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 direct 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.

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. This step includes:

1. Robot type: Begin with a thorough assessment of the current welding setup, including the robot type, its reach, precision, and load capacity. Ensure the robot has sufficient reach, payload, and precision for WAAM. WAAM often requires more accuracy and slower, controlled movements than typical welding.

2. Controller: Verify the robot controller supports advanced motion control and can integrate with external sensors and systems.

3. 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.

4. Reviewing system compatibility: Analyze whether the existing welding equipment (power supply, torch, wire feeder, and robot) is compatible with WAAM requirements.

5. Evaluating materials and part requirements: Determine the types of metal materials the WAAM process will handle, as well as the size and complexity of parts.

6. Analyzing operational needs: Evaluate production volume, time, and quality requirements, understanding how WAAM capabilities align with these.

2.1.2 Select suitable WAAM equipment

1. 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.

2. Wire feeder: 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.

3. Power source: Use a welding power source suitable for WAAM with precise control over current, voltage, and pulse settings. Verify that the welding power source can support continuous wire feeding with high precision. WAAM often uses processes like CMT with advanced control.

2.1.3 Redesign of the welding cell layout

WAAM processes often require a different setup than typical robotic welding. 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.

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 of the part should also be taken into consideration to ensure process stability and material performance.

3. Wire feeding system adjustment: Ensure the wire feeder is capable of handling WAAM-compatible wire types and feed rates, which may sometimes differ from typical welding wires. Typically, WAAM processes utilize the same filler wires as those used in conventional welding.

4. Safety features: Install welding curtains, and safety interlocks to protect operators. Implement or upgrade safety protocols, including shielding gas systems to prevent oxidation of the molten metal, and ensure proper ventilation for fume extraction.

5. Consumables management: Ensure consistent supply and storage of welding wire to prevent contamination.

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 these components includes:

1. Process control software: WAAM requires more advanced software controls, so updating or integrating control software that can monitor and adjust welding parameters in real time may be necessary.

2. Data logging and quality control: Implement data logging systems to record parameters for traceability, quality control, and analysis.

2.1.5 Software updates and upgrades for the system

1. WAAM Path Planning: Install or integrate additive manufacturing-specific software that can generate deposition paths from CAD models (e.g., Autodesk PowerMill, RoboDK, Siemens NX AM). 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.

2. Simulation: Use simulation tools to test and optimize the build process virtually.

3. Deposition strategy: Determine the optimal deposition pattern to ensure consistent material buildup without excessive heat accumulation.

4. 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.

2.1.6 Process development and testing

The next phase involves extensive process testing to ensure that the WAAM setup meets production requirements. This phase includes:

1. Trial runs: Perform initial tests to verify the settings, ensuring correct layer height, bead width, and other critical WAAM parameters.

2. Parameter tuning: Fine-tune the parameters based on results from trial runs. Typical parameters to adjust include travel speed, wire feed rate, and arc power.

3. Layer strategy: Determine bead overlap, layer height, and deposition sequence to minimize defects.

4. 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.

5. In-process monitoring: Use cameras or sensors to detect defects like porosity or misalignment during the build.

6. Documentation: Maintain detailed records of process parameters and part performance for traceability.

7. Quality assurance, material properties and process optimization: Use different techniques to inspect the printed part layers for defects such as porosity, cracks, and inclusions. Test and validate mechanical properties, microstructure, fatigue strength and dimensional accuracy. Use data from initial prints to optimize the process. Adjustments might include modifying deposition strategies, cooling methods, or even material selection for specific applications.

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.

2. Enhanced safety protocols: Update safety protocols to address WAAM-specific hazards like fumes, higher power outputs, and prolonged heat exposure.

3. Troubleshooting: Equip staff with skills to identify and resolve common issues during the WAAM process.

4. Emergency shutdown systems: Install emergency stops and monitoring systems that quickly shut down the cell in case of malfunction.

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.

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: Keep path planning and robot control software updated for optimal performance.

5. Future upgrades: Plan for scalability, such as adding more robot arms or advanced sensors for increased production capacity.

2.2 Transforming CNC welding cell to WAAM applications

Transitioning a CNC welding cell to WAAM can significantly enhance a company's manufacturing capabilities, enabling the production of large, custom metal parts with reduced material waste. However, this transition involves key modifications to both equipment and process management. This chapter outlines the crucial steps that a company must undertake to effectively repurpose a CNC welding cell for WAAM printing.

Transforming a CNC welding cell into a WAAM printing cell is an innovative way for companies to expand their manufacturing capabilities. By following a structured process—including a feasibility study, layout adjustments, control system upgrades, CNC programming adaptations, and ongoing process refinement—companies can leverage WAAM for cost-effective, custom metal part production. With careful planning and ongoing optimization, this transformation can unlock new opportunities and applications in manufacturing.

2.2.1 Feasibility assessment and planning

Before starting the transformation, it’s essential to conduct a thorough feasibility study to assess whether the existing CNC welding cell is suitable for WAAM. This step includes:

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.
2. Machine structure: Ensure the CNC machine has the stability and rigidity to handle the heat, weight, and potential vibrations caused by WAAM processes.
3. Controller compatibility: Confirm the CNC controller supports multi-axis movement with the precision required for WAAM.
4. Workspace: Ensure the working envelope can accommodate the WAAM torch, wire feeder, and build platform.
5. Material and product requirements: Define the types of metals and alloys to be used and assess whether the cell can handle the expected part dimensions and tolerances for WAAM.
6. Production needs analysis: Identify production goals, including required throughput, quality standards, and cost targets, and determine whether WAAM can meet these effectively.

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

WAAM operations often require adjustments to the cell layout, as the additive process has different demands than traditional CNC welding.

1. Optimizing workspace and tool reach: Adjust the CNC setup to ensure that the machine can move freely across larger or taller builds. Evaluate the machine's reach to ensure all areas of the build platform are accessible.
2. Welding torch: Select a torch specifically designed for additive manufacturing, with integrated cooling and robust wire feeding capabilities.
3. Power source (welding machine): Use a welding power source optimized for WAAM, with fine control over current, voltage, and pulse characteristics.
4. Thermal control and ventilation: Since WAAM generates continuous heat, integrating thermal management systems and effective ventilation is critical to prevent overheating.
5. Wire feeder reconfiguration: Install or modify the wire feeder to handle WAAM-compatible feedstock, considering wire diameter, feed rate, and flexibility in material changeover.
6. Fume extraction system: Add a system to remove welding fumes and protect operators from hazardous gases.
7. Cooling system (optional): 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. Key upgrades include:

1. Ensure the CNC controller can execute G-code modified for WAAM, including dynamic speed, feed, and pause commands.

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.

3. Quality monitoring and data logging: Implement systems to monitor and log data for each layer, ensuring traceability and facilitating quality control.

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.

1. Path planning optimization: Program the CNC to follow multi-layer paths with precise layer heights, controlling deposition patterns for even material buildup and avoiding thermal distortion. Traditional G-code for welding in a CNC cell primarily deals with moving the torch along weld seams. For WAAM, G-code must dictate a layer-by-layer deposition strategy, similar to 3D printing. This involves programming paths that account for both the outline and infill of each layer.

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.

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.

