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POST-PROCESS MAGNETIC FIELD-ASSISTED ANNEALING AND IN-SITU MAGNETIC FIELD APPLICATIONS IN WIRE-DED ADDITIVE MANUFACTURING: SYSTEM DESIGN AND IMPLEMENTATION

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Abstract

Wire-directed energy deposition (Wire-DED) provides a flexible route for manufacturing and repairing metallic components; however, its rapid and repeated thermal cycles can significantly influence the resulting microstructure and material properties. This study presents and comparatively evaluates two magnetic-field-assisted strategies for Wire-DED: post-process magnetic field-assisted annealing (MFA) and in-situ magnetic field-assisted processing. The post-process approach employs an existing laboratory-scale system incorporating a superconducting magnet and a custom heating arrangement, enabling controlled application of temperature and magnetic field after deposition. In contrast, the in-situ approach introduces a magnetic field directly into the deposition region during layer-by-layer manufacturing, integrating magnetic-field exposure with the thermal cycle generated by Wire-DED. The configurations, working principles, controllable process variables, implementation requirements, and practical limitations of both approaches are discussed, with particular attention to magnetic field strength and orientation, thermal conditions, exposure sequence, and process integration. The proposed framework establishes an experimental basis for subsequent comparative investigations of post-process and in-situ magnetic-field-assisted processing of Wire-DED-fabricated NiTi shape memory alloys and for evaluating their influence on processing–microstructure–property relationships.

Keywords: Wire-directed energy deposition (Wire-DED); magnetic field-assisted annealing (MFA); in-situ magnetic-field-assisted processing; NiTi shape memory alloy; additive manufacturing.

1. INTRODUCTION

Additive manufacturing (AM) has emerged as an important manufacturing approach for the fabrication, repair, and functional modification of metallic components with complex geometries. Among metal AM technologies, directed energy deposition (DED) is particularly attractive for the production and repair of medium- to large-scale components because feedstock material is supplied directly into a localized melt pool generated by a concentrated energy source [1,2]. Wire-fed DED offers additional advantages such as high material utilization, relatively high deposition efficiency, and suitability for large-volume metallic components [2, 3]. Recent developments in wire-laser directed energy deposition (Wire-DED) have further expanded its potential for near-net-shape manufacturing and repair applications [3, 4].

Despite these advantages, the layer-by-layer nature of DED produces a complex thermal history involving localized melting, rapid solidification, repeated heating and cooling, and heat accumulation between successive layers. These thermal conditions influence melt-pool behavior, solidification characteristics, grain morphology, phase

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formation, residual stresses, and the resulting material properties [1, 4]. Consequently, controlling the thermal history and solidification behavior remains an important challenge in wire-fed DED.

Post-processing heat treatments are commonly employed to modify the microstructure and properties of additively manufactured components [2, 5]. An additional approach is the application of an external magnetic field either during post-processing or directly during deposition. Interactions between an applied magnetic field and the electrically conductive molten material can influence melt-pool convection, heat and mass transfer, and solidification behavior [6–8]. Recent investigations have demonstrated the feasibility of incorporating externally generated magnetic fields into DED processes, including wire-laser DED [7–9].

In this context, two different magnetic-field-assisted processing strategies can be considered, as schematically illustrated in Fig. 1. In post-process magnetic field-assisted annealing (MFA), the previously deposited component is subjected to a controlled thermal cycle under an externally applied magnetic field. In contrast, in-situ magnetic field-assisted processing introduces the magnetic field directly into the deposition region during melting and solidification. The former enables independent control of magnetic and thermal treatment conditions after fabrication, whereas the latter integrates magnetic-field exposure directly with the Wire-DED thermal cycle.

