RESEARCH ARTICLE OPEN ACCESS

Microstructural Analysis and Defect Characterization of WAAM-Fabricated Nitinol Shape Memory Alloy

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Abstract:

Wire Arc Additive Manufacturing (WAAM) has emerged as a promising metal additive manufacturing technique for fabricating large-scale components with high deposition rates and reduced material waste. However, processing shape memory alloys such as Nitinol using WAAM presents significant challenges due to their sensitivity to thermal cycling, composition variation, and defect formation. In this study, a detailed experimental investigation is carried out to analyze the microstructural characteristics and defect mechanisms in WAAM-fabricated Nitinol components. The influence of process parameters on porosity, cracking, and grain morphology is examined using stereo microscopy, optical microscopy, and scanning electron microscopy. Phase analysis is conducted using X-ray diffraction, while mechanical behavior is evaluated through hardness and tensile testing before and after heat treatment. The results reveal a strong correlation between heat input, microstructural evolution, and defect distribution. The findings provide valuable insights into process stability and quality challenges in WAAM of Nitinol and contribute toward establishing a reliable processing window for advanced aerospace and actuator applications.

Keywords — **Wire Arc Additive Manufacturing, Nitinol Shape Memory Alloy, Microstructure, Defect Analysis, Additive Manufacturing.**

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I. INTRODUCTION

Additive manufacturing (AM) technologies have transformed the production of complex metallic components by enabling near-net-shape fabrication with reduced material waste and enhanced design flexibility. Among various metal AM techniques, Wire Arc Additive Manufacturing (WAAM) has gained significant attention for its capability to fabricate large structural parts with high deposition rates and comparatively lower operational costs [1], [2]. WAAM employs an electric arc as a heat source and metal wire as feedstock, making it particularly suitable for aerospace, marine, and tooling applications.

Shape memory alloys (SMAs), especially near-equiatomic nickel–titanium (Nitinol), exhibit unique properties such as shape memory effect and superelasticity, which make them highly attractive for actuators, biomedical devices, and adaptive aerospace structures [3], [4]. Despite these advantages, processing Nitinol using conventional and additive manufacturing routes remains challenging. The material is highly sensitive to compositional changes, thermal gradients, and repeated thermal cycling, all of which can significantly influence its phase transformation behavior and mechanical performance [5].

When fabricated using WAAM, Nitinol components are subjected to complex thermal histories due to layer-by-layer deposition and high heat input. These conditions often result in microstructural heterogeneity, porosity, solidification cracks, and elemental segregation [6]. Such defects can adversely affect both functional and mechanical properties, limiting the applicability of WAAM-fabricated Nitinol components in critical applications. Therefore, understanding the relationship between WAAM process parameters, microstructural evolution, and defect formation is essential for improving process reliability.

Previous studies on WAAM of titanium- and nickel-based alloys have reported that heat input and interpass thermal conditions play a crucial role in determining grain morphology and defect density [7], [8]. However, limited experimental work has focused specifically on Nitinol fabricated through WAAM, particularly with respect to detailed defect characterization and microstructural analysis using multiple microscopy techniques. Most existing studies emphasize process feasibility rather than systematic evaluation of quality challenges.

The objective of this study is to experimentally investigate the microstructural characteristics and defect mechanisms in WAAM-fabricated Nitinol shape memory alloy components. Stereo microscopy, optical microscopy, and scanning electron microscopy are employed to examine porosity, cracking, and grain structure, while X-ray diffraction is used to analyze phase constitution. Mechanical properties are evaluated through hardness and tensile testing to establish correlations with observed microstructural features. The outcomes of this work aim to contribute toward developing a stable WAAM process window for Nitinol and provide a foundation for future optimization and intelligent manufacturing strategies.

II. LITERATURE REVIEW

Wire Arc Additive Manufacturing (WAAM) has emerged as a high-deposition-rate metal additive manufacturing technique capable of producing large-scale components with reduced material waste and improved buy-to-fly ratios. Compared to powder-based additive manufacturing processes, WAAM offers advantages in terms of deposition efficiency, cost-effectiveness, and suitability for structural applications [1], [2]. As a result, WAAM has been extensively investigated for materials such as titanium alloys, aluminum alloys, and steels, particularly for aerospace and marine applications.