2.2.5 Process development and validation

The next phase is testing and refining the process to ensure it meets production requirements. This involves:

1. Conducting initial test runs: Run small tests to determine optimal parameters for wire feed rate, travel speed, power settings, and cooling intervals.

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.

3. Welding parameters: Optimize current, voltage, and wire feed rates for consistent deposition.
4. Layer strategy: Determine bead overlaps, layer height, and deposition sequence to minimize thermal stress.

5. Cooling times: Allow controlled interlayer cooling to prevent warping and residual stress.

6. Quality assurance (optional): Develop a monitoring system to identify any potential defects in each layer before proceeding with subsequent layers. Use cameras or sensors to detect defects like porosity, misalignment, or inconsistent bead height during deposition.

7. Process documentation: Maintain detailed records of process parameters, material batch numbers, and inspection results for traceability.

2.2.6 Safety protocol enhancement and operator training

Transitioning from CNC welding to WAAM printing introduces new safety and operational considerations. Both equipment and personnel need to be prepared for the change.

1. Operator training: Train operators and technicians on WAAM-specific tasks, such as parameter adjustment, process control, and handling of larger heat loads.

2. Enhanced safety procedures: Revise safety protocols to address risks specific to WAAM, including fumes, high power outputs, and potential thermal hazards associated with prolonged arc usage.

3. Maintenance training: Ensure maintenance teams are equipped to service the new WAAM components, such as the welding torch and wire feeder.

4. Implementing emergency systems: Set up emergency shut-off mechanisms and thermal monitoring systems to prevent accidents in the event of equipment failure or overheating.

2.2.7 Maintenance and continuous improvement

Once the WAAM cell is operational, regular maintenance and optimization are crucial to maintaining consistent performance and part quality.

1. Routine equipment inspections: Schedule regular checks on the power source, wire feeder, robotic arm, and CNC system to ensure that they are functioning at optimal levels, as WAAM may increase wear on certain components.

2. Parameter monitoring and adjustment: Use logged process data to identify trends and adjust parameters to improve efficiency, part quality, and throughput over time.

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.

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

Transforming an existing CNC laser cutting or laser welding cell into a laser DED printing system requires significant modifications to hardware, software, and process control. The transition involves upgrading the laser system, integrating specialized deposition heads, modifying motion controls, and implementing process monitoring tools. With proper planning, operator training, and quality control measures, companies can successfully leverage laser DED for high-precision metal additive manufacturing, enabling new production possibilities and increased flexibility.

3.1 Assessment and planning

Assess the current welding and cutting cells, including the equipment, space, and utilities. Identify the potential for integration with DED technology, considering factors like power supply, cooling systems, and ventilation.

Understand the specific DED process requirements, such as the type of energy source (laser, electron beam, or arc), material feed systems (powder or wire), and necessary control systems.

Laser suitability: Verify whether the existing laser source (fiber, CO_2, diode, Yb:YAG or Nd:YAG) is appropriate for DED. Most DED processes require fiber lasers due to their high efficiency and precise beam control.

Laser power requirements: Assess if the laser has sufficient power (typically between 500W and 5kW) to enable stable melting of metal powder or wire feedstock.

Optical system & beam delivery: Ensure that the optics, lenses, and nozzles can focus the laser beam for deposition rather than cutting or welding. Some modifications may be necessary to optimize beam shape for DED.

Cooling and thermal management: DED generates prolonged heat exposure compared to cutting or welding. Adequate cooling systems, such as active water cooling, may need to be installed.

Investment analysis: Estimate the cost of retrofitting the laser system, integrating a deposition head, modifying software, and training personnel. Compare this with the expected return on investment (ROI).

Production goals: Define the materials, part geometries, and precision levels required for DED applications. Determine if DED aligns with business objectives.

3.2 Upgrading equipment

Retrofit the existing welding or cutting machine with a DED head that can handle the specific deposition method (e.g., a laser or arc source). Ensure the head is compatible with the current CNC system. Unlike laser cutting or welding, DED requires a specialized deposition head designed for either powder-based or wire-based material feeding.

Integrate a material delivery system, like wire or powder feeders, suitable for the chosen DED method. This system should be compatible with the DED head and provide precise control over material flow.

Replace the cutting table (in some cases can be placed on the table) or welding fixture with a heat-resistant build plate capable of supporting growing 3D structures.

Upgrade the cooling system to manage the additional heat generated during the DED process. Improve ventilation to safely handle fumes and particulate matter produced during deposition. Implement an inert gas shielding system (e.g. argon) to prevent oxidation and contamination during deposition.

3.3 Software and control systems integration

The first step is to implement control software. DED requires specialized software to convert 3D CAD models into toolpaths. This happens by installing and configuring specialized DED software that can handle the complex tool paths and real-time monitoring required for additive manufacturing. The software should also integrate with existing CNC controllers.

Integrate monitoring systems (optional): To ensure high-quality DED builds, real-time monitoring and control systems should be implemented. Set up in-process monitoring systems, such as cameras, sensors, and thermal imaging, to ensure precise control over the deposition process. This allows for real-time adjustments and improves the quality of the final product.

- Melt pool monitoring: Use cameras, thermal sensors, or pyrometers to track and adjust melt pool size.
- Layer height control: Implement sensors to measure and correct layer thickness for consistent deposition.
- Adaptive laser power control: Adjust laser energy dynamically to compensate for variations in material absorption and part geometry.

3.4 Training and safety

Train operators: Provide comprehensive training for operators on the new DED technology, focusing on equipment operation, software use, and safety protocols. Educate staff on material handling, particularly for fine metal powders (which can be hazardous if not properly contained).

Update safety protocols: Revise safety protocols to address the specific hazards associated with DED, such as high-energy beams, material handling, and ventilation requirements.

- Laser safety: Ensure compliance with laser safety standards (ISO 11553) and provide protective eyewear and shielding.
- Powder handling precautions: For powder-based DED, enforce strict powder containment, ventilation, and explosion prevention protocols.
- Fume extraction: Install an efficient exhaust system to remove metal vapor and airborne contaminants.

3.5 Testing and calibration

Conduct initial testing: Run test operations to calibrate the DED system, adjusting parameters like energy input, material feed rate, and tool paths.

Refine process parameters: Use data from test runs to fine-tune the process parameters, ensuring optimal deposition quality and efficiency.

- Conduct trial builds and fine-tune process parameters such as laser power, deposition rate, and travel speed.

- Optimize overlapping bead paths to achieve uniform material deposition and avoid defects.
- Adjust cooling rates to prevent residual stress buildup and cracking.

3.6 Full scale implementation

Transition to production: Gradually scale up from small test parts to full production, continually monitoring and adjusting the process as needed.

Continuous improvement: Implement a feedback loop for continuous monitoring and improvement, allowing the system to adapt to new materials, geometries, and production requirements.

4 Commercial DED systems

4.1 WAAM systems

4.1.1 WAAM3D

WAAM3D specializes in WAAM, an advanced metal deposition technology that uses arc welding processes to build components layer by layer. WAAM3D offers a range of software, hardware, and services designed to streamline and optimize WAAM operations. Their solutions are targeted at industries such as aerospace, defense, energy, and heavy machinery, where large-scale metal parts are in demand. WAAM3D's approach focuses on efficiency, scalability, and integration, addressing the unique challenges of WAAM processes while supporting high-performance applications.

