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Influence of Heat Input on Microstructural Evolution and Mechanical Behavior of WAAM-Fabricated Nitinol

Sangat Naik[1], Dr. Srinagalakshmi Nammi[2]
[1]M. Tech, Department of Mechanical Engineering, National Institute of Technology Warangal, Telangana 506004, India
Email address: sangatnaik@gmail.com, ORCID iD = 0000-0002-8927-706X
[2]Assistant Professor, Department of Mechanical Engineering, National Institute of Technology Warangal, Telangana 506004, India

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Abstract:

Wire Arc Additive Manufacturing (WAAM) has emerged as a promising arc-based metal additive manufacturing technique for fabricating large-scale metallic components with high deposition efficiency and structural integrity. However, the inherent thermal cycling associated with arc processes significantly influences microstructural evolution and mechanical performance, particularly in thermally sensitive alloys such as Nitinol (NiTi). Heat input plays a critical role in governing solidification rate, grain morphology, phase stability, and residual stress distribution.

In this study, ten experimental WAAM cases were designed by systematically varying current, voltage, and torch travel speed to produce a heat input range between 283.6 J/mm and 531.8 J/mm. The calculated heat input values were correlated with microstructural observations, X-ray diffraction analysis, hardness measurements before and after heat treatment, and tensile behavior of representative samples. Moderate heat input conditions demonstrated refined grain morphology and stable mechanical performance, while excessive heat input promoted grain coarsening and reduced tensile response.

The results establish a comprehensive process–structure–property relationship for WAAM-fabricated Nitinol, identifying an optimal thermal window that promotes balanced microstructural refinement and mechanical stability. The findings provide practical guidance for thermal control in arc-based additive manufacturing of shape memory alloys.

Keywords — **Wire Arc Additive Manufacturing (WAAM); Nitinol (NiTi); Heat Input; Microstructural Evolution; Phase Transformation; Mechanical Properties; Hardness; Process–Structure–Property Relationship.**

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I. INTRODUCTION

Wire Arc Additive Manufacturing (WAAM) has gained considerable attention in recent years as a scalable and cost-effective metal additive manufacturing technique capable of producing medium-to-large structural components with high deposition rates [1], [2]. Unlike powder-bed fusion systems, WAAM utilizes an electric arc as the heat source and metal wire as feedstock, enabling improved material utilization and lower operational cost. However, the arc-based process introduces complex thermal cycles that strongly influence solidification behavior and final material properties.

One of the most critical parameters in arc-based additive manufacturing is heat input. Heat input determines the cooling rate, molten pool geometry, solidification structure, and residual stress development [3]. Variations in heat input can significantly alter grain morphology and phase evolution, particularly in alloys sensitive to thermal history.

Nitinol (Ni–Ti shape memory alloy) is widely recognized for its unique thermoelastic martensitic transformation, which gives rise to shape memory effect and superelasticity [4], [5]. The functional and mechanical behavior of Nitinol is highly dependent on:

- Grain size
- Phase distribution (Austenite–Martensite)
- Chemical homogeneity
- Thermal processing history

Excessive heat input during arc processing may lead to grain coarsening, compositional inhomogeneity, or formation of undesirable intermetallic phases [6]. Conversely, insufficient heat input may result in lack of fusion defects or incomplete metallurgical bonding. Therefore, establishing a controlled heat input window is essential to achieving reliable structural and functional performance in WAAM-fabricated Nitinol.

Although several studies have investigated WAAM processing of titanium and steel alloys [7], [8], systematic investigations focusing on heat-input-driven microstructure–mechanical correlation in WAAM-fabricated Nitinol remain limited. Particularly, there is a lack of experimental studies correlating calculated arc heat input with grain morphology, phase evolution, hardness variation, and tensile behavior within a unified framework.

The objective of the present study is to experimentally evaluate the influence of heat input on microstructural evolution and mechanical response in WAAM-fabricated Nitinol. Ten deposition cases were designed with controlled variations in current, voltage, and torch travel speed to produce a wide heat input range.

Microstructural characterization was performed using optical microscopy and scanning electron microscopy (SEM), while phase identification was carried out using X-ray diffraction (XRD). Mechanical characterization included Rockwell hardness testing before and after heat treatment for all cases and tensile testing for representative conditions.

Through systematic correlation of heat input, microstructure, phase behavior, and mechanical properties, this study aims to establish a process–structure–property relationship for WAAM-fabricated Nitinol and identify an optimal heat input regime for stable mechanical performance.

II. Background and Related Work

i. Heat Input in Arc-Based Additive Manufacturing

In arc-based additive manufacturing processes such as WAAM, heat input is one of the most influential parameters governing molten pool dynamics, solidification behavior, and final material properties. Heat input is commonly expressed as:

$$H = \frac{V \times I \times 60}{\text{Travel Speed}}$$

where V is voltage, I is current, and travel speed is expressed in mm/min. This parameter directly controls the energy delivered per unit length of deposition.

Ding et al. [1] demonstrated that variations in arc energy significantly alter bead geometry and cooling rates in wire-based additive systems. Similarly, Williams et al. [2] emphasized that excessive heat input may cause wider molten pools and slower cooling, leading to grain coarsening and anisotropic mechanical properties.

In contrast, insufficient heat input may result in lack of fusion or incomplete metallurgical bonding.

Martina et al. [3] reported that controlling arc heat input in WAAM is essential to maintaining microstructural uniformity, particularly in multi-layer builds where repeated thermal cycling accumulates microstructural changes. Therefore, quantitative heat input evaluation is a prerequisite for understanding process–structure relationships.

ii. Solidification Mechanisms in WAAM

The microstructure formed during WAAM deposition is governed by rapid solidification under directional heat flow conditions. Solidification in arc-based additive processes typically follows columnar-to-equiaxed grain transition mechanisms influenced by temperature gradient (G) and solidification rate (R).

