

**ENHANCING THE MECHANICAL PROPERTIES OF DIRECTED ENERGY
DEPOSITION ARC (DED-Arc) VIA PROCESSING INNOVATIONS**

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Abstract: Directed Energy Deposition (DED) processes offer the advantage of producing larger parts with higher deposition rates compared to Powder Bed Fusion (PBF) additive manufacturing (AM). However, DED typically results in simpler geometries and lower resolution. When using Wire and Arc-based DED, even larger components can be manufactured at an accelerated rate, but the higher heat input may lead to undesirable microstructures, adversely affecting mechanical properties.

To ensure defect-free depositions, precise process control is essential, including optimizing deposition paths, regulating inter-layer temperature, and maintaining a consistent nozzle-to-layer distance. One effective approach to improving material integrity is the application of in-situ vibrations during deposition. This technique helps reduce porosity and grain size while also enhancing surface waviness and mitigating residual stress buildup. Further refinement of material properties can be achieved through appropriate thermo-mechanical processing, leading to mechanical characteristics comparable to conventionally produced steel. This paper explores the impact of in-situ vibrations and heat treatment through case studies, analysing their effects on surface waviness, residual stress distribution, porosity, microstructure, grain size, mechanical properties, and fracture toughness. The findings demonstrate the significant benefits of these process enhancements in improving the mechanical performance of DED-fabricated components.

Keywords: Directed Energy Deposition (DED); Wire and Arc Additive Manufacturing (WAAM); in-situ vibrations; heat treatment; porosity reduction; residual stress; grain refinement; surface waviness; mechanical properties; fracture toughness; Computed Tomography (CT) Scan.

1. INTRODUCTION

Additive Manufacturing (AM), often referred to as 3D printing, is a technology enabling the layer-by-layer construction of objects from digital designs [1]. Among the various AM processes, Direct Energy Deposition (DED) techniques are recognized for their efficiency, particularly in manufacturing large-scale components. Direct Energy Deposition-Arc (DED-Arc), also widely known as Wire Arc Additive Manufacturing (WAAM), represents a significant advancement in metal AM by leveraging mature welding technologies. This process utilizes an electric arc as the heat source to melt a metallic wire feedstock, which is then deposited layer upon layer using a computer numerical control (CNC) or robotic manipulator. Common arc-based welding processes like Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW) or high deposition processes as Tandem GMAW form the basis of many DED-Arc systems [2].

Compared to powder-based AM processes such as Powder Bed Fusion (PBF) and powder-fed DED-Laser Beam (DED-LB), which are often limited by small build chamber sizes and thin layer thicknesses (typically 3–30 μm), DED-Arc offers substantial advantages in terms of build size and deposition rate. DED-Arc can deposit material with layer thicknesses closer to 3 mm, leading to significantly faster build times – up to 100 times faster deposition rates than PBF [3]. This capability makes WAAM highly suitable for manufacturing medium-to-large complex parts, reducing material wastage and lead time while enabling customized designs. Other benefits include lower capital costs compared to some other metal AM techniques, efficient material utilization (reducing waste), and potential environmental advantages. DED-Arc also facilitates the production of complex geometries and near net shape parts, potentially eliminating the need for extensive tooling and re-fixturing. Specialties of the WAAM process include in-situ alloying and the production of functionally graded materials (FGMs) [4], [5].

Despite these compelling advantages, the DED-Arc process presents inherent challenges largely stemming from the high energy input and complex thermal cycles involved in melting and depositing metal wire at high rates. The localized heat input and subsequent cooling affect the deposited material's microstructure and can introduce defects and residual stresses. This can result in significant variations in material properties and dimensional inaccuracies. Consequently, extensive post-processing is often required to achieve the desired metallurgical characteristics, mechanical properties, and dimensional tolerances. The development of standardized procedures for DED AM is still underway, highlighting the complexities in ensuring consistent quality and performance [6].

This review will delve into the critical challenges faced by DED-Arc technology and explore the state-of-the-art research and solutions being developed to overcome these limitations, with a focus on in-situ processing with thermal management, process control, process

simulations, defect mitigation, path planning, and post-processing strategies.

2. CHALLENGES IN DIRECT ENERGY DEPOSITION-ARC

A primary challenge in DED-Arc originates from the high heat input associated with arc welding processes, material physical properties and the resulting complex thermal cycling during the layer-by-layer deposition process [7]. Each deposited layer is subjected to repeated heating and cooling from subsequent layers, leading to significant thermal gradients and distortions, which are related to physical and mechanical properties of material used [8]. This thermal environment has several detrimental consequences such as a) Residual Stresses and Distortion, b) Microstructural Non-homogeneity, c) Deposition defects, d) Surface Quality, d) Path Planning Limitations and e) Process Control.

The non-uniform heating and cooling inherent in DED-Arc generate significant residual stresses within the manufactured part. These stresses can lead to substantial distortion of the component, affecting dimensional accuracy and potentially requiring significant post-build straightening or stress relief treatments. Issues like the deformations and lifting of the base plate from the bench are observed in WAAM, which in extreme situations leads also to braking of the deposit from the base plate if later is firmly fixed. One solution for this is production of symmetrical parts with sequential deposition or simultaneous deposition [9].

The repeated thermal cycles and high cooling rates influence the solidification process and solid-state phase transformations [10]. This often results in a non-uniform microstructure throughout the deposited part, characterized by features like coarse columnar grains, and elongated grains especially in the as-deposited state. In addition, non-metallic inclusions, intermetallic phases and segregations occurs. Non-metallic inclusions and intermetallic phases often arise in AM primarily due to the distinct thermal cycles involving rapid heating and cooling rates. These conditions lead to non-equilibrium solidification and significant elemental segregation, where alloying elements concentrate in interdendritic areas. This localized chemical enrichment promotes the formation of secondary phases and intermetallic compounds, such as Laves phases in some nickel alloys or specific carbides and iron phases in steels depending on their composition [11]. The inherent chemical composition of the wire feedstock is also a determining factor in which phases are thermodynamically possible and likely to form under these conditions. The resulting as-built microstructure is typically inhomogeneous with these segregated regions and phases. Materials like maraging steel exhibit very long crystal grains and microsegregations oriented in the heat sink direction in the as-built state. This lack of microstructural homogeneity, including the presence of transitional layers or undesirable secondary phases, can compromise the mechanical properties and performance consistency of the material. Consequently, post-processing heat treatments are often applied to dissolve detrimental phases, homogenize the microstructure, and

promote desirable precipitate formation [10], [12]. If material microstructure cannot be repaired by a heat treatment a mechanical treatment such rolling, hammering or some sort of shot-peening is used to get more uniform microstructure.

The DED-Arc process is susceptible to various defects that can impair the integrity and performance of the manufactured part. Critical defects include porosity, lack of fusion, and cracking [13]. Porosity can result from issues like gas entrapment from shielding gas or moisture/hydrocarbon residue on the wire feedstock. A high purity material should be used together with careful storage and handling to avoid porosities. Lack of fusion can occur if insufficient heat input prevents proper melting between layers or tracks. Cracks, particularly solidification or liquation cracks, can form due to thermal stresses or unfavourable solidification microstructures and segregations [13]. Achieving high quality DED-Arc process parameters and control is essential to avoid these defects.