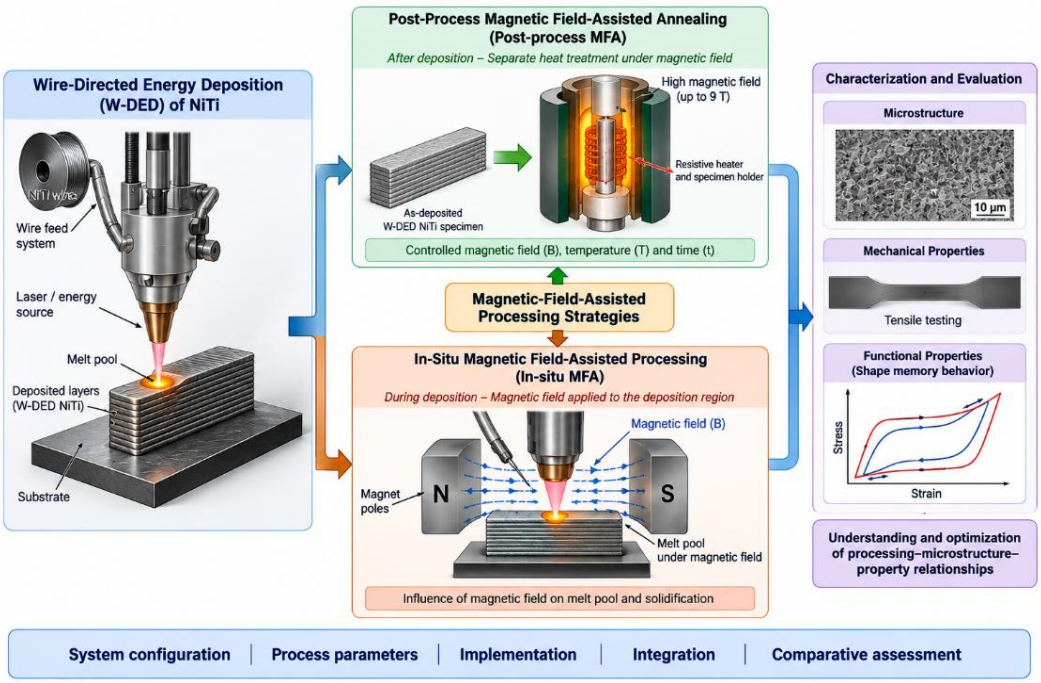


Fig. 1. *Conceptual framework of post-process and in-situ magnetic-field-assisted processing strategies for wire-directed energy deposition.*

The distinction between these approaches is particularly relevant for functional materials such as NiTi shape memory alloys, whose microstructure, phase transformation characteristics, and functional response are strongly dependent on processing and thermal history [10]. As illustrated in Fig. 1, magnetic-field-assisted processing introduces an additional process variable either during Wire-DED fabrication or during subsequent post-processing, providing a framework for investigating processing – microstructure–property relationships. However, the physical

conditions associated with post-process and in-situ magnetic-field exposure are fundamentally different and therefore require different system configurations and implementation strategies.

Accordingly, the present study describes and comparatively assesses two magnetic-field-assisted processing strategies in the context of Wire-DED additive manufacturing: a post-process MFA system based on a high-field magnetic processing facility with controlled thermal treatment, and an in-situ magnetic-field system intended for integration with the Wire-DED deposition region. Rather than reporting material-property results, the study focuses on system configuration, operating principles, controllable process parameters, implementation, and process integration. The resulting framework establishes the experimental basis for subsequent investigations of post-process and in-situ magnetic-field-assisted processing of NiTi shape memory alloys fabricated by Wire-DED.

2. MAGNETIC FIELD-ASSISTED PROCESSING

2.1. Fundamentals of Magnetic Field-Assisted Processing

External magnetic fields provide an additional process variable in metal additive manufacturing. During DED, interactions between the applied magnetic field and the electrically conductive molten material can influence melt-pool convection, heat and mass transfer, and solidification behavior [6, 11, 12]. Experimental studies have also demonstrated that magnetic-field conditions can affect melt-pool behavior and microstructural evolution during DED [7–9].

2.2. Main Process Parameters

Magnetic-field-assisted processing is governed by the combined effects of magnetic, thermal, temporal, and spatial variables. For in-situ applications, these variables additionally interact with the conventional Wire-DED processing conditions. The principal parameters considered within the present framework are summarized in Table 1.

Table 1. *Principal parameters considered in magnetic-field-assisted Wire-DED processing.*

Parameter group	Principal variables	Applicable approach
Magnetic	Magnetic-field strength (B), field orientation	Post-process / In-situ
Thermal	Treatment temperature, heating rate, cooling conditions	Primarily post-process
Temporal	Holding/exposure time, field-application sequence	Post-process / In-situ
Spatial	Specimen position, field-source distance, field orientation relative to the specimen/deposition zone	Post-process / In-situ
Wire-DED process	Energy input, wire-feed rate, travel speed, deposition strategy, interlayer thermal history	In-situ
Integration	Relative position of field source, melt pool, wire, substrate, and deposition direction	In-situ

In post-process MFA, the magnetic and thermal variables can be controlled largely independently of the preceding deposition process. In the in-situ approach, however, magnetic-field parameters become directly coupled with the Wire-DED process and its transient thermal history. This distinction determines the different system configurations described in the following sections.