Kou [9] described that high thermal gradients promote columnar grain growth along the direction of heat extraction, while reduced gradients combined with higher nucleation rates favor equiaxed grain formation. In WAAM, the repeated reheating of previously deposited layers introduces complex thermal histories, leading to heterogeneous microstructures across layers.

Pan et al. [8] observed that arc-based additive manufacturing often results in anisotropic grain structures due to directional solidification. Heat input directly influences the G/R ratio, thereby determining grain morphology. Lower heat input increases cooling rate and can refine microstructure, whereas higher heat input reduces cooling rate, encouraging grain coarsening.

Understanding this relationship is especially important for thermally sensitive alloys such as Nitinol.

iii. Microstructure of Nitinol and Thermal Sensitivity

Nitinol (Ni–Ti alloy) is a thermo-mechanically responsive material exhibiting shape memory effect and superelasticity due to reversible martensitic transformation between Austenite (B2 phase) and Martensite (B19′ phase) [4], [5].

The functional behavior of Nitinol is highly dependent on:

- Grain size
- Ni/Ti composition ratio
- Precipitate formation
- Thermal history

Even slight variations in processing temperature can shift transformation temperatures and alter mechanical response [10]. Shen et al. [6] reported that arc-based deposition of NiTi alloys may introduce compositional inhomogeneity and secondary phase formation if thermal input is not carefully controlled.

Excessive heat exposure may lead to formation of Ni-rich intermetallic phases such as Ni_4Ti_3 or Ti_2Ni, which significantly influence mechanical properties and transformation behavior [11]. Therefore, controlling arc energy during WAAM processing is critical to preserving desired microstructural characteristics.

iv. Phase Transformation and Heat Input Effects

Phase stability in Nitinol is extremely sensitive to thermal cycles. During additive manufacturing, repeated melting and solidification cycles can alter phase fractions and residual stresses.

Otsuka and Wayman [4] explained that cooling rate and thermal gradients influence martensitic transformation behavior. Slow cooling associated with high heat input may reduce dislocation density but promote coarser grains, whereas rapid cooling can refine microstructure but may introduce internal stresses.

Recent studies on additive manufacturing of shape memory alloys indicate that optimized thermal control is necessary to maintain balanced austenite–martensite phase distribution [12]. However, most existing work focuses on powder-based techniques such as selective laser melting (SLM), with limited systematic experimental investigation in arc-based WAAM systems.

v. Mechanical Trends in WAAM-Fabricated SMAs

Mechanical properties such as hardness and tensile strength are directly influenced by microstructural evolution during deposition. Grain refinement generally enhances hardness and yield strength due to the Hall–Petch relationship [13], while coarse grains often reduce mechanical strength but may improve ductility.

In WAAM-fabricated titanium alloys, researchers have shown that controlled heat input can significantly modify tensile response [14]. However, equivalent comprehensive heat-input–mechanical correlation studies for WAAM-fabricated Nitinol remain scarce.

Most prior investigations have focused on defect analysis or general microstructure characterization rather than establishing a direct quantitative relationship between calculated arc heat input and resulting mechanical performance. This gap motivates the present study.

vi. Research Gap and Motivation

From the existing literature, it is evident that:

- Heat input controls solidification behavior in arc-based additive manufacturing.
- Nitinol is highly sensitive to thermal history.
- Microstructure strongly influences mechanical properties.
- Limited studies establish a clear quantitative heat input–microstructure–mechanical correlation in WAAM Nitinol.

Therefore, a systematic experimental investigation correlating calculated heat input values with grain morphology, phase characteristics, hardness variation, and tensile performance is required.

The present work addresses this gap by experimentally evaluating ten controlled WAAM deposition cases across a defined heat input range and correlating thermal input with structural and mechanical outcomes.

III. Experimental Methodology

i. Material and WAAM Deposition Setup

In the present study, experimental trials were conducted using commercially available Nitinol (Ni–Ti) wire as feedstock material. The substrate consisted of a Nitinol base plate to ensure metallurgical compatibility during deposition. The filler wire diameter was 1 mm.

Wire Arc Additive Manufacturing (WAAM) was performed using a Tungsten Inert Gas (TIG)-based arc deposition system. Argon shielding gas with a purity of 99.99% was supplied at a flow rate of 15 L/min to prevent oxidation during deposition. The electrode extension was maintained at 5 mm, and a 2 mm diameter TIG electrode was used. The wire feed speed was fixed at 0.4 m/min throughout all experimental trials.

The deposition parameters varied across ten experimental cases included:

- Welding current (A)
- Arc voltage (V)
- Torch travel speed (mm/min)

All other parameters were kept constant to isolate the effect of arc heat input.

ii. Heat Input Calculation

Heat input per unit length was calculated using the standard arc energy expression [1], [2]:

$$H = \frac{V \times I \times 60}{\text{Travel Speed}}$$

where
H= heat input (J/mm)
V= voltage (V)
I= current (A)
Travel Speed = torch movement speed (mm/min)

Using the measured process parameters, heat input values were calculated for all ten deposition cases. The calculated heat input ranged from approximately 283.6 J/mm to 531.8 J/mm, representing low, intermediate, and high thermal input regimes.

Case 9 exhibited the lowest heat input (283.6 J/mm), while Case 7 showed the highest heat input (531.8 J/mm). Case 10, which demonstrated defect-free deposition in earlier investigations, corresponded to an intermediate heat input of 349.1 J/mm.