Several studies have reported that WAAM-fabricated components exhibit columnar grain structures due to high thermal gradients and directional solidification during layer-by-layer deposition [3]. The repeated thermal cycling inherent in WAAM processes has been shown to significantly influence microstructural evolution, residual stress development, and mechanical properties [4]. Process parameters such as welding current, wire feed rate, travel speed, and heat input play a critical role in determining deposition stability and part quality [5].

Nitinol (NiTi), a near-equiatomic nickel–titanium shape memory alloy, is widely valued for its shape memory effect and superelastic behavior. These functional properties arise from reversible martensitic phase transformations, which are highly sensitive to composition, microstructure, and thermal history [6], [7]. Conventional manufacturing of Nitinol is challenging due to its poor machinability, work hardening behavior, and sensitivity to contamination and composition changes. Consequently, additive manufacturing has been explored as an alternative route for fabricating complex Nitinol components.

Powder-based additive manufacturing techniques such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM) have been widely studied for Nitinol fabrication. Researchers have reported that rapid solidification in these processes can refine grain structure but may also introduce porosity, compositional inhomogeneity, and residual stresses [8], [9]. Maintaining precise Ni/Ti ratios during processing remains a major challenge, as even small deviations can significantly alter transformation temperatures and functional performance.

In contrast, limited studies have investigated the application of WAAM to Nitinol fabrication. Arc-based additive manufacturing introduces higher heat input and slower cooling rates compared to laser-based processes, which can exacerbate issues such as elemental segregation, solidification cracking, and coarse grain formation [10]. Experimental investigations have reported the presence of porosity and microcracks in arc-deposited Nitinol components, often attributed to unstable arc conditions, improper shielding, and thermal stress accumulation [11].

Microstructural characterization techniques play a crucial role in understanding defect formation and material behavior in WAAM-fabricated alloys. Stereo microscopy has been widely used for identifying macroscopic defects such as surface porosity and cracks, while optical microscopy provides insight into grain morphology and solidification patterns [12]. Scanning electron microscopy (SEM), combined with energy-dispersive spectroscopy, enables detailed examination of microstructural features and elemental distribution. Additionally, X-ray diffraction (XRD) is commonly employed to identify phase constitution and confirm the presence of austenite and martensite phases in Nitinol alloys [13].

Despite existing research, there remains a lack of comprehensive experimental studies that systematically correlate WAAM process parameters with defect formation, microstructural evolution, and mechanical behavior in Nitinol shape memory alloys. Most reported works focus on process feasibility rather than detailed quality assessment. This gap highlights the need for integrated microstructural and defect analysis using multiple characterization techniques, which forms the basis of the present study.

III. EXPERIMENTAL METHODOLOGY

This study adopts an experimental approach to investigate the microstructural characteristics and defect formation in Wire Arc Additive Manufacturing (WAAM) of Nitinol shape memory alloy. The experimental methodology encompasses material selection, WAAM deposition setup, process parameter selection, sample preparation, and characterization techniques used for microstructural and mechanical evaluation.

i. Material Selection

Near-equiatomic nickel–titanium (NiTi) shape memory alloy wire was selected as the feedstock material for the WAAM process due to its well-known shape memory and superelastic properties. The wire composition was chosen to closely match equiatomic NiTi in order to promote the formation of austenite and martensite phases essential for functional behavior. A commercially available titanium-based substrate plate was used as the base material to ensure metallurgical compatibility and adequate bonding during deposition.

ii. WAAM Deposition Setup

The WAAM process was carried out using a robotic arc welding system equipped with a tungsten inert gas (TIG) welding torch. A multi-axis robotic manipulator was employed to achieve controlled and repeatable deposition paths. The welding torch was mounted on the robotic arm, while the wire feed system delivered the Nitinol wire at a constant rate. High-purity argon shielding gas was used to minimize oxidation and contamination during deposition.

