Implementation of DeD AM in future manufacturing (IDiD)

Guidelines for Transforming Existing Manufacturing Systems for DED Implementation

Abstract

Guideline

Implementation of DeD AM in future manufacturing (IDiD)

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Directed Energy Deposition (DED) is an additive manufacturing technology gaining significant traction in industries such as aerospace, automotive, and energy, where the ability to produce large, complex metal parts or repair high-value components offers considerable advantages. Leveraging existing infrastructure, such as robot welding cells, CNC welding cells, or CNC cutting cells, for DED applications is a cost-effective strategy for manufacturers aiming to integrate this advanced technology. This transformation process involves careful evaluation, system upgrades, and integration of specialized components to enable precise material deposition.

The first step in this transformation is to assess the compatibility of the existing equipment. Robot welding cells typically have the fundamental elements required for DED, such as robotic arms and welding power sources. However, modifications are necessary to accommodate DED-specific equipment, including multi-axis motion control, higher precision, and additional thermal management systems. Retrofitting the robotic arm with a deposition head capable of handling wire or powder feedstock is a critical step. For CNC welding or cutting cells, the integration focuses on incorporating a DED deposition head and optimizing tool paths to suit additive manufacturing processes. In both cases, software upgrades are essential for controlling deposition parameters and enabling real-time process monitoring.

Key considerations for a successful transition include material compatibility, thermal distortion management, and workspace configuration. The deposition system must support the desired metal feedstock, such as wire or powder, and provide precise control over material flow and heat input to avoid defects like porosity or warping. Thermal distortion can be mitigated through preheating, controlled cooling, and post-processing techniques. The workspace must also be reconfigured to ensure adequate safety measures, as DED involves high-energy lasers or arcs and requires effective ventilation for fumes and particulates.

The process also involves integrating sensors and feedback systems to monitor and control parameters such as deposition rate, material flow, and temperature in real-time. Advanced software tools must be implemented to simulate and optimize deposition paths, ensuring accuracy and material efficiency. In addition, training operators in both the technical and safety aspects of DED is critical for maximizing the effectiveness of the system and minimizing downtime during the transition.

By transforming existing robot and CNC cells into DED-capable systems, manufacturers can unlock new capabilities, including the production of near-net-shape parts, reduced material waste, and the ability to repair or modify existing components. This approach leverages existing assets while minimizing capital expenditure, making DED an accessible and scalable solution for a wide range of industrial applications. The transformation process, though complex, represents a strategic investment in advanced manufacturing technologies, enabling organizations to remain competitive in an evolving industry landscape.

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1 Introduction

The transformation of existing robotic and CNC cells into systems for wire arc additive manufacturing (WAAM) or other directed energy deposition (DED) processes presents an efficient way to leverage existing infrastructure for advanced manufacturing applications. As industries move toward incorporating additive technologies for cost-effective production, part repair, and customization, retrofitting current equipment offers a practical and economical entry point into this growing field.

This guideline is designed to provide a structured approach for converting robotic and CNC cells into DED systems, with a primary focus on WAAM. By adapting these cells, companies can utilize their existing assets to produce large, complex metal parts, repair worn components, or perform material cladding with greater flexibility and precision.

DED is an additive manufacturing technology with significant potential for industrial applications such as near-net-shape manufacturing, component repair, and material-efficient production of large metal parts. Despite its advantages, the adoption of DED in industrial environments is often limited by high investment costs and uncertainty related to system integration and process implementation. At the same time, many manufacturing facilities already operate welding, laser, robot, and CNC systems that are underutilized or suitable for upgrading.

The purpose of this guideline is to provide practical and technical guidance for transforming existing manufacturing systems into DED-capable platforms. The document focuses on the conversion of robot-based welding cells, CNC systems, and laser welding or cutting cells into WAAM or laser-based DED systems. By leveraging existing equipment and infrastructure, companies can adopt additive manufacturing technologies in a cost-effective and low-risk manner.

This guideline presents step-by-step procedures for system conversion, covering feasibility assessment, equipment selection, layout modifications, control system upgrades, software integration, process development, and safety considerations. In addition, real industrial and laboratory experiences are reflected to support practical implementation and decision-making.

To support technology selection and benchmarking, the guideline also provides an overview of commercially available DED systems, WAAM welding processes, and software tools for robotic and CNC-based additive manufacturing. The target audience includes industrial companies, system integrators, engineers, and researchers seeking to implement or expand DED capabilities within existing production environments.

By offering a structured and comprehensive approach, this guideline aims to accelerate the adoption of DED technologies, enhance manufacturing flexibility, and support sustainable and competitive industrial production.

2 Procedure for Converting Robot or CNC Cell for WAAM Applications

2.1 Welding robot cell conversion to WAAM applications

Wire arc additive manufacturing (WAAM) is a technology that leverages arc welding processes to build parts layer by layer using metal wire feedstock. This transformation can be beneficial for companies looking to repurpose robotic welding cells, allowing for greater flexibility in manufacturing and the production of complex metal parts. This chapter will discuss the key considerations, and process steps a company must undertake to convert a robotic welding cell into a WAAM printing cell.

Repurposing a robotic welding cell for WAAM is a valuable transformation that enables companies to diversify their manufacturing capabilities. Following these steps, starting with a feasibility study, redesigning the cell layout, upgrading hardware and software, and implementing a process control strategy—can help ensure a successful conversion. Regular maintenance and ongoing optimization are essential for sustaining quality and efficiency in WAAM operations. This process allows companies to expand into new manufacturing domains, unlocking the potential for custom, on-demand metal parts.

2.1.1 Assessment, feasibility study and evaluation of the current robot cell capabilities

The first step in converting a robotic welding cell to WAAM involves conducting a comprehensive assessment to ensure the transformation is feasible. The conversion process begins with a thorough assessment of the existing welding robot cell. Key aspects include robot reach, payload capacity, positioning accuracy, repeatability, and available workspace. The suitability of the current welding power source for WAAM applications must be evaluated, along with the condition of wire feeding systems, torch compatibility, cooling capacity, and electrical infrastructure. Safety systems, enclosure design, and fume extraction must also be reviewed to confirm compliance with WAAM operational requirements.

This step includes:

1. Robot mechanical capability: The robot’s mechanical characteristics must be assessed, including payload capacity, reach, repeatability, stiffness, and thermal robustness. WAAM involves continuous deposition, additional tool weight (torch, cables, wire feeder), and prolonged operation at elevated temperatures. The robot must be capable of maintaining consistent positioning accuracy and smooth motion under these conditions.

2. Workspace: The available workspace must be reviewed to confirm that it accommodates the intended build size, layer-by-layer growth of parts, and safe robot motion. Clearance for complex geometries, part rotation (if external axes are used), and maintenance access should be verified. Build platform size and load capacity must also be considered.

3. Controller: The robot controller must provide smooth, continuous motion with high repeatability. WAAM requires constant travel speed and stable torch orientation to ensure uniform bead geometry and consistent layer bonding. The controller should support multi-axis coordinated motion and continuous path execution without interruptions. It would be good if controller is capable of real-time communication with the welding power source. This includes the ability to send and receive signals for arc on/off control, wire feed rate, current, voltage, and process status.

4. Software compatibility: Check if the existing robot control software can be adapted or if it needs to be upgraded to handle the path planning and deposition strategies required for WAAM. Software compatibility is a key factor in successful WAAM implementation, as additive manufacturing requires

close integration between design, path planning, robot programming, and process control. The robot controller must support a flexible software ecosystem to enable efficient and reliable operation.

5. Thermal management and process stability: WAAM introduces significant heat input to both the part and surrounding environment. The system must support adequate thermal management, including interpass temperature control, cooling strategies, and heat dissipation. The impact of heat on robot accuracy, fixturing, and surrounding equipment should be evaluated.

6. Safety: The existing safety concept must be reviewed and updated to address welding and additive manufacturing risks. This includes arc radiation, hot surfaces, spatter, fumes, fire risk, and extended operation times. Compliance with relevant industrial safety standards and regulations must be ensured.

2.1.2 Evaluation of welding power source suitability for WAAM

1. Power source: The welding power source is a critical component in WAAM systems, as it directly influences process stability, deposition quality, and achievable material properties. A systematic evaluation is required to determine whether a selected welding power source is suitable for WAAM use.

   - The first step is to verify that the welding power source supports welding processes commonly used in WAAM, such as Gas Metal Arc Welding (GMAW), Cold Metal Transfer (CMT), or other controlled short-circuit or pulsed arc processes. Stable arc behavior and controlled heat input are essential for achieving consistent bead geometry and reliable layer bonding.

   - The power source must allow precise control of key welding parameters, including current, voltage, wire feed rate, and arc length. WAAM often requires long, continuous deposition cycles, so the power source must maintain stable output over extended periods without drift or interruptions.

   - The welding power source should be compatible with the robot controller and support digital communication interfaces. This enables synchronized control between robot motion and welding parameters, including arc start/stop commands and real-time parameter adjustments during printing.

   - WAAM processes impose higher thermal loads compared to conventional welding. The power source must have a sufficient duty cycle and thermal management capability to operate continuously without overheating. Cooling systems, such as water cooling, should be evaluated for long-duration printing tasks.

2. Welding torch: Choose a torch optimized for additive manufacturing with features like cooling and reliable wire feed control. Torches generally used in robotic welding are also suitable for WAAM use. Water cooling is generally advantageous for WAAM printing.

3. Wire feeder: Stable and accurate wire feeding is essential for WAAM. The power source / wire feeder should support reliable wire feeders with precise speed control and minimal feed interruptions. Compatibility with different wire diameters and materials should also be assessed. Ensure compatibility with the welding process and materials (e.g., stainless steel, carbon steel, high-strength carbon steel, aluminum). Ensure the wire feeding mechanism can handle the continuous supply of wire for extended periods without jamming or inconsistency, which is critical for the quality of the print.

2.1.3 Redesign of the welding cell layout

WAAM processes often require a different setup than typical robotic welding. Redesigning the welding cell layout is a critical step when adapting an existing cell for WAAM. Unlike conventional welding, WAAM involves continuous, multi-layer deposition, larger build volumes, and longer operation times. The layout must therefore support stable printing, safe operation, and efficient workflow. Therefore, reconfiguring the layout of the welding cell is essential. Important considerations include:

1. Optimizing movement and reach: Ensure sufficient space for robot movement and the build platform. Adjust the position of the robot and the work surface to maximize its movement range and to handle larger or more complex WAAM parts. The robot should have clear and continuous access to all deposition areas. The layout must minimize extreme joint configurations, singularities, and abrupt changes in torch orientation. Smooth, continuous paths improve deposition stability and reduce mechanical stress on the robot.

2. Thermal management: WAAM processes generate significant heat. The layout should include sufficient cooling systems or allow for pauses to avoid overheating. Also, consider implementing controlled cooling for WAAM parts, as it can enhance productivity and, for certain materials, improve final material properties. In certain cases, preheating or cooling of the part should also be taken into consideration to ensure process stability and material performance.

3. Positioning of the build platform: The build platform or fixture must be rigid, thermally stable, and capable of supporting the weight of the part during deposition. It should be positioned to maximize robot reach and allow optimal torch orientation. In some cases, the use of a rotary table or positioner improves accessibility and enables better control of bead orientation.

4. Safety features: Install welding curtains, and safety interlocks to protect operators. The redesigned layout must comply with industrial safety standards. This includes proper enclosure design, safety interlocks, emergency stops, and safe access for operators during setup, inspection, and maintenance. The layout should also allow safe handling of heavy parts and consumables. Implement or upgrade safety protocols, including shielding gas systems to prevent oxidation of the molten metal, and ensure proper ventilation for fume extraction. Effective fume extraction is essential due to prolonged arc operation. The layout should include appropriately positioned extraction hoods or localized fume extraction systems that do not interfere with robot motion or shielding gas coverage.

2.1.4 Upgrading control systems

Standard welding cells may not have control systems suited to WAAM requirements, which may need higher precision and stability. Upgrading the control system is a key requirement when adapting a robot cell for WAAM. WAAM processes require precise synchronization between robot motion, welding parameters, and auxiliary systems to ensure stable deposition and consistent part quality. Upgrading these components includes:

1. Establish communication between robot controller and welding power source: The first step is to enable reliable digital communication between the robot controller and the welding power source. This allows coordinated control of arc ignition, wire feed rate, current, and voltage. Communication is typically achieved using industrial fieldbus protocols or manufacturer-specific interfaces.

2. Enable real-time process synchronization: WAAM requires synchronized control of robot motion and welding parameters. The control system must support real-time adjustment of process variables based on robot speed, layer transitions, or sensor feedback. This may require software upgrades or additional control modules within the robot controller.

3. Integrate external devices and sensors: To improve process stability and quality, the control system should support integration of external devices such as temperature sensors, cameras, seam tracking systems, or laser scanners. These devices provide feedback that can be used for monitoring or adaptive control during printing.

4. Data logging and quality control: Implement data logging systems to record parameters for traceability, quality control, and analysis. The upgraded control system should allow logging of key process parameters, including robot motion data, welding settings, and sensor inputs. Data logging supports quality assurance, traceability, and process optimization.

2.1.5 Software updates and upgrades for the system

Software updates and upgrades are essential when converting a robot cell for WAAM. Additive manufacturing imposes different requirements than conventional robotic operations, including continuous multi-layer motion, synchronized process control, and advanced path planning. The software environment must therefore be adapted to support reliable and efficient WAAM production. The availability and upgradability of software also depend strongly on the robot's age and model, as well as on whether the manufacturer has invested in developing 3D printing–specific software solutions for the robot.

1. Upgrade robot controller firmware and system software: The first step is to ensure that the robot controller firmware and system software are up to date and compatible with WAAM operation. Updated firmware improves motion smoothness, communication stability, and support for external devices. Compatibility with welding interfaces, external axes, and modern communication protocols should be verified before implementation.

2. WAAM path planning: Many robot manufacturers offer optional software modules for continuous path execution, multi-layer motion, or additive manufacturing applications. These packages enable smoother trajectories, better speed control, and enhanced synchronization with welding processes. Installing such modules is often required for stable WAAM printing. Install or integrate additive manufacturing-specific software that can generate deposition paths from CAD models. Implement specialized software for generating deposition paths and layer strategies. Program multi-layer paths that consider the specific geometry of the part. These paths often require more complex 3D trajectories than typical welding.

3. Simulation and offline programming: Use simulation tools to test and optimize the build process virtually. WAAM requires specialized software to generate deposition paths from CAD models. Offline programming (OLP) tools should be installed and configured to match the robot controller environment. This enables slicing, bead placement planning, collision checking, and efficient generation of robot programs.

4. Welding process control software: Software interfaces that allow control of welding parameters from the robot program must be configured. This includes arc start/stop commands, wire feed control, and parameter changes between layers or deposition segments. Stable software-level integration between the robot controller and the welding power source is essential.

5. Real-time monitoring: Integrate sensors (e.g., vision systems, temperature monitors) or software for monitoring temperature, bead geometry, or arc stability if high-quality deposition is needed. If sensors such as temperature monitoring, cameras, or laser scanners are used, the corresponding software must be installed and integrated into the control system. These tools support real-time monitoring, data collection, and adaptive process control, improving print reliability and quality.

2.1.6 Process development and testing

The next phase involves extensive process testing to ensure that the WAAM setup meets production requirements. Process development and testing are critical steps when upgrading a welding robot for WAAM. Unlike conventional welding, WAAM requires stable, repeatable deposition over long build times and across multiple layers. A structured approach ensures reliable print quality, consistent material properties, and safe operation. This phase includes:

1. Trial runs, process objectives and requirements: The development process begins by defining target applications, materials, and performance requirements. This includes identifying acceptable bead geometry, layer height, deposition rate, surface quality, and mechanical properties. These objectives guide parameter selection and testing strategies.

2. Parameter tuning: Fine-tune the parameters based on results from trial runs. Initial welding and deposition parameters are selected based on material type, wire diameter, and welding process (e.g. GMAW or CMT). Key parameters include current, voltage, wire feed speed, travel speed, shielding gas composition, and torch orientation. Manufacturer recommendations and prior WAAM experience are commonly used as starting points.

