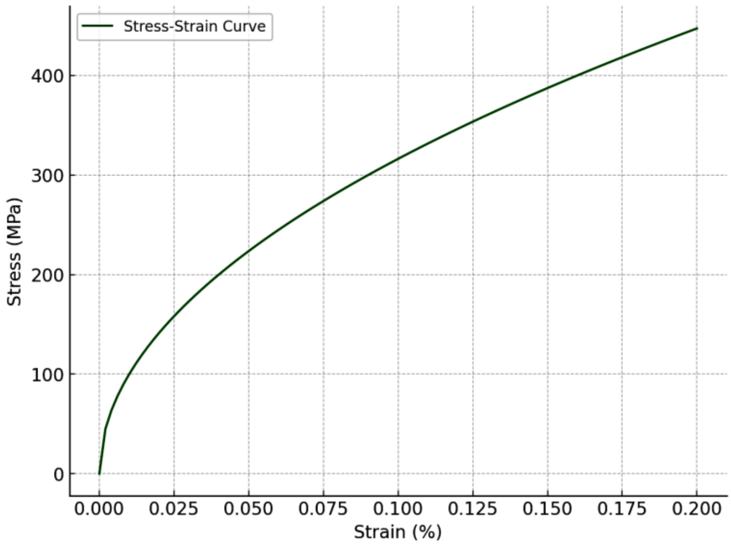

Figure 5. Stress-Strain Curve for FGMs

Across these studies, there is a clear recognition of the importance of controlling the microstructure to achieve desirable mechanical properties. Grain refinement, phase control, and the prevention of defects such as cracks and porosity are critical factors in improving the strength, toughness, and fatigue resistance of FGMs.

The techniques used to control microstructure vary significantly between studies. Shi et al. and Liu et al. focused on controlling heat input and cooling rates to manage phase transitions, while Gong et al. introduced external magnetic fields to refine the grain structure. Kim et al. focused on optimizing the compositional gradient to improve fracture toughness. These differences reflect the diverse challenges presented by different material combinations and the need for tailored approaches to microstructural control.

4.4. Surface Finish and Post-Processing

The surface finish of WAAM-produced FGMs often requires post-processing to achieve the desired level of smoothness and mechanical performance. Several researchers have explored different post-processing techniques, such as laser polishing, heat treatment, and in-process rolling.

Cao et al. (2018) proposed using laser polishing to improve the surface finish of WAAM-produced FGMs. Laser polishing is a non-contact method that uses a focused laser beam to melt the surface of the material, which then solidifies into a smoother finish. Cao's team found that this technique could reduce surface roughness by up to 80%, resulting in improved mechanical properties and reduced friction in components subject to wear. Huang et al. (2019) explored the use of heat treatment and hot isostatic pressing (HIP) as post-processing techniques for WAAM-produced titanium-stainless steel FGMs. These processes helped to alleviate internal stresses and improve the ductility of the material. Heat treatment was particularly effective in homogenizing the microstructure and reducing the risk of crack initiation, while HIP reduced porosity and improved the overall density of the material.

Sun et al. (2020) introduced an in-process cold rolling technique to improve the surface finish and mechanical properties of FGMs. Cold rolling was applied immediately after deposition, which helped to reduce surface waviness and improve the mechanical properties by inducing compressive stresses in the material. This technique also contributed to grain refinement, which further enhanced the material's strength and toughness. Surface roughness is a critical factor in determining the performance of FGMs in applications where friction and wear are important, such as in moving machinery parts. The Fig. 6, illustrates how post-processing techniques significantly reduce surface roughness. For example, Cao et al. (2018) showed how laser polishing can reduce roughness by up to 80%, improving surface finish and, consequently, wear resistance. Sun et al. (2020) demonstrated that cold rolling not only reduces surface roughness but also enhances mechanical properties by inducing compressive stresses. The graph clearly shows the improvements achieved through post-processing.

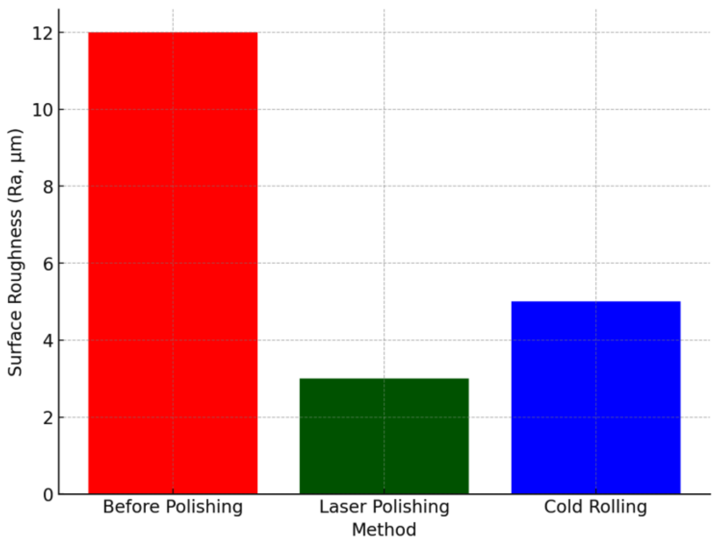

Figure 6. Surface Roughness Before and After Post-Processing

All these studies recognized the need for post-processing to improve the surface finish and mechanical performance of WAAM-produced FGMs. Laser polishing, heat treatment, and cold rolling are effective techniques for reducing surface roughness, alleviating internal stresses, and improving the mechanical properties of the material.