The nature of the arc welding process and the relatively large layer thickness in DED-Arc often lead to increased surface roughness and surface waviness compared to powder-based techniques. Temperature is a key factor in surface waviness, as excessive heat input, thermal gradients from rapid cooling, and interlayer temperature control influence molten metal spreading, solidification, and bead geometry, impacting waviness. Surface tension gradients, which drive Marangoni flow, can smooth the surface [14]. Material physical properties, including thermal expansion and surface energy characteristics influenced by composition and volatile elements, also affect wetting behaviour and shrinkage that contribute to the final surface profile. This typically necessitates extensive machining or other surface finishing operations as part of post-processing. Irregular grain geometry due to excessive heat input also contributes to the machining process and obtained surface roughness [15].

Traditional path planning methods for DED-Arc are often limited to 2.5 degrees of freedom (DOF), which can be inefficient and may require support structures for complex geometries. While 5-DOF path planning exists, its industrial implementation is still limited. The chosen deposition pattern can significantly impact mechanical effects, defect occurrence during the deposition, deposition shape and distortion due to of residual stresses [16].

Ensuring consistent and repeatable deposition quality, dimensional accuracy, and material properties requires precise control over numerous process parameters, including welding current, voltage, deposition speed, wire feed speed, shielding gas flow, and interpass temperature/time. Achieving robust and adaptive process control remains a challenge. FEM simulations can provide a valuable information for process control to meet the desired part shape, by optimizing deposition paths based on non-uniform temperature distribution of the layer. Simulations can additionally predict time of pauses between the depositions and manufacturing time, residual stresses and distortion [17].

These challenges collectively pose key knowledge gaps to the widespread adoption of DED-Arc, particularly for

high-performance applications where material integrity and dimensional accuracy are paramount.

3. STATE-OF-THE-ART RESEARCH AND SOLUTIONS

Significant research efforts are underway to address the challenges inherent in DED-Arc, focusing on improving in-situ: thermal management, enhancing process control, vibration assisted deposition to improve microstructure, mitigating defects, optimizing deposition strategies, and refining post-processing techniques.

3.1. Thermal management

Strategies to better manage the thermal environment are crucial for controlling microstructure and minimizing residual stress and distortion. Approaches include a) deposition with lower heat input, b) preheating, interlayer cooling and active cooling, and c) Advanced Simulation and Modelling (Figure 1) [18].

The Cold Metal Transfer (CMT) process, a modified version of GMAW-based WAAM, allows for lower heat input, which can reduce distortion, minimize the heat-affected zone (HAZ), and potentially decrease porosity. Heat input can also be minimized by using GTAW or PTA deposition, but deposition rate usually decreases and new challenges regarding off-centre wire deposition arise [19].

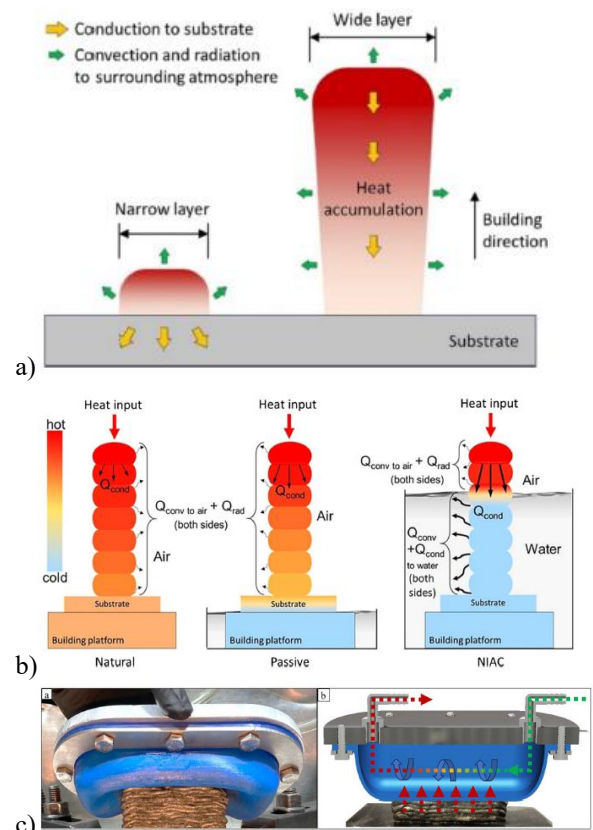


Figure 1: Schematic illustration a) of width variation along the height of a wall in DED-Arc without proper thermal management, and b) and c) different thermal management approaches [18].

Advanced thermal management techniques are crucial for controlling the heat flow during the build process and ensuring part quality and integrity [18]. Preheating the substrate helps to reduce thermal gradients between the base material and deposited layers, thereby minimizing residual stresses and the risk of cracking, particularly in high-strength alloys; this is typically achieved using electrical resistance heaters, induction heaters, or gas torches. Equally important is the control of interpass temperature, which involves pausing between layers, utilizing active cooling systems like fans or air jets, and monitoring temperatures through thermocouples or infrared sensors to prevent microstructural degradation. Active cooling systems, such as air or water-based cooling, and even cryogenic cooling with liquid nitrogen, are employed to dissipate heat rapidly and manage thermal gradients, especially in builds involving thermally conductive materials. Additionally, heat sink integration, either through high-conductivity inserts or by leveraging the build plate, assists in drawing heat away from critical regions [6]. Maintaining interpass temperatures above transformation thresholds—such as above the martensite start temperature or at levels like 250 °C depending on the welding parameters—is essential for achieving strong metallurgical bonding. Innovative in-situ cooling methods, like conformal conductive upper cooling, are under exploration to provide precise thermal regulation, potentially enabling as-deposited parts to achieve properties comparable to post-processed materials. While other approaches such as thermoelectric heat sinks and bypass arcs offer additional heat extraction mechanisms, they may introduce drawbacks like porosity or reduced upper-layer efficiency. Techniques like air jet impingement further exemplify the expanding toolkit for effective thermal management in DED-Arc AM, underscoring the potential for achieving high-performance, near-net-shape metal parts directly from the build process [6].

3.2. Vibration assisted deposition

In situ vibration techniques, including base plate vibration (Figure 2), wire vibration, and arc pulsing, have demonstrated significant potential in refining microstructures, reducing porosity, and enhancing mechanical properties of fabricated components [20]. Base plate vibration introduces mechanical energy that disrupts dendritic growth during solidification, leading to grain refinement and improved mechanical strength. For instance, applying in situ vibration during the deposition of low-carbon steel reduced the average grain size from 9.8 μm to 7.1 μm in fine-grain zones and from 10.6 μm to 7.4 μm in coarse-grain zones, resulting in a 10% increase in ultimate tensile strength and a 13.8% increase in yield strength [20]. Applying vibrations during DED-Arc deposition of AlMg5 led to a notable 25% reduction in grain size and reduced microstructural anisotropy. Vibrations also contribute to material homogenization, decreasing segregation and refining precipitate dispersion. Furthermore, gas porosity is substantially reduced, decreasing from $1.5 \pm 0.04\%$ in as-built parts to $0.34 \pm 0.07\%$ in vibration-assisted deposition. Base plate vibrations also improved the deposition shape and surface