The deposition was performed in a controlled laboratory environment. Interpass cooling time was maintained between successive layers to limit excessive heat accumulation and reduce thermal distortion. The layer-by-layer deposition strategy enabled the fabrication of vertically built wall structures suitable for subsequent microstructural and mechanical analysis.

iii. Process Parameter Selection

Process parameters were selected based on preliminary trials and prior experimental experience to achieve stable arc conditions and continuous bead formation. Key parameters included welding current, arc voltage, wire feed rate, and travel speed. These parameters directly influenced heat input, bead geometry, and solidification behavior.

Multiple parameter combinations were explored to assess their effect on defect formation and microstructural evolution. Heat input variations were intentionally introduced to study their influence on porosity, cracking tendency, and grain morphology. The selected parameter window ensured adequate fusion between layers while avoiding excessive melt pool instability.

iv. Sample Preparation

After deposition, WAAM-fabricated samples were sectioned from the built walls using electrical discharge machining (EDM) to avoid introducing additional mechanical deformation or thermal damage. The specimens were prepared for metallographic examination through standard grinding and polishing procedures. Final polishing was carried out using fine diamond suspensions to obtain mirror-like surfaces suitable for microscopic analysis.

For selected samples, post-deposition heat treatment was performed to study its effect on microstructure and mechanical properties. Heat-treated and as-deposited samples were analyzed comparatively to evaluate the influence of thermal processing.

v. Microstructural Characterization

Stereo microscopy was initially employed to examine surface morphology and identify macroscopic defects such as porosity, lack of fusion, and surface cracks. Optical microscopy was subsequently used to analyze grain structure, grain size variation, and solidification patterns across different layers. Grain size measurements were conducted following ASTM E112 standards.

Scanning electron microscopy (SEM) was utilized for detailed microstructural examination, including defect morphology and phase distribution. X-ray diffraction (XRD) analysis was carried out to identify phase constituents and confirm the presence of austenite and martensite phases in the fabricated Nitinol samples.

vi. Mechanical Characterization

Mechanical behavior was evaluated through microhardness testing and tensile testing. Hardness measurements were performed at multiple locations across the deposited layers to assess spatial variations in mechanical properties. Tensile specimens were extracted from the deposited structures, and tests were conducted to evaluate ultimate tensile strength and elongation. Mechanical test results were correlated with observed microstructural features and defect distribution.

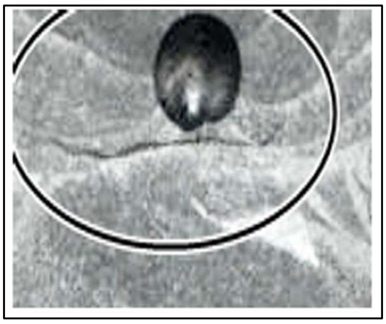
IV. DEFECT ANALYSIS USING STEREO MICROSCOPY

Stereo microscopy was employed as a preliminary characterization technique to examine surface morphology and identify macroscopic defects in WAAM-fabricated Nitinol samples. Owing to its ability to provide three-dimensional surface visualization at low magnification, stereo microscopy is particularly effective for detecting surface-connected defects such as porosity, lack of fusion, and solidification cracks prior to detailed microstructural analysis [17].

i. Surface Porosity

Surface porosity was observed in several deposited layers, with defect density varying across different process parameter combinations. The porosity appeared predominantly as rounded or irregular cavities distributed along the bead surface and interlayer regions. Such defects are commonly associated with unstable arc behavior, improper shielding gas coverage, and gas entrapment during solidification.

At higher heat input conditions, increased melt pool turbulence was observed, which promoted gas entrapment and pore coalescence. In contrast, samples deposited at optimized heat input exhibited relatively smoother surfaces with reduced porosity levels. These observations suggest that heat input plays a critical role in controlling melt pool stability and porosity formation.