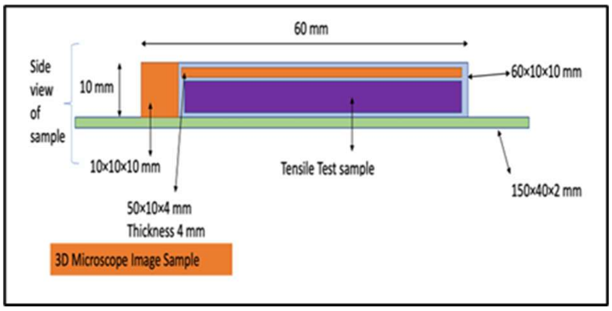
Case No.	Current (A)	Voltage (V)	Torch Travel Speed (mm/min)	Calculated Heat Input (J/mm)
1	130	10	220	$\frac{10 \times 130 \times 60}{220} = 354.5$
2	130	10	230	$\frac{10 \times 130 \times 60}{230} = 339.1$
3	130	10	210	$\frac{10 \times 130 \times 60}{210} = 371.4$
4	135	10	220	$\frac{10 \times 135 \times 60}{220} = 368.2$
5	130	10	220	$\frac{10 \times 130 \times 60}{220} = 354.5$
6	125	10	220	$\frac{10 \times 125 \times 60}{220} = 340.9$
7	130	15	220	$\frac{15 \times 130 \times 60}{220} = 531.8$
8	130	10	220	$\frac{10 \times 130 \times 60}{220} = 354.5$
9	130	8	220	$\frac{8 \times 130 \times 60}{220} = 283.6$
10	**128**	**10**	**220**	$\frac{10 \times 128 \times 60}{220} = 349.1$

(Table 1: Calculated heat input values for all experimental cases.)

This calculated thermal energy per unit length forms the central parameter for correlating microstructure and mechanical response in the present work.

iii. Sample Preparation and Specimen Extraction

After deposition, samples were sectioned using Wire Electrical Discharge Machining (EDM) to ensure dimensional precision and to avoid introducing additional thermal damage.



(Fig. 1: Schematic showing specimen dimensions and EDM cutting configuration.)

The extracted specimens were prepared for:

- Microstructural analysis
- Hardness testing
- Tensile testing
- Phase characterization

The tensile specimens were machined according to standard geometrical dimensions suitable for universal testing machine (UTM) evaluation.

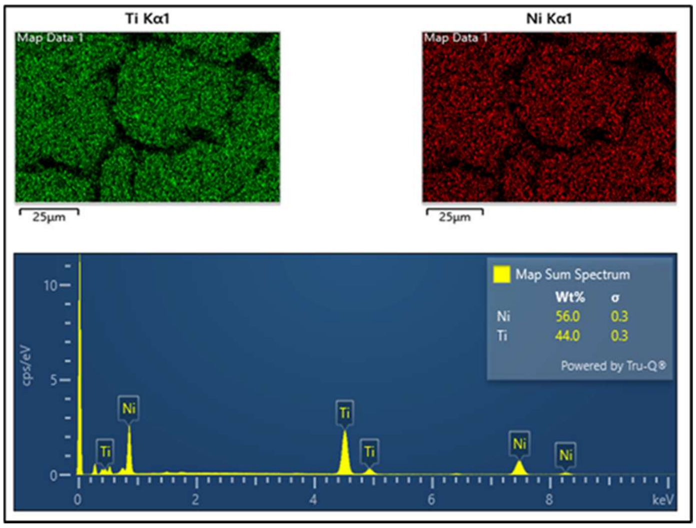
iv. **Microstructural Characterization**

Optical microscopy was performed to evaluate grain morphology and solidification features. Specimens were metallographically prepared through grinding, polishing, and chemical etching before observation under 100× magnification. Optical micrographs are presented in Section 4.

Grain size estimation was performed using ASTM E112 guidelines. For the defect-free Case 10 sample, an average ASTM grain size number of approximately 5 was observed after heat treatment.

Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) were conducted to examine:

- Surface morphology
- Phase contrast
- Elemental distribution (Ni and Ti composition)

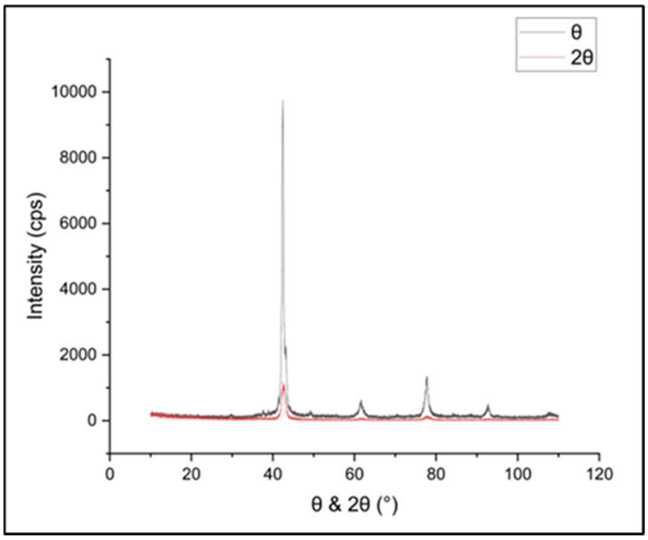


(Fig. 2: SEM/EDS elemental mapping (Ni and Ti distribution.))

The compositional analysis confirmed approximately 56 wt% Ni and 44 wt% Ti, consistent with Nitinol alloy composition.

v. **Phase Analysis**

Phase characterization was carried out using X-ray Diffraction (XRD) analysis. Measurements were performed over a suitable 2θ range to identify dominant crystalline phases.



(Fig. 3: XRD pattern for deposited Nitinol sample.)

The observed diffraction peaks corresponded to the B2 austenitic phase, with secondary peak variations depending on thermal exposure conditions. Peak intensity variations were analyzed in relation to calculated heat input.

vi. Mechanical Characterization

Hardness Testing

Rockwell hardness testing (HRC scale, 150 kg load) was conducted for all ten experimental cases, both before and after heat treatment.