quality improve by reducing surface waviness, while residual stress anisotropy decreased by 60% and tensile strength anisotropy is effectively eliminated. A slight increase in average hardness was also observed, due to grain refinement and solid solution strengthening [21]. Wire vibration, particularly through ultrasonic assistance, has been effective in disrupting columnar grain structures and promoting equiaxed grain formation. This technique enhances melt pool dynamics, leading to a more uniform microstructure and improved mechanical properties. In the fabrication of 2319 Al-Cu alloy, the integration of ultrasonic vibration with ZrO_2 particle addition resulted in a 13.8% increase in tensile strength and a 92.4% improvement in elongation, attributed to the uniform distribution of fine grains and precipitates [22]. Arc pulsing, involving the modulation of current and voltage during deposition, influences the thermal profile and solidification behavior of the molten pool. Adjusting pulse frequency and current has been shown to reduce porosity and refine grains in aluminum alloys. For example, in the deposition of AlSi5 alloy, increasing the pulse frequency to 50 Hz improved density and refined grains, leading to enhanced tensile strength [23]. Moreover, in the wire-arc DED of 7075 aluminum alloy, optimizing wire feeding rates and employing pulsed arc modes significantly reduced porosity by up to 95.8% and improved mechanical properties, achieving an ultimate tensile strength of 527.80 MPa and elongation of 7.57% after heat treatment [24]. These findings underscore the efficacy of in situ vibration techniques in DED-Arc processes. By tailoring vibration methods, whether through base plate oscillation, ultrasonic wire agitation, or arc pulsing, manufacturers can achieve refined microstructures, reduced porosity, and enhanced mechanical performance in additively manufactured metal components.

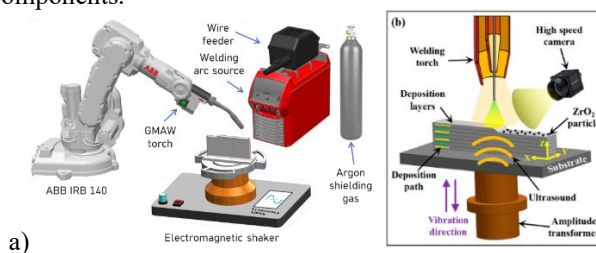


Figure 2: Schematic illustration vibrations-assisted DED-Arc process a) lower [21] and b) ultrasonic frequency [22].

3.3. Advanced process control

Process control is a critical aspect of DED-Arc essential for mitigating challenges such as high heat input and heat accumulation, which lead to issues like geometric inaccuracies, distortion, residual stress, and non-uniform microstructure and mechanical properties [25]. Effective process control aims to achieve precise, efficient weld quality, reduce human errors, and execute complex tasks with high accuracy and repeatability. Research focuses on various strategies to enhance part quality, geometric accuracy, and mechanical properties by managing these thermal effects. These strategies often involve the

development of both feedforward methods, which use process planning techniques to compensate for accumulated errors, and feedback methods, which utilize closed-loop control to improve building accuracy (Figure 3). Feedback control systems are commonly used to dynamically adjust welding parameters based on real-time sensor feedback signals. Control approaches range from maintaining constant parameters and optimizing travel speed or other parameters to implementing feedback loops for layer height or geometry control, adaptive process control, and dynamic in-process path replanning based on detected deviations [26]. Process control actions can be classified into various levels based on complexity and hierarchy, involving stages like sensor input, workpiece detection, path planning, trajectory generation, motion control, welding process control, feedback control, and error handling. The system can adapt parameters and make real-time adjustments to achieve the desired weld quality while effectively managing errors and faults by executing these steps [27], [28].

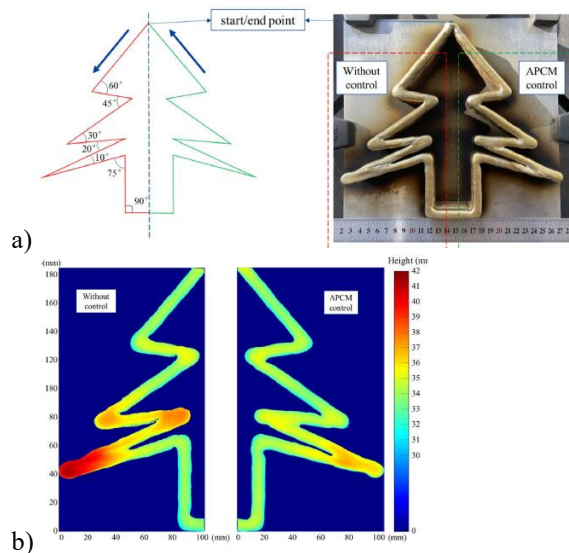


Figure 3: a) The component after depositing 15 layers and b) surface contour height without and with process control.

Sensor technologies play a crucial role in DED-Arc control systems, enabling real-time monitoring of welding parameters and ensuring optimal process control [27]. Sensors help improve weld accuracy and quality and ensure they meet desired specifications. Various types of sensors are utilized in welding robots, emphasizing their contribution to enhancing weld quality and overall system performance. Common monitoring techniques include the analysis of arc current, vision systems for tracking bead and melt pool geometry or layer height, temperature measurement using sensors like pyrometers or IR cameras, force sensors, arc sensors for process stability monitoring, current sensors for monitoring welding current, and distance or position sensors for CTWD or layer height measurement [29]. These sensors provide feedback data, such as joint positions, weld quality, and temperature, which are compared with desired values to generate error signals used by control algorithms. The controller then generates signals to actuators to adjust

welding parameters like torch position and wire feed rate. Sensors are critical in DED-Arc and multi-pass welding processes by providing real-time feedback, enabling the robot to adjust its movements, welding parameters, and heat input. Seam tracking in robotic welding, weld cladding and DED-Arc mainly relies on sensors to monitor and adjust the position of the welding torch precisely. Recent advancements include the use of novel sensors like the coherent range-resolved interferometry (RRI) sensor for capturing layer and wall shape information, which has been used in closed-loop layer-by-layer processes for wall height compensation [30]. Despite their importance, challenges such as sensor calibration, signal noise, and environmental interference have been identified, indicating the need for further research. Integrating various control components, including sensors, actuators, and control algorithms, into a coherent system remains a primary challenge. Effective control methods, often combining different approaches, are required to balance competing quality factors and achieve robust and precise DED-Arc manufacturing [26].

3.4. Process simulation

Process simulation is a vital tool in DED-Arc primarily utilizing Finite Element Modeling (FEM). It is essential for understanding and predicting the complex thermal and mechanical behaviour inherent to the process (Figure 4) [17]. These simulations are employed to predict crucial outcomes like thermal cycles, distortion, residual stress distribution, and microstructure evolution. Simulation can also aid in predicting defects such as porosity. Studies highlight that accurate prediction, particularly of distortion and residual stress, is significantly improved when using physically derived instantaneous arc power and heat source parameters, with validation often involving comparing simulated thermal cycles to experimental measurements. Simulation results are instrumental in developing effective process control strategies, optimizing parameters, pause times and path planning, and predicting part quality and manufacturing time. Furthermore, process simulation efficiently reduces the need for extensive experimental pre-processing tests for optimization, contributing to more sustainable manufacturing and supporting the realization of smart manufacturing frameworks in DED-Arc [31]. The virtualization of DED-Arc is recognized as a future research challenge. It enables process validation that is more sustainable as it avoids material waste and significant energy consumption compared to physical testing. Simulation can also help visualize complex results, aiding user understanding of effects like distortions and informing decisions on aspects such as fixture placement. Specific applications include simulating thermal behaviour for path planning considerations and FEM analysis of residual stress in components like repair welds or thin-wall structures. Methods have been developed within FEM to mitigate thermal gradients and accurately prescribe heat transfer boundary conditions [17].