3. Single-bead deposition testing: Single-bead tests are conducted to evaluate arc stability, bead shape, penetration, and surface quality. These tests help identify suitable parameter windows and ensure consistent material deposition before moving to multi-layer builds.

4. Multi-layer and wall build testing: Once stable single-bead deposition is achieved, multi-layer tests are performed to assess layer bonding, heat accumulation, and dimensional stability. Interpass temperature control and cooling strategies are evaluated to prevent defects such as excessive distortion or lack of fusion.

5. Layer and printing path strategy: Deposition path strategies are tested and refined, including bead overlap, layer sequencing, and travel direction. Robot motion is optimized to ensure smooth, continuous movement and consistent deposition speed, minimizing start–stop defects and thermal variations.

6. Monitoring and data collection: During testing, process data such as welding parameters, temperatures, and robot motion are recorded. Monitoring enables identification of instabilities and supports correlation between process parameters and resulting material quality.

7. Cooling strategy: Plan interlayer (interpass temperature) cooling times to prevent distortions, ensure material quality and ensure structural integrity. You can use pyrometer to control the interpass temperature.

8. Material and mechanical testing: Printed test specimens are evaluated through visual inspection, dimensional measurements, microstructural analysis, hardness testing, and mechanical testing as required. These evaluations confirm whether the developed process meets performance requirements. Universities and different research groups provide valuable support in conducting these tests.

9. Documentation: Maintain detailed records of process parameters and part performance for traceability. Once a stable and repeatable process is achieved, the final process parameters, path strategies, and operating procedures are documented. Validation builds are performed to confirm repeatability and readiness for production use.

2.1.7 Training and safety measures

Adapting a robotic welding cell to WAAM involves new safety risks and skill requirements. Training personnel and updating safety protocols are essential:

1. Personnel training: Train operators on WAAM-specific procedures, focusing on process control, parameter adjustment, and quality assurance. Training is crucial for operators to understand the nuances of WAAM compared to traditional welding. This also includes understanding the software,

handling new hardware. When an existing welding robot cell is converted for WAAM use, both training and safety measures must be expanded beyond those required for conventional welding. WAAM involves continuous, multi-layer deposition, longer operation times, and higher cumulative heat input, which introduce new technical and safety-related challenges. As a result, operators, programmers, and engineers must be trained in WAAM-specific principles, including additive manufacturing fundamentals, layer-by-layer deposition behavior, heat accumulation, interpass temperature control, and typical WAAM-related defects. Training should also cover robot programming strategies for continuous paths, offline programming and simulation, welding process control during long print cycles, and quality awareness related to bead geometry, surface condition, and post-processing requirements.

2. Enhanced safety protocols: Comprehensive welding and additive manufacturing safety training is required. Personnel must be aware of the risks associated with prolonged arc operation, arc radiation, hot surfaces, molten metal, spatter, and shielding gas handling. Fire prevention and emergency response procedures are particularly important due to the extended operating times typical of WAAM processes. Also troubleshooting is important and staff should be educated with skills to identify and resolve common issues during the WAAM process.

3. Control system safety: Control system–related safety functions must also be reviewed and updated. Emergency stop circuits, safety interlocks, and safety-rated inputs and outputs must cover both the robot and the welding equipment. Clear procedures for safe start-up, shutdown, and controlled restart after interruptions are essential to prevent damage to equipment and ensure operator safety.

2.1.8 Ongoing maintenance and optimization

Once the WAAM cell is operational, companies need to maintain the system to ensure consistent performance and quality. Ongoing maintenance of a WAAM-enabled robot cell should focus on both mechanical reliability and process stability. Regular inspection of the welding torch, contact tips, nozzles, liners, and wire feeders is required, as these components are subject to increased wear due to prolonged arc operation and continuous wire feeding. Consumables should be replaced proactively to avoid arc instability, inconsistent bead geometry, or unexpected process interruptions. Cables, hoses, and cooling lines must be checked frequently for heat damage, abrasion, or fatigue, and proper cable routing should be maintained to prevent excessive mechanical stress during long print cycles.

1. Regular equipment checks: Schedule periodic checks of welding equipment, robot joints, and safety systems. Establish a schedule for maintenance on the robot, torch, wire feeder, and power supply, as WAAM can impose higher wear and tear than traditional welding.

2. Process optimization: Continuously review and optimize process parameters based on production results. Adapting parameters over time can lead to improved build quality and reduced cycle time.

3. Data-driven Improvements: Use data collected during the process to analyze trends, anticipate maintenance needs, and make incremental improvements.

4. Software updates and optimization: Keep path planning and robot control software updated for optimal performance. Software and control system optimization should also be part of ongoing operation. Robot programs, path planning strategies, and deposition sequences can be refined based on production experience to reduce cycle time, improve material utilization, and minimize thermal distortion. Software updates should be implemented in a controlled manner, with proper validation to ensure compatibility and stability.

5. Future upgrades and continuous improvement: Plan for scalability, such as adding more robot arms or advanced sensors for increased production capacity. Continuous improvement should be supported by operator feedback, documentation updates, and periodic review of process performance. Lessons

learned from production builds should be incorporated into updated work instructions, training materials, and maintenance plans. This systematic approach ensures that the WAAM system remains reliable, efficient, and capable of meeting evolving industrial requirements.

2.2 Transforming a CNC welding cell to WAAM applications

Transforming a CNC welding cell into a WAAM system enables the production of large, customized metal components with improved material efficiency and reduced lead times. Compared to conventional CNC welding operations, WAAM introduces continuous, layer-by-layer deposition, placing new requirements on machine structure, control systems, software, and process stability.

This section describes the key technical steps required to convert an existing CNC welding cell into a WAAM-capable system. The procedure covers feasibility assessment, mechanical and hardware modifications, control system upgrades, CNC programming adaptations, process development, safety considerations, and long-term maintenance. The objective is to support a reliable, industrially applicable WAAM implementation using existing CNC-based infrastructure.

2.2.1 Feasibility assessment and planning

Before initiating the conversion, a feasibility assessment should be carried out to determine whether the existing CNC welding cell is suitable for WAAM operation. This assessment should include the following aspects:

1. System compatibility analysis: Evaluate if the current CNC welding cell’s components, such as the welding power supply, wire feeder, and tooling system, can support WAAM requirements. Each component must be assessed for its suitability for continuous, multi-layer deposition and prolonged operating cycles typical of WAAM processes. Particular attention should be given to the condition, remaining service life, and upgrade possibilities of critical components.

2. Machine structure: Ensure the CNC machine has the stability and rigidity to handle the heat, weight, and potential vibrations caused by WAAM processes. The mechanical structure and rigidity of the CNC machine are key factors in WAAM feasibility. WAAM introduces increased thermal loads, higher deposited mass, and longer processing times compared to conventional welding. The machine must be capable of maintaining positional accuracy and dimensional stability under these conditions. Any susceptibility to thermal deformation, vibration, or mechanical drift should be identified and addressed during the planning stage.

3. Controller compatibility: Controller capability is another critical aspect of the assessment. The CNC controller must support smooth and continuous multi-axis motion, precise synchronization between movement and welding parameters, and reliable execution of long and complex programs. Compatibility with WAAM-adapted G-code, external process control interfaces, and data logging functions should be verified. Limitations in controller performance or software support may require upgrades or influence the achievable complexity of WAAM parts.

4. Workspace: Ensure the working envelope can accommodate the WAAM torch, wire feeder, and build platform. The available workspace and build envelope must be carefully reviewed. WAAM components grow layer by layer, often reaching significant heights and volumes. The working area must accommodate not only the final part dimensions but also the WAAM torch, wire feeder, shielding gas delivery, cooling systems, and potential monitoring equipment. Accessibility for setup, inspection, and maintenance should also be considered in the layout planning.

5. Material and product requirements: Material and application requirements should be clearly defined during the feasibility phase. This includes identifying the target materials and alloys, wire diameters, expected mechanical properties, and quality requirements. The suitability of WAAM for the intended applications should be evaluated by considering achievable tolerances, surface quality, and post-processing needs.

6. Production needs analysis: Production objectives and economic considerations form an important part of feasibility planning. Expected production volumes, build times, productivity targets, and cost constraints should be analyzed and compared against alternative manufacturing methods. This analysis helps determine whether WAAM offers clear benefits in terms of cost efficiency, lead time reduction, or design flexibility for the specific use cases.

2.2.2 Modifying the CNC layout for WAAM requirements and upgrading the hardware

The next step is to modify the physical layout of the cell and upgrade the required hardware to support additive manufacturing operations. WAAM imposes different mechanical, thermal, and operational demands than conventional CNC welding, and the system layout must be adapted accordingly.

1. Optimizing workspace and tool reach: the optimization of the workspace and build area. WAAM parts are produced layer by layer and can grow significantly in height and volume during the build process. The CNC layout must therefore provide sufficient clearance for part growth, tool movement, and safe operation throughout the entire build. The build platform should be positioned to maximize accessibility and minimize extreme machine movements, which could negatively affect deposition stability and accuracy.

2. Power source (welding machine): The welding power source plays a central role in WAAM performance and must be selected or upgraded to support continuous deposition with fine control over process parameters. The power source should provide stable arc behavior and allow precise adjustment of current, voltage, and wire feed rate. Compatibility with the CNC control system and the ability to support advanced arc modes are important considerations to ensure process stability and flexibility.

3. Welding torch: The selection and integration of a suitable welding torch are critical for WAAM operation. The torch should be specifically designed for continuous welding and capable of stable, long-duration operation. It must provide consistent wire feeding, effective cooling, and reliable arc characteristics. Torch mounting must be rigid and precisely aligned to ensure repeatable deposition and accurate layer placement.

4. Thermal control: Thermal management is a key aspect of hardware modification. WAAM generates continuous heat input, which can affect both the machine structure and the quality of the printed part. Measures such as heat shielding, improved ventilation, and localized cooling should be implemented to manage heat accumulation. In some cases, active cooling systems may be required to maintain stable operating conditions and prevent thermal deformation of machine components.

5. Wire feeding system: The wire feeding system must be configured for reliable and uninterrupted operation. WAAM requires consistent wire delivery over long build times, and the feeder should support the required wire diameters, materials, and feed rates. Attention should be paid to wire routing, liner condition, and feed stability, as irregular wire feeding can lead to defects and process interruptions.

6. Fume extraction system: Effective fume extraction and ventilation systems must be installed or upgraded to handle the increased fume generation associated with prolonged arc operation. The

extraction system should be positioned to remove fumes efficiently without disturbing the shielding gas coverage or interfering with machine motion. Compliance with occupational health and safety regulations must be ensured. Especially when printing stainless steels and aluminium, fume extraction is very important.

7. Additional hardware and cooling system (optional): Additional hardware considerations may include the integration of temperature sensors, cameras, or other monitoring devices. Space and mounting provisions for these systems should be included in the layout design, allowing future upgrades and process monitoring capabilities without major reconfiguration. Install active cooling to manage heat buildup in the machine and prevent thermal deformation.

2.2.3 Upgrading control systems

To meet WAAM's specific control demands, upgrades may be necessary to ensure precise and consistent deposition of material. Upgrading the control system is a critical step in adapting a CNC welding cell for WAAM. Unlike conventional welding operations, WAAM requires precise synchronization between machine motion, welding parameters, and auxiliary systems throughout long, continuous build processes. The control system must therefore support stable execution of complex, multi-layer deposition strategies while maintaining process reliability and safety. Key upgrades include:

1. Controller upgrade: Ensure the CNC controller can execute G-code modified for WAAM, including dynamic speed, feed, and pause commands. The CNC controller must be capable of executing WAAM-adapted G-code that supports continuous toolpaths, dynamic feed rate control, and controlled pauses between layers or deposition segments. Traditional CNC welding programs typically consist of short, discrete welding paths, whereas WAAM programs involve extended, uninterrupted motion over multiple layers. The controller must be able to handle large program files and ensure smooth trajectory execution without unintended stops or speed fluctuations.

2. Advanced process control software: Integrate software that can handle multi-layer additive manufacturing paths, monitor real-time parameters, and adjust deposition settings based on feedback. Close integration between the CNC controller and the welding power source is essential. The control system must support reliable communication interfaces that allow coordinated control of arc ignition, current, voltage, and wire feed rate. This synchronization ensures that material deposition remains consistent even when travel speed or path geometry changes. Where available, digital communication protocols should be used to enable real-time parameter adjustment and process feedback. Advanced process control capabilities are highly beneficial for WAAM operation. The control system should support the integration of software modules or external controllers capable of managing multi-layer deposition logic, interpass temperature control, and adaptive process behavior. These capabilities allow the system to respond to thermal accumulation, geometry changes, or sensor feedback during printing, improving stability and part quality.

3. Quality monitoring and data logging: Implement systems to monitor and log data for each layer, ensuring traceability and facilitating quality control. Data acquisition and logging functionality should be incorporated into the upgraded control system. Recording key process parameters—such as motion data, welding current and voltage, wire feed rate, and temperature—provides valuable information for quality assurance, traceability, and process optimization. Logged data enables analysis of process consistency and supports continuous improvement efforts. Support for external devices and sensors should also be considered during the control system upgrade. The CNC controller should allow integration of sensors such as pyrometers, thermal cameras, or bead monitoring systems. These devices can be used for real-time monitoring, process validation, or closed-loop control, depending on the complexity of the WAAM implementation.

2.2.4 Reprogramming CNC movements and path planning

CNC programming for WAAM is quite complex, as the process involves building parts with different geometries. Usually 3-axis system of CNC-machine limits part geometries. Reprogramming CNC movements and developing appropriate path planning strategies are central to successful WAAM implementation. Unlike conventional CNC welding, which typically involves short and discrete weld seams, WAAM requires continuous, layer-by-layer deposition following additive manufacturing principles. This shift places new demands on CNC programming, motion control, and process coordination.

1. Path planning optimization: The starting point for WAAM path planning is the definition of deposition strategies based on the target component geometry. CAD models must be translated into layer-based representations that define the contour and, where applicable, infill of each layer. The CNC program must control the deposition path for every layer in a manner that ensures uniform material buildup, consistent bead geometry, and stable thermal conditions. Special attention should be paid to the start and end points of deposition paths to avoid defects caused by excessive heat input or arc instability. Most CNC welding cells are based on three-axis motion, which imposes limitations on achievable geometries compared to multi-axis robotic systems. These kinematic constraints must be considered during path planning. Geometries should be designed or adapted to ensure that deposition can be carried out with a fixed torch orientation and without undercuts or unsupported overhangs. If more complex geometries are required, the feasibility of adding rotary axes or positioners should be evaluated during system planning.

2. Adaptive layering: Set up the program to adapt layer height and width according to the desired part geometry. This includes accommodating complex shapes and overhangs where material control is critical. Layer height, bead width, and overlap must be carefully programmed to achieve consistent layer bonding and dimensional accuracy. The CNC program should allow adjustment of these parameters between layers or within specific regions of the part to accommodate changes in geometry or thermal behavior. Adaptive layering strategies can be used to improve surface quality and reduce the need for extensive post-processing.

3. Real-time sensor integration: Incorporate sensors to monitor parameters like temperature, bead width, and layer height in real time, adjusting the process dynamically for consistency. Where available, integration of real-time sensors can enhance path planning and process control. Temperature sensors, cameras, or bead monitoring systems may be used to monitor layer height, bead shape, or thermal conditions during deposition. The CNC program can be designed to respond to sensor feedback by adjusting travel speed, wire feed rate, or interpass cooling time, thereby improving consistency and reducing the risk of defects.

4. Offline programming: Offline programming and simulation tools are strongly recommended for WAAM applications. These tools allow path strategies to be generated, simulated, and validated prior to execution on the CNC machine. Simulation helps identify potential collisions, reach limitations, and thermal issues, reducing setup time and improving process reliability.

2.2.5 Process development and validation

Process development and validation are essential steps in ensuring that a CNC-based WAAM system operates reliably and produces components that meet defined quality and performance requirements. Unlike conventional welding, WAAM involves prolonged deposition, complex thermal behavior, and multi-layer material buildup, making systematic process development critical before production use. This involves:

1. Conducting initial test runs: The process development phase begins with the selection of initial deposition parameters based on the chosen material, wire diameter, and welding process. Key parameters include welding current, voltage, wire feed rate, travel speed, shielding gas composition,

and torch orientation. These parameters should be selected using manufacturer recommendations, prior experience, or published WAAM data as starting points.

