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COMPARATIVE IMPLEMENTATION OF WIRE-DIRECTED ENERGY DEPOSITION AND WIRE ARC ADDITIVE MANUFACTURING: PROCESS CONFIGURATION AND PRELIMINARY MANUFACTURING ASSESSMENT

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Abstract
Wire-based metal additive manufacturing provides flexible routes for producing metallic components using continuous wire feedstock and localized thermal energy input. This study presents the preliminary implementation and comparative assessment of wire-directed energy deposition (Wire-DED) and wire arc additive manufacturing (WAAM) on robotic manufacturing platforms as a preparatory stage for subsequent NiTi Wire-DED experiments. Initial manufacturing trials were conducted using 1.0 mm diameter ER70S-6 mild-steel wire to understand system operation, establish stable wire deposition, investigate the accessible processing window, and gain practical experience with robotic layer-by-layer manufacturing. Process parameters were varied within the operating limits of the manufacturing systems while considering parameter ranges reported for ER70S-6 in the literature. Particular attention was given to wire feeding, energy delivery, robotic motion, melt-pool and bead formation, layer development, and practical process control. The preliminary trials were used to progressively identify suitable operating conditions and assess the manufacturing capabilities and practical limitations of the robotic manufacturing platforms. The resulting experience provides an experimental foundation for subsequent NiTi Wire-DED investigations involving post-process and in-situ processing strategies within the broader research program.

Keywords: Wire-directed energy deposition (Wire-DED); wire arc additive manufacturing (WAAM); ER70S-6 steel; robotic additive manufacturing; preliminary manufacturing.

1. INTRODUCTION

Metal additive manufacturing (AM) enables the layer-by-layer fabrication of near-net-shape metallic components with high material utilization and considerable geometric flexibility. Among metal AM technologies, directed energy deposition (DED) is particularly attractive for the manufacture and repair of medium- and large-scale components because feedstock and thermal energy are delivered directly to a localized deposition region [1–3]. Wire feedstock offers additional advantages such as high material utilization, simplified handling, and compatibility with robotic and multi-axis manufacturing systems [2–4].

Among wire-based AM processes, wire-directed energy deposition (Wire-DED) and wire arc additive manufacturing (WAAM) employ continuous metallic wire but differ fundamentally in their energy-delivery mechanisms. Wire-DED uses concentrated laser energy to establish a localized melt pool, whereas WAAM employs an electric arc to melt and deposit the wire [3–8]. Consequently, the two processes exhibit different characteristics in terms of thermal

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input, deposition behavior, geometric control, productivity, surface condition, and process flexibility [3–8]. Wire-DED can be integrated with robotic systems and coaxial wire delivery for multi-directional deposition [3, 5], while WAAM is particularly attractive for large-scale manufacturing because of its high deposition capability and comparatively simple process architecture [6–8]. Repeated thermal cycling and heat accumulation can influence dimensional stability, microstructure, residual stress, and mechanical behavior, making process control and thermal management important considerations [6–8, 11–13, 16].

ER70S-6 low-carbon steel has been investigated in both laser/wire DED and WAAM because of its commercial availability and suitability for wire-based deposition research [9–17]. Previous studies have examined the effects of process parameters, build orientation, travel speed, thermal history, heat treatment, and deposition conditions on the microstructure and mechanical behavior of ER70S-6 deposits [9–17].

In the present study, 1.0 mm diameter ER70S-6 mild-steel wire was employed for preliminary Wire-DED and WAAM manufacturing trials. The experiments were conducted to gain practical experience with the robotic manufacturing systems, establish wire-feeding and layer-deposition procedures, investigate suitable operating conditions, and evaluate the practical characteristics of the two manufacturing routes before progressing to NiTi Wire-DED experiments. Parameter selection considered both the operating limits of the manufacturing systems and processing conditions reported for ER70S-6 in the literature. Accordingly, these trials were intended as a systematic preparatory stage rather than a comprehensive material-property or formal process-optimization study.

This study therefore examines the system configurations, working principles, principal process variables, and preliminary implementation of Wire-DED and WAAM. Particular emphasis is placed on robotic system operation, stable deposition, progressive adjustment of process parameters, and identification of practical operating conditions. The experience gained provides an experimental and methodological foundation for subsequent NiTi Wire-DED investigations within the broader research program.