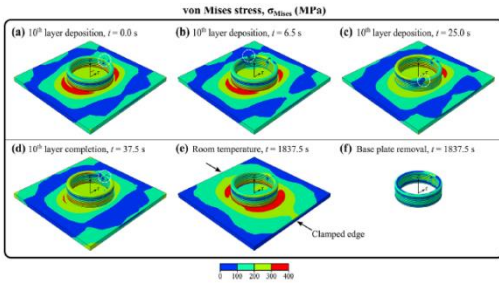


Figure 4: Computed von Mises stress field history [17].

3.5. Path planning

Path planning is an important data pre-processing step in DED-Arc, transforming a CAD model into the deposition trajectory used by the printer head or heating source. It is a key step in production planning and is essential for controlling material deposition and heat distribution. Path planning directly influences part quality, impacting geometric accuracy, distortion, residual stresses, and the occurrence of defects like voids or insufficient material filling [25]. A core challenge lies in dealing with intricate geometries such as thin walls, internal bottlenecks, wide internal areas, and overhangs, as the specificities of arc deposition can render traditional static path strategies unreliable across various topologies [14]. Furthermore, arc starts and stops within a path can induce transient phenomena that affect deposition accuracy.

into distinct regions like thin walls, contours, bottlenecks, or large internal areas, enabling the application of tailored deposition strategies such as offset contours, zigzag patterns, or oscillatory paths [35]. These methods leverage techniques like image-based processing of binary images to map regions and generate paths (Figure 5). Adaptive slicing and multi-directional deposition are employed to manage complex geometries and overhangs by dynamically adjusting layer heights or building directions, often after decomposing complex parts into simpler geometries [36]. Continuous path strategies, such as helical-based methods, are used to minimize disruptive arc stops, potentially leading to more uniform layers. Path planning is also explored for specific features like strut structures, sharp corners, or deposition on non-planar surfaces, with weaving trajectories sometimes employed, including adapting weaving amplitude for varying thickness (Figure 6). The introduction of new paths, such as the 3D weaving path, is being investigated to improve wetting behaviour and reduce surface micro-waviness. This path promotes metal spreading and reduces the contact angle, leading to improved surface smoothness. Experimental results suggest that the 3D weaving path can significantly reduce surface waviness compared to conventional paths [14]. Combining different deposition strategies, such as depositing an initial outline before filling the interior, has shown potential for better surface finishes. Studies are also analysing how parameters like the overlap angle between passes influence the texture of the deposited part [37].

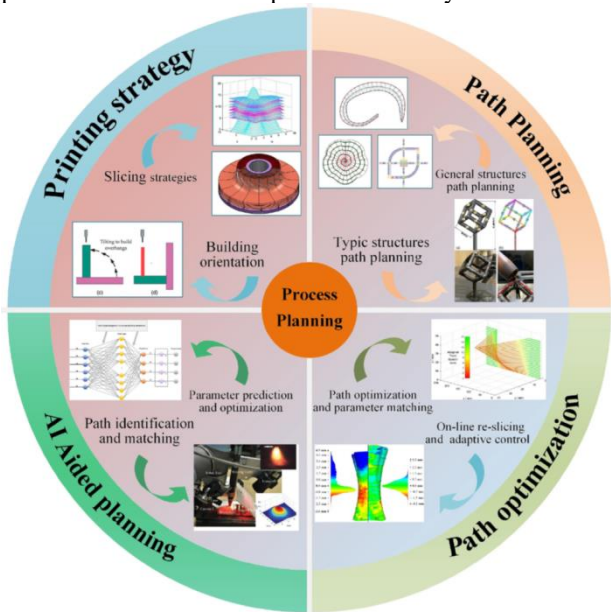


Figure 5: Schematic illustration of process planning [32].

To address these challenges, a variety of path planning strategies have been developed, including basic raster, zigzag, contour, spiral, continuous, and hybrid paths. Geometric-oriented strategies focus on the features of the part; for example, the Medial Axis Transformation (MAT) algorithm has been proposed to solve filling gap issues in contour-based planning and is particularly applied to thin-walled structures, sometimes allowing for continuous alteration of deposition width [34]. Modular or feature-based approaches segment 3D models or layers

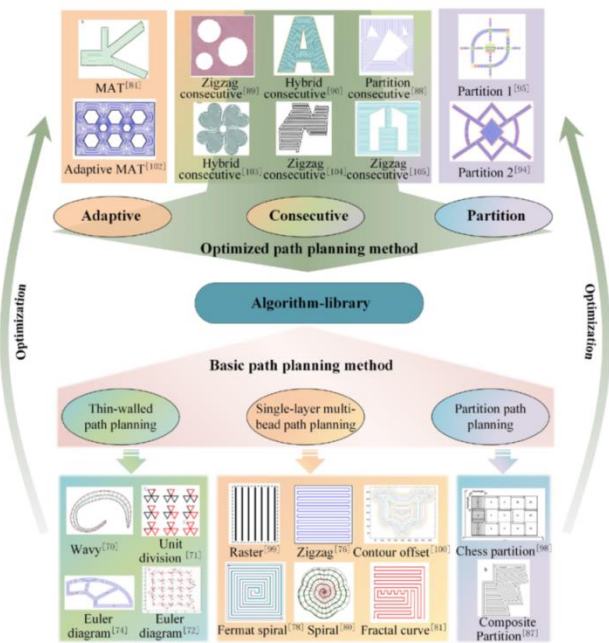


Fig. 9. A summary of the path planning approach that can be applied in DED-Arc.

Figure 6: A summary of path planning approaches that can be used in DED-Arc [32].

Path planning is linked with process parameters such as travel speed and heat input, which are matched to the generated paths. It is considered a form of intrinsic thermal management because the chosen deposition strategy directly influences the temperature evolution and cooling rates of the layers by defining the heat input distribution. Advanced approaches integrate process

parameter planning directly into the path strategy based on prior knowledge. Dynamic path planning further combines path planning with process control by using online monitoring (e.g., of layer height variation) to trigger in-process adjustments like re-slicing if necessary [25]. Tools like process simulation are instrumental in validating path plans by predicting thermal behaviour and distortion. Extended Reality (XR) can potentially aid in visualizing complex path plans, assisting in collision avoidance and testing robot trajectories before physical deposition. Furthermore, identifying manufacturing restraints, such as minimum wall thickness or overhang limitations, through experimental case studies using specific path plans can inform subsequent design and path planning decisions [38]. Despite significant research, accurately mapping complex regions and generating truly optimal paths remains a challenge, and current methods are often limited in their degrees of freedom, highlighting the need for continued work, particularly on non-planar path planning.

3.6. Post processing

While research aims to minimize the need for post-processing, it remains a vital step for achieving the required material properties and mitigating defects [2], [7].

Post-deposition heat treatments, such as solution annealing and aging, are essential for many alloys, including maraging steel and Inconel 625, to obtain uniform, fine-grained microstructures and achieve mechanical properties comparable to conventionally manufactured materials. Specific heat treatment protocols have been developed for maraging steel deposited by DED-Arc to achieve tensile strength and hardness comparable to forged material. For Inconel 625 fabricated by WAAM-CMT, heat treatment at specific temperatures (e.g., 1100 °C) followed by water quenching has shown the best overall performance [9]. Heat treatment can also improve corrosion resistance.

Applying mechanical deformation, such as rolling, hammering or shot-peening, between deposited layers (Figure 7) is an effective technique to refine the coarse columnar grains characteristic of the as-deposited state and significantly reduce residual tensile stresses. This can lead to improved mechanical properties [19].