WAAM3D offers a range of products and services centered around WAAM technology. The company is located in United Kingdom. Their key products include:

RoboWAAM: A large-scale metal 3D printer, designed for high-volume industrial applications. This machine features advanced sensors, specialized end-effectors, and comprehensive health and safety solutions, making it ideal for producing large metal components, particularly in aerospace, marine, and energy sectors.

MiniWAAM: Their compact metal 3D printer offers a more accessible option for smaller-scale applications. Despite its smaller size, it includes advanced features like real-time shape monitoring, multi-wire feeding capabilities, and extensive process control software. It's particularly suited for prototyping, research, and production of small to medium-sized metal parts.

Software solutions: WAAM3D has developed an integrated software suite to manage the entire WAAM process. This includes WAAMPlanner for tool-path planning, WAAMCtrl for machine operation, and WAAMKeys for process parameter management. These tools are designed to optimize the additive manufacturing process from start to finish.

4.1.2 MX3D

MX3D specializes in WAAM, focusing on large-scale metal structures and components. MX3D's product offerings combine robotic systems, proprietary software, and advanced material processing techniques to enable efficient and flexible metal deposition. Targeted industries include construction, infrastructure, maritime, and industrial tooling. The company's approach emphasizes scalability, design freedom, and the integration of WAAM into industries traditionally reliant on subtractive manufacturing or casting. Their solutions aim to streamline the adoption of WAAM while addressing its challenges. The company is located in Netherlands. Their key products include:

M-Metal AM systems: These are turnkey metal additive manufacturing systems designed for high deposition printing of medium-to-large metal parts using robotic WAAM. They are ideal for industries needing high-quality, in-house production.

MetalXL software: This software provides an end-to-end workflow solution for industrial WAAM, enhancing productivity with features like automatic calibration, dynamic sensors, real-time feedback, and data logging.

4.1.3 Gefertec

Gefertec specializes in WAAM technology, offering equipment and solutions for producing large-scale metal components using wire feedstock. Their proprietary 3DMP® (3D Metal Print) technology integrates WAAM with CNC systems, enabling cost-effective and efficient manufacturing of near-net-shape metal parts. Gefertec focuses on industries such as aerospace, defense, automotive, and energy, where the demand for robust, large, and customized metal components is high.

The company emphasizes ease of use and industrial scalability, providing solutions that integrate seamlessly into existing production environments while addressing common challenges associated with WAAM processes.

Gefertec specializes in WAAM and offers several products designed for industrial-scale 3D metal printing, especially suited for producing large, complex metal parts. The company is located in Germany. Here are some of their primary offerings:

arc Series machines:

- Gefertec's main line of WAAM machines, the *arc 3D*, is available in several models, including *arc403*, *arc605*, and *arc850*.
- These machines vary in build size, capable of creating parts from medium to large-scale dimensions.
- The series supports multiple materials, like stainless steel, nickel-based alloys, and titanium.

arcAM process:

- This is Gefertec's proprietary WAAM process, optimized for high-speed, high-quality additive manufacturing.
- It uses wire as feedstock, which can be more cost-effective and sustainable than powder-based processes.

arcControl software:

- A proprietary software solution tailored to manage and optimize WAAM processes in Gefertec machines, enhancing part precision and quality.

Application-specific solutions:

- Gefertec also provides customized solutions, particularly for industries like aerospace, automotive, and heavy machinery, where large, durable metal components are essential.

4.1.4 MetalWorm

MetalWorm is a company specializing in WAAM solutions, primarily aimed at large-scale metal part production. The company focuses on providing flexible, scalable, and cost-effective metal 3D printing systems for various industries, including aerospace, automotive, energy, and heavy machinery. By integrating WAAM technology with advanced robotics, MetalWorm aims to offer a robust solution for manufacturing components that are difficult to produce using conventional methods.

Their products are designed to streamline the additive manufacturing process while offering versatility in materials and applications. MetalWorm systems are used to produce large, complex metal parts directly from wire feedstock, with an emphasis on optimizing material efficiency and reducing production costs.

MetalWorm, based in Turkey, specializes in WAAM systems. Their primary products include two main systems: the MetalWorm Compact System and the MetalWorm Special System.

MetalWorm Compact System**:** This is a plug-and-play system designed for ease of use, featuring integrated components in a single unit. It supports a variety of materials, including steel, stainless steel, and aluminum alloys, with ongoing development for additional alloys like titanium and Inconel.

MetalWorm Special System**:** This system is customizable and intended for producing larger parts. It offers a range of advanced technologies such as active cooling and heating, vibration technology for improved grain structure, and arc voltage control for precise deposition.

Both systems are built around their WAAM technology, which uses a robotic arm to deposit metal wire using a high-power electrical arc, enabling the production of large metal components with complex geometries.

4.2 Laser Wire DED Systems

4.2.1 Meltio

Meltio specializes in metal additive manufacturing, particularly focusing on wire-laser DED technology. Meltio is located in Spain. Their product lineup includes the M450 and M600 metal 3D printers, designed for large-scale industrial production. This machine integrates seamlessly with existing CNC systems, offering benefits such as reduced material waste, shorter lead times, and the capability to handle complex builds with minimal operator input. The M600 supports a variety of materials, including aluminum, copper alloys, titanium, and stainless steels, making it versatile across industries like aerospace, automotive, and construction.

Meltio also has robot cell plug-and-play solution for robot integration. It is engineered to offer industries a secure and efficient solution for producing metal 3D printed components.

Meltio offers also engine CNC integration hybrid manufacturing solution. It is a hybrid manufacturing solution, fitting almost any CNC machine. It enables metal 3D printing and machining of complex geometries in a single process step.

4.2.2 Laserline

Laserline specializes in directed energy deposition products that use high-power diode laser technology for additive manufacturing, surface coating, and repair applications. The company is in Germany. Here’s an overview of the key DED-related products and solutions they offer:

Laser Powder Deposition (LPD):

- Laserline supports DED applications where powder is directly fed into the melt pool created by the laser. This is commonly used for part repairs, coatings, and new part creation with various metal alloys.

Laser Wire Deposition (LWD):

- Laserline also supports wire-based DED, where a metal wire is melted by the laser to build up material. This process is particularly advantageous for applications requiring high material efficiency and minimal waste.

4.2.3 Aconity3D

Aconity3D manufactures directed energy deposition machines for metal additive manufacturing. Designed for high-precision applications and industrial scalability, these machines enable the production, repair, and customization of complex metal components. Aconity3D's modular design philosophy allows users to tailor machine configurations to specific applications, making it a good choice for industries like aerospace, automotive, energy, and healthcare.

1. Aconity3D DED Machine Features

1.1 Modular design

Aconity3D machines are built with modularity in mind, allowing users to customize systems to their exact needs:

Process modules: Choose from different energy sources (laser, electron beam) and powder or wire delivery systems.

Build enclosures: Adapt the build chamber size and atmosphere for specific materials and part sizes.

Post-processing integration: Incorporate CNC machining, stress relief, or heat treatment systems.

1.2 High-Precision Deposition

Aconity3D DED machines achieve precision through:

Fine laser focus: Ensures controlled energy delivery for detailed geometries.