2. FUNDAMENTALS OF WIRE-BASED METAL ADDITIVE MANUFACTURING

The fundamental operating principles of the two wire-based additive manufacturing routes considered in this study are schematically compared in Fig. 1. Although both processes employ continuous metallic wire as feedstock and produce components through successive track and layer deposition, they differ fundamentally in the mechanism used to generate the melt pool. In Wire-DED, the wire is supplied to a localized melt pool generated by concentrated laser energy, whereas in WAAM, the feedstock wire is melted using an electric arc.

2.1. Wire-Directed Energy Deposition (Wire-DED)

Wire-directed energy deposition (Wire-DED) is a DED-based metal additive manufacturing process in which continuous metallic wire is supplied to a localized melt pool generated by concentrated laser energy. The synchronized control of laser power, wire-feed rate, travel speed, and robotic motion enables successive tracks and layers to be deposited according to a predefined tool path [2–5]. Compared with powder-fed systems, wire feedstock provides high material utilization and simplified material handling while avoiding issues associated with loose powder delivery [2–4].

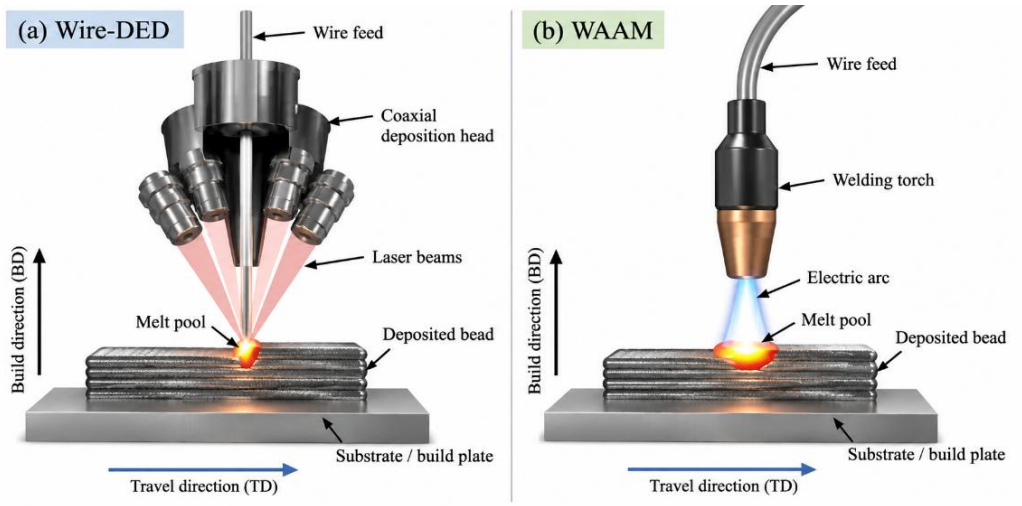


Fig. 1. *Schematic representation of the operating principles of: (a) Wire-DED and (b) WAAM.*

In robotic Wire-DED systems, the deposition head, wire-feeding mechanism, energy source, shielding system, and robotic motion operate as an integrated manufacturing platform. Process variables such as laser power, wire-feed rate, travel speed, layer height, shielding conditions, and deposition strategy directly affect melt-pool stability, bead formation, and layer geometry [3–5, 9]. As illustrated in Fig. 1(a), the process relies on the coordinated interaction of continuous wire feeding, localized laser energy, melt-pool formation, and controlled deposition motion.

2.2. Wire Arc Additive Manufacturing (WAAM)

Wire arc additive manufacturing (WAAM) employs an electric arc as the thermal energy source and continuously supplied metallic wire as the feedstock. The wire is melted within the arc-generated melt pool and deposited as successive beads to produce a three-dimensional component layer by layer [6–8]. The process can be integrated with industrial robotic systems and is particularly suitable for relatively large metallic components and high-deposition-rate applications [6–8].

The repeated thermal cycles generated during successive deposition make heat accumulation and interlayer thermal conditions important considerations in WAAM. Process variables such as welding current and voltage, wire-feed rate, travel speed, shielding conditions, deposition strategy, and interlayer dwell time influence bead formation and layer development [6–8,11–17]. As illustrated in Fig. 1(b), WAAM follows the same general wire-fed layer-by-layer manufacturing principle as Wire-DED but employs an electric arc to generate the melt pool.