2. Parameter adjustment: Based on test results, fine-tune parameters to ensure consistent layer deposition, control over material buildup, and reduction of defects like warping or porosity. Initial testing should focus on single-bead and single-layer depositions to evaluate arc stability, bead geometry, penetration behavior, and surface quality. These tests help identify suitable parameter windows and reveal potential issues such as lack of fusion, excessive spatter, or irregular wire feeding. Once stable single-bead deposition has been achieved, multi-layer wall structures should be produced to assess layer bonding, heat accumulation, and dimensional stability.

3. Thermal management: Thermal management plays a key role during process development. Interpass temperature, cooling time between layers, and deposition sequence must be evaluated and optimized to control residual stresses, distortion, and microstructural evolution. Controlled pauses, alternating deposition directions, or segmented deposition strategies may be applied to achieve more uniform heat distribution throughout the build.

4. Quality assurance (optional): Following geometric and thermal validation, material performance should be evaluated. Test specimens extracted from WAAM builds may be subjected to visual inspection, dimensional measurement, microstructural analysis, hardness testing, and mechanical testing as required by the intended application. These evaluations verify that the developed process meets mechanical property and fatigue performance requirements.

5. Process documentation: Throughout the process development and validation phase, detailed documentation must be maintained. This includes recording all process parameters, material batch information, build conditions, and inspection results. Comprehensive documentation supports traceability, quality assurance, and future process optimization.

2.2.6 Safety protocol enhancement and operator training

The transition from conventional CNC welding to WAAM introduces new operational and safety challenges that must be addressed through enhanced safety protocols and targeted operator training. WAAM processes involve prolonged arc operation, increased heat input, continuous material deposition, and extended machine run times, all of which require updated safety measures and competencies.

1. Operator training: Train operators and technicians on WAAM-specific tasks, such as parameter adjustment, process control, and handling of larger heat loads. Safety protocol enhancement should begin with a comprehensive risk assessment of the modified CNC cell. Existing safety systems must be reviewed and updated to account for WAAM-specific hazards, including prolonged exposure to arc radiation, hot surfaces, molten material, spatter, and increased fume generation. The physical enclosure of the CNC cell should provide adequate shielding against arc radiation and heat, and all safety interlocks, emergency stop functions, and access controls must be verified for proper operation.

2. Enhanced safety procedures: Effective fume extraction and ventilation systems are essential due to the continuous nature of WAAM deposition. Ventilation solutions should be designed to remove welding fumes efficiently without disturbing the shielding gas coverage or interfering with machine motion. Fire safety measures must also be enhanced, particularly for long-duration or semi-unattended WAAM builds. This may include the use of fire-resistant materials within the cell, thermal monitoring systems, and, where required, automatic fire detection or suppression systems.

3. Maintenance training: Maintenance personnel should be trained specifically on WAAM-related equipment, including welding torches, wire feeding systems, cooling units, and monitoring devices. Proper maintenance practices are essential to prevent failures that could compromise both safety and process stability.

2.2.7 Maintenance and continuous improvement

Once the CNC-based WAAM system is operational, systematic maintenance and continuous improvement are essential to ensure long-term reliability, consistent part quality, and efficient production. WAAM processes impose higher thermal and mechanical loads on equipment compared to conventional CNC welding, increasing the importance of proactive maintenance and performance monitoring.

1. Routine equipment inspections: Regular maintenance activities should focus on all critical system components. Welding-related components, including the welding power source, torch, contact tips, nozzles, liners, and wire feeding system, must be inspected frequently due to accelerated wear caused by prolonged arc operation and continuous wire feeding. Consumable components should be replaced proactively to prevent process instability, inconsistent bead geometry, or unplanned downtime.

2. Parameter monitoring and adjustment: Process-related maintenance and optimization are equally important. Logged process data should be reviewed regularly to monitor trends in welding parameters, wire feed stability, shielding gas flow, and interpass temperature. Deviations from established process windows may indicate equipment wear, sensor drift, or the need for parameter adjustments. Data-driven analysis supports early detection of issues and informed process optimization.

3. Continuous improvement based on data analysis: Leverage data collected during the WAAM process to make data-driven decisions, refine process parameters, and implement minor adjustments that can enhance the cell’s productivity and reliability. Continuous improvement should be supported through structured feedback and documentation. Lessons learned from production builds, maintenance activities, and quality inspections should be incorporated into updated process parameters, operating procedures, and training materials. Regular review meetings and performance assessments help identify opportunities for further efficiency gains, quality improvements, and system upgrades.

3 Transformation of the existing laser welding and cutting cells into laser DED applications

Transforming an existing laser welding or laser cutting cell into a laser-based Directed Energy Deposition (DED) system enables high-precision additive manufacturing of metal components. Compared to conventional laser cutting or welding, laser DED requires continuous energy input, precise control of material deposition, and advanced monitoring to ensure stable melt pool behavior and consistent layer formation. As a result, the transformation involves significant modifications to hardware, software, control systems, and safety arrangements.

This section outlines the key steps required to convert an existing laser-based manufacturing cell into a laser DED system. The procedure covers assessment and planning, equipment upgrades, software and control system integration, training and safety considerations, testing and calibration, and full-scale implementation.

3.1 Assessment and planning

The transformation of an existing laser welding or laser cutting cell into a laser-based DED system must begin with a comprehensive assessment and planning phase. This phase is essential to determine technical feasibility, identify necessary system modifications, and reduce implementation risks before significant investments are made.

The assessment should start with a detailed evaluation of the existing laser cell infrastructure. This includes the laser source, beam delivery optics, motion system, machine enclosure, utilities, and auxiliary equipment. The objective is to determine whether the current system can support the continuous, layer-by-layer deposition required in laser DED, which differs significantly from the intermittent operation typical of laser cutting or welding.

Laser source suitability is a critical consideration. The type of laser (fiber, diode, CO_2, Nd:YAG, or Yb:YAG) must be evaluated for DED compatibility. In practice, fiber lasers are most commonly used due to their high electrical efficiency, stable beam quality, and suitability for coaxial or off-axis deposition heads. The available laser power must be sufficient to achieve stable melting of the selected feedstock material. Typical laser DED applications require power levels ranging approximately from 500 W to 5 kW, depending on material type, deposition rate, and layer geometry. If the available laser power is insufficient or poorly controllable, system upgrades or replacement may be required.

The optical system and beam delivery components must also be assessed. Optics designed for cutting or welding are often optimized for narrow kerf widths or deep penetration rather than controlled melt pool formation. For DED applications, the beam shape, focal position, and interaction zone must be suitable for stable deposition. This may require changes to focusing optics, protective windows, or beam shaping components to ensure reliable and repeatable material buildup.

Thermal management capability is another key element of the assessment. Laser DED introduces prolonged heat input compared to conventional laser processes. Existing cooling systems must be evaluated to ensure they can manage continuous operation without overheating optical components, laser sources, or mechanical structures. Additional cooling capacity, such as enhanced water cooling or localized thermal shielding, may be required to maintain stable operating conditions.

The motion system and working envelope must be reviewed in parallel. The available build volume, axis configuration, positioning accuracy, and dynamic performance of the CNC or motion platform must be sufficient to support multi-layer deposition and growing part geometries. Accessibility for the deposition head, material feed system, and monitoring equipment should be verified, along with clearance for part growth and maintenance activities.

Utilities and supporting infrastructure must also be assessed. This includes electrical power availability, shielding gas supply, powder or wire handling systems, ventilation, and fume extraction. Laser DED processes often generate fine particulates and metal vapors, particularly in powder-based systems, requiring enhanced ventilation and filtration solutions.

Technical considerations, production and application requirements should be clearly defined during the planning phase. Target materials, part sizes, geometric complexity, dimensional tolerances, surface quality requirements, and post-processing needs must be identified. These factors determine whether laser DED is the most suitable manufacturing method and influence system configuration choices.

An investment and cost-benefit analysis should be conducted as part of the assessment. The costs associated with retrofitting the laser cell, including deposition heads, material feed systems, software, training, and safety upgrades—should be compared against expected benefits such as increased manufacturing flexibility, reduced lead times, material savings, and new application opportunities.

Safety and regulatory requirements must be incorporated into the planning process. The use of high-power lasers, continuous operation, and, in some cases, metal powders introduces additional safety considerations. Compliance with applicable laser safety standards, occupational health regulations, and environmental requirements must be ensured from the outset.

3.2 Upgrading equipment

Upgrading equipment is a central step in transforming an existing laser welding or cutting cell into a laser-based DED system. While many core elements of the original laser cell can be reused, additive manufacturing places new demands on deposition hardware, material delivery systems, thermal management, and system robustness. Careful equipment selection and integration are therefore required to ensure stable, repeatable, and safe DED operation.

The most critical upgrade is the integration of a dedicated laser DED deposition head. Deposition heads used for laser DED differ significantly from cutting or welding optics, as they must provide controlled energy delivery and precise alignment between the laser beam and the feedstock material. Depending on the selected DED approach, the deposition head may be designed for powder-based or wire-based material feeding. Powder deposition heads typically use coaxial or off-axis nozzles to deliver metal powder into the laser-induced melt pool, while wire-based systems feed solid wire directly into the interaction zone. The selected head must be compatible with the existing laser source, optical interfaces, and motion system.

Material delivery systems must be installed or upgraded to support continuous and stable feedstock supply. For powder-based DED, this includes powder feeders, carrier gas supply, hoses, and nozzles capable of delivering consistent powder flow with minimal fluctuations. Powder handling systems must also address issues related to contamination, moisture control, and powder recovery. For wire-based DED, reliable wire feeding systems with precise feed rate control are required. The wire feeder must be synchronized with laser power and motion speed to ensure uniform deposition and stable melt pool behavior.

The build platform and fixturing arrangements must be adapted for additive manufacturing. Conventional cutting tables or welding fixtures are typically not designed to support growing three-dimensional structures or prolonged thermal loading. A rigid, heat-resistant build plate should be installed to provide stable support for WAAM or laser DED parts throughout the build process. In some cases, additional fixturing or clamping solutions may be required to minimize distortion or movement during deposition.

Thermal management and cooling systems require particular attention during equipment upgrades. Laser DED introduces sustained heat input that can affect the laser optics, deposition head, machine structure, and surrounding equipment. Existing cooling systems must be evaluated and, where necessary, upgraded to handle continuous operation. Additional cooling circuits, enhanced water cooling, or localized thermal shielding may be required to protect sensitive components and maintain process stability.

Shielding gas systems must also be adapted for DED operation. Inert gas shielding is typically required to protect the melt pool and deposited material from oxidation. Gas delivery systems should provide stable flow rates and appropriate coverage of the deposition zone without disturbing the powder or wire feed. In some applications, local shielding or controlled atmosphere enclosures may be considered to improve material quality.

Fume extraction and filtration systems must be upgraded to handle the increased generation of metal vapors and fine particulates associated with laser DED, particularly in powder-based processes. Extraction systems should be designed to capture fumes effectively while avoiding interference with laser optics, shielding gas flow, or material deposition.

Additional equipment upgrades may include the integration of monitoring and diagnostic systems. Cameras, melt pool sensors, layer height measurement devices, or optical sensors can be installed to provide real-time feedback on process stability and deposition quality. These systems support process optimization and early detection of defects but require careful positioning and protection from heat, spatter, and contamination.

All upgraded equipment must be mechanically and electrically integrated into the existing laser cell in a robust and maintainable manner. Cable routing, hose management, and protective enclosures should be designed to withstand continuous operation and facilitate safe access for maintenance and inspection.

Overall, equipment upgrades should be planned as a coherent system-level modification rather than isolated component replacements. Proper integration of deposition hardware, material delivery, thermal management, and monitoring systems is essential to achieving reliable and industrially viable laser DED performance.

3.3 Software and control systems integration

Effective software and control system integration is a key requirement for successful laser-based DED implementation. Unlike conventional laser cutting or welding, laser DED relies on continuous, multi-layer deposition that requires precise coordination between motion control, laser power, and material feed. The software environment must therefore support advanced path planning, real-time process control, and reliable system communication.

The integration process begins with ensuring that the existing CNC or motion controller is capable of supporting additive manufacturing operations. The controller must execute long and complex programs with smooth, continuous motion while maintaining stable synchronization with laser power and feedstock delivery. Any limitations in processing capacity, memory, or communication interfaces should be identified and addressed through controller upgrades or external control solutions.

Dedicated additive manufacturing software is required to generate laser DED toolpaths from CAD models. This software converts three-dimensional geometries into layer-based deposition paths, defining parameters such as layer height, bead overlap, travel direction, and deposition sequence. The selected software must be compatible with the existing control architecture and able to export programs or commands in a format supported by the motion controller. Offline programming and simulation tools are strongly recommended, as they allow verification of toolpaths, collision checking, and optimization of deposition strategies prior to execution on the machine.

Close integration between the motion controller and the laser source is essential for stable DED operation. The control system must support synchronized control of laser power, travel speed, and material feed rate. Digital communication interfaces are preferred to enable precise and repeatable parameter control. In advanced implementations, the control system may allow dynamic adjustment of laser power or feed rate in response to changes in geometry, deposition speed, or thermal conditions.

Material feed systems, whether powder- or wire-based, must also be integrated into the control architecture. The software should allow coordinated control of powder flow or wire feed rate in relation to laser power and motion. Stable and predictable material delivery is critical for maintaining consistent bead geometry and layer bonding.

Monitoring and feedback systems play an increasingly important role in laser DED. The software environment should support integration of sensors such as melt pool cameras, photodiodes, temperature sensors, or layer height measurement systems. Data from these sensors can be used for real-time process monitoring, quality assurance, and, in some cases, closed-loop control. The ability to log and store process data supports traceability and continuous process improvement.

User interfaces and system usability should also be considered during software integration. Operators should have access to clear and intuitive interfaces for monitoring process status, adjusting parameters within defined limits, and responding to alarms or deviations. Well-designed interfaces reduce operator error and improve overall system reliability.

All software and control system integrations must be thoroughly tested and validated before production use. Trial builds should be conducted to verify stable communication, correct parameter synchronization, and reliable execution of long-duration deposition processes. Software configurations, interfaces, and operating procedures should be documented to ensure reproducibility and ease of maintenance.

3.4 Training and safety

The conversion of an existing laser welding or cutting cell into a laser-based DED system introduces new operational, technical, and safety-related requirements. Laser DED involves continuous high-energy laser operation, material deposition, and, in some cases, handling of metal powders, all of which require enhanced safety protocols and targeted training for personnel.

Training should be provided for all personnel involved in operating, programming, maintaining, and supervising the laser DED system. Operators and engineers must be trained in the fundamental principles of laser DED, including layer-by-layer deposition behavior, melt pool dynamics, thermal accumulation, and the interaction between laser power, material feed rate, and motion speed. Understanding these principles is essential for maintaining stable process conditions and recognizing abnormal process behavior during operation.

In addition to process knowledge, training must cover the operation of upgraded hardware and software systems. This includes use of additive manufacturing software, interpretation of process monitoring data, adjustment of process parameters within defined limits, and execution of safe start-up, shutdown, and recovery procedures. Maintenance personnel should receive specific training on laser DED components such as deposition heads, optical systems, powder or wire feeders, cooling systems, and monitoring equipment.

Safety protocols must be reviewed and enhanced to address hazards specific to laser DED. High-power laser radiation presents significant risks, requiring appropriate laser safety classifications, protective enclosures, interlocks, and access controls. Personnel must be trained in laser safety principles, including the use of protective eyewear, controlled access zones, and emergency procedures in accordance with applicable laser safety standards.

If powder-based DED is used, additional safety measures are required for powder handling. This includes training on safe storage, handling, and disposal of metal powders, as well as awareness of explosion and inhalation risks. Ventilation and filtration systems must be designed to capture fine particulates and metal vapors generated during deposition, and operators must be trained in their correct use and maintenance.

Fire safety is a critical consideration due to continuous laser operation and elevated temperatures. Safety protocols should include fire-resistant materials within the cell, monitoring of critical temperatures, and clear procedures for responding to abnormal conditions. In some cases, automatic fire detection or suppression systems may be required, particularly for long-duration or semi-unattended operation.