3. POST-PROCESS MAGNETIC FIELD-ASSISTED ANNEALING SYSTEM

3.1. System Configuration and Experimental Setup

The post-process MFA configuration is based on the high-field magnetic processing facility available at the University of Kentucky. The experimental platform incorporates a superconducting magnet

capable of generating magnetic fields up to 9 T, together with a custom heating arrangement for the simultaneous application of magnetic and thermal conditions. This configuration enables additively manufactured specimens to be subjected to a prescribed magnetic field and thermal cycle after completion of the deposition process. The main components of the experimental setup include the magnet and heating assembly, specimen stage and holder, temperature-control unit, thermocouples, equipment cooling system, and associated power, instrumentation, and monitoring equipment. The overall laboratory configuration and the principal components of the post-process MFA system are shown in Fig. 2.

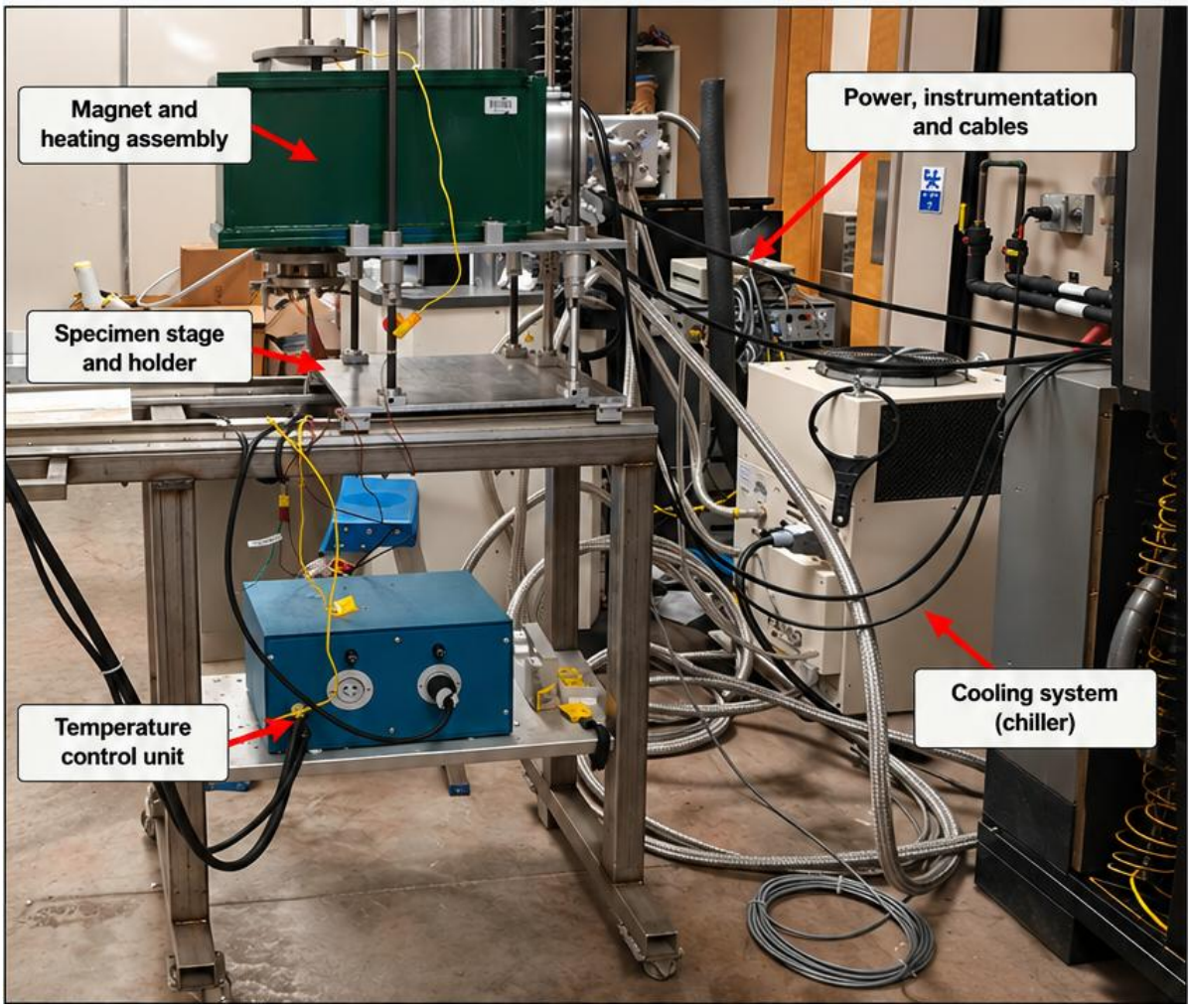


Fig. 2. *Laboratory setup of the post-process magnetic field-assisted annealing system.*

For magnetic-field-assisted heat treatment, the specimen is positioned within the designated treatment region and its temperature is monitored during the prescribed thermal cycle. A schematic representation of the heating and specimen arrangement is presented in Fig. 3. The cross-sectional representation in Fig. 3(a) illustrates the relative positioning of the magnetic-field region, heating assembly, specimen holder, specimen, and temperature-monitoring elements, while the enlarged view in Fig. 3(b) provides further detail of the specimen region. This arrangement provides the experimental basis for controlling the magnetic and thermal conditions during post-process MFA.