Other techniques like Hot Isostatic Pressing (HIPing) and hot rolling are also employed to reduce porosity, mitigate defects, and improve mechanical properties. HIPing is mentioned in the context of Inconel 718 to reduce surface-connected defects [1].

Research continues to expand the range of materials processable by DED-Arc and explore novel structures. A wide variety of materials are being investigated, including various steels (stainless, maraging, mild), titanium alloys (Ti-6Al-4V), aluminum alloys, nickel alloys (Inconel 718, Inconel 625), Co-Cr, and tungsten [19]. The potential for manufacturing radial bimetallic structures with enhanced properties through in-situ mechanical interweaving has been demonstrated, showing improved compressive strength.

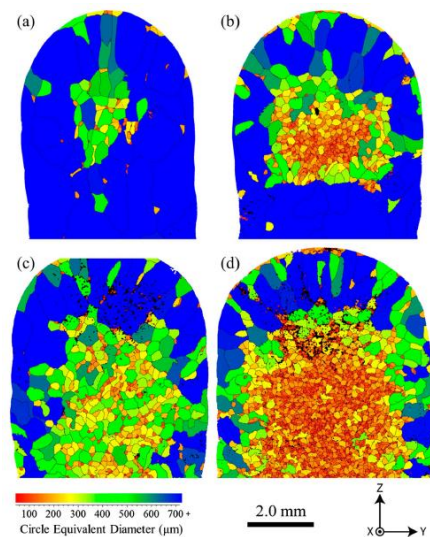


Figure 7: EBSD map of the effect of rolling on beta grain size: a) and b) to second last layer only and c) and d) to each layer (50 and 75 kN) [8].

4. CASE STUDIES

The following chapter shows three case studies dealing with a) in-process height control for improving geometry precision, b) in-situ vibration assisted DED-Arc deposition and c) post-processing heat treatment to improve microstructure and mechanical properties.

4.1. In-process height control for improving geometry precision

The inherent variability in layer height can lead to geometric inaccuracies, affecting the quality of the final product. To mitigate this, the research integrated combined in-process path replanning with real-time layer height control. By adjusting deposition parameters based on continuous feedback, the method aims to maintain consistent layer heights, thereby enhancing the precision and reliability of WAAM processes.

The developed system integrates toolpath planning, real-time monitoring, and adaptive control to ensure consistent layer height. Initially, the user sets process parameters (layer height, travel speed, wire feed rate, and interpass temperature) via a GUI. A slicer algorithm generates toolpaths layer-by-layer. During deposition, arc current is monitored continuously. Since arc current is influenced by electrical resistance, which depends on the wire stickout (distance between contact tip and workpiece), variations in layer height are detected through changes in current (Figure 8). After each layer, the arc stops and cooling is monitored using an IR sensor until the surface reaches the defined interpass temperature. The substrate is then lowered, and the next layer begins. For the first three layers, height increments remain fixed to stabilize current data. From the fourth layer onward, arc current serves as feedback for adaptive height control. If the actual part deviates from the CAD model beyond a threshold, the system re-slices and replans toolpaths accordingly.

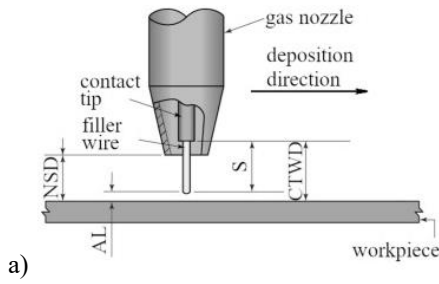


Figure 8: Working principle for determining height distance from gas nozzle to contact surface.

To ensure consistent layer height in DED-Arc, a layer height control algorithm was developed and tested based on working principle of filler wire distance as shown in Figure 9a. Figure 9b shows a torch Z position when building walls with constant Z_{incr} and with layer height controller based on exponential moving average (EMA) of arc current. Due to the changes of wall thickness, which is caused by heat dissipation to the substrate or to the air, the average layer height is changing. At the bottom of the part the average layer height was constant, but at higher levels the average height became lower. This was the reason for lower height of the sample test piece shown on the figure 10b.

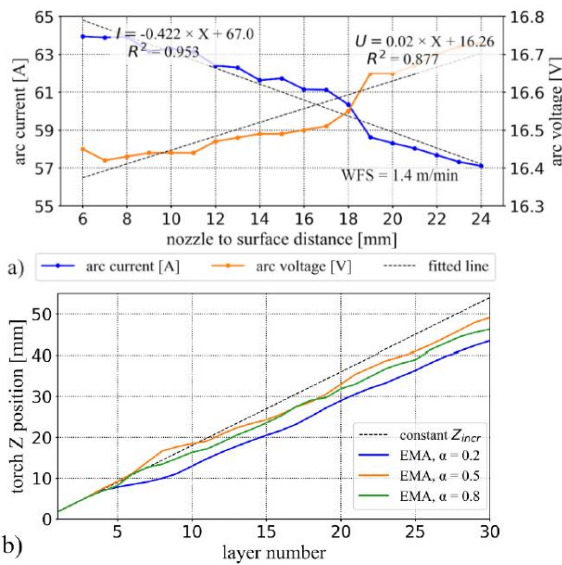


Figure 9: a) An average arc current and voltage as a function of CTWD with the WFS of 1.4 m/min. b) Torch Z position when building walls with constant Z_{incr} and with layer height controller based on exponential moving average (EMA) of arc current.

The re-slice controller was added to the EMA controller. After deposition with the same process parameters, the finished parts have variation in the final height Figs 10 and 11. It ranged from 148.33 mm for the part built using EMA layer height controller to 159.86 mm for part built using EMA controller combined with the re-slice controller, while the CAD model was 160 mm tall (Figure 10.).

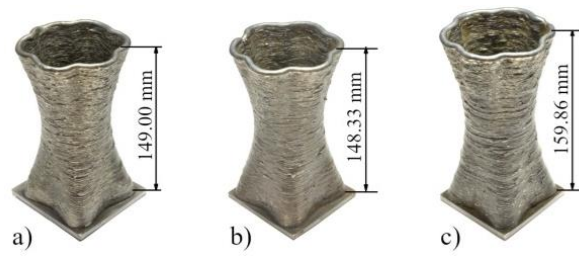


Figure 10: As deposited shell parts: a) constant height increment Zincr, b) EMA layer height controller and c) EMA layer height controller combined with the re-slice controller.

Figure 11 illustrates that the combined control strategy results in fewer zones with material excess or deficiency. However, some localized deviations still occur, particularly in the form of small blobs in the middle and upper regions of the build. These are attributed to irregularities during arc ignition and termination, which cause transient instability in material deposition. Despite these minor imperfections, the overall part geometry is much closer to the CAD model, confirming the effectiveness of the re-slice control in enhancing dimensional fidelity during DED-Arc fabrication.

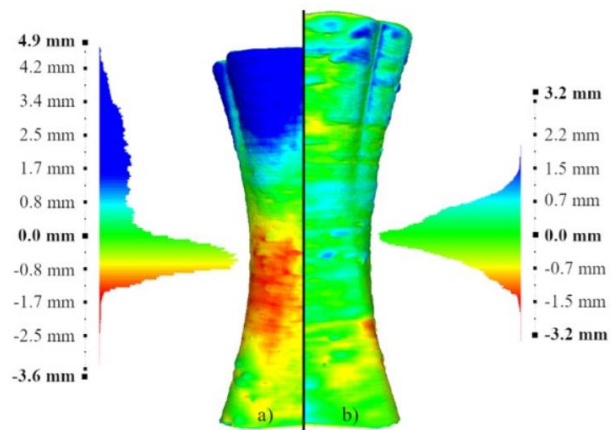


Figure 11: Laser scanning for determining geometry of case study sample: a) As built sample, b) with added height control and reslicing algorithm.