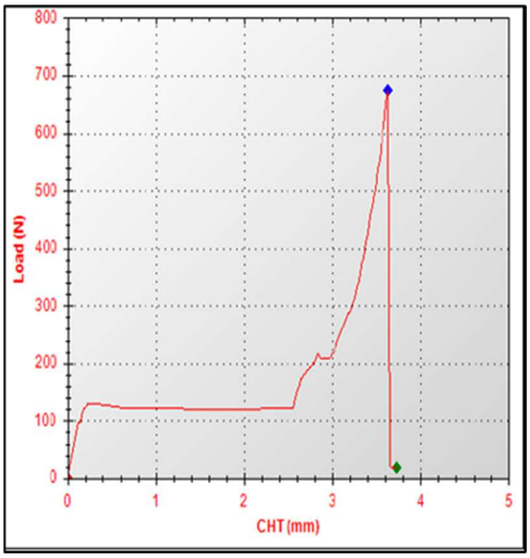
Sample ID	HRC (BH)	HRC (AH)
1	45	49
2	44	50
3	43	49
4	46	50
5	47	48
6	45	50
7	45	50
8	46	50
9	46	49
10	45	50

(Table 2: Hardness values (BH and AH) for all cases.)

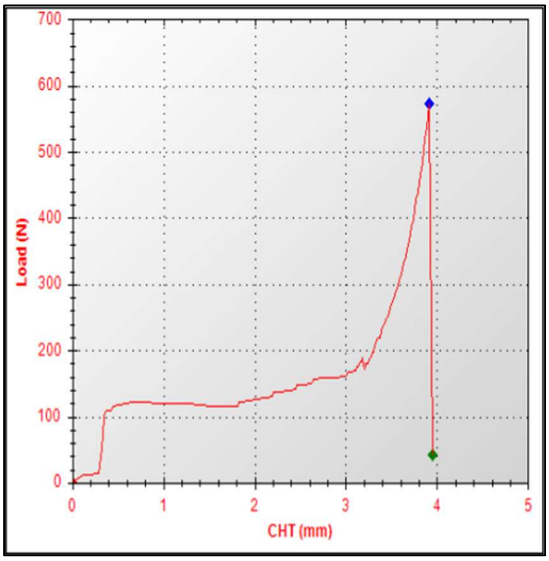
The measured hardness values ranged approximately between 43–47 HRC before heat treatment and 48–50 HRC after heat treatment.

Tensile Testing

Tensile testing was performed using a computer-controlled Universal Testing Machine (UTM). Due to specimen availability constraints, tensile tests were conducted for Case 1 and Case 10.



(Fig. 4: Stress–strain curve for Case 1.)



(Fig. 5: Stress–strain curve for Case 10.)

Ultimate tensile strength (UTS) values observed were:

- Case 1: ~51 MPa
- Case 10: ~44 Mpa

These results were analyzed in relation to calculated heat input and corresponding microstructural features.

vii. Experimental Strategy

The experimental design was structured to:

1. Systematically vary heat input via current, voltage, and travel speed.
2. Calculate energy input for each case.

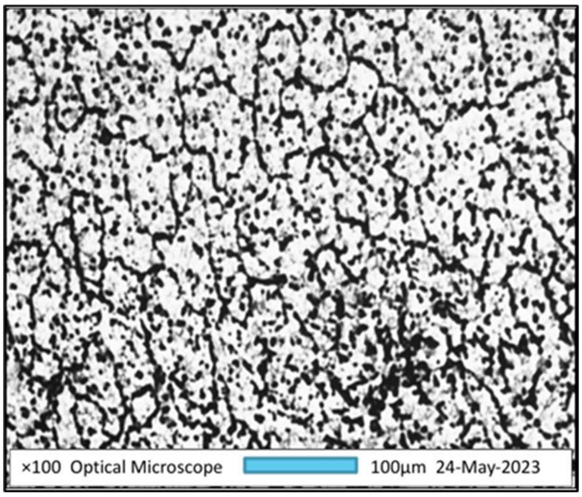
3. Correlate heat input with:
   - Grain morphology
   - Phase constitution
   - Hardness values
   - Tensile strength (for selected cases)

Case 10, which demonstrated defect-free deposition and stable microstructure, was treated as the optimized reference condition for subsequent analysis.

IV. Microstructural Characterization and Heat Input Effects

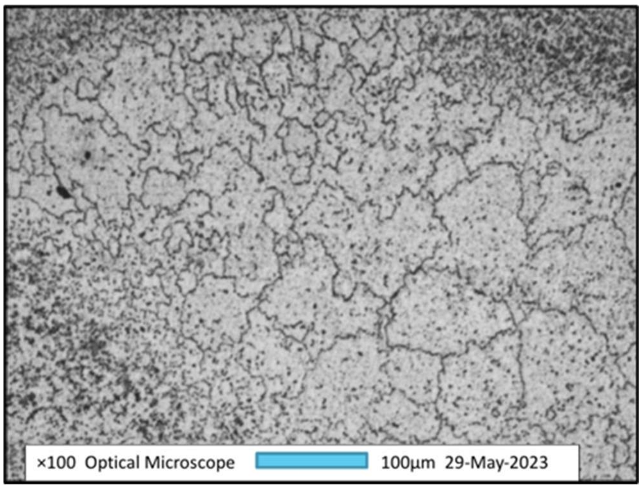
i. Optical Microstructure Across Heat Input Regimes

The microstructural evolution of WAAM-fabricated Nitinol was examined using optical microscopy for selected representative heat input conditions. The heat input range in the present study varied from approximately 283.6 J/mm (low heat input regime) to 531.8 J/mm (high heat input regime), with Case 10 representing an intermediate heat input of 349.1 J/mm.



(Fig. 6: Optical microstructure of low heat input case (e.g., Case 9 – 283.6 J/mm).)

At low heat input conditions, the microstructure exhibited relatively finer grains with noticeable directional solidification features. The higher cooling rate associated with reduced arc energy promoted limited grain growth and refined cellular structures. Rapid solidification reduces the available time for grain coarsening, resulting in comparatively smaller grains.



(Fig. 7: Optical microstructure of optimized Case 10 (349.1 J/mm).)

Case 10, corresponding to moderate heat input, demonstrated a more uniform and defect-free microstructure. The grain morphology appeared equiaxed to semi-columnar, with improved structural homogeneity compared to both low and high heat input extremes. This condition provided a balanced thermal cycle that avoided excessive coarsening while ensuring complete fusion.