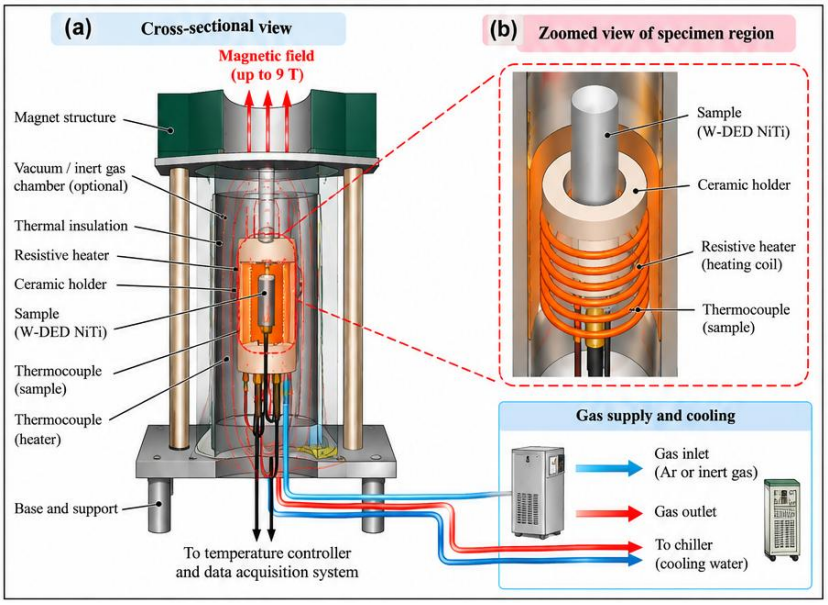


Fig. 3. *Schematic of the heating and specimen arrangement inside the magnetic field region: (a) cross-sectional view and (b) enlarged view of the specimen region.*

3.2. Working Principle

In the post-process configuration, the Wire-DED fabricated specimen is positioned within the designated treatment region of the magnetic-field system. The required magnetic field strength and thermal cycle are then defined according to the selected treatment conditions. The specimen is heated to the prescribed temperature and maintained at this temperature for the specified holding time under the applied magnetic field. Following the holding period, the specimen is removed from the MFA system and subsequently cooled outside the system. The overall operating sequence of the post-process MFA approach is schematically illustrated in Fig. 4.