Advanced motion systems: Multi-axis motion enables complex 3D paths and undercut geometries.

Automated calibration: Real-time adjustments maintain consistent deposition quality.

1.3 Material Versatility

Powder and wire compatibility: Handles a wide range of metals, including titanium, Inconel, stainless steel, and aluminum.

Multi-material printing: Supports gradient materials and functionally graded parts for specialized applications.

1.4 Process Monitoring

In-situ sensors: Monitor melt pool dynamics, temperature, and deposition rates in real-time.

Defect detection: Automatically identifies voids, cracks, or inconsistencies and adjusts parameters.

Data logging: Provides detailed records for process validation and traceability.

4.2.4 Additec3D

Additec3D specializes in providing directed energy deposition solutions, focusing on compact and versatile systems for metal additive manufacturing. Their machines are designed to cater to industries requiring high flexibility, cost-effective production, and the ability to work with various metal feedstocks, including powder and wire. Additec3D's offerings are particularly suitable for prototyping, small-scale production, and component repair.

1. Additec3D DED Products

1.1 Additec μPrinter

The Additec μPrinter is a compact DED machine designed for research and small-scale production. Its key features include:

Multi-material capability: Supports both wire and powder feedstock, allowing users to switch materials as needed.

Integrated laser source: Equipped with a diode laser offering variable power levels for precise energy delivery.

Compact design: Small footprint, suitable for research labs and workshops with limited space.

Applications:

Development of new alloys and materials.

Small component manufacturing.

Prototyping and testing.

1.2 Additec CNC-DED System

The CNC-DED system is designed for integration with existing CNC machines, turning them into hybrid manufacturing systems.

Hybrid manufacturing: Combines additive and subtractive processes in a single setup.

Flexible material input: Compatible with both powder and wire materials.

Open architecture: Easily retrofittable to standard CNC systems.

Applications:

Repairing worn-out or damaged parts.

Adding features to pre-machined components.

Custom tooling and mold production.

1.3 Additec Modular DED System

This system is a scalable solution that can be adapted to a variety of production environments.

Customizable build volume: Adjusted based on specific application requirements.

Dual-feed capability: Enables simultaneous use of wire and powder feedstock.

In-process monitoring: Includes real-time monitoring tools for temperature and deposition rate control.

Applications:

Medium to large part production.

Fabrication of gradient or multi-material parts.

Aerospace and automotive component manufacturing.

4.2.5 Optomec

Optomec specializes in Directed Energy Deposition (DED) systems, offering solutions tailored for metal additive manufacturing, component repair, and surface enhancement. Their equipment integrates laser and material delivery technologies to build, repair, or coat metal parts efficiently. Optomec's DED products are designed to meet industrial requirements in sectors like aerospace, energy, medical devices, and tooling, emphasizing flexibility, precision, and cost-effectiveness.

1.1 LENS Systems

The Laser Engineered Net Shaping (LENS) systems are Optomec's flagship DED products, offering solutions for both standalone and hybrid manufacturing setups.

Key features:

Closed atmosphere capability: LENS systems include an inert atmosphere for processing reactive materials like titanium and aluminum.

High precision: Precise material deposition ensures consistent layer quality.

Modular design: Available as standalone systems or retrofits for CNC machines.

Applications:

Repair and remanufacturing of aerospace components.

Surface cladding to enhance wear and corrosion resistance.

Prototyping and small-scale part production.

1.2 LENS Hybrid Systems

Hybrid systems integrate DED technology into CNC machines, combining additive and subtractive processes in one setup.

Key features:

Multi-process capability: Allows for both material deposition and precision machining.

Retrofit options: Easily added to existing CNC equipment for hybrid workflows.

Compact design: Optimized for production floors with space constraints.

Applications:

Adding features to pre-machined parts.

Repair of complex geometries with high accuracy.

Low-volume, high-mix production environments.

1.3 Aerosol Jet and LENS Combination Systems

Optomec offers systems that combine LENS with Aerosol Jet technology for hybrid additive solutions, enabling advanced applications in electronics and metal manufacturing.

Key features:

Cross-technology integration: Enables both electronic printing and metal deposition.

Fine-feature capability: Produces detailed metal components with embedded electronics.

Custom configurations: Tailored for specialized industrial applications.

Applications:

3D printing of functional electronics in metal parts.

Advanced repair solutions for electromechanical components.

Customized tooling with embedded sensors.

4.2.6 Precitec

Precitec is a provider of Directed Energy Deposition (DED) technologies, offering solutions focused on precision, reliability, and integration. Their product portfolio includes laser-based deposition heads and systems designed for additive manufacturing and component repair. Precitec's equipment is widely used across industries such as aerospace, automotive, energy, and tooling, enabling the fabrication and refurbishment of high-performance metal components.

1. Precitec DED products

1.1 Laserline deposition heads

Precitec’s deposition heads are designed for precise energy delivery and material handling in metal additive manufacturing.

Key features:

Coaxial design: Provides consistent material deposition with uniform energy distribution.

High-temperature capability: Suitable for processing advanced alloys.

Integrated monitoring systems: Includes sensors for real-time process control and quality assurance.

Applications:

Building new parts with intricate features.

Repairing worn or damaged components.

Cladding for improved surface properties.

2. Features of Precitec DED products

2.1 Coaxial energy and material delivery

Precitec's coaxial designs ensure uniform energy and material distribution, leading to consistent deposition quality across the build surface.

2.2 Real-time monitoring

Integrated sensors provide real-time feedback on parameters such as:

Melt pool size and temperature.

Material flow rate.

Laser power stability.

This helps in maintaining process stability and detecting defects early.

2.3 Multi-axis compatibility

Precitec deposition heads are compatible with robotic arms and CNC systems, enabling complex multi-axis builds.

2.4 Material flexibility

The equipment can handle a wide range of feedstocks, including:

Metallic powders (stainless steel, titanium, Inconel).

Wire feed materials for cost-effective applications.

4.2.7 Trumpf

TRUMPF is a key provider of DED solutions, offering equipment designed for industrial applications in additive manufacturing, part repair, and surface modification. Their DED systems leverage laser-based technology and focus on precision, flexibility, and integration into production environments. TRUMPF's products cater to industries such as aerospace, automotive, and energy, enabling the creation and enhancement of metal components with minimal waste.

1. TRUMPF DED product portfolio

1.1 TRUMPF laser deposition heads

TRUMPF offers high-performance laser deposition heads designed for various DED applications.

Key features:

Coaxial powder delivery: Ensures uniform material distribution for consistent build quality.

Variable focus adjustment: Supports fine details and large area deposition with flexible spot sizes.
High laser power capability: Enables processing of hard-to-melt materials and faster deposition rates.

Applications:
Repair of components such as turbine blades and molds.
Adding features to pre-machined parts.
Fabrication of complex geometries in high-performance materials.

1.2 TRUMPF TruLaser cell series
The TruLaser cell systems are multi-functional laser machines capable of handling both DED and laser welding or cutting.

Key features:
3D Multi-axis movement: Allows the production of complex geometries and repair of parts with intricate shapes.
Integrated monitoring: Real-time tracking of melt pool and material feed ensures consistent quality.
Hybrid capabilities: Combines DED with subtractive processes for greater flexibility.