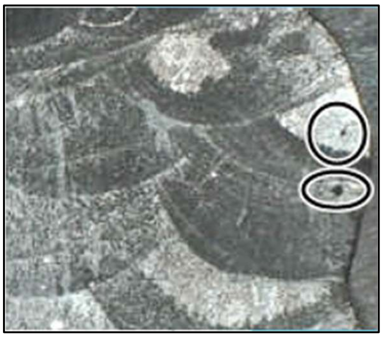


(Fig. 1: Stereo microscope image showing surface porosity in WAAM-fabricated Nitinol sample at higher heat input.)

ii. Solidification Cracking

Stereo microscopy also revealed the presence of surface cracks in selected regions of the deposited structures. These cracks were primarily oriented along the deposition direction and were more prominent near interlayer boundaries. The formation of such cracks can be attributed to high thermal gradients and residual stresses induced during rapid heating and cooling cycles inherent in the WAAM process.

Nitinol's sensitivity to compositional variation and thermal stress further exacerbates crack formation, particularly when heat dissipation is non-uniform. The observed cracking behavior is consistent with reported findings in arc-based additive manufacturing of nickel-based alloys, where solidification cracking is often linked to tensile stresses exceeding local material strength during cooling [18].



(Fig. 2: Stereo microscope image illustrating surface crack formation along the deposition direction.)

iii. Lack of Fusion and Interlayer Defects

In certain samples, lack of fusion defects were identified at interlayer interfaces. These defects manifested as discontinuities or unbonded regions between successive layers, indicating insufficient energy input or improper overlap during deposition. Lack of fusion defects are particularly detrimental as they act as stress concentrators and can significantly degrade mechanical performance.

The occurrence of interlayer defects highlights the importance of maintaining consistent process parameters and appropriate interpass temperature control. Stereo microscopy provided a rapid and effective means of identifying such defects prior to more detailed microstructural examination.

(Fig. 3: Stereo microscope image showing lack of fusion defect at interlayer interface.)

iv. Summary of Defect Observations

Based on stereo microscopic analysis, the dominant defects observed in WAAM-fabricated Nitinol samples include surface porosity, solidification cracks, and lack of fusion between layers. The frequency and severity of these defects were strongly influenced by heat input and deposition stability. While optimized process conditions reduced defect density, complete elimination of defects remains challenging due to the inherent thermal complexity of WAAM processing.

The findings from stereo microscopy serve as a foundation for subsequent optical and scanning electron microscopy analysis, enabling correlation between macroscopic defects and underlying microstructural features.

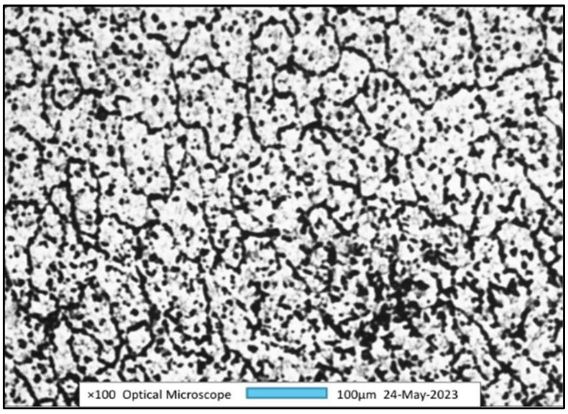
V. MICROSTRUCTURAL CHARACTERIZATION

Microstructural characterization was carried out to examine grain morphology, phase distribution, and microstructural heterogeneity in WAAM-fabricated Nitinol samples. Optical microscopy and scanning electron microscopy (SEM) were employed to analyze both as-deposited and heat-treated specimens. These techniques enabled correlation between process-induced thermal history and resulting microstructural features.

i. Optical Microscopy Analysis

Optical microscopy was used to study the general grain structure and solidification behavior across different layers of the deposited samples. The micrographs revealed a predominantly columnar grain morphology aligned along the build direction, which is characteristic of arc-based additive manufacturing processes. This grain orientation can be attributed to the strong directional heat flow from the molten pool toward the substrate during solidification.