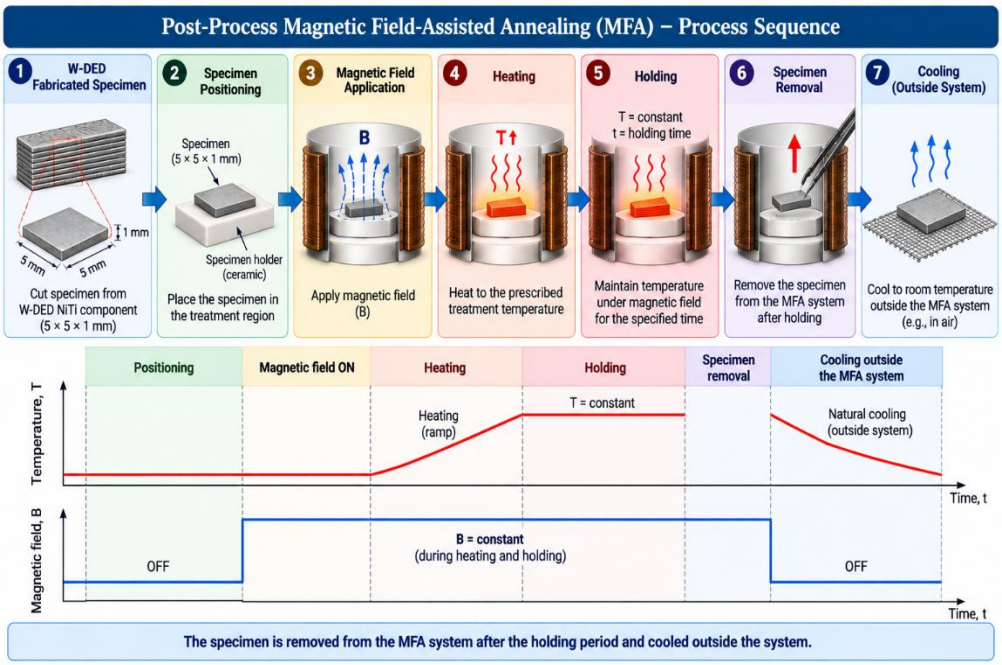


Fig. 4. *Schematic operating sequence of post-process magnetic field-assisted annealing, showing specimen positioning, magnetic-field application, heating, holding, specimen removal, and subsequent cooling outside the MFA system.*

Unlike the in-situ approach, magnetic-field exposure and thermal treatment are performed after completion of the Wire-DED process. Consequently, the magnetic and thermal treatment parameters can be prescribed independently of the original deposition conditions, enabling controlled investigation of their subsequent effects on the deposited material.

3.3. Controllable Process Parameters

The post-process MFA system enables the magnetic and thermal treatment conditions to be defined independently of the preceding Wire-DED process. The principal controllable parameters and their functions within the post-process treatment are summarized in Table 2.

Table 2. *Controllable parameters of the post-process MFA system and their experimental functions.*

Parameter	Experimental function
Magnetic-field strength, B	Defines the magnitude of the applied magnetic field
Magnetic-field orientation	Defines the field direction relative to the specimen
Treatment temperature, T	Defines the thermal-treatment condition
Heating rate	Determines the rate at which the prescribed treatment temperature is reached
Holding time, t	Defines the duration of exposure at the prescribed treatment temperature
Field-application sequence	Defines the stages of the thermal cycle during which the magnetic field is applied
Specimen orientation	Defines the orientation of the specimen relative to the applied magnetic field
Specimen position	Defines the location of the specimen within the treatment region

The independent control of these parameters provides a systematic basis for designing post-process MFA experiments. In the present configuration, particular attention is given to the combined effects of magnetic-field strength, treatment temperature, and holding time, while specimen position and orientation are controlled to ensure consistent treatment conditions.

3.4. Application to Wire-DED Fabricated Components

The post-process MFA system is intended for the treatment of specimens produced by Wire-DED after completion of the deposition process. In the present framework, tensile, microstructural, and microhardness specimens are extracted from Wire-DED fabricated NiTi components by wire EDM. The tensile specimens have nominal dimensions of 25.4 × 6.4 × 1 mm, whereas the specimens for microstructural and microhardness characterization are 5 × 5 × 1 mm. Two sets of specimens are prepared for each experimental condition and subsequently subjected to post-process MFA.

As illustrated in Fig. 5, the proposed experimental route consists of Wire-DED fabrication, specimen preparation, post-process MFA, and subsequent material characterization. Following MFA treatment, the specimens can be evaluated using microstructural, microhardness, and mechanical characterization methods to investigate the effects of the selected magnetic and thermal processing conditions.

This workflow provides the basis for future systematic assessment of the relationships among Wire-DED processing, post-process MFA conditions, microstructure, and material properties.