3. EXPERIMENTAL MANUFACTURING PLATFORM AND PROCESS CONFIGURATIONS

3.1. Feedstock Material

The preliminary Wire-DED and WAAM manufacturing trials were conducted using 1.0 mm diameter Meltio Mild Steel ER70S-6 wire, classified according to AWS A5.18. The wire was supplied in uncoated condition on a BS300 spool. According to the manufacturer's material datasheet, the feedstock has a density of 7.8 g/cm³ and a nominal composition of Fe balance, 0.07 wt.% C, 1.45 wt.% Mn, 0.85 wt.% Si, 0.02 wt.% S, and 0.01 wt.% P [18]. The principal specifications and nominal chemical composition are summarized in Table 1.

The same ER70S-6 wire was used for both manufacturing routes to provide a common material basis for the preliminary implementation and comparative assessment of Wire-DED and WAAM.

Table 1. *Specifications and nominal chemical composition of the ER70S-6 wire used in the preliminary manufacturing trials [18].*

Property	Specification / nominal value
Feedstock	Meltio Mild Steel
Classification	ER70S-6 / AWS A5.18
Wire diameter	1.0 mm
Wire condition	Uncoated
Spool type	BS300
Density	7.8 g/cm³
Fe	Balance
C	0.07 wt.%
Mn	1.45 wt.%
Si	0.85 wt.%
S	0.02 wt.%
P	0.01 wt.%

3.2. Robotic Wire-DED System Configuration

The preliminary Wire-DED trials were performed using a robot-integrated Wire-DED system equipped with a Meltio deposition unit. The deposition head was integrated with an industrial robotic arm to provide controlled multi-axis motion during deposition. The system combines continuous wire feeding, concentrated laser energy, shielding, cooling, and robotic motion within a coordinated manufacturing platform. An overall view of the robotic Wire-DED system is shown in Fig. 2(a), while Fig. 2(b) presents the deposition head and build region. The wire is delivered coaxially toward the processing zone, while multiple laser beams are arranged around the wire to generate a localized melt pool [5].

During the preliminary trials, the 1.0 mm ER70S-6 wire was continuously supplied to the laser-generated melt pool while the robotic arm followed the programmed deposition path. The coordinated interaction of wire feeding, laser energy, and robotic motion enabled track and subsequent layer formation. The coaxial wire-delivery architecture reduces directional dependence and facilitates multi-directional robotic deposition [3, 5]. A representative first-layer deposition obtained during the preliminary trials is shown in Fig. 2(c).