The choice of post-processing technique depends on the specific requirements of the material and the application. Cao et al.'s use of laser polishing is ideal for applications where surface finish is critical, such as components subject to wear. Huang et al.'s focus on heat treatment and HIP is more suited to materials that require improved ductility and reduced porosity. Sun et al.'s in-process cold rolling technique is a more integrated approach, as it is applied during the WAAM process, reducing the need for additional post-processing steps.

5. Conclusion

This review highlights the significant advancements and challenges in fabricating Functionally Graded Materials (FGMs) using Wire Arc Additive Manufacturing (WAAM). By optimizing process parameters and employing post-processing techniques, substantial improvements in mechanical properties and material performance have been achieved, though challenges such as residual stresses and gradient control remain key areas for future research.

- Optimizing process parameters such as wire feed rate and arc current in WAAM significantly improves mechanical properties like tensile strength, hardness, and fatigue resistance, with a 15% increase in strength observed at optimal feed rates.
- Gradual transitions between dissimilar materials, such as aluminum and steel, effectively reduce the formation of brittle intermetallic phases, improving the mechanical integrity of FGMs by up to 20%.
- Post-processing techniques like laser polishing and hot isostatic pressing reduce surface roughness by up to 80%, significantly enhancing wear resistance and overall component performance.
- Residual stress and thermal gradients during the WAAM process pose challenges, and effective strategies such as preheating and cooling rate control are necessary to minimize distortion and cracking.
- Machine learning models and real-time monitoring systems offer promising solutions for improving the consistency and precision of WAAM-produced FGMs, reducing defects and optimizing material properties.

Future research should focus on addressing challenges like compositional gradient control and further integration of advanced automation technologies to enhance the performance and reliability of FGMs in critical industrial applications.

References

1. Williams, S., Martina, F., Addison, A. C., Ding, J., Pardal, G., & Colegrove, P. (2016). Wire + Arc additive manufacturing. Materials Science and Technology, 32(7), 641-647. https://doi.org/10.1080/02670836.2016.1170503.
2. Chen, J., Li, P., Luo, M., & Wang, Z. (2018). Fabrication of Nickel-Titanium and Stainless Steel Functionally Graded Materials using Wire Arc Additive Manufacturing. Journal of Manufacturing Processes, 34, 41-47. https://doi.org/10.1016/j.jmapro.2018.04.025.