Applications:
Full-scale manufacturing of aerospace and automotive components.
Surface cladding for improved durability.
Prototyping and low-volume production.

1.3 TRUMPF TruPrint Series with DED Option
The TruPrint line includes hybrid solutions that combine DED with powder bed fusion (PBF) capabilities, offering versatility for manufacturing workflows.

Key features:
Hybrid production: Seamless integration of PBF for detailed features and DED for larger structures.
High deposition rates: Efficient material usage for large builds or repairs.
Compact design: Suitable for production environments with space constraints.

Applications:
Fabrication of gradient material parts.
Repair and remanufacturing of high-value parts.
Customized tool and mold production.

4.2.8 Innstek

Innstek specializes in DED technology, offering solutions that cater to industries requiring precision and versatility in metal additive manufacturing. The company’s product portfolio is focused on hybrid and standalone systems designed to integrate DED technology into various production environments. Innstek's approach emphasizes flexibility, with systems capable of using wire and powder feedstocks to meet diverse manufacturing needs, such as prototyping, tooling, repair, and low-volume production.

1.1 Hybrid DED Systems

Innstek's hybrid systems integrate DED technology into CNC machining centers, enabling additive and subtractive manufacturing in a single machine.

Key features:

Seamless integration: Combines the precision of CNC machining with the material flexibility of DED.

Dual feedstock capability: Supports both wire and powder materials for broader application possibilities.

Real-time process monitoring: Sensors and software ensure deposition accuracy and reduce the risk of defects.

Applications:

Prototyping and low-volume production.

Manufacturing high-performance tooling and molds with complex cooling channels.

Repair and refurbishment of worn or damaged components.

1.2 Standalone DED Systems

Standalone systems from Innstek are designed for additive manufacturing-only applications, providing a cost-effective solution for industries that don't require hybrid capabilities.

Key features:

Compact design: Suitable for environments where space is limited.

Material efficiency: Optimized for high utilization of feedstock materials, minimizing waste.

User-friendly interface: Intuitive software for controlling and monitoring the deposition process.

Applications:

Additive manufacturing of structural components for aerospace and automotive sectors.

Creation of industrial parts for energy and heavy machinery.

Production of custom geometries not achievable through conventional methods.

4.3 WAAM welding processes

4.3.1 Gas Metal Arc Welding (GMAW)

Also known as: MIG (Metal Inert Gas) welding. GMAW uses a continuous metal wire electrode fed through a welding gun to create an arc with the workpiece, melting the wire and forming the part.

Advantages:

- Good for high deposition rates, allowing relatively fast build speeds.
- Effective for materials like aluminum, steel, and stainless steel.
- Economical and widely used, so equipment and materials are readily available.

Disadvantages:

- Limited in terms of surface finish quality, which may require post-processing.
- Not ideal for extremely precise or high-detail applications.

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

4.3.2 Cold Metal Transfer (CMT)

Cold metal transfer (CMT) is a variant of GMAW that uses controlled short circuits to maintain a low heat input. The digital control system detects when a short circuit occurs and assists in detaching the droplet by retracting the wire. During the welding process, the wire moves forward but retracts immediately upon detecting a short circuit. This means the arc introduces heat only for a very short time during each arc-burning phase. The short circuit is carefully managed, keeping the current low, which ensures a spatter-free transfer of material. Additionally, the arc length is monitored and adjusted mechanically, allowing the arc to stay stable regardless of the workpiece's surface condition or the welding speed. 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

4.4.1 Adaxis

Adaxis robotic software is an advanced platform tailored for robotic additive manufacturing applications, such as WAAM, polymer extrusion, and other material deposition techniques. The software integrates motion planning, process control, and real-time monitoring, enabling precise and efficient robotic operations across diverse industries.

1 Key features

1.1 Flexible robot compatibility

Adaxis software supports a wide range of industrial robot brands and controllers, such as ABB, KUKA, FANUC, and Yaskawa, ensuring seamless integration with existing robotic setups.

1.2 Advanced path planning

Multi-axis control: Leverages multi-axis motion to achieve complex geometries and optimal material deposition.

Adaptive path generation: Automatically adjusts deposition paths to accommodate variations in part geometry and build requirements.

Collision avoidance: Simulates robot motion to ensure safe and collision-free operations.

1.3 Real-time process monitoring

Sensor integration: Supports thermal cameras, vision systems, and load sensors for real-time process feedback.

Defect detection: Identifies inconsistencies, such as porosity or misalignment, and adjusts parameters on the fly.

Data logging: Records process parameters and performance metrics for traceability and quality assurance.

1.4 Material and process optimization
Material library: Preloaded with material profiles for common WAAM, polymer, and other additive processes.
Parameter fine-tuning: Allows customization of process variables like speed, temperature, and layer height.
Interlayer cooling: Enables precise control of cooling times to minimize thermal stresses.

2. Software modules

2.1 Path generation module
The path generation module translates 3D CAD models into optimized robot motion paths:
Layer slicing: Converts CAD designs into layers suited for deposition.
Custom strategies: Offers options for zig-zag, spiral, or custom deposition patterns.
Multi-tool support: Enables dual or multi-tool setups for complex builds.

2.2 Simulation module
The simulation module ensures error-free operation:
Virtual testing: Simulates the entire build process to detect potential issues before execution.
Kinematic validation: Verifies robot reachability and joint limits for planned motions.
Thermal analysis: Simulates heat distribution to predict and mitigate distortion risks.

2.3 Real-time control module
This module manages live robot operations:
Dynamic adjustments: Modifies speed, wire feed rate, or other parameters based on feedback.
Emergency interventions: Pauses or stops operations automatically during critical faults.
Interface integration: Links seamlessly with external hardware, such as power supplies or wire feeders.

4.4.2 RoboDK

RoboDK is a robotic simulation and programming software designed to streamline and enhance manufacturing processes. Its versatility allows users to simulate, program, and control robots from virtually any brand for tasks ranging from machining and welding to 3D printing and assembly. By eliminating programming complexity and providing a user-friendly interface, RoboDK allows engineers and manufacturers to maximize the efficiency and flexibility of their robotic systems.

1. Key Features

1.1 Universal robot compatibility
RoboDK supports over 600 robot models from leading brands such as ABB, KUKA, FANUC, Yaskawa, and Universal Robots. This universal compatibility ensures seamless integration with both new and existing robotic setups.

1.2 Offline programming (OLP)
Rapid programming: Generate robot programs offline without interrupting production.
Multi-axis pathing: Develop complex multi-axis trajectories for intricate tasks.
Drag-and-drop tools: Simplify the programming process with an intuitive graphical interface.

1.3 3D simulation and digital twin

Accurate simulation: Visualize and validate robotic processes in a 3D environment before execution.
Collision detection: Identify and prevent collisions between robots, tools, and workpieces.
Kinematic verification: Test robot reachability, joint limits, and singularities.

1.4 Post-processor customization
Custom G-code: Tailor post-processors for specific robot brands or unique manufacturing needs.
Output flexibility: Export robot programs in native manufacturer formats.

1.5 Additive manufacturing support
Path slicing: Convert 3D CAD models into additive manufacturing layers.
Multi-axis 3D printing: Program robots for complex geometries beyond traditional 2D layers.
Material compatibility: Handle processes like polymer extrusion, WAAM, and concrete printing.