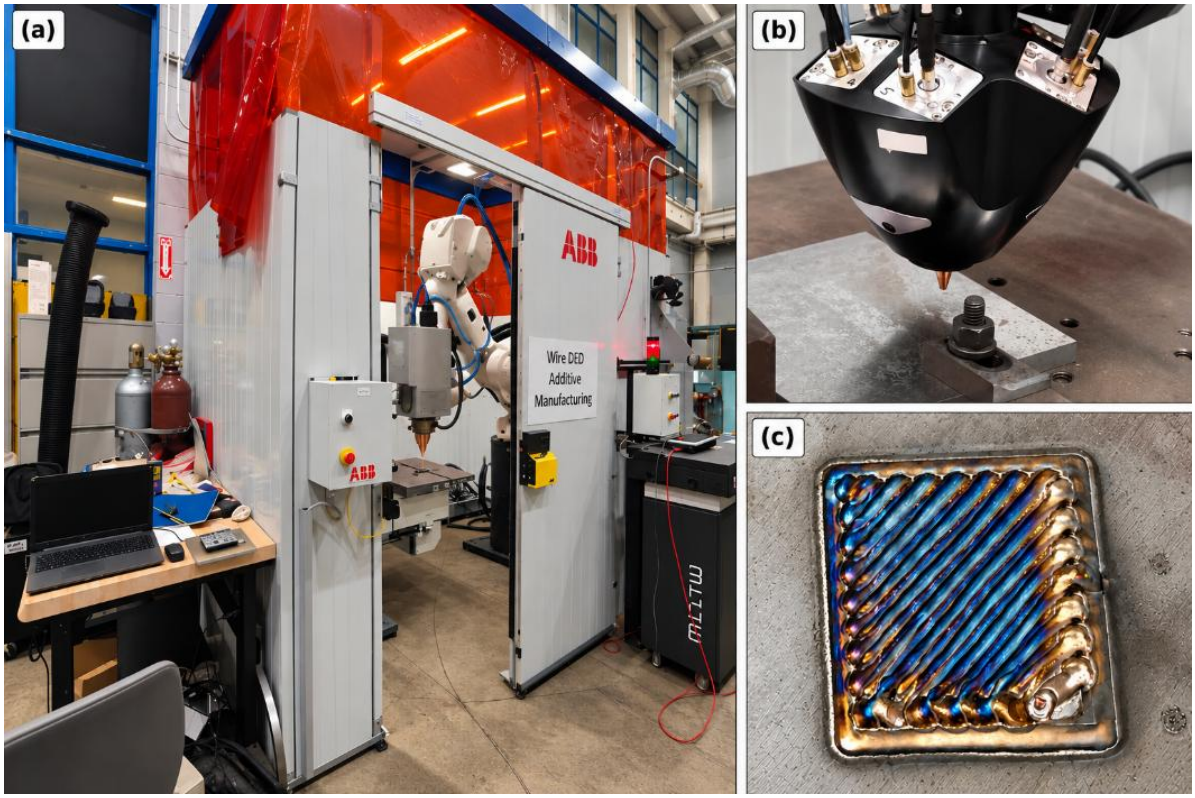


Fig. 2. *Experimental robotic Wire-DED system used in the preliminary ER70S-6 trials: (a) overall manufacturing cell, (b) deposition head and build region, and (c) representative first-layer deposition.*

3.3. Robotic WAAM System Configuration

The preliminary WAAM trials were performed using a robot-integrated wire arc additive manufacturing system, in which continuous metallic wire was deposited using an electric arc as the heat source. The system consisted principally of an industrial robotic manipulator, welding torch and power source, wire-feeding unit, shielding-gas supply, substrate, and associated control equipment. An overall view of the robotic WAAM system is shown in Fig. 3(a), while Fig. 3(b) presents a closer view of the deposition system and build region.

As in the Wire-DED trials, 1.0 mm ER70S-6 wire was used as the feedstock, providing a common material basis for the preliminary implementation of the two manufacturing routes. During WAAM, the continuously supplied wire was melted by the electric arc and deposited along the programmed robotic tool path. The coordinated control of wire feeding, arc energy, travel speed, and robotic motion enabled successive bead and layer formation. Representative ER70S-6 deposits obtained during the preliminary WAAM trials are shown in Fig. 3(c).

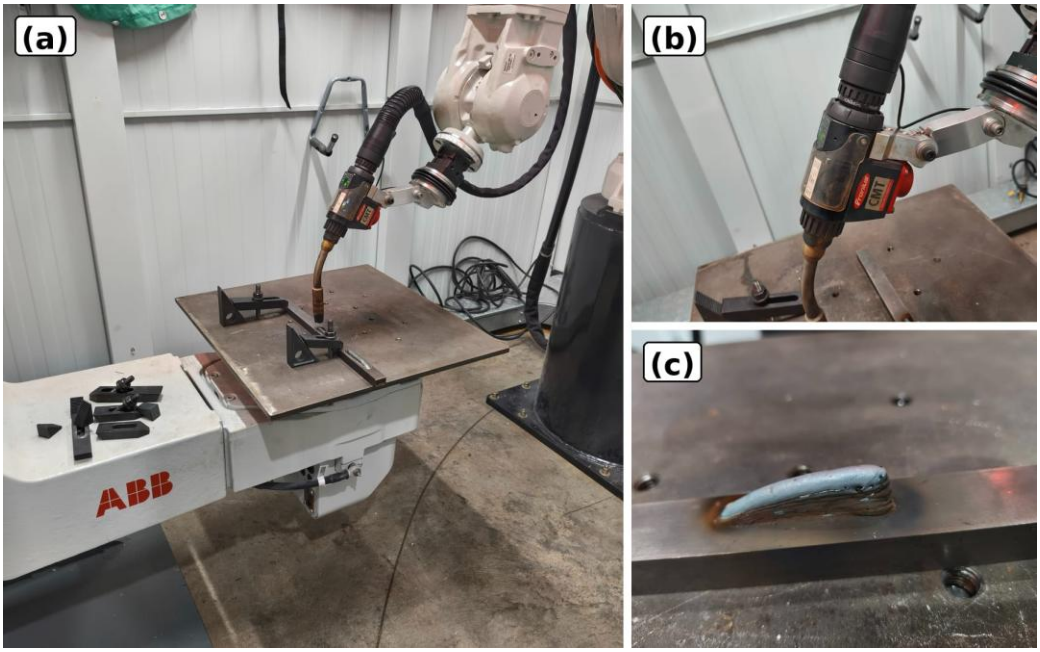


Fig. 3. *Experimental robotic WAAM system used in the preliminary ER70S-6 trials: (a) overall robotic WAAM system, (b) deposition system and build region, and (c) representative ER70S-6 deposits obtained during the preliminary trials.*