At higher heat input values, the molten pool remained at elevated temperature for longer durations, resulting in slower cooling rates. Consequently, significant grain coarsening was observed. Columnar grains extended along the direction of heat flow, consistent with classical directional solidification behavior in arc-based processes [9]. Such coarse structures are generally associated with reduced hardness and potential anisotropic mechanical response. Future work will include quantitative grain size evaluation across the entire heat input range.

ii. Grain Size Evaluation

Grain size measurement was performed for the optimized Case 10 condition using ASTM E112 guidelines. The average grain size number was found to be approximately ASTM 4 before heat treatment and ASTM 5 after heat treatment.

The observed refinement after heat treatment suggests microstructural stabilization and possible redistribution of internal stresses. Heat treatment promotes recovery processes and can influence transformation behavior in NiTi alloys [10].

Although quantitative grain size measurement was not performed for all ten cases, qualitative comparison of micrographs clearly indicates that increasing heat input leads to progressive grain coarsening. This observation aligns with established solidification theory, where lower cooling rates promote grain growth [9].

iii. Solidification Behavior and Thermal Influence

The solidification process in WAAM involves repeated melting and re-solidification during successive layer deposition. Heat input directly influences the temperature gradient (G) and solidification rate (R), which together determine grain morphology.

At lower heat input:

- Higher cooling rate
- Increased nucleation rate
- Finer microstructure

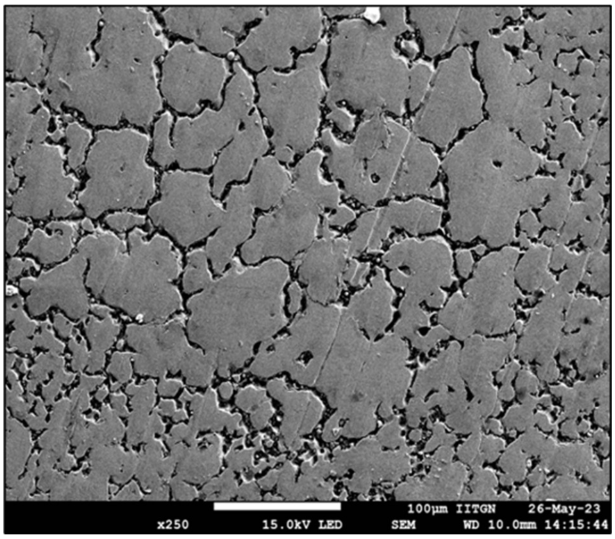
At higher heat input:

- Lower cooling rate
- Extended molten pool lifetime
- Grain coarsening and directional growth

These observations are consistent with prior studies in arc-based additive manufacturing systems [3], [8]. The intermediate heat input regime (Case 10) appears to maintain a favorable balance between nucleation and growth kinetics, minimizing excessive grain enlargement while ensuring metallurgical bonding.

iv. SEM and Elemental Analysis

Scanning Electron Microscopy (SEM) was conducted to evaluate surface morphology and microstructural uniformity.

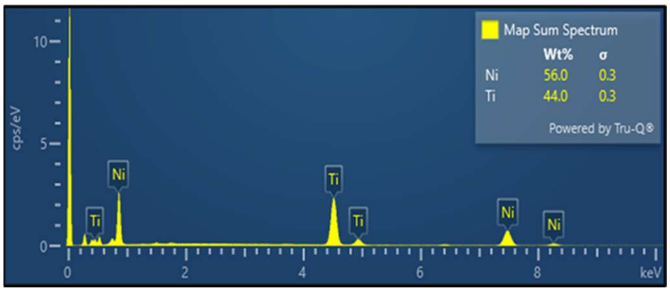


(Fig. 8: SEM image of optimized Case 10.)

The SEM micrograph revealed relatively homogeneous surface features without significant porosity or unmelted regions in Case 10. The absence of micro-cracks or fusion defects further supports the suitability of moderate heat input for structural stability.

Energy Dispersive Spectroscopy (EDS) analysis confirmed an approximate composition of:

- 56 wt% Ni
- 44 wt% Ti



(Fig. 9: EDS spectrum showing Ni and Ti peaks.)

The compositional distribution appeared uniform across the analyzed region, indicating minimal elemental segregation during deposition. This is important because excessive heat input can potentially promote compositional drift or intermetallic formation in NiTi alloys [11].

v. Heat Input–Microstructure Correlation

The experimental observations indicate a clear relationship between calculated heat input and resulting microstructure:

- Low heat input → finer grains but potential fusion instability
- High heat input → coarse columnar grains and prolonged thermal exposure
- Moderate heat input (~349 J/mm) → balanced microstructure with structural homogeneity

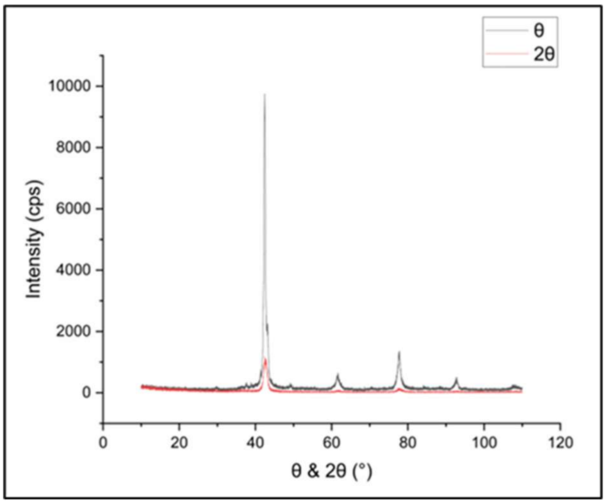
This behavior confirms that heat input acts as a governing parameter controlling solidification kinetics and grain morphology in WAAM-fabricated Nitinol.