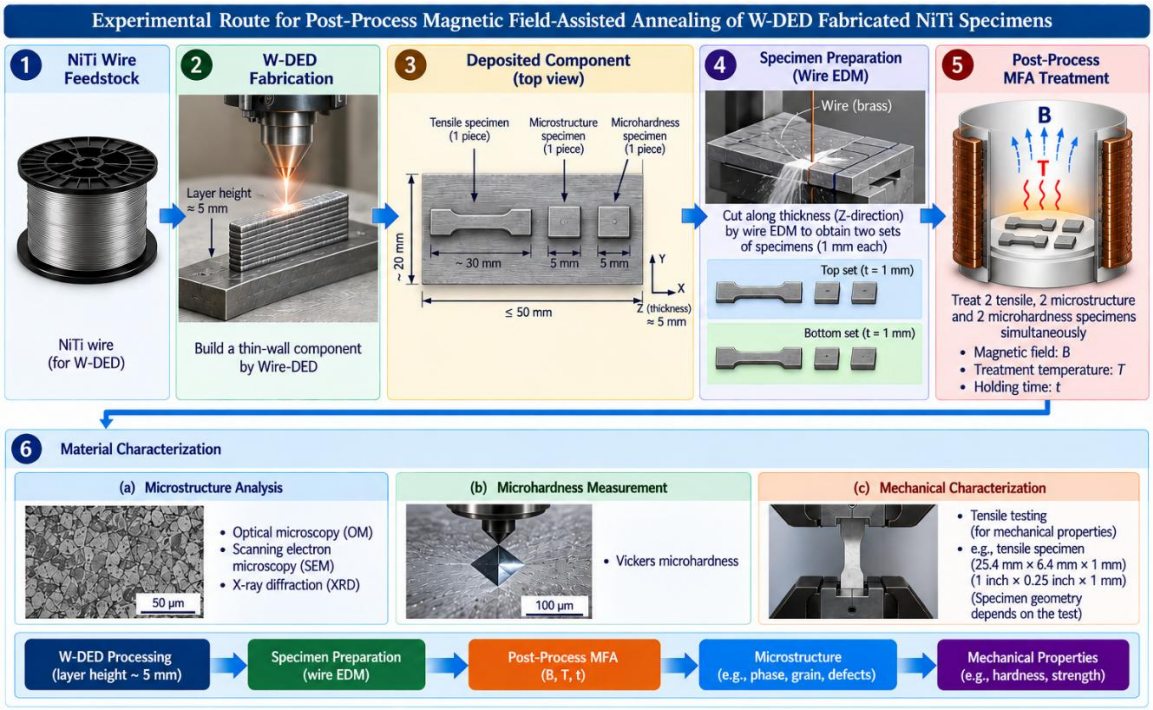


Fig. 5. *Experimental route for post-process magnetic field-assisted annealing of Wire-DED fabricated NiTi specimens and subsequent material characterization.*

4. IN-SITU MAGNETIC FIELD-ASSISTED SYSTEM

4.1. Motivation for an In-Situ Magnetic Field Approach

Post-process MFA enables independent control of magnetic-field and thermal-treatment conditions; however, the magnetic field is applied after completion of the deposition process and therefore does not directly interact with the melt pool during solidification. In contrast, previous studies have demonstrated that externally applied magnetic fields during DED can influence melt-pool behavior, solidification, and the resulting material characteristics [6–8]. Magnetic-field integration with wire-laser DED has also demonstrated the feasibility of applying a magnetic field directly during wire deposition [9]. Based on these considerations, an in-situ magnetic-field fixture was developed for integration with the Wire-DED system used in the present study.

4.2. Design, Manufacturing, and Assembly of the In-Situ Magnetic Field System

A dedicated fixture was designed to enable the application of an external magnetic field directly in the deposition region during Wire-DED. The fixture was designed using SolidWorks, with particular attention to maintaining an open central working region for the build plate and deposition process while positioning the magnetic-field components on opposite sides of the deposition zone. The design also provides sufficient accessibility for the Wire-DED deposition head and wire delivery without interfering with the deposition path.

Following the design stage, the fixture components were manufactured in the departmental machine shop and subsequently assembled into the configuration shown in Fig. 6(a). The assembled fixture consists of opposing structural sections, magnetic-field components, threaded rods, and transverse supporting members. The threaded connections facilitate assembly and positional adjustment, while the central opening provides the working space required for installation of the build plate/substrate. As shown in Fig. 6(b), the build plate is positioned within the central region of the

fixture between the opposing magnetic-field components. The completed assembly was subsequently prepared for integration with the Wire-DED system. An initial implementation of the developed fixture during wire deposition is illustrated in Fig. 6(c), where the Meltio Wire DED head operates over the build plate while the magnetic-field components are positioned adjacent to the deposition region. This configuration enables magnetic-field exposure to be introduced directly during material deposition and provides the experimental platform for subsequent in-situ magnetic-field-assisted Wire-DED investigations.