3.4. Process Parameters and Operating Variables

The preliminary manufacturing trials were designed to investigate the practical operating behavior of the robotic Wire-DED and WAAM systems before the subsequent NiTi Wire-DED experiments. Parameter selection was based on three complementary sources: the operating capabilities of the experimental systems, manufacturer-recommended conditions for ER70S-6, and processing conditions reported in the literature. The objective was not to conduct a formal statistical optimization of ER70S-6, but to progressively establish stable deposition conditions and identify suitable operating ranges.

For Wire-DED, the principal variables considered were laser power, wire-feed speed, robotic travel speed, shielding-gas flow rate, layer height, deposition path, and interlayer conditions. These variables govern the balance between energy input and material delivery and consequently influence melt-pool stability, wire melting,

track continuity, and layer formation. For the 1.0 mm ER70S-6 wire used in this study, the manufacturer's reference processing conditions and representative parameter ranges reported in the literature were considered during the planning of the preliminary trials [9, 18]. These reference conditions are summarized in Table 2.

For WAAM, the principal operating variables included welding current and voltage, wire-feed speed, robotic travel speed, shielding-gas conditions, deposition strategy, and interlayer dwell time. Because the wire-melting behavior and heat input are closely associated with the arc conditions, the selection of WAAM parameters requires coordinated consideration of the electrical, wire-feeding, travel, and thermal variables [6–8, 10–17]. Representative ER70S-6 WAAM conditions reported in the literature are also included in Table 2.

Table 2. *Representative ER70S-6 processing conditions reported by the manufacturer and in the literature and considered as reference conditions for the preliminary trials.*

Process parameter	Wire-DED: ER70S-6 literature conditions	WAAM: ER70S-6 literature conditions
Feedstock	ER70S-6 [9,18]	ER70S-6 [10,17]; low-carbon steel [16]
Wire diameter	1.0 mm [18]	0.8 mm [17]; 0.9 mm [10]; 1.2 mm [16]
Energy source	Laser [9,18]	Electric arc [10,16,17]
Laser power	1100 W [18]; 1000–1500 W [9]	—
Welding current	—	80 A [16]; 300 A [17]
Welding voltage	—	Process- and equipment-dependent [6–8,10,16,17]
Travel speed	7.5 mm/s [18]; 6–12 mm/s [9]	120–180 mm/min (2–3 mm/s) [17]; 400 mm/min (6.67 mm/s) [16]
Wire-feed speed	9.6 mm/s (0.576 m/min) [18]; 1.5–3.0 m/min [9]	5.5 m/min [17]; process-dependent [10,16]
Shielding gas	Ar [18]	99.99% Ar [17]; 82% Ar + 18% CO_2 [16]
Shielding-gas flow rate	10 L/min [18]	12 L/min [17]; 15 L/min [16]
Layer height / thickness	1.0 mm [18]	Process-dependent [10,16,17]
Interlayer dwell time	Geometry- and thermal-history-dependent	0, 60 and 120 s [16]
Principal control variables	Laser power, wire-feed speed, travel speed, layer height, shielding conditions [3–5,9,18]	Current/voltage, wire-feed speed, travel speed, shielding conditions, interlayer thermal control [6–8,10,16,17]

Accordingly, the preliminary experiments followed a progressive parameter-selection strategy in which manufacturer recommendations and literature-reported ER70S-6 processing conditions provided an initial reference framework, while subsequent adjustments were guided by the observed deposition behavior. This approach was used to explore practical operating conditions for both robotic manufacturing systems before the subsequent NiTi Wire-DED experiments.