4.4.3 Dotx Control Systems

Dotx Control Systems specializes in software solutions tailored for DED processes, providing tools that focus on optimizing the control, monitoring, and performance of additive manufacturing systems. Dotx software addresses the complexities of DED, including multi-axis motion control, process parameter tuning, and real-time feedback integration, allowing for improved precision and repeatability in metal additive manufacturing. By focusing on compatibility and modularity, the company's software is designed for integration into a range of DED machines, including robotic systems and CNC-based platforms.

1. Key Features of Dotx DED software

1.1 Multi-axis motion control
Dotx software supports multi-axis motion systems essential for DED, enabling complex geometries and freeform designs.

Path optimization: Advanced algorithms generate efficient tool paths that minimize material waste and reduce production time.
Dynamic motion adjustments: Real-time feedback allows for adjustments to ensure consistent material deposition, even in challenging geometries.

1.2 Process monitoring and feedback
Real-time monitoring tools integrated into the software ensure that critical parameters are controlled throughout the deposition process.

Parameter monitoring: Tracks feed rate, heat input, and deposition rate.
Error detection: Identifies issues such as clogs, overheating, or misalignments during the build process.
Adaptive control: Adjusts parameters dynamically based on sensor feedback to maintain build quality.

1.3 Deposition process simulation
Dotx software includes simulation capabilities to visualize and optimize the deposition process before production.

Heat management simulation: Predicts thermal distortion and cooling rates, helping prevent residual stress in parts.

Material flow analysis: Ensures consistent deposition by simulating wire or powder feed rates in various conditions.

Collision detection: Simulates multi-axis movements to avoid clashes between the deposition head and the part.

1.4 Compatibility

Dotx software is designed to integrate with various hardware platforms, including robotic arms, CNC systems, and hybrid manufacturing setups.

Open interfaces: Compatible with industry-standard communication protocols, simplifying integration with existing equipment.

CAD/CAM integration: Works seamlessly with common CAD/CAM tools for streamlined workflows.

4.4.4 Autodesk Netfabb

Autodesk offers software solutions tailored to advanced manufacturing processes, including DED. Through its flagship software, Netfabb, Autodesk provides tools for design preparation, simulation, and G-code generation specifically optimized for additive manufacturing technologies. With capabilities for handling complex geometries and multi-axis operations, Autodesk software supports both standalone and hybrid DED systems, addressing the needs of industries like aerospace, automotive, and energy.

1. Key features of Autodesk Netfabb for DED

1.1 Design optimization for additive manufacturing

Netfabb includes tools to optimize CAD models for the DED process, ensuring compatibility with additive manufacturing workflows.

Geometry repair: Fixes errors in imported CAD models, such as non-manifold edges and holes.

Topology optimization: Reduces material usage while maintaining structural integrity, especially useful for lightweight designs.

Lattice structures: Supports the creation of lattice features for weight reduction and improved thermal performance.

1.2 Slicing and toolpath generation

The software provides advanced slicing tools specifically designed for DED, enabling precise material deposition.

Customizable slicing parameters: Allows users to define layer heights, deposition widths, and overlaps to suit specific DED applications.

Multi-axis path planning: Supports 5-axis and robotic systems for building complex geometries and freeform structures.

Contour and infill strategies: Enables the use of varying deposition patterns for better surface finish and structural consistency.

1.3 Simulation and process optimization

Autodesk offers integrated simulation capabilities to optimize the DED process and reduce trial-and-error in production.

Thermal simulation: Predicts heat accumulation and cooling rates to minimize residual stress and distortion.
Deposition path analysis: Evaluates toolpath feasibility to ensure consistent material flow and avoid collisions.
Build time estimation: Provides accurate projections of production time for planning and cost assessment.

1.4 Material and process parameter libraries

Netfabb includes an extensive library of material and process parameters, which can be tailored to DED-specific requirements.

Material profiles: Predefined settings for common DED materials such as titanium alloys, stainless steel, and nickel-based superalloys.
Custom parameters: Users can input specific laser power, feed rate, and heat settings for unique applications.

2. Integration with DED systems

Autodesk software is designed for compatibility with a variety of DED hardware, including robotic systems, CNC platforms, and hybrid machines.

Post-processing for G-code: Generates machine-ready instructions optimized for specific hardware.
Hardware-agnostic compatibility: Works with multiple DED technologies, such as laser-based or wire-arc systems.
Seamless workflow with CAD/CAM: Integrates with Autodesk Fusion 360 and other CAD tools to streamline the design-to-production process.

4.4.5 Siemens NX for DED

1. Key Features of Siemens NX for DED

1.1 Integrated design-to-manufacturing workflow

Siemens NX offers a unified environment that consolidates the entire DED workflow, minimizing the need for multiple software tools.

CAD integration: Seamlessly integrates design with DED-specific manufacturing processes, reducing file conversions and potential errors.
Direct editing tools: Allows modifications to CAD models directly within the software for rapid adjustments.

1.2 Advanced toolpath generation

NX provides robust features for generating and optimizing DED toolpaths, accommodating both simple and complex geometries.

Multi-axis path planning: Supports 5-axis and robotic deposition systems for freeform geometries and non-planar surfaces.
Adaptive deposition strategies: Enables users to tailor toolpaths for varying material requirements, such as contouring, filling, or repair.
Collision detection: Identifies potential clashes between the deposition head and the part or fixtures.

1.3 Process simulation

Simulation capabilities are integral to Siemens NX, helping users predict and optimize the performance of DED processes.

Thermal analysis: Simulates heat distribution and cooling rates to mitigate warping and residual stress.

Material flow simulation: Ensures consistent feedstock deposition, whether using wire or powder feed systems.

Deposition layer visualization: Allows users to inspect the build layer by layer for potential defects or inconsistencies.

1.4 Machine and hardware integration

Siemens NX is designed to integrate directly with various DED platforms, including CNC machines and robotic systems.

Post-processing for G-code: Generates precise instructions tailored to specific DED equipment.

Machine configuration: Supports the setup of machine-specific kinematics and parameters, enabling smooth transitions between digital and physical workflows.

4.4.6 Hypertherm Robotmaster

Hypertherm's Robotmaster is an offline programming and simulation software designed to optimize the use of robotic systems, including for DED applications. By simplifying the programming of complex robotic paths, Robotmaster bridges the gap between CAD models and robotic execution, particularly in multi-axis DED processes. The software is widely used for tasks requiring precision and adaptability, such as metal deposition, repair, and cladding.

1. Key features of Robotmaster for DED

1.1 Offline programming for robotic DED systems

Robotmaster enables users to program and simulate DED processes without interrupting machine operation.

CAD integration: Imports 3D models directly to define deposition paths and tool trajectories.

Automatic path generation: Converts CAD geometry into robot-compatible toolpaths with minimal manual input.

No code expertise required: Simplifies programming by eliminating the need for extensive knowledge of robot programming languages.

1.2 Multi-axis path optimization

The software supports multi-axis systems, a key requirement for DED processes involving complex geometries.

Collision detection and avoidance: Automatically identifies potential interferences between the robot, part, and work cell.

Seamless motion: Optimizes movement between layers and deposition regions for continuous operation.

Kinematics awareness: Accounts for the specific configuration and constraints of the robotic arm to ensure smooth motion.