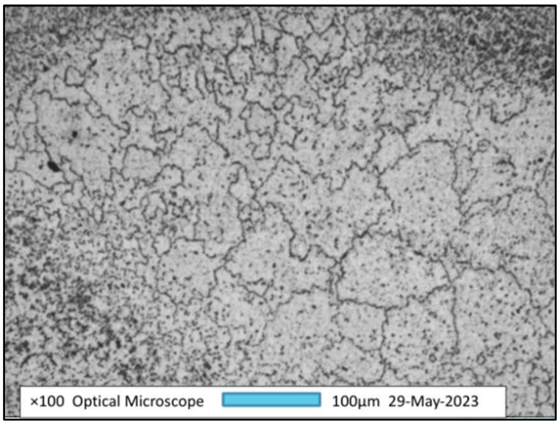
In the as-deposited condition, elongated grains extending across multiple layers were observed, indicating epitaxial grain growth driven by repeated thermal cycling. The grain size varied locally, with coarser grains appearing in regions subjected to higher heat input. Such variation highlights the influence of process parameters and interpass thermal conditions on microstructural evolution.



(Fig. 4: Optical micrograph showing columnar grain structure in as-deposited WAAM-fabricated Nitinol sample.)

Grain size measurements were conducted in accordance with ASTM E112 standards. The results indicate non-uniform grain distribution across the build height, with finer grains near the substrate and coarser grains toward the top layers. This trend is consistent with the progressive accumulation of heat during deposition, leading to reduced cooling rates in upper layers.

For heat-treated samples, optical micrographs showed partial grain refinement and improved microstructural homogeneity. Heat treatment promoted stress relief and reduced microstructural anisotropy, suggesting its potential role in enhancing material performance.

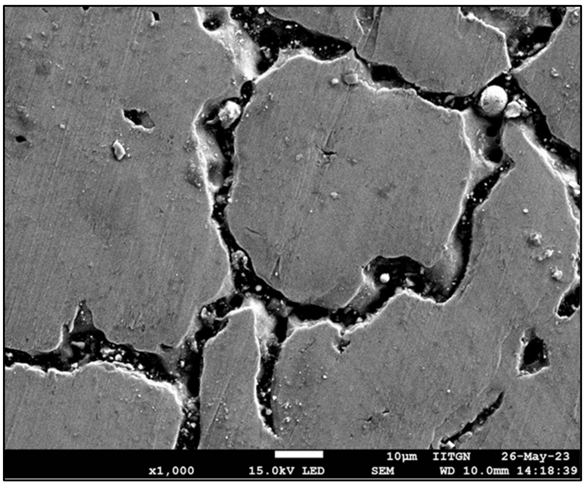


(Fig. 5: Optical micrograph comparing grain structure after heat treatment.)

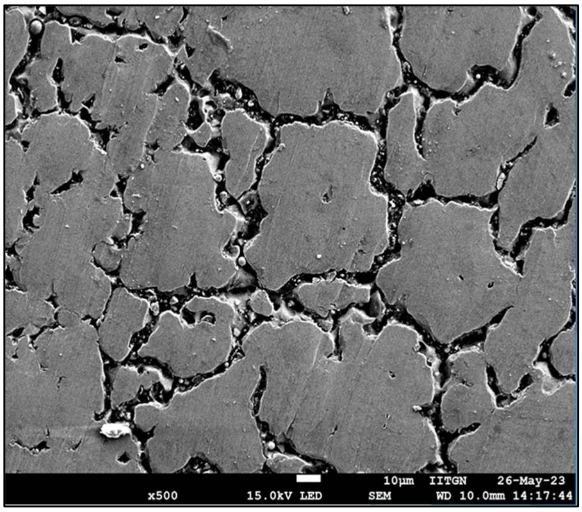
ii. Scanning Electron Microscopy (SEM) Analysis

Scanning electron microscopy was employed to examine microstructural features at higher magnification and to investigate defect morphology not clearly resolved by optical microscopy. SEM images revealed the presence of microvoids and fine porosity distributed within the deposited material. These features were more pronounced in samples fabricated under higher heat input conditions, where prolonged melt pool residence time facilitated gas entrapment.

SEM observations also highlighted microstructural heterogeneity near interlayer boundaries, where repeated thermal cycling influenced local solidification patterns. In some regions, microcracks were observed propagating along grain boundaries, indicating the role of thermal stresses and compositional sensitivity of Nitinol during solidification.



(Fig. 6: SEM image showing microvoids and porosity in WAAM-fabricated Nitinol.)