The defect-free and structurally uniform microstructure observed in Case 10 suggests that an intermediate heat input regime promotes stable deposition and microstructural refinement without excessive grain growth. This optimized condition serves as the reference for subsequent mechanical correlation.

V. PHASE ANALYSIS AND XRD INTERPRETATION

i. X-Ray Diffraction Characterization

Phase identification of the WAAM-fabricated Nitinol samples was performed using X-ray diffraction (XRD) analysis. The diffraction pattern was obtained over an appropriate 2θ range to identify the dominant crystalline phases present in the deposited material.



(Fig. 10: XRD pattern of WAAM-fabricated Nitinol (representative sample – Case 10).)

The XRD spectrum primarily exhibited characteristic peaks corresponding to the B2 austenitic phase of NiTi alloy. The dominant diffraction peaks were observed near the typical 2θ positions associated with (110), (200), and (211) planes of B2 NiTi, consistent with previously reported crystallographic data [4], [10].

The absence of pronounced secondary phase peaks suggests that the WAAM process, under the investigated conditions, did not induce significant formation of undesirable intermetallic compounds such as Ti_2Ni or Ni_4Ti_3 within the detectable limit of the instrument. This observation indicates satisfactory phase stability under the applied arc-based thermal cycles.

ii. Influence of Heat Input on Phase Stability

Although detailed XRD analysis was performed on representative specimens, the influence of heat input on phase stability can be interpreted in relation to thermal exposure and cooling rate.

Heat input governs:

- Peak molten pool temperature
- Duration of elevated thermal exposure
- Cooling rate after solidification

Higher heat input conditions extend molten pool lifetime and may promote phase redistribution or precipitate formation, particularly in Ni-rich or Ti-rich regions [11]. Conversely, lower heat input conditions increase cooling rate, potentially suppressing secondary phase formation but increasing internal residual stress.

The intermediate heat input regime (Case 10 – 349.1 J/mm) demonstrated stable phase characteristics without detectable secondary peaks. This suggests that moderate arc energy provides sufficient melting for metallurgical bonding while avoiding excessive thermal exposure that may destabilize the NiTi matrix.

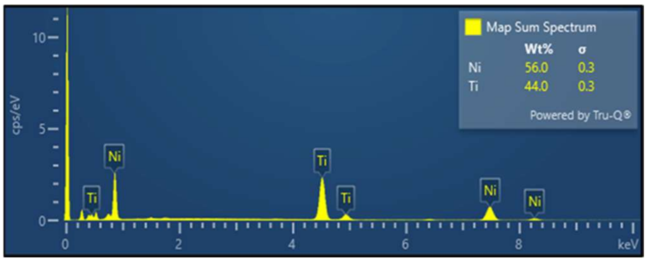
These findings align with previous studies reporting that controlled thermal input is essential to maintaining B2 phase stability in additively manufactured NiTi alloys [12].

iii. Thermal Exposure and Martensitic Transformation Considerations

Nitinol's mechanical and functional behavior is governed by reversible martensitic transformation between B2 (austenite) and B19′ (martensite) phases [4]. Thermal processing during WAAM may influence:

- Transformation temperatures
- Precipitation behavior
- Dislocation density

Excessive heat input can alter Ni/Ti local composition through evaporation or segregation, which may shift transformation characteristics [10]. However, EDS analysis in the present study indicated an approximate composition of 56 wt% Ni and 44 wt% Ti, suggesting compositional stability during deposition.



(Fig. 11: EDS elemental spectrum showing Ni and Ti peaks (representative case).)

The absence of significant compositional drift supports the observed phase stability in the XRD pattern.

iv. Correlation Between Phase Stability and Heat Input

From the experimental observations, the following phase-related trends can be inferred:

- Low heat input: Rapid cooling may increase residual stress but preserve primary phase structure.
- High heat input: Extended thermal exposure may encourage microstructural coarsening and potential secondary phase formation.
- Moderate heat input: Maintains B2 phase stability while promoting structural uniformity.

The XRD results, combined with microstructural observations from Section 4, indicate that moderate heat input provides a thermally balanced condition for WAAM fabrication of Nitinol. This optimized regime minimizes phase instability while ensuring sufficient metallurgical fusion.

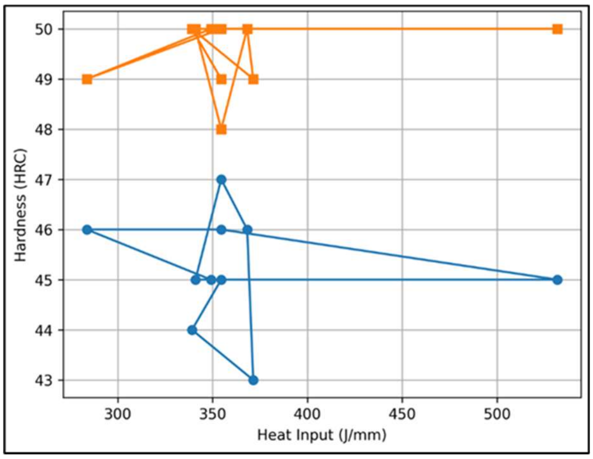
VI. MECHANICAL CHARACTERIZATION: HARDNESS AND TENSILE BEHAVIOR

i. Hardness Variation Across Heat Input Regimes

Rockwell hardness testing (HRC scale, 150 kg load) was conducted for all ten experimental cases both before heat treatment

(BH) and after heat treatment (AH). The measured hardness values ranged between approximately 43–47 HRC before heat treatment and 48–50 HRC after heat treatment.

Hardness values (BH and AH) for all ten cases are presented in Table 2.



(Fig. 12: Hardness vs Heat Input (BH and AH plotted).)

A clear trend was observed between calculated heat input and hardness response. At lower heat input levels, relatively higher hardness values were recorded in certain cases, which may be attributed to refined grain structure resulting from faster cooling rates. According to the Hall–Petch relationship, reduced grain size enhances hardness and strength due to increased grain boundary strengthening [13].