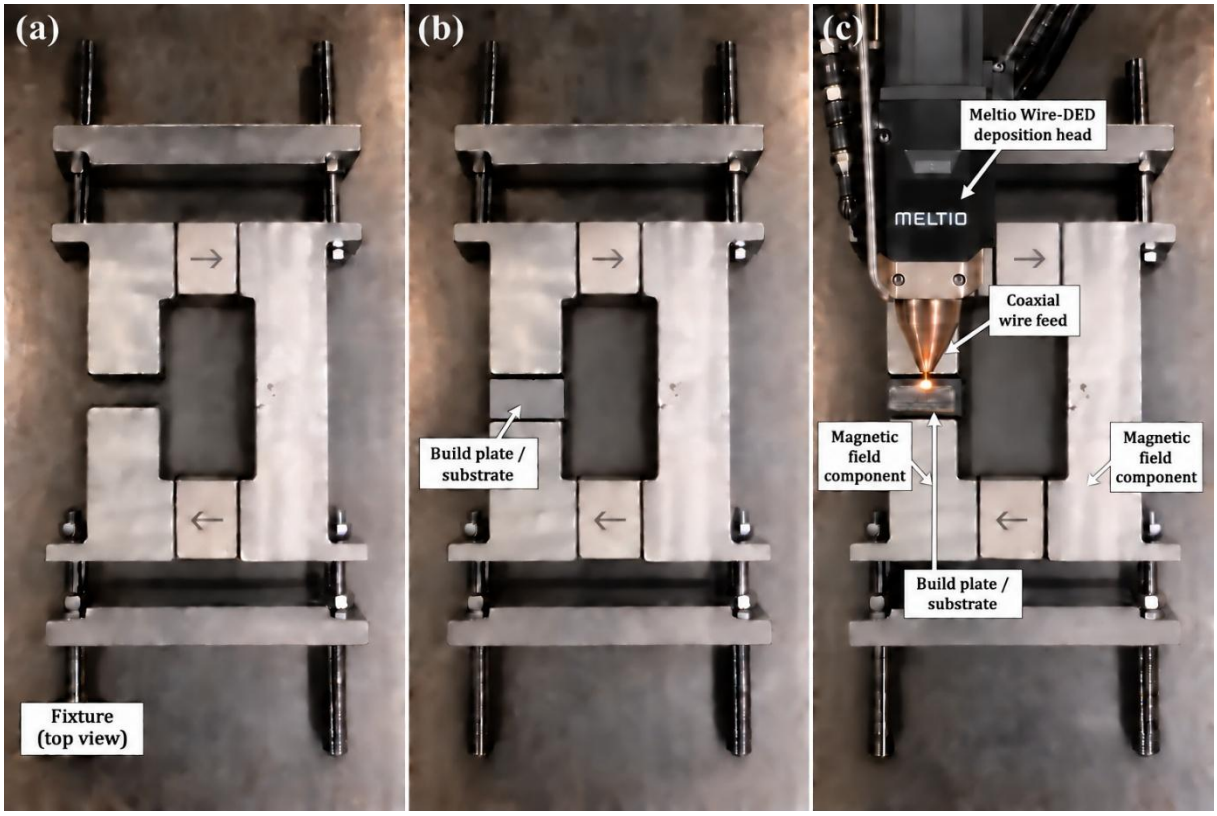


Fig. 6. *In-situ magnetic field fixture for Wire-DED: (a) top view of the fixture, (b) top view with the build plate/substrate installed, and (c) in-situ magnetic field-assisted Wire-DED during wire deposition using the Meltio Wire DED head.*

4.3. Integration and Application of the In-Situ Magnetic Field System with Wire-DED

The developed in-situ magnetic-field fixture was designed for integration with the Meltio-based Wire-DED system. During integration, the fixture is positioned relative to the deposition system so that the build plate is located within the central working region, while the magnetic-field components are positioned on opposite sides of the deposition zone. This arrangement allows the Wire-DED deposition head to access the build surface while maintaining the magnetic-field source in close proximity to the region in which melting and solidification occur.

As illustrated in Fig. 6(c), the Meltio Wire DED head operates above the build plate while the magnetic-field fixture surrounds the deposition region, maintaining access for the deposition head and wire delivery. In this configuration, magnetic-field exposure is applied directly during wire deposition rather than after completion of the manufacturing process. Consequently, the deposited material is exposed to the magnetic field during the transient thermal cycle associated with melting, solidification, and subsequent layer deposition.

The integrated configuration therefore provides a platform for systematically investigating in-situ magnetic-field-assisted Wire-DED. In subsequent experiments, the effects of magnetic-field conditions can be examined together with conventional Wire-DED process parameters and compared with specimens subjected to post-process MFA. This approach enables the two magnetic-field-assisted processing strategies to be evaluated within a common Wire-DED experimental framework.

5. COMPARISON OF POST-PROCESS AND IN-SITU MAGNETIC FIELD-ASSISTED APPROACHES

The post-process and in-situ approaches represent two different strategies for introducing magnetic-field effects into the Wire-DED manufacturing route. In post-process MFA, magnetic-field exposure is applied after completion of the deposition process together with a prescribed thermal treatment. In contrast, the in-situ approach introduces the magnetic field directly into the deposition region during Wire-DED, allowing magnetic-field exposure to coincide with melting, melt-pool evolution, and solidification. Previous studies have demonstrated that externally applied magnetic fields during DED can influence melt-pool flow, heat and mass transfer, solidification conditions, and deposition behavior [6, 7, 9, 11, 12]. The principal differences between the two approaches considered in the present study are summarized in Table 3.