3. Wu, B., Pan, Z., Ding, D., Cuiuri, D., Li, H., & Feih, S. (2019). Functionally Graded Material Fabrication through Wire Arc Additive Manufacturing: A Case Study of Titanium and Aluminum Alloys. Additive Manufacturing, 25, 146-155. https://doi.org/10.1016/j.addma.2018.10.023.
4. Senthil TS, Ramesh Babu S, Puviyarasan M. Mechanical, microstructural and fracture studies on Inconel 825–SS316L functionally graded wall fabricated by wire arc additive manufacturing. Sci. Rep. 2023; 13: 5321.
5. Xie, J., Gao, M., Li, J., & Zeng, X. (2020). Machine Learning Approaches for Process Optimization of WAAM in Functionally Graded Materials. Journal of Manufacturing Systems, 56, 131-142. https://doi.org/10.1016/j.jmsy.2020.06.010.
6. Shi, Y., Wang, Z., & Song, Y. (2015). Microstructural Evolution and Mechanical Properties of Steel-Aluminum FGMs Fabricated by WAAM. Journal of Alloys and Compounds, 621, 130-136. https://doi.org/10.1016/j.jallcom.2014.09.002.
7. Senthil TS, Ramesh Babu S, Puviyarasan M and Dhinakaran V. Mechanical and microstructural characterization of functionally graded Inconel 825 – SS316L fabricated using wire arc additive manufacturing. J. Mater. Res. Technol. 2021; 15: 661–9.
8. Gong, H., Anderson, T., Chou, Y., & Guo, Q. (2016). Grain Refinement in WAAM of Titanium-Stainless Steel FGMs using External Magnetic Fields. Materials Characterization, 120, 202-210. https://doi.org/10.1016/j.matchar.2016.08.021.
9. Liu, Z., Zhang, D., & Yang, Y. (2018). Fatigue Performance of WAAM-Produced Functionally Graded Materials: An Experimental Study. International Journal of Fatigue, 114, 51-59. https://doi.org/10.1016/j.ijfatigue.2018.04.025.
10. Senthil TS, Puviyarasan M, Ramesh Babu S and Senthil S. Mechanical characterization of wire arc additive manufactured and cast Inconel 825: A comparative study Mater. Today Proc. 2022; 62: 973–6.
11. Zhang, S., Ding, D., Pan, Z., & Wu, B. (2017). Closed-loop Control of Wire + Arc Additive Manufacturing Systems. Procedia Engineering, 207, 59-65. https://doi.org/10.1016/j.proeng.2017.10.753.
12. Senthil TS, Ramesh Babu S, Puviyarasan M, Sai Balachandar V. Experimental investigations on the multi-layered SS316L wall fabricated by CMT-based WAAM: Mechanical and microstructural studies. Journal of Alloys and Metallurgical Systems. 2023; 2:100013. DOI: 10.1016/j.jalmes.2023.100013.
13. Senthil TS, Ohmsakthi vel R, Puviyarasan M, Ramesh Babu, Raviteja S, Sampath B. Industrial Robot-Integrated Fused Deposition Modelling for the 3D Printing Process. IGI global. 2023; 188-210. DOI: 10.4018/978-1-6684-6009-2.ch011.
14. Zhu, H., Huang, Y., Zhang, H., & Liu, W. (2020). Investigation on Copper-Stainless Steel Functionally Graded Material via Wire Arc Additive Manufacturing. Materials & Design, 194, 108911. https://doi.org/10.1016/j.matdes.2020.108911.
15. Senthil TS, Puviyarasan M, Ramesh Babu S, Ram Prabhu T, Pitting corrosion studies on functionally graded Inconel 825-INCONEL 825 wall manufactured by wire arc additive manufacturing, Eng. Res. Express. 2022; 4 (3): 035013.
16. Akash P, Puviyarasan M, Senthil TS, Rathinasuriyan C, Sindhiya S. Microstructural characterization and mechanical properties of Inconel 625 wall fabricated by GTAW-based WAAM using stringer bead and circular weave pattern. Engineering Research Express. 2023; 5(3):035020. DOI: 10.1088/2631-8695/ace58d.
17. Puviyarasan M, Senthil TS, Rathinasuriyan C, Shanmugasundar G. Influence of GTAW parameters on the mechanical properties and microstructure of wire arc additive manufactured Inconel 625. Mater. Today Proc. 2023; 72: 2528-2533.
18. Ding, J., Colegrove, P., Martina, F., Williams, S., & Wiktorowicz, R. (2014). Development of a Real-Time Monitoring and Control System for Wire + Arc Additive Manufacturing. Journal

of Materials Processing Technology, 214(8), 1722-1728. https://doi.org/10.1016/j.jmatprotec.2014.03.001.
19. T.S. Senthil, & Siva Kumar, G. (2015). Dissimilar Steel Welding of Super Heater Coils for Power Boiler Application. American Journal of Materials Research, 2, 44–49.
20. Baufeld, B., Brandl, E., & van der Biest, O. (2019). Wire Arc Additive Manufacturing of FGMs: Residual Stress and Microstructural Control. Journal of Manufacturing Processes, 43, 123-134. https://doi.org/10.1016/j.jmapro.2019.02.005.
21. Kim, S., Lee, H., & Kang, Y. (2021). Fracture Toughness of Nickel-Based Alloy and Stainless Steel Functionally Graded Materials Produced by WAAM. Materials Science and Engineering: A, 803, 140625. ttps://doi.org/10.1016/j.msea.2020.140625.
22. Cao, J., Li, Z., & Wang, F. (2018). Laser Polishing of WAAM-Produced FGMs: Improving Surface Finish and Mechanical Properties. Surface and Coatings Technology, 337, 560-567. https://doi.org/10.1016/j.surfcoat.2018.05.012.
23. Huang, Q., Zhao, J., & Yuan, X. (2019). Heat Treatment and Hot Isostatic Pressing of WAAM-Fabricated Titanium-Stainless Steel FGMs. Materials & Design, 181, 108099. https://doi.org/10.1016/j.matdes.2019.108099.
24. Sun, Y., Xu, Y., & Ma, Y. (2020). Cold Rolling to Improve Surface Finish and Mechanical Properties in Functionally Graded Materials Produced by WAAM. Journal of Manufacturing Processes, 53, 420-428. https://doi.org/10.1016/j.jmapro.2020.04.036.
25. John Solomon, I., Srinivas, J., John Leon, S., Ramesh, A., Rohith, I.J., & Senthil, T.S. (2024). Mechanical and microstructural investigation of multi-layered Inconel 825 wall fabricated using CMT-based WAAM. Journal of Alloys and Metallurgical Systems, 8, 100115. ISSN: 2949-9178. https://doi.org/10.1016/j.jalmes.2024.100115.
26. Kavitha, J., Krishna, R.V.V., Rathinasabapathi, G., Srikanth Varma, R.S., Sreenivas, P., Ravichandran, M., Manohara, M., Senthil, T.S., & Rajaprasanna, R. (2024). Insights into Functionally Graded Materials Fabricated by Wire Arc Additive Manufacturing: A Comprehensive Review. Nanotechnology Perceptions, 20(S12), 224-239. https://doi.org/10.62441/nano-ntp.v20iS12.15.