Clear operational procedures and work instructions must be developed and communicated to all personnel. These documents should define roles and responsibilities, safe operating limits, maintenance routines, and actions to be taken in the event of process deviations or equipment failure. Emergency stop systems and safety interlocks must be tested regularly to ensure proper function.

3.5 Testing and calibration

Before a converted laser welding or cutting cell can be used for production-level laser DED, comprehensive testing and calibration must be carried out. This phase is essential to verify system functionality, ensure process stability, and confirm that the upgraded equipment, software, and control systems operate together as intended.

Testing should begin with system-level verification of all integrated components. This includes confirming correct operation of the laser source, deposition head, material feed system, motion platform, shielding gas delivery, cooling systems, and monitoring equipment. Communication between the motion controller, laser power source, and material feeder must be verified to ensure accurate synchronization of laser power, travel speed, and feed rate.

Calibration of the laser deposition head is a critical step. The alignment between the laser beam and the material feed (powder stream or wire) must be precisely adjusted to ensure that the feedstock enters the melt pool consistently. Incorrect alignment can lead to unstable deposition, poor bonding, or excessive spatter. Focal position, beam spot size, and working distance should be calibrated according to the selected deposition strategy and material.

Material feed calibration must be performed to ensure stable and repeatable delivery. For powder-based systems, powder flow rate, carrier gas pressure, and nozzle alignment should be calibrated and tested for consistency over extended operation. For wire-based systems, wire feed speed and synchronization with laser power must be verified to avoid irregular bead formation or feed interruptions.

Process parameter testing should then be conducted using trial builds. Initial tests typically focus on single-track and single-layer depositions to evaluate melt pool stability, bead geometry, and surface quality. These tests help establish suitable parameter windows for laser power, feed rate, travel speed, and shielding gas flow. Once stable deposition is achieved, multi-layer structures should be produced to assess layer bonding, heat accumulation, and dimensional stability.

Thermal behavior should be carefully evaluated during testing. Temperature measurements and visual monitoring can be used to assess heat buildup, cooling effectiveness, and the risk of thermal distortion or cracking. Based on these observations, interpass cooling times, deposition sequences, or parameter adjustments may be required to achieve stable thermal conditions.

Monitoring and sensor systems should also be tested and calibrated during this phase. Cameras, melt pool sensors, or layer height measurement devices must be aligned and configured to provide reliable data. Alarm thresholds and data logging functions should be validated to ensure effective process monitoring and traceability.

Validation builds should be performed to confirm repeatability and robustness of the developed process. Identical test components should be produced using the same parameters to verify consistent deposition behavior and quality. All testing and calibration results should be documented, including finalized process parameters, calibration settings, and inspection outcomes.

3.6 Full scale implementation

Following successful testing and calibration, the laser DED system can be transitioned to full-scale industrial implementation. This phase focuses on moving from controlled validation builds to reliable and repeatable production while maintaining process stability, quality, and safety.

Full-scale implementation should be introduced gradually. Initial production runs should be limited in scope and closely monitored to confirm that the validated process performs consistently under real production conditions. During this phase, attention should be given to system robustness during extended operation, including laser stability, material feed reliability, thermal behavior, and motion system performance over long build durations.

Standard operating procedures must be finalized and implemented prior to regular production use. These procedures should cover system setup, parameter selection, start-up and shutdown sequences, monitoring practices, and handling of process deviations. Clear documentation ensures consistent operation across different operators and shifts and reduces the risk of errors during production.

Quality assurance measures should be integrated into the production workflow. This includes routine visual inspections, dimensional checks, and, where required, non-destructive or destructive testing of representative parts. Process data collected during production, such as laser power, feed rates, temperatures, and monitoring signals, should be reviewed regularly to verify that the process remains within validated limits.

Production planning considerations are also important during full-scale implementation. Build times, material consumption, post-processing requirements, and machine availability should be analyzed to optimize scheduling and throughput. Laser DED offers high flexibility, but efficient utilization requires careful coordination between additive manufacturing, machining, inspection, and finishing operations.

Maintenance routines must be fully integrated into production planning. Preventive maintenance schedules for laser optics, deposition heads, material feed systems, cooling units, and safety systems should be established and followed consistently. Proactive maintenance minimizes unplanned downtime and supports stable long-term operation.

Operator feedback and production data should be actively used to drive continuous improvement. Lessons learned during early production builds can be used to refine process parameters, path planning strategies, and system configurations. Incremental optimization may lead to improved productivity, reduced energy consumption, enhanced surface quality, or expanded material and application capability.

Scalability and future development should be considered as part of full-scale implementation. The system should be evaluated for its ability to accommodate new materials, larger components, or more complex geometries. Planning for future upgrades, such as enhanced monitoring, automation, or additional axes, ensures that the laser DED system remains adaptable and competitive over its operational lifetime.

3.7 Laser DED Feasibility Checklist

This checklist supports the evaluation of whether an existing laser welding or cutting cell can be successfully converted into a laser-based DED system. All items should be reviewed during the assessment and planning phase.

1. Laser source and optics

☐ Laser type (fiber, diode, CO_2, etc.) is suitable for DED applications
☐ Available laser power is sufficient for target materials and deposition rates
☐ Laser power can be controlled accurately and dynamically
☐ Existing optics can be adapted or replaced for deposition use
☐ Protective optics and contamination protection are feasible

2. Motion system and build envelope

☐ CNC or motion system supports smooth, continuous multi-axis motion
☐ Positioning accuracy and repeatability meet WAAM/DED requirements
☐ Available build volume accommodates expected part size and growth
☐ Motion system can handle long-duration operation without drift

3. Deposition hardware

☐ Suitable laser DED deposition head (powder or wire) can be integrated
☐ Material feed system provides stable and repeatable delivery
☐ Wire or powder feed can be synchronized with laser power and motion
☐ Build platform and fixturing are heat-resistant and rigid

4. Thermal management and utilities

☐ Cooling capacity is sufficient for continuous laser operation
☐ Thermal shielding can be implemented where required
☐ Electrical power supply supports laser, feeders, and auxiliary systems
☐ Shielding gas supply is adequate and stable

5. Software and control systems

☐ CNC/controller supports additive manufacturing–type programs
☐ Software for laser DED path planning is available and compatible
☐ Laser power, motion, and material feed can be synchronized
☐ Data logging and monitoring capabilities are available or expandable

6. Monitoring and quality control

☐ Melt pool or process monitoring systems can be integrated
☐ Temperature or layer height monitoring is feasible
☐ Process data can be stored for traceability and analysis

7. Safety and compliance

☐ Laser safety classification and enclosure requirements can be met
☐ Fume extraction and filtration are sufficient for DED operation
☐ Fire risk can be mitigated for long-duration builds
☐ Powder handling safety (if applicable) can be ensured
☐ Emergency stop and interlock systems are compatible

8. Materials and applications

- ☐ Target materials are suitable for laser DED processing
- ☐ Required mechanical properties and tolerances are achievable
- ☐ Post-processing requirements are understood and manageable

9. Production and economic considerations

- ☐ Expected production volumes justify the conversion
- ☐ Retrofit costs are acceptable relative to benefits
- ☐ Lead time reduction or flexibility provides clear value
- ☐ Internal expertise or training capability is available

10. Scalability and future development

- ☐ System allows future upgrades (materials, sensors, automation)
- ☐ Layout supports expansion or higher productivity
- ☐ Long-term maintenance and supplier support are available

4 Commercial DED systems

4.1 WAAM systems

This is an overview of selected commercially available WAAM systems. The systems described here are intended for industrial or research use cases involving medium to large metal components, repair applications, and near-net-shape manufacturing. The descriptions focus on system characteristics, typical applications, and software capabilities rather than marketing claims.

4.1.1 WAAM3D

WAAM3D is a UK-based developer and supplier of industrial WAAM systems, spun out from research at Cranfield University. The company focuses on commercializing WAAM technology for large-scale metal additive manufacturing and supports industries such as aerospace, energy, mining, marine, and defense with both hardware and software solutions.

WAAM3D's product ecosystem is designed to enable repeatable, controlled large-format WAAM production. Core offerings include high-performance systems built for industrial applications as well as smaller, more accessible platforms for prototyping, research, and process development.

Their key products include:

RoboWAAM series: The RoboWAAM family encompasses large-format robotic WAAM systems engineered for industrial part production. These platforms integrate advanced sensing hardware, specialized end-effectors, and a comprehensive software ecosystem to provide real-time process monitoring, automated data logging, and enhanced health and safety management. RoboWAAM systems are suited for multi-tonne components and include features such as global shielding, inert atmosphere control, fume management, and configurable enclosures

MiniWAAM: Introduced in 2024, MiniWAAM provides WAAM3D's deposition and monitoring capabilities in a more compact, cost-effective package. It is built on a three-axis overhead CNC system with an additional rotary table, offering a build volume of approximately 800 × 800 × 600 mm. The system includes dual wire feeders that can operate independently for higher deposition rates or multi-material and graded structures, and incorporates proprietary sensors such as interferometric ShapeTech™ for in-process layer height measurement and double-point thermometry for thermal tracking. MiniWAAM targets research, development, mechanical test part production, and pilot manufacturing while maintaining compatibility with WAAM3D's software suite.

Software solutions: WAAM3D supplies an integrated software ecosystem that covers the complete WAAM workflow:

WAAMPlanner for toolpath planning and geometry slicing

WAAMCtrl for machine control, real-time monitoring, and process governance

WAAMKeys for parameter database management and process setup

These tools support path planning, deposition simulation, data logging, and quality traceability, enabling users to execute and monitor builds with industrial rigor.

4.1.2 MX3D

MX3D is a Dutch company based in Amsterdam that develops industrial-scale robotic WAAM systems for large metal 3D printing applications. Founded in 2014 with roots in experimental work at the Joris Laarman Lab, MX3D has become a recognised pioneer in combining conventional robotic welding technology with advanced additive manufacturing to build complex, high-value metal components for multiple industries.

MX3D's WAAM systems are designed to support the production of medium-to-very-large parts with high material deposition rates, extensive build volumes, and real-time process control. The company's technology is used across sectors such as energy (including nuclear and oil & gas), maritime, aerospace, automotive, manufacturing, architecture, and infrastructure, where large and geometrically complex metal components are needed.

Their key products include:

M1 metal AM system: The M1 system is MX3D's turnkey WAAM solution optimised for medium-to-large metal parts. It integrates an industrial robotic arm with a high-productivity welding power source and MX3D's proprietary MetalXL software suite. The M1 enables advanced path planning, process monitoring, and data logging, making it suitable for qualified production runs and in-house manufacturing. The system is capable of printing parts up to several tonnes in weight and supports continuous operation for demanding industrial environments.

MX metal AM system: This family of systems extends the capabilities of the M1 platform with larger robots and enhanced automation for heavy-duty industrial applications. These solutions are tailored for manufacturers producing large components — including parts exceeding four meters in length and 10+ tonnes in weight — enabling high deposition productivity and flexible build strategies. Like the M1, these systems leverage MX3D's MetalXL technology for integrated process control and monitoring.

Software and process integration:

Central to MX3D's WAAM systems is the MetalXL software suite, which provides end-to-end control of the additive manufacturing workflow. MetalXL includes modules for:

- Toolpath planning and slicing with advanced CAM capabilities, including strategies for multiple metal alloys and geometry optimisation.
- Real-time process monitoring and control, enabling users to track deposition behaviour and intervene when necessary.
- High-resolution data logging and analytics, supporting quality assurance and traceability for industrial builds.

This software-first approach ensures consistent, repeatable print execution and facilitates integration into industrial production environments.

4.1.3 Gefertec

GEFERTEC GmbH is a German developer and manufacturer of industrial WAAM systems, based in Berlin. Since its founding in 2015, the company has focused on commercializing WAAM through its patented 3DMP® (3D Metal Print) technology, combining mature arc welding processes with modern CAM and CNC control to produce large metal components in a resource-efficient manner.

GEFERTEC's WAAM systems are used across industries where large format metal parts, rapid delivery, and cost-efficient production are required. Notable application areas include energy, aerospace, rail and infrastructure, marine, and industrial spare parts production. GEFERTEC systems are already in industrial use, such as WAAM production of turbine components for Siemens Energy in serial manufacturing.

Here are some of their primary offerings:

arc80X Series:

The arc80X platform represents GEFERTEC's latest generation of industrial WAAM machines. It is designed for manufacturing large metal parts with high build volumes—up to approximately 8 m³—and high material throughput. The system can be configured with CNC-controlled linear axes for consistent motion precision and process stability across the working envelope. Available configurations include:

- 3-axis mode: Assembly space up to ~2 × 2 × 2 m and a maximum part weight of ~8 000 kg.
- 5-axis mode: Capability to produce parts with complex geometries with assisted rotary motion and additional degrees of freedom.

The arc80X includes advanced automation features such as integrated tool measurement, gas nozzle cleaning, wire cutting, and automated replacement of wear parts, reducing manual intervention and increasing production uptime. A comprehensive process monitor records and stores key data during builds to support quality assurance and process optimization. Optional features include an inert gas box for controlled atmospheres, enabling sensitive materials like titanium to be processed.

4.1.4 MetalWorm

MetalWorm Additive Manufacturing Technologies Inc. is a technology provider specialising in robotic WAAM systems. Based in Ankara, Turkey, MetalWorm offers a flexible range of robotic WAAM platforms that combine arc-based additive manufacturing with process monitoring and intelligent software support. The company's solutions are designed for industrial production, research environments, and hybrid manufacturing workflows.

MetalWorm's WAAM technology uses a robotic arm to deposit metal wire into an electric arc, building parts layer by layer in a DED process. The platform supports a variety of arc welding processes (e.g., Gas Metal Arc Welding and Gas Tungsten Arc Welding) and is compatible with different industrial robot models from major manufacturers such as ABB, KUKA, and FANUC.

Key WAAM systems:

MetalWorm offers a family of configurable robotic WAAM systems tailored to different production scales and application needs:

Compact system:
A plug-and-play robotic WAAM cell designed for easy integration and straightforward operation. Typical configurations include systems with working envelopes of approximately Ø0.7 m × 0.7 m. These units commonly feature six-axis industrial robots with additional rotary axes or positioners, enabling flexible deposition strategies for mid-sized parts.

Special system series:
Designed for larger and heavier parts, these systems support extended working envelopes and high payloads—capable of handling components up to ~Ø2 m in diameter and multiple meters in height. These configurations integrate advanced motion peripherals like skyhook positioners and multi-axis setups for enhanced accessibility and deposition control.

Lab / Research systems:

Compact and configurable platforms intended for academic or R&D environments, supporting WAAM process development, materials research, and pilot-scale production. Some units are optimised for use with collaborative robots (cobots) and smaller power sources to enable lower entry-cost adoption.

4.2 Laser Based DED Systems

Laser wire and laser powder DED systems use a focused laser beam as the energy source and metal wire or powder as the feedstock. Compared to arc-based processes, laser DED typically enables higher dimensional accuracy, smaller bead sizes, and improved surface quality. These systems are widely applied in high-value manufacturing, repair, and hybrid additive–subtractive workflows, particularly in aerospace, tooling, energy, and automotive industries.

Laser DED solutions are available as standalone additive manufacturing systems, hybrid CNC-integrated platforms, and robot-based cells. The following sections provide an overview of commercially available laser DED system providers relevant to industrial implementation.

4.2.1 Meltio

Meltio specializes in laser wire DED technology with a strong emphasis on modularity, material efficiency, and ease of integration into existing manufacturing environments. Meltio’s solutions use metal wire as feedstock, which significantly reduces material waste, improves material handling cleanliness, and simplifies process logistics. These characteristics make Meltio systems particularly attractive for industrial production and repair applications.

Meltio offers both dedicated metal additive manufacturing machines and integration solutions for robotic and CNC platforms. The Meltio M450 and M600 systems are industrial-grade metal 3D printers designed for medium- and large-scale components. These machines operate in controlled atmospheres and support a broad range of materials, including stainless steels, tool steels, titanium alloys, aluminum alloys, and copper-based materials. The multi-laser deposition head enables controlled energy input and stable material transfer, contributing to consistent bead geometry and improved surface quality compared to many arc-based processes.