4.2. In-situ vibration assisted DED-Arc

In recent years, innovative mid-processing techniques like interlayer rolling and ultrasonic vibrations have emerged as transformative solutions to improve material properties and manufacturing efficiency. Among this, vibration assisted deposition emerged as promising solution to address challenges such as residual stresses, gas porosity, and surface quality. The figure 2a illustrates the scheme of vibration-assisted DED-Arc, highlighting its potential to enhance microstructural homogeneity and energy-efficient fabrication processes.

The system consists of traditional DED-Arc equipment, the 6-axis robot with mounted GMAW torch. The robot projects the desired trajectory of the desired 3D shape. In our case, ER5356 was used as filler material, hence the argon shielding gas was used. The electromagnetic shaker

was used to induce vibrations onto the substrate and consequently onto the molten pool via deposition.

4.2.1. Geometry improvement

In Figure 12.a, the deposited layer of as-build (AB) sample shows significant waviness, as indicated by the red dashed lines. This waviness suggests inconsistent melt pool dynamics, resulting in uneven layer deposition.

Figure 12.b illustrates the effect of vibration assistance (VA). The melt pool exhibits a partial collapse, shown by the orange arrows, indicating more dynamic melt pool behavior. The vibrations help break up the surface tension of the melt pool, leading to better flow and redistribution of material. This agitation flattens the deposited layer, reducing surface waviness compared to the AB sample, resulting in a smoother, more consistent deposition.

Table 1 contains the waviness measurements and building efficiency factors for the AB and VA samples in the DED-Arc process. The AB sample exhibits higher maximum waviness (+420 μm and +370 μm) compared to the VA sample (+160 μm), indicating more distinct transitions between deposited layers due to inadequate melt pool stabilization. The reduced waviness in the VA sample, with a minimum of -90 μm, reflects smoother layer transitions attributed to vibration-assisted melt pool agitation, which enhances material flow.

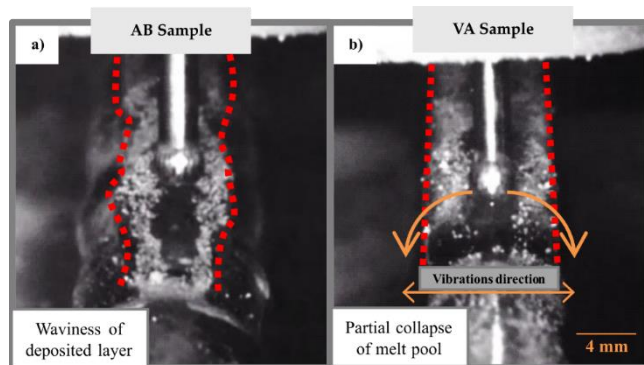


Figure 12: Melt pool geometry: a) AB and, b) VA sample.

Table 1: Waviness measurements and building efficiency results.

Sample	Profile	Max Waviness (μm)	Min Waviness (μm)	RMS Waviness (μm)	Building efficiency (%)
AB Sample	W ₁	+420	-430	420	78.5
AB Sample	W ₂	+370	-430	370	
VA Sample	W ₁	+160	-90	160	92.25
VA Sample	W ₂	+150	-120	150	

Consequently, the building efficiency improves significantly from 78.5% for the AB sample to 92.25% for the VA sample, demonstrating the effectiveness of vibrations in promoting superior surface quality and operational efficiency in additive manufacturing processes.

4.2.2. Gas porosity reduction

In the AB sample porosity decreases as the interpass temperature increases from the bottom to the top of manufactured product. At the bottom significant porosity and larger merged pores are visible, indicating poor degassing at low temperatures, due to high cooling rate. As the interpass temperature increases toward the middle and top, the porosity reduces slightly, but remains substantial, with large pores still present due to insufficient melt pool agitation and gas entrapment during deposition (Figure 13).

In contrast, the VA sample shows a significant reduction in porosity at all cross-sectional levels. Vibration-assisted deposition promotes better melt pool agitation, enhancing degassing and preventing pore formation. The combination of vibrations and increased temperature promotes more efficient gas escape from the melt pool, leading to a more homogenous and less porous structure throughout the part. The comparison clearly highlights the benefits of vibration assistance, where the continuous agitation of the melt pool, combined with rising interpass temperatures, effectively enhances degassing, reduces porosity, and leads to improved material quality.

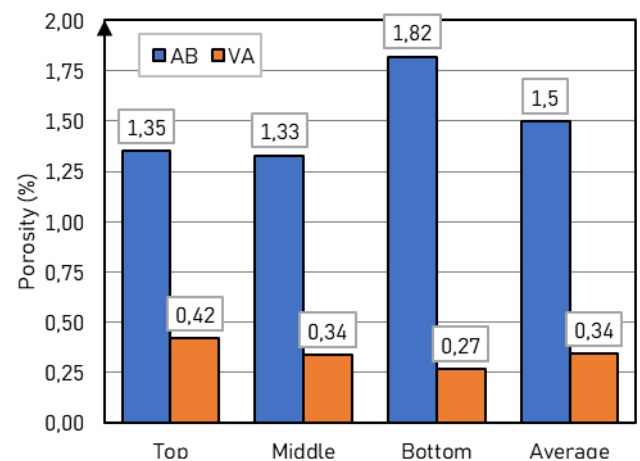


Figure 13: Gas porosity in different area of manufactured samples.

Table 2 shows detailed geometry properties of gas porosity particles.

Table 2: Detailed geometry of gas porosity particles.

Sample Type	Location	Temperature (°C)	Porosity (%)	Average Pore Area (μm ²)
AB Sample	Bottom	45	1.82	2771.8 ± 4410.2
	Middle	135	1.33	1937.0 ± 2820.0
	Top	185	1.35	1931.7 ± 2560.7
VA Sample	Bottom	50	0.42	1292.7 ± 2554.3
	Middle	130	0.34	833.66 ± 1359.8
	Top	170	0.27	856.9 ± 1082.0

4.2.3. Tensile testing results

Figure 14a presents the stress-strain curves for AB and VA specimens, measured along the x and z directions. The black and yellow curves represent AB samples, while the green and blue curves show VA samples. A notable improvement in tensile strength is observed for VA samples in the z-direction, with a 12.1% increase compared to the AB sample (268 MPa vs. 239 MPa). This indicates that the VA samples exhibit a more isotropic mechanical state, with only a 0.4% difference between the x and z directions, whereas the AB samples show a larger 7.9% difference in UTS between these directions.

Figure 14b summarizes the average ultimate tensile strength (UTS) and elongation at break for both AB and VA samples. The VA samples show higher UTS at 267 ± 1 MPa, compared to 248.5 ± 9.5 MPa for AB samples. Additionally, the VA samples exhibit greater ductility, with an elongation at break of $32.5 \pm 1.5\%$, versus $28 \pm 6\%$ for AB samples. The improved mechanical properties in VA samples are attributed to a 25% reduction in grain size, decreased gas porosity, and a significant relaxation of residual stress in the z-direction due to in-situ vibrations, which contributes to their more uniform and isotropic behavior.