(Fig. 7: SEM image illustrating interlayer microstructural variation and crack initiation.)

The SEM analysis confirms that microstructural defects identified at the macroscopic level using stereo microscopy are closely linked to underlying microstructural features. These observations emphasize the importance of controlling heat input and deposition stability to minimize defect formation and achieve uniform microstructure.

iii. Microstructural Implications

The combined optical and SEM analyses demonstrate that WAAM-fabricated Nitinol exhibits strong microstructural anisotropy resulting from directional solidification and thermal cycling. While columnar grain growth enhances build continuity, it may also contribute to anisotropic mechanical behavior. The presence of microvoids and grain boundary cracks further underscores the need for optimized process control and post-deposition heat treatment.

The insights gained from microstructural characterization provide a critical foundation for understanding mechanical performance and defect sensitivity, which are discussed in subsequent sections.

VI. Mechanical Characterization

Mechanical characterization was carried out to evaluate the influence of WAAM processing conditions and microstructural features on the mechanical behavior of Nitinol samples. Microhardness testing and tensile testing were performed on both as-deposited and heat-treated specimens to establish correlations between mechanical properties, defect distribution, and microstructural evolution.

i. Microhardness Analysis

Microhardness measurements were conducted across the deposited layers to assess local variations in mechanical properties resulting from thermal cycling and microstructural heterogeneity. Indentations were placed at regular intervals along the build height to capture spatial variations in hardness.

The as-deposited samples exhibited noticeable hardness variation across different regions. Higher hardness values were generally observed near the substrate and lower layers, which can be attributed to relatively finer grain structures and faster cooling rates in these regions. In contrast, upper layers showed slightly reduced hardness, corresponding to coarser grain structures formed under prolonged thermal exposure.

Sample ID	HRC
1	45
2	44
3	43
4	46
5	47
6	45
7	45
8	46
9	46
10	45

(Fig. 8: Microhardness distribution along build height for as-deposited WAAM-fabricated Nitinol.)

Post-deposition heat treatment resulted in a more uniform hardness distribution across the samples. The reduction in hardness gradients suggests stress relaxation and microstructural homogenization during heat treatment. This behavior is consistent with the observed grain refinement and reduced microstructural anisotropy identified in optical and SEM analyses.

Sample ID	HRC (BH)	HRC (AH)
1	45	49
2	44	50
3	43	49
4	46	50
5	47	48
6	45	50
7	45	50
8	46	50
9	46	49
10	45	50

BH = Before Heat Treatment AH = After Heat Treatment

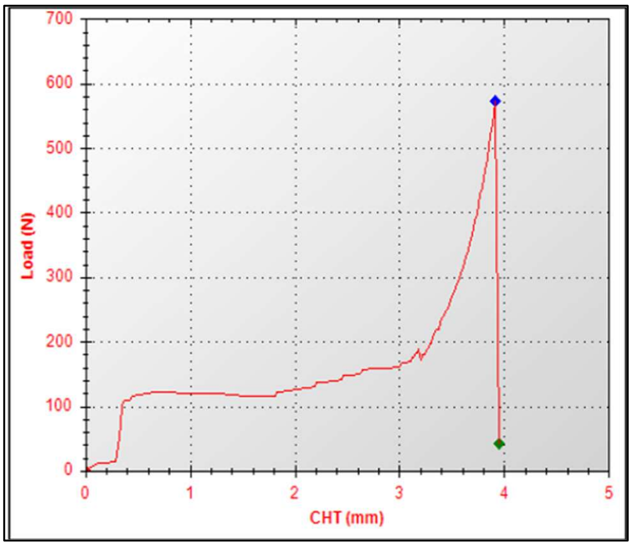
(Fig. 9: Comparison of microhardness profiles before and after heat treatment.)

ii. Tensile Testing

Tensile testing was performed to evaluate the macroscopic mechanical performance of WAAM-fabricated Nitinol samples. Specimens were extracted from the deposited structures using EDM to preserve microstructural integrity. The tests were conducted under quasi-static loading conditions to determine ultimate tensile strength and elongation.