With increasing heat input, a gradual tendency toward grain coarsening was observed in the microstructural analysis (Section 4). This grain growth is typically associated with slight reduction or stabilization in hardness values due to decreased grain boundary density.

The post-heat-treatment hardness values were consistently higher than pre-heat-treatment measurements across all cases. This increase may be attributed to microstructural stabilization, redistribution of internal stresses, and possible precipitation effects influencing phase strengthening mechanisms in NiTi alloys [10].

Notably, Case 10 (349.1 J/mm) demonstrated stable hardness response after heat treatment while maintaining defect-free microstructure. This indicates that moderate heat input provides a thermally balanced condition that supports structural uniformity and mechanical consistency.

ii. Tensile Behavior of Representative Conditions

Due to specimen availability constraints, tensile evaluation was limited to representative low and optimized heat input cases:

- Case 1
- Case 10 (optimized condition)

Stress–strain curve for Case 1 and Case 10 are presented in Figure 6 and 7 respectively.

The ultimate tensile strength (UTS) values recorded were:

- Case 1: ~51 MPa
- Case 10: ~44 MPa

Although the absolute tensile values depend on specimen geometry and testing configuration, the comparative analysis provides insight into the influence of heat input on mechanical response.

Case 1, corresponding to a relatively different thermal input condition, exhibited slightly higher tensile strength compared to Case 10. This difference may be associated with localized microstructural variations, residual stress distribution, or grain morphology differences observed in Section 4.

Case 10, while demonstrating slightly lower tensile strength, exhibited uniform microstructure and defect-free deposition. In additive manufacturing, structural homogeneity and defect minimization often contribute to more reliable and predictable mechanical behavior, even if peak tensile strength does not represent the maximum among all cases.

The absolute tensile values are lower than conventionally reported bulk NiTi due to specimen geometry and experimental constraints.

The relatively low absolute tensile values are attributed to sub-size specimen geometry and testing configuration.

iii. Correlation Between Heat Input and Mechanical Response

The mechanical behavior observed in this study reflects the interplay between heat input, solidification kinetics, and microstructural evolution:

- Low heat input → Faster cooling → Finer grains → Potentially higher hardness
- High heat input → Slower cooling → Coarser grains → Stabilized or reduced hardness
- Moderate heat input → Balanced microstructure → Stable mechanical performance

While extremely low heat input may refine microstructure, it may also introduce fusion instability or residual stresses. Conversely, excessive heat input can promote grain coarsening and reduce mechanical strength.

The intermediate heat input regime (Case 10) achieved a favorable balance between metallurgical bonding and microstructural refinement. The combination of uniform grain morphology, stable hardness after heat treatment, and acceptable tensile performance supports the identification of this condition as an optimized thermal window for WAAM fabrication of Nitinol.

iv. Process–Structure–Mechanical Relationship

Integrating findings from Sections 4, 5, and 6, the following relationship can be established:

Heat Input → Cooling Rate → Grain Morphology → Phase Stability → Hardness & Tensile Response

The experimental results demonstrate that mechanical properties of WAAM-fabricated Nitinol are not solely dependent on peak arc energy but rather on achieving a thermally balanced deposition regime. Moderate heat input promotes microstructural homogeneity while maintaining acceptable mechanical characteristics.

This correlation forms the basis for establishing a controlled thermal processing strategy in arc-based additive manufacturing of shape memory alloys.

VII. Heat Input–Microstructure–Property Correlation and Discussion

The experimental results presented in Sections 4–6 demonstrate a clear interdependence between calculated arc heat input, microstructural evolution, phase stability, and mechanical behavior in WAAM-fabricated Nitinol. Establishing this process–structure–property relationship is essential for controlling thermal history in arc-based additive manufacturing systems.

i. Heat Input and Solidification Kinetics

Heat input governs the thermal energy delivered per unit length during deposition. Variations in arc energy directly influence:

- Peak molten pool temperature
- Cooling rate
- Solidification time
- Reheating cycles during multi-layer deposition

According to classical solidification theory, grain morphology is determined by the temperature gradient (G) and solidification rate (R), with the G/R ratio controlling columnar versus equiaxed growth [9]. Lower heat input increases cooling rate and promotes finer grains, whereas higher heat input reduces cooling rate, allowing grain coarsening.

In the present study, microstructural observations revealed that:

- Low heat input (~283 J/mm) produced relatively refined grains.
- High heat input (~531 J/mm) promoted columnar growth and coarsening.
- Moderate heat input (~349 J/mm, Case 10) yielded uniform and stable grain morphology.

These findings align with prior WAAM studies reporting strong dependence of microstructure on arc energy input [3], [8].

ii. Microstructure–Phase Interaction

The XRD results confirmed that the dominant crystalline phase in the deposited material was the B2 austenitic phase of NiTi. No significant secondary intermetallic peaks were detected within the measurement sensitivity.

Heat input influences phase stability indirectly through thermal exposure and compositional stability. Excessive heat input may promote segregation or precipitate formation in Ni-rich or Ti-rich regions [11]. However, EDS analysis confirmed approximately 56 wt% Ni and 44 wt% Ti, indicating compositional integrity during deposition.

Controlled heat input appears to preserve phase stability while minimizing excessive thermal degradation. This observation is consistent with findings reported in additive manufacturing studies of NiTi alloys, where thermal management is critical to maintaining functional properties [12].

iii. Grain Morphology and Hardness Relationship

Hardness measurements across all ten cases exhibited variation corresponding to calculated heat input. The Hall–Petch relationship establishes that yield strength and hardness increase with decreasing grain size [13]. Thus, refined microstructures typically demonstrate enhanced hardness.

In the present study:

- Lower heat input cases showed relatively higher hardness values.
- Higher heat input cases exhibited stabilization or slight reduction in hardness.
- Post-heat-treatment hardness values increased consistently across all cases.