In addition to standalone machines, Meltio provides robotic integration kits that allow existing robot cells to be upgraded for laser wire DED with relatively limited mechanical modification. This approach supports cost-effective adoption of additive manufacturing by leveraging existing robotic infrastructure. The robotic solutions are well suited for large-scale components, complex geometries, and repair operations where multi-axis deposition is required.

Meltio also offers CNC integration solutions that transform conventional CNC machining centers into hybrid manufacturing platforms. In these configurations, additive deposition and subtractive machining can be performed within a single setup, enabling near-net-shape manufacturing followed by precision finishing. This hybrid capability is particularly beneficial for repair and remanufacturing applications, as it reduces part handling, improves geometric accuracy, and shortens overall production lead times.

From a software perspective, Meltio systems support both proprietary and third-party CAM solutions for toolpath generation and process control. This flexibility allows users to adapt deposition strategies to different part geometries and materials, which is especially important when integrating the technology into diverse industrial environments. Overall, Meltio’s laser wire DED solutions represent a versatile and scalable option for companies seeking high-quality metal additive manufacturing with strong potential for integration into existing production systems.

4.2.2 Laserline

Laserline is a leading supplier of high-power diode laser systems for industrial manufacturing applications, including laser-based Directed Energy Deposition (DED), cladding, and component repair. Unlike turnkey additive manufacturing machine providers, Laserline focuses on delivering laser sources and process optics, which are typically integrated into robotic or CNC-based systems by system integrators or end users. This approach provides a high degree of flexibility for tailoring DED solutions to specific industrial requirements.

Laserline's diode laser systems are well suited for laser wire DED processes, offering high electrical efficiency, excellent beam stability, and precise control of energy input. The use of wire feedstock enables efficient material utilization and clean operation, making these systems attractive for production environments where material waste, contamination, and process repeatability are critical considerations. Laser wire DED systems based on Laserline technology are commonly applied in repair and refurbishment operations, surface coating, and the additive manufacturing of large or high-value components.

A key advantage of Laserline's solutions is their scalability in laser power and system configuration. Laser sources are available across a wide power range, enabling adaptation to different materials, deposition rates, and component sizes. Combined with suitable deposition heads and wire feeding systems, this flexibility allows Laserline-based DED systems to be optimized for applications ranging from fine-feature deposition to high-deposition-rate manufacturing.

Laserline systems are frequently integrated into multi-axis robotic cells or CNC machines, supporting complex deposition paths and multi-directional material placement. This makes them particularly suitable for retrofitting existing manufacturing infrastructure for DED applications. Integration typically includes synchronization of laser power, wire feed rate, and machine motion, which is essential for achieving stable melt pool behavior and consistent bead geometry.

From a software and control perspective, Laserline laser sources can be interfaced with a wide range of industrial control systems and CAM software solutions. This compatibility supports the development of customized DED workflows, including offline programming, simulation, and process monitoring. As a result, Laserline-based solutions are widely used in demanding industrial sectors such as aerospace, energy, and heavy machinery, where high process reliability, long equipment lifetimes, and precise energy control are required.

4.2.3 Aconity3D

Aconity3D develops modular DED systems designed for high-precision industrial and research applications. The company's approach emphasizes configurability and openness, allowing systems to be tailored to specific process requirements, materials, and application domains. This modular design philosophy makes Aconity3D systems particularly suitable for environments where process development, validation, and advanced control strategies are required.

Aconity3D offers DED platforms that support both wire- and powder-based feedstock, combined with laser energy sources. The systems can be configured with different build volumes, motion systems, and atmospheric control options, including inert or controlled environments for processing reactive materials. Multi-axis motion capabilities enable deposition on complex geometries and support advanced manufacturing strategies such as multi-directional deposition and functionally graded materials.

A key strength of Aconity3D systems is their strong integration of process monitoring, data acquisition, and control. The machines are equipped with in-situ sensors for monitoring melt pool behavior, temperature, and deposition quality. These monitoring capabilities provide valuable data for process optimization, quality assurance, and traceability, which are increasingly important in industrial additive manufacturing applications.

From a control and software perspective, Aconity3D systems are designed to support open and customizable process control. Users have access to detailed process data and system parameters, enabling the development of advanced control strategies and the integration of external software tools. This openness is particularly beneficial for research institutions and industrial users who require flexibility beyond standard turnkey solutions.

Aconity3D DED systems are commonly used in aerospace, energy, automotive, and tooling applications, where high process reliability and material performance are critical. The combination of modular hardware, advanced monitoring, and flexible software architecture makes these systems well suited for both production and process development. Overall, Aconity3D provides a versatile platform for laser-based DED applications where precision, adaptability, and data-driven process control are key requirements.

4.2.4 Additec3D

Additec develops compact and modular DED systems with a focus on flexibility, hybrid manufacturing, and accessibility. The company's solutions are designed to support both wire- and powder-based DED, making them suitable for a wide range of applications, including prototyping, component repair, tooling, and small- to medium-scale production.

Additec's DED systems are available as standalone machines as well as integration solutions for CNC machining centers and robotic platforms. The company places particular emphasis on hybrid manufacturing, enabling additive deposition and subtractive machining to be performed within a single machine environment. This hybrid capability allows near-net-shape components to be produced and finished with high dimensional accuracy without the need for additional setups, which is especially advantageous for repair and remanufacturing applications.

A notable characteristic of Additec systems is their compact footprint and modular architecture. These features make the systems suitable for laboratory environments, research institutions, and industrial facilities where space and flexibility are important considerations. The modular design also allows systems to be configured and expanded according to specific process requirements, such as build volume, material feedstock, and monitoring capabilities.

From a software and control perspective, Additec systems are designed to interface with standard CAM software and CNC controllers. This compatibility facilitates integration into existing digital manufacturing workflows and reduces the learning curve for operators familiar with conventional machining environments. Toolpath strategies can be adapted to support a variety of deposition geometries and materials, supporting both additive-only and hybrid manufacturing processes.

Additec's DED solutions are commonly applied in tooling, mold repair, aerospace component refurbishment, and research-driven material development. Overall, the company's focus on compact, adaptable, and hybrid-capable systems makes Additec a practical option for organizations seeking to introduce DED technology with moderate investment and high operational flexibility.

4.2.5 Optomec

Optomec is a long-established supplier of DED systems, best known for its laser engineered net shaping (LENS) technology. The company has extensive industrial experience in additive manufacturing, repair, and surface engineering, and its systems are widely used in aerospace, energy, defense, and heavy industry applications.

Optomec offers both standalone additive manufacturing systems and hybrid CNC-integrated solutions. LENS systems utilize a laser energy source and metal feedstock, typically in powder form, to enable precise material deposition with good control over melt pool behavior and dimensional accuracy. The systems are commonly operated in controlled atmospheres, allowing the processing of reactive and high-performance materials such as titanium alloys, aluminum alloys, and nickel-based superalloys.

A key strength of Optomec's technology is its strong focus on repair, remanufacturing, and feature addition. LENS systems are frequently applied to restore worn or damaged components, add functional features to existing parts, and apply wear- or corrosion-resistant coatings. The ability to deposit material directly onto existing components with high accuracy makes these systems particularly suitable for extending component service life and reducing material waste.

Optomec's hybrid manufacturing solutions integrate DED capability directly into CNC machining centers. In these configurations, additive deposition and machining operations can be performed within a single machine setup. This hybrid approach improves geometric accuracy, reduces part handling, and shortens production lead times, especially in repair and low-volume production scenarios. The integration also enables efficient transition between additive and subtractive steps, supporting near-net-shape manufacturing workflows.

From a software and control perspective, Optomec systems support integration with industrial CAM software and process monitoring tools. Process parameters such as laser power, feed rate, and deposition path can be precisely controlled and adjusted to suit different materials and geometries. The company also provides monitoring and control solutions that support process repeatability and quality assurance.

Overall, Optomec's LENS technology represents a mature and industrially proven DED solution. Its strong capabilities in repair, hybrid manufacturing, and processing of high-value materials make Optomec systems particularly relevant for organizations seeking reliable and well-established laser-based DED solutions for production and remanufacturing applications.

4.2.6 Precitec

Precitec is a supplier of laser-based deposition heads, optics, and process monitoring solutions for DED and laser material processing applications. Rather than offering complete turnkey additive manufacturing machines, Precitec focuses on providing high-precision system components that are typically integrated into robotic cells or CNC-based platforms by system integrators or end users. This approach enables highly customized DED solutions tailored to specific industrial requirements.

Precitec's laser DED deposition heads are designed for stable and precise energy delivery, often employing coaxial wire or powder feeding concepts. Coaxial designs allow uniform material delivery into the melt pool regardless of deposition direction, which is particularly advantageous for multi-axis and multi-directional manufacturing. This capability supports consistent bead geometry and improved process stability when producing complex geometries or performing repair operations on curved surfaces.

A key strength of Precitec's solutions is the integration of process monitoring and sensing technologies. The company offers monitoring systems for observing melt pool behavior, laser power, seam geometry, and process emissions in real time. These monitoring capabilities support quality assurance, process optimization, and traceability, which are increasingly important in industrial additive manufacturing environments.

Precitec equipment is commonly integrated into multi-axis robotic systems and CNC machines, making it well suited for retrofitting existing manufacturing infrastructure for laser DED applications. The modular nature of the deposition heads and sensors allows system integrators to select appropriate configurations based on material type, deposition rate, and component size.

From a software and control perspective, Precitec systems are designed to interface with industrial laser controllers, robot controllers, and CNC systems. This compatibility enables synchronization between machine motion, laser output, and material feeding, which is critical for achieving stable and repeatable deposition. The openness of the system architecture also allows integration with third-party CAM software and advanced control strategies.

4.2.7 Trumpf

TRUMPF is a global supplier of industrial laser systems and manufacturing solutions, offering a comprehensive portfolio of technologies for laser-based DED, surface processing, and hybrid manufacturing. The company provides both complete DED systems and laser sources and deposition heads that can be integrated into robotic cells or CNC-based platforms, enabling flexible implementation across different industrial environments.

TRUMPF's laser DED solutions are designed for high process stability, precision, and industrial reliability. The company offers laser deposition heads compatible with both wire and powder feedstocks, allowing users to select the most appropriate configuration based on application requirements. TRUMPF systems are commonly applied in additive manufacturing, component repair, and surface modification, particularly in industries where quality assurance and repeatability are critical.

A key offering in TRUMPF's portfolio is the TruLaser Cell series, which combines multi-axis motion systems with laser-based material deposition. These systems support complex geometries and enable hybrid manufacturing workflows that integrate additive deposition with subtractive machining operations. The ability to perform multiple manufacturing steps within a single machine setup improves dimensional accuracy and reduces overall production lead times.

TRUMPF's laser DED solutions are supported by advanced control systems and software integration. The company provides tools for process monitoring, parameter control, and system diagnostics, enabling consistent deposition quality and facilitating industrial-scale production. Integration with industrial CAM software allows efficient generation of deposition paths and supports simulation and offline programming.

In addition to standalone DED systems, TRUMPF offers hybrid manufacturing platforms that combine laser metal deposition with powder bed fusion or conventional machining technologies. This hybrid approach enables flexible production strategies for large, complex, or functionally optimized components, particularly in aerospace, automotive, and energy applications.

4.2.8 Innstek

Innstek develops DED systems for industrial additive manufacturing, with a strong focus on hybrid manufacturing solutions that integrate additive deposition with conventional CNC machining. The company offers both standalone DED machines and hybrid CNC-based platforms, enabling flexible implementation depending on production requirements and existing manufacturing infrastructure.

Innstek's hybrid systems combine laser-based DED capability with multi-axis CNC machining in a single machine tool. This configuration allows additive deposition and subtractive finishing operations to be performed within one setup, improving dimensional accuracy and reducing handling time. Such hybrid systems are particularly well suited for component repair, remanufacturing, and the production of complex geometries requiring high precision.

The company's DED solutions support both wire and powder feedstocks, allowing adaptation to a wide range of materials and deposition strategies. Real-time process monitoring is an integral part of Innstek's systems, enabling control of key process variables such as melt pool behavior, deposition rate, and thermal input. These monitoring capabilities support consistent deposition quality and facilitate process optimization.

From a system integration perspective, Innstek solutions are designed for industrial environments requiring robust performance and long-term reliability. The CNC-based architecture enables precise motion control and compatibility with standard CAM software used in machining operations. This compatibility simplifies integration into existing digital manufacturing workflows and reduces the need for specialized additive manufacturing software.

Innstek systems are commonly applied in tooling, mold manufacturing, aerospace component repair, and energy-sector applications, where high-value components benefit from hybrid manufacturing approaches. Overall, Innstek provides industrial-grade DED solutions that emphasize precision, flexibility, and efficient integration of additive and subtractive processes, making them a strong option for organizations seeking advanced hybrid manufacturing capabilities.

4.3 WAAM welding processes

Wire arc additive manufacturing (WAAM) relies on arc welding processes as the energy source for material deposition. The choice of welding process has a significant influence on deposition rate, heat input, surface quality, dimensional accuracy, and the mechanical properties of the printed component. This section outlines the most commonly used welding processes in WAAM applications and discusses their advantages and limitations.

4.3.1 Gas Metal Arc Welding (GMAW)

Gas Metal Arc Welding (GMAW), also known as Metal Inert Gas (MIG) welding, is one of the most widely used processes in WAAM. In GMAW, a continuous metal wire electrode is fed through a welding torch and melted by an electric arc formed between the wire and the workpiece. The molten metal is deposited layer by layer to build the component.

Advantages:

- High deposition rates, enabling relatively fast build speeds for large components.
- Suitable for a wide range of materials, including carbon steels, stainless steels, and aluminium alloys.
- Mature and widely adopted technology with readily available equipment, consumables, and technical expertise.
- Cost-effective solution for industrial-scale WAAM applications.

Disadvantages:

- Higher heat input compared to controlled arc variants, which can increase thermal distortion and residual stresses.
- Surface finish quality is typically limited, often requiring post-processing.
- Less suitable for applications requiring fine geometric detail or tight dimensional tolerances.

Common manufacturers of GMAW welding equipment include Kemppi, ESAB, EWM, Lincoln Electric, Wallius, Fronius, and Parweld.

4.3.2 Cold Metal Transfer (CMT)

Cold Metal Transfer (CMT) is a controlled variant of GMAW that utilizes digitally regulated short-circuit transfer to significantly reduce heat input. During the welding process, the wire advances toward the weld pool and retracts automatically upon short-circuit detection, assisting droplet detachment. This precise control results in minimal arc burning time and stable material transfer.

CMT technology enables controlled arc length and adapts dynamically to changes in surface conditions and welding speed, making it well suited for WAAM applications requiring improved thermal management and dimensional accuracy. This flexibility makes CMT suitable for use in any position and on a wide range of applications. [1]

Advantages:

- Reduced heat input. CMT uses a lower heat input compared to traditional welding processes. This minimizes thermal distortion, residual stresses, and cracking in the printed components, resulting in better dimensional accuracy and improved mechanical properties.
- Enhanced control of the deposition process and lower residual stress in parts.
- The precise control of the arc and wire feeding in CMT allows for better deposition accuracy, leading to finer details and smoother surfaces in the final part.
- Practically no spatters with the most common materials. The controlled transfer of molten metal in CMT significantly reduces spatter, resulting in cleaner builds and less post-processing effort.
- Improved process stability. The dynamic adjustment of current and voltage in CMT ensures stable arc conditions, enhancing the repeatability and reliability of the WAAM process.
- The precise wire feeding system allows for better control over the layer thickness, facilitating the production of intricate geometries and complex parts.

Disadvantages:

- Only one machine manufacturer (Fronius). However, for example, EWM's React process challenges Fronius.
- More expensive welding machine compared to GMAW welding machines. CMT systems involve advanced technology, such as precise control of current and voltage, which makes the equipment more expensive than traditional arc welding systems.
- Not as productive as standard GMAW processes. Compared to other WAAM techniques, CMT typically has lower deposition rates, which can increase the build time for large components.

4.3.3 Other processes

4.3.3.1 EWM React

The EWM React welding process is an advanced arc welding technology developed by EWM. This process is similar to the CMT process. It uses intelligent real-time control to dynamically adjust arc characteristics during welding. This results in improved arc stability and reduced spatter. It offers precise, stable automated welding with full control over droplet transfer. It ensures reliable weld seams at high speeds by combining spray arc deposition with short arc benefits—low spatter, cooler arc, and high productivity.