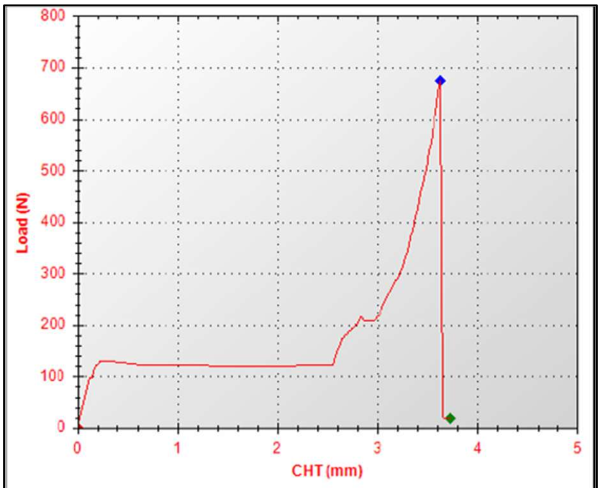
The as-deposited samples demonstrated moderate tensile strength with limited ductility, which can be attributed to the presence of porosity, microcracks, and columnar grain structures aligned along the build direction. These defects act as stress concentrators and contribute to early fracture initiation during tensile loading.

UTS = 44 N/mm^2



(Fig. 10: Engineering stress–strain curve for as-deposited WAAM-fabricated Nitinol sample.)

Heat-treated samples exhibited improved tensile behavior, characterized by increased elongation and slightly enhanced tensile strength. The improvement in ductility is primarily associated with reduced residual stresses and more homogeneous microstructure following heat treatment. These results indicate that post-deposition thermal processing plays a crucial role in enhancing the mechanical performance of WAAM-fabricated Nitinol.



Case 1 UTS 51 N/mm^2

(Fig. 11: Comparison of stress–strain curves for heat-treated samples.)

iii. Correlation Between Microstructure and Mechanical Properties

The mechanical characterization results demonstrate a strong correlation between microstructural features and mechanical behavior. Regions exhibiting coarse grains and higher defect density correspond to reduced hardness and tensile performance. Conversely, heat-treated samples with refined and homogenized microstructures show improved mechanical consistency.

The combined hardness and tensile data confirm that controlling WAAM process parameters and implementing appropriate post-processing treatments are essential for achieving reliable mechanical properties in Nitinol components. These findings complement the microstructural observations discussed in earlier sections and provide quantitative evidence of process–structure–property relationships in WAAM-fabricated Nitinol.

VII. Results and Discussion

The experimental results obtained from stereo microscopy, optical microscopy, SEM analysis, and mechanical testing collectively demonstrate the strong interdependence between WAAM process parameters, microstructural evolution, defect formation, and mechanical performance of Nitinol shape memory alloy components. The findings highlight both the potential and challenges associated with arc-based additive manufacturing of thermally sensitive alloys.

i. Influence of Process Parameters on Defect Formation

Stereo microscopy revealed that surface porosity, solidification cracks, and lack of fusion were the dominant defects present in WAAM-fabricated Nitinol samples. These defects were observed to be strongly influenced by heat input and deposition stability. Higher heat input conditions promoted increased melt pool turbulence and prolonged solidification time, leading to gas entrapment and pore formation. Conversely, insufficient heat input resulted in lack of fusion at interlayer boundaries.

Crack formation was primarily associated with high thermal gradients and residual tensile stresses generated during rapid cooling. Nitinol's sensitivity to compositional and thermal variations further exacerbated cracking behavior. These observations are consistent with reported defect mechanisms in arc-based additive manufacturing of nickel-based alloys [18], [14].

ii. Microstructural Evolution and Thermal Effects

Optical microscopy results indicated pronounced columnar grain growth aligned along the build direction, a characteristic feature of WAAM processing. This grain morphology results from directional heat flow during solidification and repeated thermal cycling between successive layers. Grain coarsening was more evident in upper layers, where cumulative heat input reduced cooling rates.