4. PRELIMINARY MANUFACTURING TRIALS

Following the establishment of the manufacturing configurations described in Section 3, preliminary deposition trials were conducted using 1.0 mm ER70S-6 wire to evaluate the practical operation of the robotic Wire-DED and WAAM systems. These experiments were intended as a preparatory process-development stage rather than a comprehensive material-characterization or statistical optimization

study. The primary objectives were to establish stable deposition procedures, examine track and layer formation, and progressively identify practical operating conditions for subsequent experimental work. In the Wire-DED trials, particular attention was given to the coordinated interaction of wire feeding, laser energy, and robotic travel. Initial trials focused on achieving stable wire–melt-pool interaction and continuous track formation, including the representative first-layer deposition shown in Fig. 2(c). In the WAAM trials, the corresponding emphasis was placed on stable arc and wire deposition, coordinated robotic travel, continuous bead formation, and successive layer development, as represented by the deposits shown in Fig. 3(c). For both processes, operating conditions were progressively adjusted with reference to the system capabilities and the ER70S-6 processing conditions summarized in Table 2. The preliminary trials highlighted the different practical control requirements associated with the two energy-delivery mechanisms. Wire-DED required coordinated control of laser energy, wire feeding, robotic travel, and wire positioning relative to the localized melt pool, whereas WAAM additionally required control of arc-related conditions and interlayer thermal accumulation. Overall, the trials provided practical experience in robotic system operation, wire delivery, energy–material interaction, track and layer formation, and parameter adjustment, establishing the experimental basis for the subsequent NiTi Wire-DED investigations within the broader research program.

5. COMPARATIVE ASSESSMENT AND PROCESS SELECTION

As summarized in Table 3, Wire-DED and WAAM share the fundamental requirements of continuous wire feeding, controlled robotic motion, shielding, and layer-by-layer deposition, but differ primarily in their energy-delivery mechanisms. Wire-DED employs concentrated laser energy and coaxial wire delivery, providing localized melt-pool formation and flexibility for multi-directional robotic deposition. In contrast, WAAM uses an electric arc, making deposition behavior strongly dependent on arc conditions, wire transfer, travel speed, and interlayer thermal accumulation. These differences result in distinct requirements for process control, tool-path planning, and thermal management [3, 5–8, 16, 17].

Table 3. *Comparative assessment of the principal characteristics of Wire-DED and WAAM based on the preliminary manufacturing trials and reported process characteristics [3–8, 16, 17].*

Characteristic	Wire-DED	WAAM
Feedstock form	Continuous metallic wire	Continuous metallic wire
Energy source	Concentrated laser energy	Electric arc
Robotic implementation	Multi-axis robotic deposition	Multi-axis robotic deposition
Principal process variables	Laser power, wire-feed speed, travel speed, layer height, shielding conditions	Current/voltage, wire-feed speed, travel speed, shielding conditions, interlayer thermal conditions
Energy–material interaction	Localized laser-generated melt pool	Arc-generated melt pool
Thermal input characteristics	More localized energy delivery	Broader arc-based thermal input
Deposition control	Strongly dependent on laser–wire–melt-pool interaction	Strongly dependent on arc stability, wire transfer, and thermal accumulation
Directional flexibility	Favored by coaxial wire delivery	Governed by torch, wire, and travel configuration
Layer development	Controlled track-by-track and layer-by-layer deposition	Successive weld-bead-based layer deposition
Interlayer thermal management	Important for stable multilayer deposition	Particularly important because of heat accumulation during successive arc deposition
Role in the present study	Primary preparatory platform for subsequent NiTi Wire-DED experiments	Comparative wire-based additive manufacturing route

Process selection should therefore consider the required deposition characteristics, energy input, thermal management, robotic flexibility, and component geometry rather than treating either process as universally superior. In the present research program, the preliminary ER70S-6 trials provided practical experience with both manufacturing routes and supported the selection of Wire-DED as the primary platform for the subsequent NiTi investigations, including the planned post-process and in-situ processing strategies.

6. CONCLUSIONS

This study presented the preliminary implementation and comparative assessment of robotic Wire-DED and WAAM using ER70S-6 steel wire as a preparatory stage for subsequent NiTi additive manufacturing experiments. The trials enabled practical evaluation of system operation, wire feeding, energy delivery, robotic motion, and track and layer formation for both manufacturing routes.

The preliminary trials highlighted the different process-control requirements associated with the two energy-delivery mechanisms. Wire-DED relies on the coordinated interaction of laser energy, wire feeding, and robotic motion, whereas WAAM additionally involves arc-related conditions and interlayer thermal accumulation. The experience gained from the ER70S-6 trials provided a practical basis for understanding the operating characteristics of both robotic manufacturing routes and for establishing suitable conditions for subsequent experimental work.

Future work will focus on NiTi Wire-DED manufacturing using the knowledge gained from these preliminary trials. The subsequent experimental program will investigate selected Wire-DED processing conditions together with post-process and in-situ processing strategies to evaluate their influence on the processing and resulting characteristics of Wire-DED-manufactured NiTi specimens.

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