EWM React process offers benefits in WAAM printing:

1. Precise droplet control: It enables controlled, stable metal transfer, ensuring consistent layer formation and reducing the risk of defects like porosity or uneven bead shape.

2. Low heat input: Combining short arc advantages with spray arc deposition keeps the process cooler, minimizing residual stresses, distortion, and improving dimensional accuracy—crucial for WAAM builds.

3. Low spatter: Produces clean welds with minimal spatter, reducing post-processing time and improving surface quality of printed parts.

4. High deposition rates: Takes advantage of spray arc-level deposition rates, which increases build speed and overall productivity.

5. Reliable weld quality: Maintains strong, defect-free welds even under demanding conditions, enhancing the mechanical properties of WAAM-printed components.

4.4 Software for Robotic Additive Manufacturing

Robotic DED and WAAM processes require specialized software to support path planning, motion control, simulation, monitoring, and system integration. Unlike conventional machining or welding, additive manufacturing demands coordinated control of motion. This is an overview of selected commercial software solutions commonly used in robotic and CNC-based DED systems. The focus is on software capabilities relevant to WAAM and laser DED applications rather than detailed feature listings.

There is no single universal WAAM software.

Successful WAAM and DED implementations rely on integrated software ecosystems, selected based on:

- Hardware platform (robot vs CNC)
- Process type (arc vs laser)
- Required geometry complexity
- Industrial maturity (R&D vs production)

4.4.1 Adaxis

ADAXIS is a software company focused on enabling and simplifying robotic additive manufacturing , including WAAM and other multi-axis metal 3D printing technologies. The company’s flagship software platform, AdaOne, provides a unified environment for design-to-manufacturing workflows in robotic AM, supporting complex toolpath generation, simulation, and process monitoring.

The software is designed to work with a wide range of industrial robots and kinematic configurations, from standard six-axis arms to systems with external axes and positioners. It supports hybrid manufacturing workflows that combine additive processes with subtractive tasks (e.g., machining and trimming), as well as in-process scanning and inspection.

Key capabilities relevant to DED and WAAM:

- Multi-axis path planning: Generates optimized robot trajectories for planar, angled, multi-planar, and conformal deposition paths, suitable for complex part geometries.
- Simulation and validation: Built-in simulation tools allow verification of reachability, collision avoidance, singularity detection, and toolpath feasibility before execution, reducing setup issues and improving first-time success rates.
- Process integration: Enables connection to robot controllers and external sensors for real-time monitoring, data logging, and dynamic visualization of deposition parameters.
- Comprehensive workflow support: Facilitates the entire workflow from 3D model import and geometry optimization through toolpath generation, robot programming, and in-process supervision.
- Broad technology support: AdaOne supports a variety of additive processes, including WAAM, wire laser AM, laser metal deposition, and others, as well as subtractive machining operations.
- Hardware compatibility: Compatible with major industrial robot brands such as ABB, KUKA, Yaskawa, FANUC, and can be adapted to complex multi-axis configurations including gantries and positioners.

Typical use cases:

- Robotic WAAM deployment: Planning and executing multi-axis WAAM programs for large metal structures with optimized deposition paths and minimized support requirements.
- Hybrid manufacturing cells: Combining additive printing with machining and inspection in a single software framework.
- Process simulation and validation: Ensuring robot and process feasibility before production builds, reducing trial-and-error time and material waste.
- Data logging and monitoring: Collecting and visualizing process data to support quality assurance and traceability.

4.4.2 RoboDK

RoboDK is a general-purpose robotic simulation and offline programming software designed for industrial robots. It enables users to simulate, program, and validate robot motions and applications offline before deploying programs to real robot controllers. Originally developed as an extended commercial version of academic robotic simulation software, RoboDK supports a wide range of robot brands and manufacturing scenarios.

Although not specific to additive manufacturing, RoboDK is widely used in applications that require advanced robot path planning and simulation, including robot-based 3D printing, welding, machining, material handling, and other automated processes where precise multi-axis motion is needed.

Key capabilities relevant to WAAM and robotic DED:

- Offline programming and robot simulation:
  RoboDK enables the creation of complete robot programs and their validation in a virtual environment, eliminating trial-and-error programming on the shop floor. Simulation supports reachability checks, collision avoidance, motion planning, and trajectory verification before execution.

- Broad robot and controller support:
  The software supports simulation and offline programming for hundreds of industrial robot models from a large number of manufacturers — including ABB, FANUC, KUKA, Yaskawa, Universal Robots, Motoman and others — as well as external axes and positioners. This hardware-agnostic support simplifies the integration of WAAM or other DED systems across diverse robot platforms.

- CAD integration and path generation:
  RoboDK can import standard 3D geometry formats (e.g., STL, STEP, IGES) and convert CAD models into robot trajectories. For additive manufacturing use cases, generic 3D printing and path planning workflows can be adapted to generate robot toolpaths from digital models, supporting offline preparation of deposition sequences.

- Collision detection and kinematic checks:
  RoboDK's motion planning environment automatically identifies potential collisions, singularities, and joint limits. It enables users to adjust robot poses or modify paths to ensure safe execution, a capability beneficial during WAAM path planning, especially for multi-axis deposition.

- API and customization:
  RoboDK provides an API that allows integration with Python, C#, C++, MATLAB, and other programming languages. This enables users to develop custom automation workflows, integrate external sensor feedback, or extend functionality for specific applications, including custom additive strategies.

Typical use cases in WAAM / Robotic DED context:

- Offline path planning:
  RoboDK is commonly used to generate and validate robot paths for WAAM and other robotic deposition tasks, reducing programming time and improving setup accuracy.

- Multi-axis motion validation:
  Engineers use RoboDK to check robot reachability and movement feasibility for complex geometries, particularly in multi-axis WAAM setups involving additional rotary axes or positioners.

- Integration with external tools:
  RoboDK can work with other software packages (e.g., CAD/CAM, slicing tools) to support the conversion of design data into robot motion programs and to simulate complex manufacturing workflows.

4.4.3 Dotx Control Systems

Dotx Control Systems GmbH is an automation software company specializing in solutions for robotic motion control, offline programming, and digital manufacturing workflows. While not exclusively focused on additive manufacturing, Dotx software is widely used in applications that require coordinated robot motion, including robotic 3D printing, welding automation, and hybrid manufacturing cells. (dotx-system.com)

Dotx is particularly known for integrating advanced path planning and motion execution capabilities with industrial robot controllers, enabling users to define, simulate, and deploy complex robot tasks across multi-axis systems.

Key capabilities relevant to WAAM / Robotic DED

- Robot offline programming and motion generation:
  Dotx software enables users to create robot motion plans offline, reducing the need for on-cell programming and minimizing commissioning time on physical hardware. For WAAM applications, this supports the generation of stable, collision-checked toolpaths that guide the robot during deposition.

- Digitized manufacturing workflows:
  Dotx supports the integration of CAD/CAM data into robot execution programs, enabling seamless conversion of part geometry into executable robot motion. This supports multi-axis robotic additive strategies and path generation for WAAM where geometry complexity and trajectory continuity are important.

- Simulation and verification tools:
  The Dotx environment typically includes simulation tools that check robot reachability, collision avoidance, and kinematic limitations before deployment. This is particularly useful in multi-axis WAAM environments where complex deposition paths must be validated prior to physical printing.

- Controller integration:
  Dotx solutions are designed to be compatible with multiple industrial robot brands and controllers, including ABB, KUKA, FANUC, and others. This compatibility simplifies integration in WAAM cells that combine robotic motion with external axis motion or advanced tooling.

- Parameter management:
  The software supports structured management of robot motion, axis transitions, and system coordinates, enabling repeatable and traceable motion control — critical for ensuring consistent deposition across long WAAM builds.

4.4.4 Autodesk Netfabb

Autodesk Netfabb is a comprehensive software platform focused on additive manufacturing (AM) preparation, simulation, and optimization. Although Netfabb is not exclusively dedicated to WAAM, it is used widely across the additive manufacturing industry — including in robotic DED/WAAM contexts — for geometry repair, slicing, support generation, build preparation, and process simulation. Netfabb integrates with CAD systems and robot programming tools to support a complete design-to-manufacturing workflow.

Netfabb's toolsets are suitable for engineers, researchers, and production teams who require flexible preparation and analysis capabilities for both powder-based and wire-based additive manufacturing processes.

Key capabilities relevant to WAAM and robotic DED

- CAD repair and pre-processing:

  Netfabb includes tools for identifying and repairing geometric defects in 3D models, such as holes, inverted normals, and non-manifold edges. This ensures that parts intended for deposition are geometrically sound before slicing or path planning.

- Slicing and geometry preparation:

  While originally developed for powder bed AM, Netfabb's slicing tools can be adapted for directed energy deposition workflows by generating cross-section layers, deposition zones, and boundary definitions that serve as the basis for WAAM toolpath strategies.

- Process simulation:

  Netfabb provides simulation capabilities that estimate heat input, deformation, and potential residual stresses based on process parameters and build strategies. In WAAM applications, simulation helps engineers evaluate thermal behavior and assess the need for fixturing, cooling strategies, or adjusted path planning before actual printing.

- Build setup and optimization:

  The software supports build orientation, support generation (where needed), and automated layout optimization. Even in WAAM, where traditional supports are less common than in powder bed systems, orientation and setup analysis help minimize travel distances and thermal distortion.

- Parameter management:

  Users can define and manage process parameters and material libraries. These capabilities support traceability and consistency across multiple builds or similar part designs.

4.4.5 Siemens NX for DED

Siemens NX is a comprehensive CAD/CAM/CAE software platform that includes dedicated modules for additive manufacturing, including DED. NX supports both laser-based and arc-based DED workflows and is particularly suited for industrial environments where additive manufacturing is integrated with conventional machining and production planning. Siemens NX is widely used in aerospace, energy, tooling, and heavy manufacturing sectors.

NX for DED provides an integrated digital workflow covering part design, additive build preparation, toolpath generation, simulation, and hybrid manufacturing operations within a single software environment.

Key capabilities relevant to DED and WAAM

- Additive toolpath generation:

  Siemens NX enables the generation of deposition toolpaths for DED processes directly from CAD models. The software supports layer-based and contour-based deposition strategies, allowing users to define build sequences, bead overlap, and deposition direction in a controlled manner.

- Hybrid manufacturing support:

One of the key strengths of Siemens NX is its ability to support hybrid manufacturing workflows. Additive deposition and subtractive machining operations can be combined within a single program, enabling near-net-shape manufacturing followed by in-process or post-process machining to achieve final tolerances.

- Simulation and verification:

  NX includes simulation tools that allow users to evaluate toolpaths, machine kinematics, and potential collisions before execution. Thermal and distortion simulation capabilities can be used to assess heat accumulation and deformation risks, supporting more robust process planning.

- Machine and controller integration:

  Siemens NX can be configured for specific machine tools, robots, and DED systems through post-processors and machine definitions. This enables generation of machine-specific code compatible with CNC controllers and robotic platforms used in DED applications.

- Data management and traceability:

  Integration with Siemens' digital manufacturing ecosystem allows management of process parameters, build data, and revision control. This supports traceability and quality assurance in regulated or production-critical environments.

4.4.6 Hypertherm Robotmaster

Hypertherm Robotmaster is an offline programming (OLP) and path planning software designed for robot-based manufacturing applications, including robotic welding, material removal (machining), trimming, and additive manufacturing. Developed by Hypertherm CAM solutions, Robotmaster enables the generation, simulation, and optimisation of robot motion programs that can be deployed to industrial controllers.

Although Robotmaster's core market is robotic automation in welding and machining, its capabilities are increasingly relevant to robotic additive manufacturing, including WAAM and other DED processes. The software supports advanced motion planning, collision avoidance, and robot kinematics for complex multi-axis paths.

Key capabilities relevant to WAAM and robotic DED

- Advanced robot path generation:

  Robotmaster generates robot trajectories from CAD models that respect robot kinematics, joint limits, and workspace boundaries. For WAAM applications, this enables the creation of continuous, collision-aware paths that guide the robot through multi-layer deposition sequences.

- CAD/CAM integration:

  The software integrates with CAD systems and imports common 3D model formats (e.g., STEP, IGES, STL). Geometry can be interpreted for deposition toolpath generation, including features such as curve extraction, surface following, and multi-directional paths often needed in complex WAAM parts.

- Simulation and verification:

  Built-in simulation provides visual and numerical verification of robot motion before physical execution. This simulation detects potential issues such as singularities, reach limits, and collisions with the workpiece or cell fixtures, reducing the risk of on-cell errors.

- Multi-axis support:

  Robotmaster supports multi-axis configurations, including robots with external axes (e.g., rotary tables or positioners). This capability is essential for WAAM systems where extended reach or additional degrees of freedom improve deposition orientation and accessibility.

- Custom Scripting and Automation:

  The software allows automation of repetitive tasks and customisation of robot behaviour through scripting, enabling tailored deposition strategies and integration with external process parameters such as feed rate or dwell control.

- Controller compatibility:

  Robotmaster supports major robot brands (e.g., ABB, FANUC, KUKA, Yaskawa) through configurable post-processors that translate generic robot programs into controller-specific code. This ensures seamless deployment of WAAM toolpaths across different hardware platforms.

4.4.7 ABB RobotStudio 3D printing PowerPac, Additive Path Planning and Robot Programming Extension

ABB RobotStudio is a widely used offline programming and simulation environment for ABB industrial robots. The 3D Printing PowerPac is an optional add-on module designed to extend RobotStudio’s capabilities specifically for additive manufacturing applications, including wire-based deposition processes such as WAAM.

While RobotStudio serves general robotic simulation and offline programming needs, the 3D Printing PowerPac enables users to generate, validate, and deploy robot paths tailored to additive manufacturing workflows, integrating with ABB controllers and production cells.

- Additive motion programming within RobotStudio:

  The PowerPac provides additive-focused functions such as path interpolation along surfaces, layer stacking control, filament/wire feed integration, and trajectory planning for continuous deposition.

- Full offline simulation and validation:

  RobotStudio allows comprehensive simulation of robot motion, including verification of reachability, collision detection, and multi-axis coordination. For WAAM, this ensures that deposition paths are feasible and safe before execution on physical hardware.

- Integration with ABB controllers:

  Programs generated using RobotStudio and the 3D Printing PowerPac are compatible with ABB robot controllers (e.g., IRC5), allowing direct deployment of additive toolpaths without manual translation or rework. This reduces commissioning time and improves consistency.

- Multi-axis support for complex geometries:

  The system supports robots with additional axes (turntables, linear rails, positioners), enabling multi-axis WAAM strategies that improve access to complex part features and optimise deposition orientation.

- Digital twin and visualization:

  RobotStudio creates a digital twin of the robot cell that includes tooling, fixtures, and workpiece geometry. Users can visualise additive builds layer by layer, inspect trajectory execution, and confirm that robot motion remains within safe operating limits throughout the build.

- Parameter control and scripting:

  The PowerPac supports parameterised control of key deposition parameters alongside motion paths. While it does not directly govern laser power or wire feed hardware, it supports the introduction of external signals into the robot program to coordinate with process equipment.

4.4.8 Visual Components

Visual Components is a 3D simulation and digital twin software platform designed to model, simulate, and validate robotic production systems and manufacturing processes. While not dedicated exclusively to additive manufacturing, Visual Components is widely used in industrial automation to simulate complex robot cells, optimize layouts, and validate motion strategies before physical implementation.

In the context of WAAM and other DED processes, Visual Components provides a virtual environment for planning robot motion, assessing workspace interactions, and verifying cell configurations. By enabling holistic simulation of multiple robots, external axes, fixturing, and tooling, it supports robust and safe deployment of robotic WAAM systems.

Key capabilities relevant to WAAM / Robotic DED

- 3D simulation of robot cells:

  Visual Components supports detailed 3D modeling of robot cells including robots, fixtures, grippers, tooling, and workpieces. For WAAM applications, this enables simulation of part geometry growth, motion sequences, and potential interference between robot movements and the evolving build.