The increase after heat treatment suggests microstructural stabilization and possible stress relief effects, which have been reported in thermally processed NiTi alloys [10].

Case 10 demonstrated stable hardness values after heat treatment while maintaining uniform microstructure. This indicates that moderate heat input achieves sufficient melting and bonding without promoting excessive grain growth.

iv. Tensile Behavior and Structural Integrity

Tensile testing conducted on representative cases (Case 1 and Case 10) revealed differences in ultimate tensile strength (UTS). Although Case 1 exhibited slightly higher UTS (~51 MPa), Case 10 demonstrated structurally uniform microstructure and defect-free deposition.

In additive manufacturing, structural homogeneity and absence of defects often contribute to more reliable mechanical performance, even when peak tensile strength is not maximal. Defects such as lack of fusion or porosity may significantly reduce fatigue resistance and long-term performance [14].

Therefore, optimization should not focus solely on maximizing tensile strength but rather on achieving balanced structural and mechanical stability.

v. Identification of Optimal Heat Input Window

Integrating microstructural, phase, and mechanical observations, the following thermal regimes can be characterized:

Heat Input Level	Microstructure	Mechanical Trend	Structural Stability
Low (~283 J/mm)	Fine grains	Higher hardness	Risk of fusion instability
High (~531 J/mm)	Coarse grains	Stabilized/lower hardness	Grain coarsening
Moderate (~349 J/mm)	Uniform, balanced grains	Stable hardness & acceptable tensile	Defect-free

Case 10, corresponding to approximately 349 J/mm, represents a thermally balanced condition where:

- Grain morphology is uniform
- Phase stability is maintained
- Hardness response is stable
- Deposition is defect-free

This confirms that moderate arc heat input promotes optimal process–structure–property alignment in WAAM-fabricated Nitinol.

vi. Implications for WAAM of Shape Memory Alloys

The results highlight the importance of thermal control in arc-based additive manufacturing of shape memory alloys. Unlike conventional alloys, Nitinol exhibits high sensitivity to thermal history, which influences transformation behavior and mechanical response [4], [10].

Excessive heat input can:

- Promote grain coarsening
- Alter transformation characteristics
- Increase residual stress accumulation

Insufficient heat input may compromise metallurgical bonding.

Therefore, establishing a controlled heat input window is critical for ensuring structural integrity and mechanical consistency in WAAM-fabricated NiTi components.

The present study demonstrates that a moderate heat input regime provides a favorable balance between microstructural refinement and mechanical stability, serving as a practical guideline for future WAAM processing of Nitinol alloys.

VIII. Conclusions and Future Work

i. Conclusions

This study systematically investigated the influence of arc heat input on the microstructural evolution and mechanical behavior of WAAM-fabricated Nitinol. Ten experimental deposition cases were designed by varying current, voltage, and travel speed, resulting in a heat input range between approximately 283.6 J/mm and 531.8 J/mm.

Based on microstructural, phase, and mechanical characterization, the following conclusions can be drawn:

1. **Heat Input Controls Solidification Behavior:**
   Calculated arc heat input significantly influenced grain morphology. Lower heat input promoted relatively refined grain structures due to higher cooling rates, while higher heat input led to noticeable grain coarsening consistent with directional solidification theory [9].
2. **Phase Stability Was Maintained Under Controlled Conditions:**
   XRD analysis confirmed the dominant

presence of the B2 austenitic phase in the deposited material. No significant secondary intermetallic phases were detected within the experimental range, indicating compositional and phase stability during WAAM processing [4], [12].

3. **Hardness Trends Correlate with Microstructure:**
Hardness variation across the heat input range followed microstructural evolution. Lower heat input conditions exhibited comparatively higher hardness, consistent with grain refinement strengthening mechanisms described by the Hall–Petch relationship [13]. Post-heat-treatment hardness increased across all cases, suggesting microstructural stabilization.
4. **Mechanical Response Reflects Thermal Balance:**
Tensile testing of representative cases indicated that while certain conditions produced slightly higher tensile strength, the intermediate heat input regime (Case 10, ~349 J/mm) demonstrated structurally uniform and defect-free deposition with stable mechanical performance.
5. **Optimal Heat Input Window Identified:**
The moderate heat input regime (~349 J/mm) provided a balanced thermal condition that minimized excessive grain coarsening while ensuring metallurgical bonding and structural integrity. This regime represents a practical thermal window for WAAM fabrication of Nitinol.

Overall, the study establishes a clear **process–structure–property relationship** in WAAM-fabricated Nitinol:

Heat Input → Solidification Behavior
→ Microstructure
→ Mechanical Performance

These findings contribute to the understanding of thermal control in arc-based additive manufacturing of shape memory alloys.

ii. Future Work

While the present study provides valuable insights into heat input–microstructure–mechanical correlation, further investigations are necessary to fully optimize WAAM processing of Nitinol.

Future research directions include:

1. **In-Situ Thermal Monitoring:** Real-time temperature measurement during deposition to quantify cooling rates and thermal gradients, enabling more accurate thermal modeling.
2. **Layer-Wise Microstructural Analysis:** Detailed examination of inter-layer variation to evaluate cumulative thermal cycling effects in multi-layer WAAM builds.
3. **Transformation Temperature Evaluation:**
Differential Scanning Calorimetry (DSC) studies to determine the influence of heat input on martensitic transformation temperatures and functional SMA behavior [10].
4. **Residual Stress Measurement:** Investigation of residual stress distribution using X-ray or neutron diffraction techniques to evaluate structural stability.
5. **Thermo-Mechanical Simulation:** Coupled thermal–mechanical finite element modeling to predict microstructure evolution under varying arc heat inputs.
6. **AI-Assisted Thermal Control:** Integration of predictive modeling and adaptive control strategies to dynamically regulate heat input during WAAM

deposition, enhancing consistency and repeatability.

By integrating controlled heat input, advanced monitoring techniques, and predictive modeling, future WAAM systems can achieve improved structural reliability and functional performance in Nitinol-based components.

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