Table 3. *Comparison of post-process MFA and in-situ magnetic field-assisted processing for Wire-DED.*

Comparison criterion	Post-process MFA	In-situ magnetic field-assisted Wire-DED
Stage of magnetic-field application	After Wire-DED	During Wire-DED [7,9]
Thermal condition	Prescribed post-process thermal treatment	Transient thermal cycle generated during deposition [9,11,12]
Interaction with melt pool	No direct interaction	Magnetic field applied to/near the active deposition and melt-pool region [6,7,9,12]
Magnetic-field control	Prescribed independently after deposition	Integrated with deposition conditions [7,9]
Temperature control	Independently prescribed during post-treatment	Primarily governed by Wire-DED thermal conditions
Exposure duration	Defined by the prescribed treatment time	Coupled to deposition sequence and local thermal history
Material condition	Previously deposited material	Material during melting and solidification
System configuration	Separate magnetic-field and heating system	Magnetic-field source integrated around the deposition region [7,9]
Process integration	Separate post-processing operation	Integrated directly with DED/Wire-DED [7,9]
Primary experimental role	Investigation of magnetic-field-assisted post-treatment	Investigation of magnetic-field interactions during deposition [6,7,9,11,12]

The comparison in Table 3 indicates that the two approaches expose the material to fundamentally different magnetic and thermal histories. In particular, previous magnetic-field-assisted DED studies have shown that applying a magnetic field during deposition can modify melt-pool convection, heat and mass transfer, metal-transfer behavior, and solidification conditions [6, 7, 9, 11, 12]. In contrast, the post-process configuration considered in the present study separates magnetic-field-assisted thermal treatment from the Wire-DED process. Therefore, the two configurations are considered complementary experimental strategies rather than interchangeable processing routes. Their implementation within a common Wire-DED framework provides a basis for subsequent comparative

investigation of their effects on the microstructure, mechanical properties, and functional behavior of deposited NiTi materials.

6. POTENTIAL APPLICATIONS, ADVANTAGES, AND LIMITATIONS

Magnetic-field assistance provides an additional processing variable that can be introduced either after fabrication or directly during Wire-DED. In particular, previous investigations have demonstrated the feasibility of applying external magnetic fields during DED and have reported interactions with melt-pool flow, solidification behavior, and material evolution [6, 7]. More recently, the integration of a magnetic-field source with wire-laser DED has also demonstrated the practical feasibility of applying magnetic fields directly during wire deposition [9]. The principal advantage of the post-process MFA approach developed in this study is the independent control of the magnetic-field and thermal-treatment conditions. Magnetic-field strength, treatment temperature, holding time, and specimen orientation can therefore be prescribed without modifying the original Wire-DED operation. However, because the treatment is performed after deposition, this approach cannot directly influence the melt pool or the solidification stage. In contrast, the in-situ configuration enables magnetic-field exposure during material deposition and therefore provides an opportunity to interact with the transient conditions associated with melting and solidification. Numerical investigations have also indicated that magnetic fields can modify heat and mass transfer within DED melt pools [11, 12]. The main limitation of this approach is the increased complexity of process integration, since the magnetic-field fixture must operate in close proximity to the deposition zone without restricting the motion of the deposition head or interfering with wire delivery and the deposition path.

For NiTi shape memory alloys, the two configurations provide complementary experimental routes for investigating magnetic-field effects at different stages of the Wire-DED process chain. Potential changes in microstructure, mechanical response, and functional behavior will therefore be investigated systematically in subsequent experimental work rather than assumed from the present system-level study.

7. CONCLUSIONS

This study presented the design and implementation of post-process and in-situ magnetic field-assisted processing strategies for Wire-DED. The main conclusions are summarized as follows:

1. A post-process MFA system was established for applying prescribed magnetic-field and thermal-treatment conditions to Wire-DED fabricated specimens after deposition.
2. A dedicated in-situ magnetic-field fixture was designed in SolidWorks, manufactured, assembled, and prepared for integration with the Wire-DED system.
3. The in-situ configuration enables the magnetic field to be applied directly within the deposition region during Wire-DED, whereas post-process MFA is performed after fabrication.
4. The two approaches provide complementary experimental strategies, enabling magnetic-field exposure at different stages of the Wire-DED process chain.
5. The developed systems establish an experimental platform for the comparative investigation of magnetic-field-assisted processing of Wire-DED fabricated NiTi shape memory alloys.

Future work will focus on systematic post-process and in-situ experiments followed by microstructural, microhardness, and tensile characterization to investigate the relationships among magnetic-field conditions, Wire-DED processing, microstructure, and material properties.

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