- Digital twin integration:

  The software enables creation of digital twins — virtual representations of physical robot WAAM cells — which can be used to visualise and analyse robotic paths, cell layout, and system coordination. This facilitates verification before physical deployment.

- Multi-robot and external axis simulation:

  Visual Components supports simulation of multiple robots and external axes (e.g., rotary tables, linear rails), which is vital for advanced WAAM setups where coordinated motion across axes improves accessibility and build strategy.

- Collision detection and motion validation:

  The platform detects potential collisions, joint limits, and reachability issues within the simulated environment. This reduces the risk of on-cell errors and supports planning of safe and efficient robot motion for additive tasks.

- Process and cycle time analysis:

  Visual Components allows users to simulate full operational cycles and compute estimated cycle times. This enables assessment of productivity, throughput, and bottlenecks in WAAM systems before actual installation.

- Integration with external tools:

  Simulations can be enriched through import of robot programs or integration with offline programming tools. While Visual Components does not generate deposition paths itself, it can visualise and analyse programs generated by other software (e.g., RoboDK, ADAXIS, RobotStudio).

4.4.9 Rhino3D and Grasshopper – CAD and Parametric Design Environment for Robotic Additive Manufacturing

Rhino3D (Rhinoceros 3D) is a widely used CAD software platform developed by Robert McNeel & Associates, known for its strong capabilities in free-form surface modeling and complex geometry creation. In robotic additive manufacturing, including WAAM and other DED processes, Rhino3D is commonly used in combination with Grasshopper, its visual parametric programming environment.

Together, Rhino3D and Grasshopper form a flexible design and geometry-driven framework that supports parametric part modeling, custom toolpath generation, and experimental deposition strategies. While the platform does not directly control robots or deposition hardware, it plays an important role in geometry preparation and deposition logic development within robotic AM workflows.

Key capabilities relevant to WAAM / robotic DED

- Advanced geometry modeling (Rhino3D):
  Rhino3D enables the creation of complex free-form surfaces, curved structures, and non-standard geometries that are well suited for WAAM applications where design freedom and near-net-shape manufacturing are important.

- Parametric design and control (Grasshopper):
  Grasshopper allows geometry, deposition paths, and process logic to be defined parametrically using a visual programming approach. In WAAM workflows, this enables rule-based generation of layer contours, variable bead spacing, adaptive wall thickness, and geometry-dependent deposition strategies.

- Custom toolpath generation:
  Using Grasshopper components and scripting (e.g. Python or C#), users can generate custom deposition paths that go beyond traditional planar slicing. This capability is particularly valuable for non-planar, multi-directional, or functionally graded WAAM strategies.

- Integration with robotic AM toolchains:
  Geometry and path data created in Rhino3D/Grasshopper can be exported to dedicated robotic path planning and offline programming software such as ADAXIS, RoboDK, Robotmaster, or ABB RobotStudio. This makes Rhino and Grasshopper effective front-end tools in robotic AM workflows.

- Extensible plugin ecosystem:
  Rhino and Grasshopper support a wide range of plugins for mesh processing, slicing, robotic interfaces, and additive manufacturing research. This extensibility allows the platform to be adapted for both industrial development and experimental WAAM applications, depending on user requirements.

4.4.10 SprutCAM X

SprutCAM X is an integrated CAD/CAM and robot programming software platform developed by Sprut Technology. It supports a wide range of manufacturing processes, including CNC machining, robotic machining, welding, and robotic additive manufacturing, such as WAAM and other DED processes.

SprutCAM X provides a unified environment for toolpath generation, simulation, and robot program creation, enabling users to prepare additive manufacturing operations directly from CAD geometry and deploy them to industrial robots or CNC-based systems.

Key capabilities relevant to WAAM / Robotic DED

- Additive toolpath generation:

  SprutCAM X includes functionality for generating additive manufacturing toolpaths, supporting layer-based deposition strategies suitable for WAAM and DED processes. Users can define deposition parameters such as layer height, bead spacing, and build direction within the CAM environment.

- Robot and CNC support:

  The software supports both robotic systems and CNC machines, enabling flexibility in WAAM implementations based on either robot arms or multi-axis CNC platforms. This makes SprutCAM X particularly suitable for hybrid or retrofitted manufacturing systems.

- Simulation and collision checking:

  SprutCAM X provides built-in simulation tools to verify toolpaths, robot motion, and machine kinematics. Collision detection, reachability analysis, and axis limit checks help ensure safe and feasible execution of additive processes before deployment to physical equipment.

- Multi-axis and hybrid manufacturing:

  The platform supports multi-axis toolpaths and hybrid workflows that combine additive deposition with subtractive machining operations. This enables near-net-shape manufacturing followed by machining to achieve final tolerances within a single software environment.

- Post-processing and controller compatibility:

  SprutCAM X includes post-processors for a variety of industrial robot brands and CNC controllers. This allows generated toolpaths to be translated into executable machine code compatible with the target hardware used in WAAM systems.

4.5 Experience of retrofitting a CNC machine for WAAM applications

The FMT research group implemented the WAAM process on a CNC machine that had previously been used for woodworking applications. As part of the conversion, a dedicated mounting solution was designed and manufactured to securely attach a welding torch to the CNC system. In addition, protective shielding structures were installed to protect the machine components from welding spatter, heat, and arc radiation.

To enable controlled initiation and termination of the welding process, a relay-based control interface was developed to allow communication between the CNC controller and the welding power source. This integration ensures synchronized control of machine motion and welding operations, which is essential for stable and repeatable WAAM deposition.

The CNC machine is controlled using PlanetCNC, an open-source CNC control software. The use of freely available software provides a cost-effective and flexible solution for WAAM implementation and allows customization of motion control and process parameters to suit additive manufacturing requirements.

To improve process monitoring and thermal control, the system was equipped with pyrometers for temperature measurement. One pyrometer is used to monitor and control the interpass temperature between deposited layers, which is a critical parameter influencing microstructure, mechanical properties, and residual stresses. A second pyrometer measures the overall temperature of the component during deposition, enabling better understanding of heat accumulation and supporting process optimization.

Overall, this conversion demonstrates that existing CNC equipment can be successfully repurposed for WAAM applications with relatively modest modifications. The approach provides a low-cost and flexible pathway for implementing wire arc additive manufacturing, particularly for research, prototyping, and repair applications.

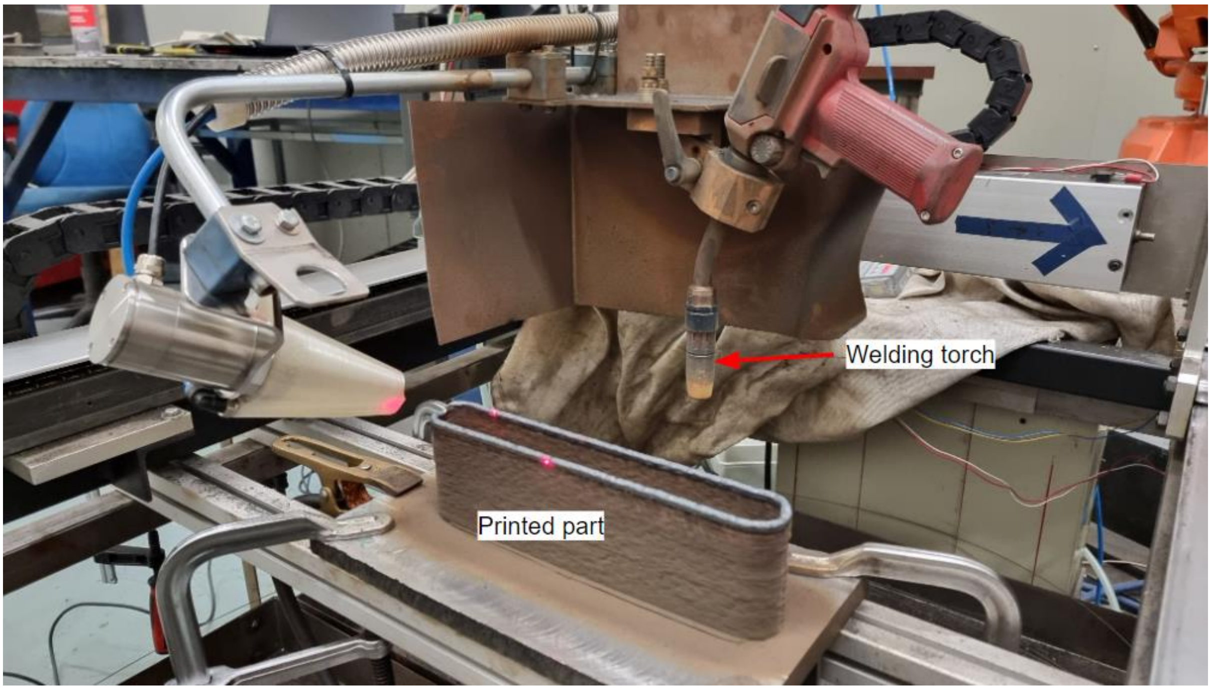

Figure. WAAM printing system.

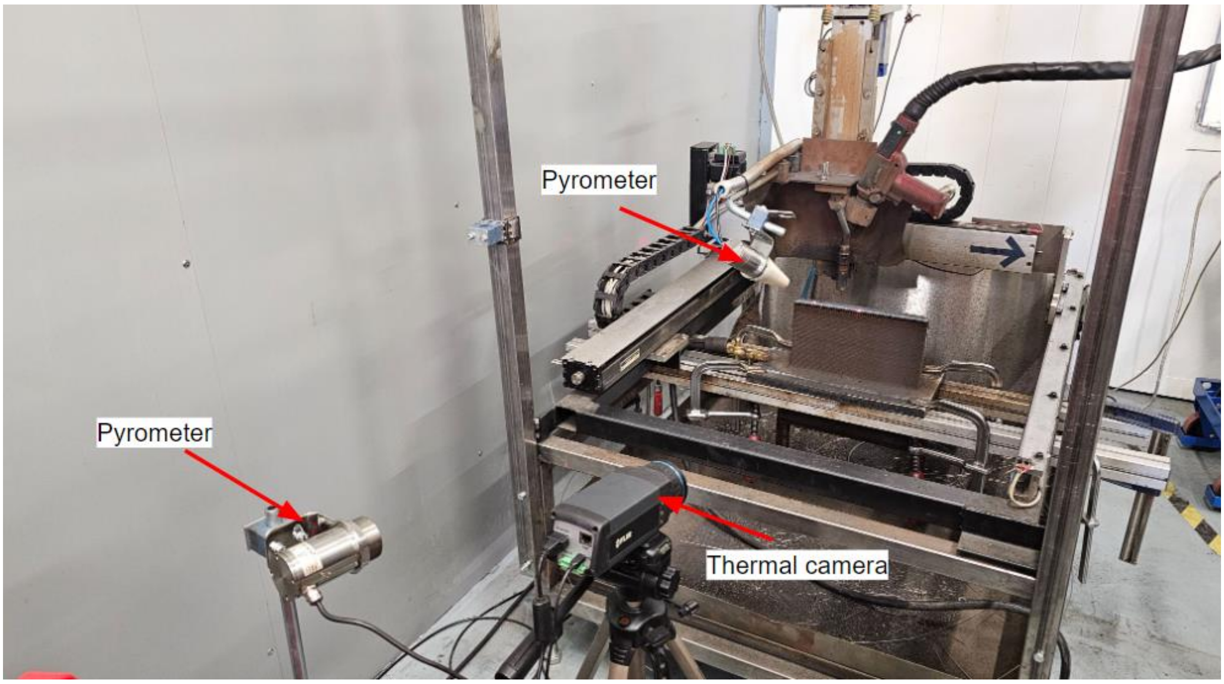

Figure. Thermal measurement and interpass temperature control.

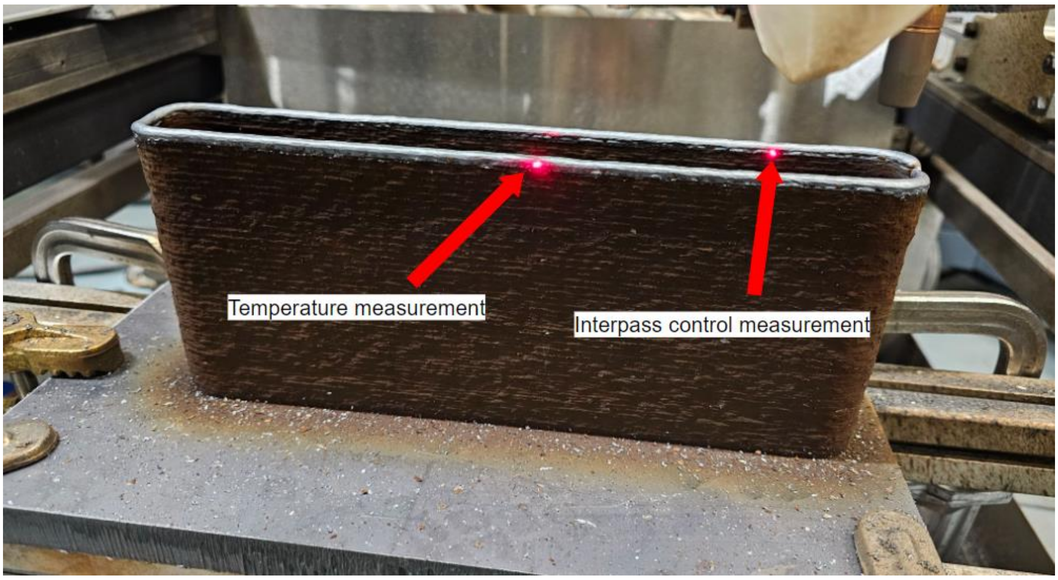

Figure. Locations of temperature measurement and interpass temperature control points

Figure. Layout for WAAM printing.

4.6 Experience of converting welding robot cell to WAAM use

The FMT research group carried out the conversion of an existing robotic welding cell for WAAM applications. The robotic cell consists of three ABB industrial robots that were originally used for conventional welding operations.

In the converted WAAM setup, the largest robot is dedicated to holding and positioning the workpiece. This robot enables controlled manipulation of the component during the printing process, allowing optimal orientation of the part relative to the welding torch. Such capability is particularly beneficial for WAAM, as it helps maintain favorable deposition conditions and improves geometric accuracy.

A smaller robot is equipped with a wire feeding unit and a welding torch, and it is responsible for material deposition. The welding process is powered by a welding power source manufactured by Wallius Oy, which provides stable and controllable arc characteristics suitable for WAAM processing. We designed and manufactured a dedicated mounting bracket for the welding torch on the smaller robot and integrated the wire feeding unit into the same assembly. The control interface for the welding power source was implemented using a digital input signal, enabling synchronized start and stop control of the welding process directly from the robot program. This solution ensured reliable coordination between robot motion and arc ignition during WAAM operation.

Originally, the robots were operated in a conventional welding cell with a dedicated safety system designed for welding tasks. As a first step in the conversion process, the existing safety system had to be dismantled and replaced with a new safety solution tailored specifically for WAAM operations. The updated safety system accounts for the continuous deposition process, extended operating times, and the coordinated motion of multiple robots, ensuring safe and reliable operation during additive manufacturing.

To support WAAM production, a custom fixture system was designed and installed on the larger robot to enable secure clamping of the printed component. This fixture system also serves a secondary function as a protective shield, reducing the exposure of the robot structure to welding spatter and thermal radiation. The integration of part fixturing and protective elements was essential for ensuring both process stability and long-term reliability of the robotic system.

During the development of printing strategies, RoboDK software was initially evaluated for programming WAAM toolpaths. Although RoboDK provides general functionality for robot simulation and offline programming, it was found to be challenging to use for WAAM-specific applications. In particular, the creation of highly complex and customized printing paths required extensive manual work, and generating toolpaths for geometrically demanding components proved to be cumbersome and time-consuming.

Following this evaluation, the workflow was shifted to Grasshopper. Grasshopper was used to generate printing paths for complex geometries, such as the blades of an impeller, where conventional CAM-based approaches are often insufficient. The parametric nature of Grasshopper enabled the generation of highly flexible and geometry-driven toolpaths, allowing printing strategies to be adapted to intricate shapes and varying local deposition requirements.