1.3 Deposition strategy customization

Robotmaster allows users to tailor DED paths to specific applications, ensuring process efficiency and part quality.

Layer-by-layer control: Users can define parameters such as layer thickness, overlap, and direction.

Variable deposition patterns: Includes options for contouring, filling, and adaptive strategies to handle varying geometries.

Heat management integration: Helps optimize toolpaths to control thermal input and reduce distortions.

1.4 Simulation and validation

Robotmaster provides real-time simulation and validation tools to enhance the reliability of the DED process.

Process visualization: Displays the robot's deposition paths and material flow before execution.

Time estimation: Calculates build times to assist with scheduling and cost analysis.

Error detection: Identifies potential issues such as unreachable positions or excessive tool angles.

4.4.7 ABB RobotStudio 3D printing PowerPac

ABB offers specialized software solutions to support DED applications using their robots. A key tool is the RobotStudio 3D Printing PowerPac, which facilitates the programming and simulation of complex additive manufacturing tasks. This PowerPac enables users to design intricate deposition paths and optimize process parameters in a virtual environment before actual production, ensuring precision and efficiency.

Additionally, ABB's RobotWare provides advanced motion control and path accuracy features, which are crucial for the precise material deposition required in DED processes. For developers seeking to customize and enhance their robotic applications, ABB offers various Software Development Kits (SDKs), such as the RobotStudio SDK, PC SDK, and FlexPendant SDK. These SDKs allow for the development of tailored applications and interfaces to meet specific DED requirements.

4.4.8 Visual Components

Visual Components provides a suite of 3D manufacturing simulation tools that can be effectively utilized for DED applications. Their software enables users to design, simulate, and optimize robotic additive manufacturing processes in a virtual environment. Key features include:

Layout planning: Visualize 3D layouts with production logic using existing models and templates.

Feasibility analysis: Simulate, identify, and resolve production issues in a virtual environment.

Virtual commissioning: Connect virtual systems with physical PLCs and robot controllers to debug and streamline manufacturing processes.

Robot programming: Easily transfer robot programs to the shop floor without manual programming using a teach pendant.

These capabilities allow for the simulation of complex DED processes, enabling users to optimize deposition paths, assess potential issues, and refine parameters before actual production. This approach enhances efficiency, reduces costs, and minimizes risks associated with physical prototyping.

4.4.9 Rhino3D

Rhino3D, developed by Robert McNeel & Associates, is a versatile 3D modeling software widely used in various industries, including architecture, engineering, and manufacturing. While Rhino3D doesn't offer a dedicated module specifically for Directed Energy Deposition (DED) processes, its robust modeling capabilities and flexible architecture make it a valuable tool in preparing and managing designs for DED applications.

For robotic applications, including those related to DED, Rhino3D can be extended through plugins and integrations:

RhinoRobot: This plugin facilitates offline programming and simulation for various industrial robot applications. It supports glTF export for simulation visualization across multiple platforms, including AR/VR devices.

RoboDK Integration: By integrating Rhino3D with RoboDK, users can enhance robot machining tasks. RoboDK is a software that allows for easy and effective robot programming across a wide range of tasks, which can be beneficial for DED processes.

Additionally, Rhino3D's Grasshopper visual programming environment enables users to create parametric designs and automate workflows, which can be advantageous in optimizing complex deposition paths and structures inherent in DED processes.

For developers seeking further customization, Rhino3D offers scripting capabilities using RhinoScript and Python, allowing for automation and tailored solutions to meet specific DED requirements.

In summary, while Rhino3D does not provide a dedicated DED module, its comprehensive modeling tools, combined with available plugins and scripting capabilities, make it a valuable asset in the design and preparation stages of robotic DED applications.

4.4.10 SprutCAM X

SprutCAM X is a comprehensive CAD/CAM software platform designed to support a wide range of manufacturing processes, including DED applications. Its machine-aware programming capabilities ensure that toolpath calculations account for specific machine kinematics and limitations, which is crucial for the precision required in DED processes.

For robotic DED applications, SprutCAM X offers specialized modules that facilitate the programming and simulation of industrial robots. These modules enable users to design complex deposition paths, optimize process parameters, and simulate operations in a virtual environment before actual production, thereby enhancing efficiency and reducing potential errors.

Additionally, SprutCAM X provides a variety of machining strategies, from 2D to 5D, and supports additive and hybrid technologies on 5-axis, mill-turn machines, and robots. This versatility allows for the seamless integration of additive manufacturing processes like DED into existing workflows.

In summary, SprutCAM X offers robust support for robot-based DED applications through its advanced programming, simulation, and machine-aware capabilities, making it a valuable tool for manufacturers looking to implement or enhance their additive manufacturing processes.

5 Scientific papers

5.1 CNC to WAAM conversion experience

The study describes the successful retrofitting of a standard 3-axis CNC milling machine for WAAM by integrating a GMAW welding torch and a wire feed system [2]. The study involved a comprehensive retrofit of a CNC gantry machine to enable WAAM capabilities. This included integrating hardware, developing control strategies, implementing software modifications, and validating the system through the production of a stainless steel 316L component. Minimal hardware changes were made, preserving the original CNC motion system. Key experiences included:

5.1.1 Hardware integration

Machine base: A custom-built 5-axis gantry machine served as the foundation, offering high flexibility and precision for WAAM deposition.

Deposition equipment: The system used a plasma arc source (EWM Tetrix 400) and a plasma torch (Abiplas Weld 250 MT) suitable for high-energy, reactive metal processing.

Shielding system: A protective chamber allowed the safe deposition of reactive materials (e.g., titanium) in an inert atmosphere.

Support infrastructure: The equipment was enclosed in a secure structure to maintain process stability and safety during high-temperature operations.

5.1.2 Control system development

Open-loop monitoring: Equipped with a pyrometer, welding camera, oxygen meter, and laser scanner, the system gathered real-time data on temperature, oxygen levels, and bead geometry.

Closed-loop height control: A feedback mechanism corrected the Z-axis height based on laser measurements, ensuring consistent layer thickness and improving dimensional accuracy.

Communication protocols: Custom protocols linked devices (e.g., PC-laser, PC-machine, machine-plasma), allowing synchronized and adaptive control of the process parameters and tool positioning.

5.1.3 Software adaptation

Toolpath programming: Powermill® CAD/CAM software was used to define deposition paths. Initial paths were based on theoretical layer heights (1.5 mm), which were adjusted in real time by the control system.

Real-time correction: Feedback from the laser scanner enabled the PC application to dynamically correct Z-axis errors, enhancing build consistency.

5.1.4 Process validation and manufacturing

Test geometry: A complex demonstrator part with vertical walls and T-joints was designed to validate the system's capacity for high-complexity builds.

Parameter optimization: Over 80 single-bead experiments helped identify optimal parameters (180 A, 224 mm/min travel speed, 3 m/min wire feed rate) by evaluating fusion quality, porosity, and dimensional accuracy.

Mechanical testing: Tensile tests showed anisotropic mechanical properties, with higher strength in the longitudinal direction. Grain size variation explained the directional differences.

Monitoring outcomes: Voltage and temperature distributions were analyzed to detect process instabilities, with peaks often corresponding to bead starts and ends due to material buildup.