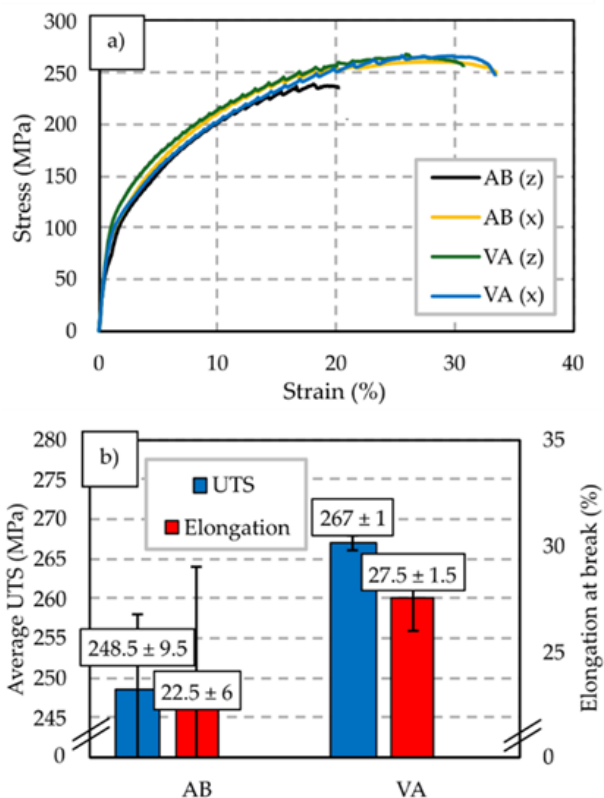


Figure 14: a) Stress - strain curves for AB and VA samples in different directions, b) average values for UTS and elongation.

4.3. Post-processing heat treatment for improving mechanical properties of 15-5 PH stainless steel

15-5 PH stainless steel is a precipitation-hardened martensitic alloy known for its high strength and corrosion resistance, making it suitable for aerospace and structural applications. DED-Arc offers a cost-effective method for producing complex geometries of this alloy. However, the as-deposited material often exhibits suboptimal mechanical properties due to rapid cooling rates and thermal gradients inherent. Tailoring post-deposition heat treatments is essential to enhance its performance. The study shows the effects of solution annealing followed by aging on the microstructure and mechanical properties of DED-Arc 15-5 PH stainless steel. Solution annealing at 1050 °C for 1 hour ensures the dissolution of solute elements into the matrix, while subsequent aging at various temperatures promotes the formation of fine precipitates, primarily copper-rich phases, which are responsible for the alloy's strengthening. This two-step heat treatment process is crucial for optimizing the material's hardness and tensile strength.

4.3.1. Heat treatment

Precipitation hardening involved three key steps: solution annealing, quenching, and aging. Typically, solution annealing for this type of steel is performed at 1038 °C for 1 hour. However, due to the unique microstructure resulting from DED-Arc, tailored heat treatment parameters are necessary. To determine the optimal conditions for DED-Arc-produced samples, solution annealing was conducted at three temperatures: 1040 °C, 1105 °C, and 1170 °C and three durations: 0.5 hours, 1.5 hours, and 2.5 hours. After each heat treatment, samples were rapidly quenched in water to 20 °C. The ideal solution annealing parameters were identified through optical microscopy (OM), scanning electron microscopy (SEM), and hardness testing, with an emphasis on achieving microstructural homogenization in the shortest time and lowest temperature possible. Following this, aging was done on samples treated with the optimal solution annealing settings. Aging was done at three temperatures: 400 °C, 500 °C, and 600 °C for 1 hour, 2.5 hours, and 6 hours respectively, with samples cooled in air down to 20 °C afterwards.

4.3.2. Microstructure

Figure 15 presents micrographs of DED-Arc-produced 15-5 PH stainless steel showing a defect-free macrostructure with large columnar grains angled at 45° to the build direction, a result of directional heat flow during solidification. The as-deposited microstructure mainly consists of lath martensite alongside a secondary lathy delta ferrite phase, enriched in chromium and silicon but depleted in nickel. This delta ferrite phase negatively impacts impact toughness and anisotropy, making its reduction through solution annealing essential. Optimal homogenization was achieved at 1105 °C for 1.5 hours, producing an equiaxed grain structure while avoiding undesirable grain growth seen at higher temperatures.

SEM analysis revealed two microstructural inclusions: spherical Fe-Mn-Cr-Si metal oxide particles originating from oxidation during DED-Arc, which have limited detrimental effects due to their small size and shape, and fine niobium carbonitride (NbC) precipitates that inhibit austenite grain growth, broadening the heat treatment window for achieving an optimal microstructure.

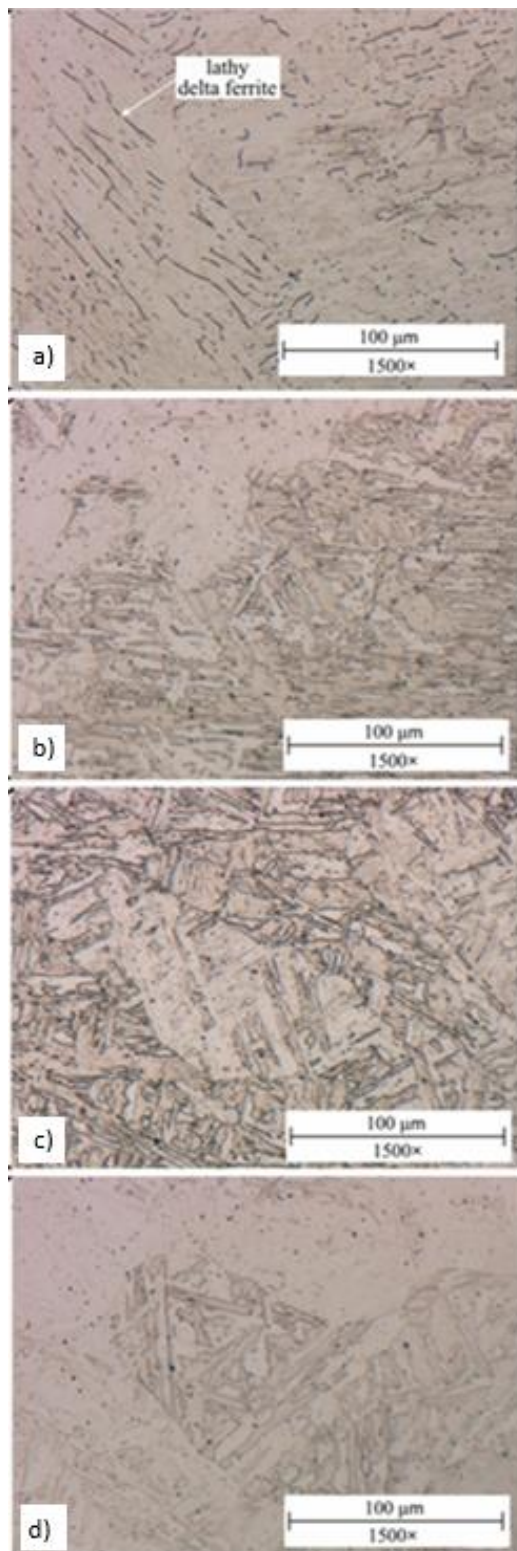


Figure 15: a) AD condition, b) S1 0.5 h 1040 °C, c) S5, 1.5 h 1105 °C, d) S9 2.5 h 1170 °C

4.3.3. Hardness

Vickers hardness (HV10) was measured in the Z–Y plane for as-deposited (AD), solution annealed (S), and solution annealed plus aged (S+A) samples. The AD condition exhibited an average hardness of 352 HV10 (± 9). After solution annealing, hardness decreased even at the lowest temperature/time (0.5h; 1040 °C) due to the dissolution of secondary phases formed during the DED-Arc process. Increasing the temperature or time of solution annealing did not significantly affect hardness, indicating that microstructure and hardness must both guide heat treatment optimization.