SEM analysis further confirmed microstructural heterogeneity across the deposited structure. Microvoids and intergranular defects were frequently observed near interlayer regions, highlighting the influence of thermal cycling and localized compositional variation. The presence of grain boundary cracks suggests that thermal stress accumulation during deposition exceeds the local ductility limits of the material under certain process conditions.

Heat-treated samples exhibited reduced microstructural anisotropy and improved homogeneity. Stress relief and partial grain refinement achieved through post-deposition heat treatment contributed to improved microstructural stability, supporting the use of thermal post-processing as an effective strategy for enhancing WAAM-fabricated Nitinol components.

iii. Mechanical Property Correlation

Mechanical characterization results showed a direct correlation between microstructural features, defect density, and mechanical performance. Variations in microhardness along the build height reflect underlying differences in grain size and thermal history. Regions with finer grain structures exhibited higher hardness values, while coarse-grained regions showed reduced hardness.

Tensile testing results revealed that as-deposited samples exhibited moderate tensile strength with limited ductility, primarily due to the presence of porosity and microcracks acting as stress concentrators. Heat-treated samples demonstrated improved elongation and more consistent tensile behavior, confirming the beneficial role of post-deposition thermal treatment in mitigating residual stresses and microstructural heterogeneity.

These findings align with previous studies reporting enhanced mechanical performance of additively manufactured Nitinol following appropriate heat treatment [13]. The observed improvements underscore the importance of integrating process optimization and post-processing strategies to achieve reliable mechanical properties.

iv. Process–Structure–Property Relationship

The results of this study establish a clear process–structure–property relationship for WAAM-fabricated Nitinol. Process parameters govern heat input and deposition stability, which in turn dictate defect formation and microstructural evolution. These microstructural characteristics directly influence mechanical behavior, including hardness distribution and tensile performance.

While WAAM offers significant advantages in terms of deposition rate and scalability, achieving defect-free Nitinol components remains challenging due to the alloy's sensitivity to thermal and compositional variations. The results emphasize that careful control of heat input, interpass temperature, and post-deposition heat treatment is essential for improving material quality and performance.

Overall, the findings demonstrate that WAAM can be a viable manufacturing route for Nitinol components when supported by optimized processing conditions and appropriate post-processing treatments.

VIII. Conclusions and Future Scope

i. Conclusions

This study presents a comprehensive experimental investigation into the microstructural characteristics, defect mechanisms, and mechanical behavior of Nitinol shape memory alloy fabricated using Wire Arc Additive Manufacturing (WAAM). Stereo microscopy revealed that surface porosity, solidification cracks, and lack of fusion are the dominant defects influencing part quality, with defect severity strongly dependent on heat input and deposition stability.

Optical and scanning electron microscopy demonstrated pronounced columnar grain growth aligned with the build direction, resulting from directional solidification and repeated thermal cycling. Microstructural heterogeneity and intergranular defects were observed, particularly near interlayer regions. Mechanical characterization showed that hardness and tensile properties vary across the build height, reflecting the underlying microstructural variations. Post-deposition heat treatment was found to improve microstructural homogeneity, reduce residual stresses, and enhance tensile ductility.

Overall, the results establish a clear process–structure–property relationship for WAAM-fabricated Nitinol and demonstrate that, while WAAM offers high deposition efficiency and scalability, careful control of process parameters and thermal history is essential to achieve reliable material performance.

ii. Future Scope

Future research should focus on systematic optimization of WAAM process parameters to minimize defect formation and enhance microstructural uniformity. Real-time monitoring of arc stability and melt pool behavior could provide improved control over deposition quality. Advanced characterization techniques, such as in-situ thermal imaging and high-resolution phase analysis, may offer deeper insight into solidification dynamics and phase transformation behavior.

Additionally, the integration of data-driven and artificial intelligence-based approaches for process optimization and defect prediction represents a promising research direction. Extending the present work to functional testing of shape memory behavior and actuator performance would further enhance the applicability of WAAM-fabricated Nitinol components for aerospace, robotics, and smart structural applications.

IX. ACKNOWLEDGMENT

The authors would like to acknowledge the Department of Mechanical Engineering, National Institute of Technology Warangal, Telangana, for providing the facilities and academic support required to carry out this research work.

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