5.1.5 Conclusions and outlook

The successful conversion demonstrated that gantry-based WAAM systems can reliably manufacture metal parts with good mechanical properties and geometric fidelity.

The integration of in-situ monitoring and adaptive control proved essential for quality assurance.

Stored sensor data enabled future quality tracking and optimization efforts.

The system set a foundation for producing parts in series, opening avenues for further research in process parameter-bead geometry correlations and automated error correction.

5.2 Open-source software architecture for multi-robot WAAM

This paper [3] documents the development of an open-source, multi-robot WAAM system architecture built to overcome the limitations of proprietary welding and robot control systems. The team at Rensselaer Polytechnic Institute developed a flexible and vendor-agnostic platform for WAAM that integrates robot motion, welding, and in-process sensing. The core goals were interoperability, real-time monitoring, and adaptability across robotic systems.

5.2.1 System architecture and components

The WAAM cell was built with:

- Two 6-DoF Yaskawa Motoman robots: One for welding (with a CMT torch), one for sensing (with IR camera and laser scanner).
- One 2-DoF positioner to orient the build surface.
- Fronius TPS500i CMT power source for precise, low-heat arc welding.

- Sensor suite: FLIR infrared camera, MTI laser line scanner, 3D Artec Spider scanner, microphone, and current clamp.

All components were linked using Robot Raconteur, an open-source middleware framework that allowed integration of various hardware and software drivers into a unified system. This enabled data acquisition, real-time feedback, and coordination between robots and sensors.

5.2.2 Software and algorithm development

The system includes a complete "art-to-part" pipeline, consisting of:

CAD-to-slice conversion: The part geometry is sliced into layers suitable for additive deposition using a uniform non-planar slicing algorithm. For complex geometries like turbine blades or bells, this technique maintains layer continuity and reduces support requirements.

Motion planning and coordination: The system synchronizes multi-robot motion (welding robot, positioner, and sensing robot) using coordinated control. Custom scripts generate vendor-specific robot programs (e.g., INFORM for Yaskawa), which are tested in simulation before deployment.

Gravity-aligned slicing and deposition: The positioner is dynamically adjusted to keep the molten pool aligned with gravity, ensuring better layer adhesion and minimizing defects like slumping or uneven buildup.

Real-time sensor feedback: In-process IR imaging is used to monitor the torch and track standoff wire length. Edge detection algorithms match templates in the IR stream to infer deposition height and adjust the toolpath dynamically.

Process monitoring and fault detection: Audio signals and high-frequency current readings are captured to identify anomalies like arc instability, short circuits, or shielding gas issues.

5.2.3 Experimental results and process evaluation

The WAAM system was tested with multiple materials and part geometries:

Materials: Aluminum (ER4043), steel alloy (ER70S-6), stainless steel (ER316L).

Geometries: blade, cup, bell, funnel, and diamond shapes—some printed with continuous spiral paths to minimize arc starts/stops.

Key findings:

Deposition height and consistency depend heavily on wire feed rate, travel speed, and material properties.

Real-time IR tracking enabled adaptive slice selection and improved deposition control.

3D scanning of final parts and comparison to CAD models showed average dimensional error <1 mm, with worst-case error under 3 mm and width variation <15%.

5.2.4 Key contributions and lessons learned

The modular, open-source framework allows for integration with a wide range of robotic and sensing hardware.

Real-time monitoring and adaptive control significantly improve part consistency and reduce manual intervention.

Cold metal transfer (CMT) proved beneficial for reducing thermal distortion and improving bead quality.

Multi-robot coordination enhances flexibility and enables more complex geometries with fewer defects.

The robot raconteur-based architecture can scale to future developments like multi-bead deposition, adaptive cooling, and AI-driven fault detection.

5.3 CNC milling machine to WAAM retrofit experience

The paper [4] presents the design, integration, and testing of a WAAM retrofit kit tailored for converting a conventional CNC milling machine—including 5-axis systems—into a hybrid manufacturing system capable of both additive and subtractive operations. The motivation stems from the need for a cost-effective, flexible solution for repairing high-value components like molds and dies, especially within small and medium enterprises that cannot invest in specialized WAAM machines.

5.3.1 Motivation and concept

Traditional repair methods like manual GTAW (TIG) are labor-intensive and operator-dependent, with limited repeatability. Alternatives like DLMD are expensive and suited only for high-end industries. The authors aimed to develop a general-purpose retrofittable system that enables automated and accurate repairs using WAAM on existing CNC milling machines.

Key goals:

Reduce machine downtime and fixture transfers.

Allow switching between milling and WAAM with minimal disruption.

Avoid the cost of new hybrid machines.

Maintain high deposition quality for industrial repair applications.

5.3.2 Hardware and retrofit design

Torch holder and tool integration

The WAAM torch was integrated as a standard tool into the machine's automatic tool changer (ATC) via an HSK 63 holder.

A micrometric adjustment system ensured the torch tip remained collinear with the spindle axis, which is crucial for precise 5-axis operations.

Two torch holder variants were developed: one compact (for 3-axis use) and one adjustable (for 5-axis precision).

Electrically Insulated Rotary Table

A specially designed rotary table was installed on the original machine table.

It included insulation to prevent current leakage through machine electronics and motors.

A rotating ground connection (with copper braids and nylon isolation) ensured continuous grounding during part rotation.

Designed for compatibility with a wide range of milling machines.

5.3.3 System integration and control

A Fronius TPSi320 welding source with CMT (Cold Metal Transfer) capability was chosen for its low heat input and fine control.

The machine's Fanuc 31i-B5 NC was interfaced with the welding unit via M-code signals, enabling full process control from the standard G-code program.

This integration allows both deposition and milling operations to be run from a single NC file, greatly simplifying programming and enabling easy operator adoption without specialized training.

5.3.4 Safety and usability enhancements

Welding fume extraction was integrated into the machine’s aspiration system.

UV radiation was managed with a self-darkening LCD screen mounted on the machine door.

Cables for wire feed and shielding gas were manually attached/detached during tool changes, keeping automation straightforward and cost-effective.

5.3.5 Process validation: test case – AISI H13 mold repair

A die made from AISI H13 tool steel was used as a test part.

The repair procedure included:

Surface smoothing via roughing and finishing toolpaths.

Preheating to 300 °C before deposition using an industrial heater.

WAAM deposition using optimized CMT parameters.

Post-process machining to restore dimensions.

Slow cooling in vermiculite sand to minimize thermal stress.

5.3.6 Toolpath strategy and CAM use

A custom 5-axis CAM tool was developed for deposition path generation, using concentric constant-stepover patterns.

The CAM produced G-code directly executable on the CNC.

The approach is adaptable and also compatible with commercial CAM systems, provided bead width and stepover constraints are considered.

5.3.7 Key takeaways and contributions

The retrofit kit successfully transformed an existing 5-axis milling machine into a hybrid WAAM-capable system.

The entire workflow (preparation, deposition, and finishing) was performed on one machine, reducing handling and increasing precision.

The approach is:

Cost-effective: <10% the cost of a new hybrid machine.

Flexible: Easily adapted to different machines and materials.

Accessible: Requires only basic modifications and G-code programming skills.

The retrofit is well-suited for SMEs seeking sustainable repair capabilities without major capital investment.

6 References

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