Table 3: Hardness measurements with HV10.

#	S1	S2	S3	S4	S5	S6	S7	S8	S9
Temp.	1040 °C			1105 °C			1170 °C		
Time [h]	0.5	1.5	2.5	0.5	1.5	2.5	0.5	1.5	2.5
HV	326	325	316	326	326	319	337	332	339
\pm	8	8	11	7	9	10	9	9	9

Aging significantly increased hardness, with peak hardness (450 HV10) achieved after 1 hour at 500 °C, comparable to conventionally produced 15-5 PH steel (~455 HV). Aging at 400 °C for 6 hours showed an increase but did not reach peak hardness. Prolonged aging beyond peak conditions led to reduced hardness due to precipitate coarsening (over-aging). Despite similar hardness values at some points, microstructural differences impact tensile and toughness properties.

4.3.4. Tensile strength

Figure 16 presents stress–strain curves for as-deposited (AD), under-aged (S+A1), peak-aged (S+A4), and over-aged (S+A9) conditions of 15-5 PH steel. The AD sample has an ultimate tensile strength (R_m) of 1085 MPa, yield strength ($R_{p0.2}$) of 585 MPa, elongation of 19.6%, and reduction in area of 59%. Under-aging (S+A1) increases yield strength significantly to 885 MPa, with a slight R_m increase to 1105 MPa, and improves ductility (elongation 23.1%). Peak-aging (S+A4, 500 °C, 1h) achieves the highest strengths ($R_{p0.2}$ = 1260 MPa, R_m = 1370 MPa) but the shortest elongation (9.2%) and high RA (52.8%), coinciding with peak hardness. Over-aging (S+A9, 600 °C, 6h) causes a marked strength drop ($R_{p0.2}$ = 875 MPa, R_m = 1002 MPa) but restores ductility (elongation 20.9%) due to copper precipitate coarsening and reverted austenite formation. These aging effects balance strength and ductility through microstructural changes.

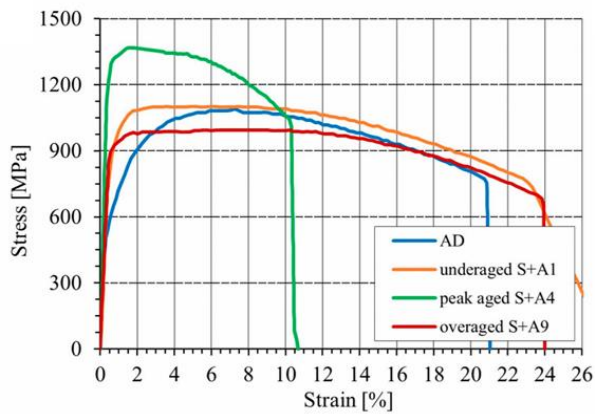


Figure 16: Stress-strain graphs for specimen in different states.

4.3.5. Impact toughness

Figure 17 presents impact toughness results for as-deposited (AD), under-aged (S+A1), peak-aged (S+A4), and over-aged (S+A9) 15-5 PH steel. The AD condition shows an average impact toughness of 56 J/cm², with energy for crack initiation (E_i) around 27.6 J, energy for crack propagation (E_p) 17.2 J, and ductile fracture fraction (DF) 87%. Under-aging at 400 °C for 1 hour (S+A1) slightly improves toughness to 61 J/cm². However, aging for 6 hours at 400 °C (S+A3) results in the lowest toughness (11 J/cm²), caused by a sharp reduction in crack initiation energy (E_i ~8–10 J) at peak-aged condition (S+A4). This leads to embrittlement and a significant drop in impact toughness. As aging continues at 500 °C and especially at 600 °C, impact toughness gradually recovers, with the highest value (77 J/cm²) observed after 6 hours at 600 °C (S+A9). This recovery is mainly driven by increased energy for crack propagation (E_p).

SEM and macrographs reveal ductile transgranular fracture with deep dimples in AD and under-aged specimens, characterized by prominent shear lips. Peak-aged specimens show a predominance of quasi-cleavage fracture and shallow dimples, indicating embrittlement under high loading rates. Over-aged samples regain ductility, exhibiting pronounced shear lips and crack arrest areas signaling the transition to ductile crack growth.

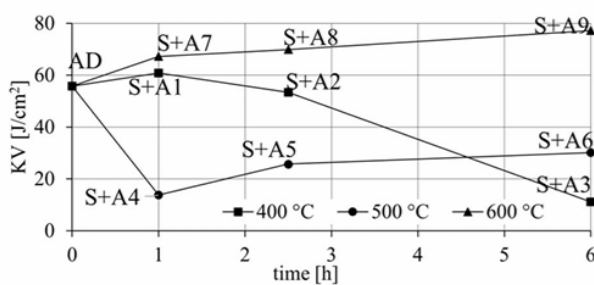


Figure 17: Impact toughness results for specimens in different states.

5. CONCLUSION

DED-Arc stands out as a highly productive metal additive manufacturing technology, offering compelling advantages in terms of build size, deposition rate, cost-effectiveness, and material efficiency, making it particularly well-suited for large-scale components. However, the intrinsic high heat input of the arc welding process poses significant challenges, leading to issues such as complex thermal cycling, microstructural non-uniformity, substantial residual stresses and distortion, and the prevalence of defects like porosity, lack of fusion, and cracking. These challenges often necessitate considerable post-processing to achieve the required material properties and dimensional accuracy.

The state-of-the-art research is actively tackling these limitations through a multi-faceted approach. Significant progress is being made in thermal management via techniques like lower heat input processes and the development of advanced in-situ cooling strategies aimed at controlling microstructural evolution and reducing the reliance on post-process heat treatments. Advancements in path planning and deposition strategies, such as the innovative 3D weaving path, are demonstrating the potential to improve surface quality and reduce defects. Furthermore, more accurate simulation models are being developed to better predict and control the thermal and mechanical behavior of the deposited material. While post-processing remains critical, techniques like heat treatment and interlayer rolling are being optimized to enhance the mechanical properties and refine the microstructure of DED-Arc parts, achieving properties comparable to conventionally manufactured materials. The exploration of new materials and novel structural designs, such as bimetallic components, continues to expand the application potential of DED-Arc.

Despite the notable progress, challenges related to consistently achieving microstructural homogeneity, minimizing residual stresses and distortion without extensive post-processing, and ensuring robust process control for a wider range of complex geometries and advanced alloys still require further investigation and development. The continued focus on integrating sophisticated control systems, enhancing thermal management strategies, and developing advanced deposition techniques will be crucial for the wider adoption and qualification of DED-Arc for demanding industrial applications. The ongoing research indicates a strong trajectory towards overcoming these challenges and unlocking the full potential of DED-Arc as a key enabler for high-speed, large-scale metal additive manufacturing.

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