While Grasshopper has a relatively steep learning curve, particularly for users without prior experience in parametric design or visual scripting, it offers significant advantages for WAAM applications. The software enables the creation of very complex and non-standard printing paths that would be difficult or impractical to implement using traditional robot programming tools. This flexibility makes Grasshopper particularly suitable for research environments and advanced industrial applications where component geometries are highly customized and process development is ongoing.

Overall, this implementation demonstrates that existing multi-robot welding cells can be effectively repurposed for WAAM applications through targeted mechanical, control, and safety modifications. The approach provides a practical and cost-efficient pathway for introducing large-scale wire arc additive manufacturing by leveraging existing robotic infrastructure.

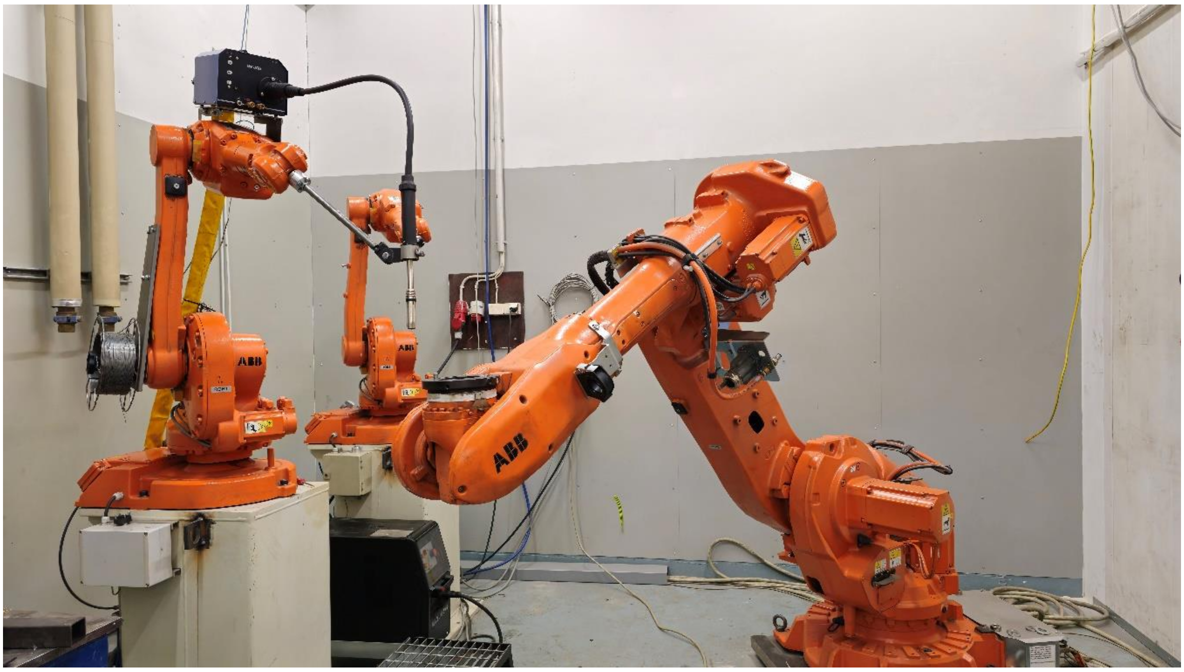
Figure. WAAM robot system.

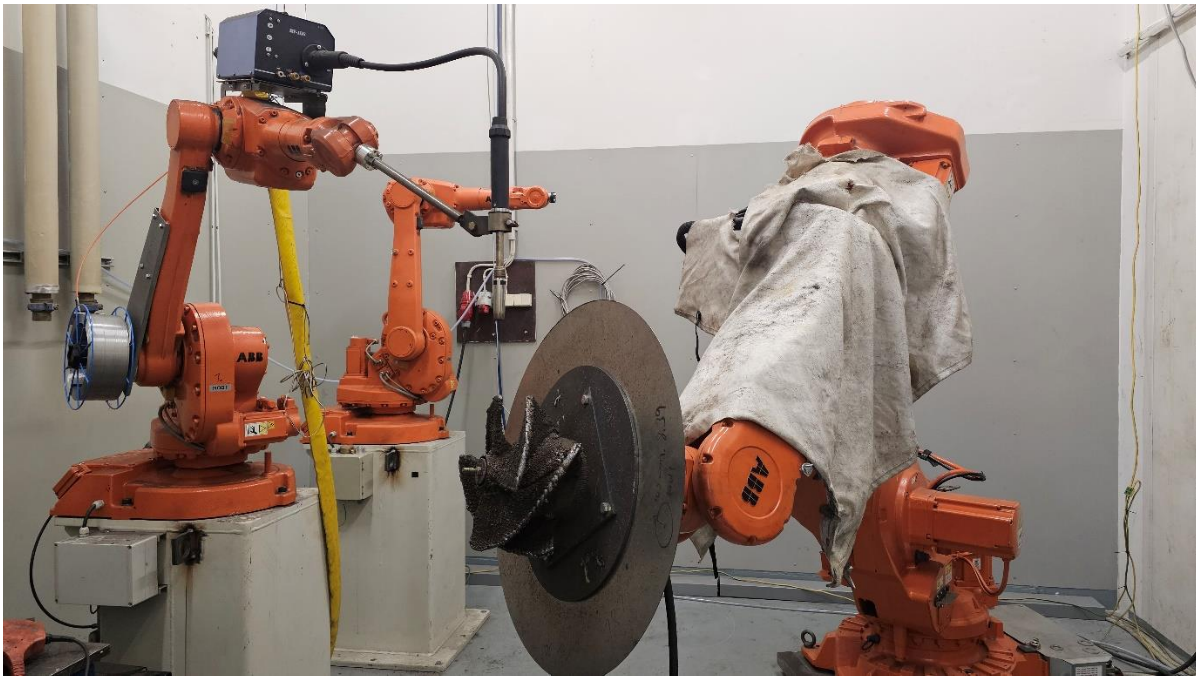
Figure. WAAM printing with robots.

5 Overview of Scientific Research on Directed Energy Deposition Technologies

5.1 Experience from CNC-to-WAAM conversion

The referenced study [2] demonstrates the successful retrofitting of a conventional CNC machine into a WAAM system by integrating a welding torch and wire feed unit. The work focused on converting a gantry-type CNC system to enable WAAM functionality with minimal modification to the original machine structure. The retrofit included hardware integration, development of control strategies, software adaptations, and system validation through the manufacturing of a stainless steel AISI 316L component. A key outcome of the study was that WAAM capability can be achieved without major changes to the original CNC motion system, preserving machine accuracy and stiffness while extending its manufacturing capabilities. Key experiences included:

Hardware integration:

The foundation of the system was a custom-built gantry-type CNC machine, providing high positional accuracy and flexibility for WAAM deposition. The deposition system consisted of a plasma arc welding power source (EWM Tetrix 400) combined with a plasma welding torch (Abiplas Weld 250 MT), enabling stable, high-energy deposition suitable for reactive and high-performance materials.

To ensure process stability and material quality, the system was enclosed within a protective chamber. This chamber enabled deposition under controlled atmospheric conditions, which is particularly important for reactive materials such as titanium. The overall infrastructure was designed to ensure operator safety and maintain consistent thermal and environmental conditions during high-temperature WAAM operations.

Control system development:

The converted system incorporated extensive process monitoring to support both open-loop and closed-loop control strategies. Sensors included a pyrometer for temperature measurement, a welding camera for visual monitoring, an oxygen sensor to track atmospheric conditions, and a laser scanner for bead geometry measurement.

A closed-loop height control system was implemented using laser scanner feedback to dynamically adjust the Z-axis position. This ensured consistent layer thickness and improved dimensional accuracy throughout the build. Communication between system components (e.g., machine controller, plasma system, and monitoring PC) was achieved through custom-developed protocols, enabling synchronized control of motion, energy input, and material deposition.

Software adaptation:

Toolpath generation was carried out using Powermill CAD/CAM software. Initial toolpaths were defined based on a nominal layer height of 1.5 mm. During manufacturing, real-time feedback from the laser scanner was used to correct deviations in bead height by dynamically adjusting the Z-axis position.

This adaptive control approach improved build consistency and reduced the accumulation of geometric errors during multi-layer deposition. The integration of software-driven corrections proved critical for achieving reliable and repeatable WAAM builds on a CNC platform.

Process validation and manufacturing:

System validation was performed by manufacturing a demonstrator component featuring complex geometries, including vertical walls and T-joints. This geometry was selected to assess the system's ability to produce challenging features with acceptable dimensional accuracy and metallurgical quality.

Process parameters were optimized through more than 80 single-bead experiments. Optimal deposition conditions were identified at approximately 180 A welding current, 224 mm/min travel speed, and 3 m/min wire feed rate. Evaluation criteria included fusion quality, porosity, and geometric accuracy.

Mechanical testing revealed anisotropic tensile properties, with higher strength observed in the longitudinal direction. These differences were attributed to grain size variations resulting from the deposition strategy and thermal history. Monitoring data showed that voltage and temperature fluctuations were most pronounced at bead start and end regions, highlighting areas prone to process instability.

Conclusions and outlook:

The study demonstrated that gantry-based CNC systems can be successfully converted into reliable WAAM platforms capable of producing structurally sound metal components with good geometric fidelity. The integration of in-situ monitoring and adaptive control was shown to be essential for maintaining consistent quality.

Additionally, the ability to store and analyze sensor data provides a strong foundation for future quality assurance, process optimization, and automation. The system enables series production of WAAM components and opens pathways for further research into the relationship between process parameters, bead geometry, and mechanical performance, as well as the development of more advanced closed-loop control strategies.

5.2 Open-source software architecture for multi-robot WAAM

An open-source software architecture for multi-robot WAAM was presented [3], addressing key limitations of proprietary robotic welding and additive manufacturing systems. The proposed architecture enables flexible integration of industrial robots, welding power sources, and third-party sensors from multiple vendors, thereby improving process adaptability, customization, and scalability.

The architecture is based on the Robot Raconteur framework, which acts as middleware for communication and control between robots, welding equipment, and sensors. The system supports a complete "art-to-part" WAAM workflow, including CAD slicing, robot motion planning, multi-robot coordination, in-process sensing, and post-process metrology. The implementation allows synchronized control of a welding robot, positioner, and a separate monitoring robot, enabling gravity-aligned deposition and improved geometric accuracy.

The developed WAAM system incorporates multiple sensor modalities, such as infrared cameras, laser scanners, microphones, and current measurement devices, enabling real-time process monitoring and data acquisition. These sensor inputs can be used for adaptive motion adjustment, process tuning, and post-process quality evaluation. The study demonstrated that integrated sensing significantly improves process robustness and enables more consistent layer geometry.

Experimental validation was carried out using a multi-robot WAAM cell equipped with industrial robots and a Cold Metal Transfer (CMT) welding power source. Various materials and geometrically complex components were successfully manufactured. The results showed sub-millimeter average geometric errors and acceptable worst-case deviations, demonstrating the feasibility of accurate WAAM production using an open and vendor-independent control architecture.

Overall, the work demonstrates that open-source, modular WAAM control architectures can significantly enhance flexibility, sensor integration, and multi-robot coordination compared to traditional closed systems. These findings support the development of adaptable and cost-efficient WAAM solutions suitable for research environments and industrial applications requiring advanced process control and customization

5.3 Experience from WAAM retrofit for repair operations on a milling machine

The referenced study [4] presents the design, implementation, and validation of a WAAM retrofit kit integrated into a conventional milling machine for the repair of worn steel components. The work addresses the need for cost-effective and flexible repair solutions in heavy industry, where damaged components often have high material value and complex geometries.

The proposed solution demonstrates that hybrid manufacturing, combining machining and WAAM deposition within a single machine tool, is technically feasible and industrially relevant. By retrofitting an existing milling machine rather than relying on a dedicated additive manufacturing system, the approach significantly reduces investment costs while extending the functional capabilities of conventional equipment.

Hardware integration and system design:

The retrofit concept was based on integrating a WAAM deposition system into a standard 5-axis milling machine. A dedicated welding torch holder was designed to be compatible with the machine’s tool magazine, enabling automatic tool changes between machining tools and the WAAM torch. Electrical insulation solutions were implemented to safely integrate the welding process into the machine environment and to protect sensitive components from electrical discharge.

Additional system modifications included the integration of shielding elements, insulation layers, and grounding solutions to ensure safe and stable operation. The study highlights that careful mechanical and electrical integration is essential when adapting conventional machine tools for WAAM-based repair operations.

Repair case study and validation:

The system was validated through the repair of an AISI H13 steel die component. The repair process consisted of surface preparation by machining, followed by WAAM deposition and subsequent finishing operations. The results demonstrated that the hybrid approach can successfully restore damaged surfaces with good geometric accuracy and metallurgical bonding.

Microstructural analysis revealed a sound fusion between the deposited material and the substrate, with a heat-affected zone typical of arc-based processes. Hardness measurements showed elevated hardness in the deposited layer and HAZ, which is acceptable for tooling applications but may require post-treatment depending on service requirements. The study confirms that WAAM-based repair can achieve functional material properties comparable to those of conventionally manufactured components.

Key findings and industrial relevance:

The work demonstrates that retrofitting existing milling machines for WAAM repair operations is a viable and scalable solution. The hybrid approach enables significant reductions in repair time, material waste, and component replacement costs. Furthermore, the integration of WAAM into conventional machine tools allows repair operations to be performed in a single setup, improving accuracy and process efficiency.

From an industrial perspective, the approach is particularly attractive for small and medium-sized enterprises, as it lowers the entry barrier for additive manufacturing adoption. The study supports the broader conclusion that DED-based repair solutions can be effectively implemented using existing production infrastructure, provided that appropriate system integration, process development, and safety measures are applied.

5.4 Experience from DED process planning and trajectory optimization

The paper [5] provides a comprehensive overview of process planning and trajectory optimization methods for arc-based DED systems. The work highlights that effective process planning is a critical enabler for reliable and repeatable DED manufacturing, particularly when using robotic or CNC-based systems with complex kinematics.

The study emphasizes that, unlike powder-bed processes, arc-based DED requires close integration between geometry processing, deposition strategy, and machine motion control. Toolpath generation must consider not only part geometry but also process-specific constraints such as heat input, bead geometry, interpass temperature, torch orientation, and gravitational effects. These factors strongly influence final part quality, dimensional accuracy, and mechanical performance.

Trajectory planning and motion control:

A key contribution of the paper is the systematic analysis of trajectory planning approaches for DED, including continuous-path strategies, multi-axis motion planning, and adaptive orientation control. The work demonstrates that optimized trajectories can significantly improve surface quality and geometric consistency, especially in curved and overhanging structures.

The paper also highlights the importance of synchronizing robot or CNC motion with process parameters such as wire feed rate, travel speed, and energy input. Poor synchronization may lead to defects such as uneven bead height, lack of fusion, or excessive heat accumulation. Advanced trajectory optimization methods are therefore necessary when retrofitting existing robotic or CNC systems for DED applications.

Software frameworks and digital integration:

The study reviews current software architecture used for DED process planning, ranging from traditional CAM-based approaches to more advanced frameworks incorporating feature-based planning, digital twins, and artificial intelligence. It is shown that conventional CAM tools often require significant customization to support arc-based DED, particularly for multi-axis systems.

The paper highlights a growing trend toward integrated software environments that link CAD, slicing, toolpath planning, simulation, and process monitoring into a unified workflow. Such integration is especially relevant for retrofitted systems, where hardware configurations and kinematic constraints vary widely. Flexible and modular software solutions enable faster system commissioning, easier parameter optimization, and improved scalability.

Monitoring, adaptation, and future development:

Another important aspect discussed is the increasing role of in-process monitoring and adaptive control. The paper shows that real-time feedback from sensors, such as thermal cameras, laser scanners, and electrical signal monitoring, can be used to adjust trajectories, layer heights, or deposition parameters during manufacturing. This capability is particularly valuable for retrofitted systems, where mechanical tolerances and thermal behavior may differ from purpose-built machines.

The paper concludes that future DED systems will increasingly rely on data-driven process planning and adaptive control strategies. The integration of trajectory optimization, process simulation, and real-time monitoring is expected to improve robustness, reduce trial-and-error during process development, and enable more complex geometries to be manufactured reliably.

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