

T5.5 Case study Problem- Based Learning (PBL)

Title of Case Study / Problem-based learning case

Technological Comparison for Dot-by-Dot Wire Arc Additive Manufacturing of Aluminium Alloys for Aerospace and Defence

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Background:

- **Material:** Aluminium alloy ER5356 wire.
- **Process & Equipment:** Directed Energy Deposition-arc (DED-arc) utilizing Fronius CMT (Cold Metal Transfer) and PMC (Pulse Multi Control) welding methods.
- **Design:** Dot-by-dot fabricated cylindrical wireframe structures (vertical and inclined columns) with diameters ranging from 4 to 7 mm.
- **Mechanical Requirements:** Minimum 150 MPa of Tensile Strength (TS) and 2% of elongation.

Context & Objective:

Aerospace applications demand lightweight, complex, and topologically optimized structures to reduce overall weight without compromising structural integrity. The "dot-by-dot" Wire Arc Additive Manufacturing (WAAM) approach is highly effective for producing load-bearing cylindrical wireframe structures while minimizing material waste.

In this case study, Aluminium alloy ER5356 wire is utilized as the material. The process involves Directed Energy Deposition-arc (DED-arc) applying dot-by-dot fabricated cylindrical wireframe structures (vertical and inclined columns) with diameters ranging from 4 to 7 mm.

However, manufacturing these thin aluminium columns introduces significant thermal management challenges. The mechanical requirements dictate a minimum of 150 MPa of Tensile Strength (TS) and 2% of elongation. Meeting these strict aerospace requirements necessitates a rigorous comparison between advanced arc welding modes, specifically CMT (Cold Metal Transfer) and PMC (Pulse Multi Control). The objective is to evaluate these two methods based on parameter optimization, dimensional accuracy, microstructural evolution, and internal defect formation.

Illustration of the case study



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Figure 1. Visual representation of the dot-by-dot WAAM process and stickman test figure
Additional pictures/information

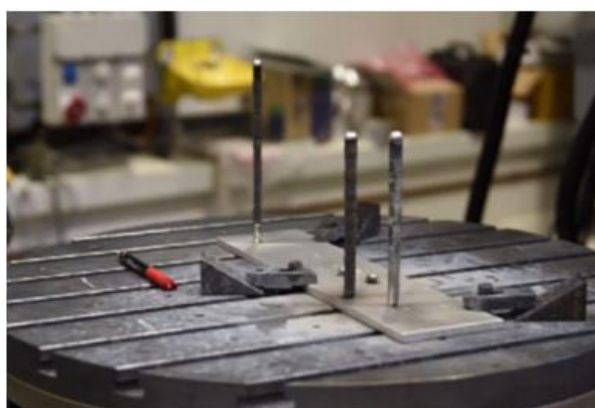
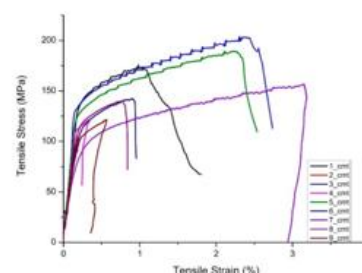
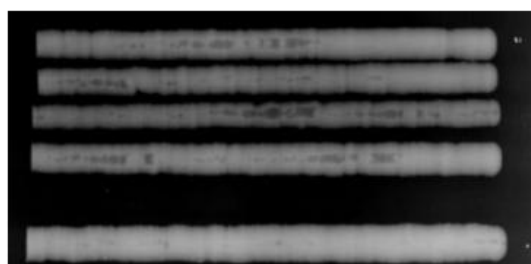
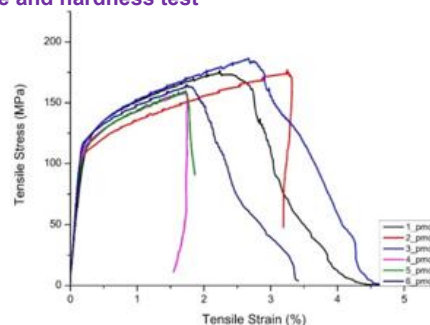
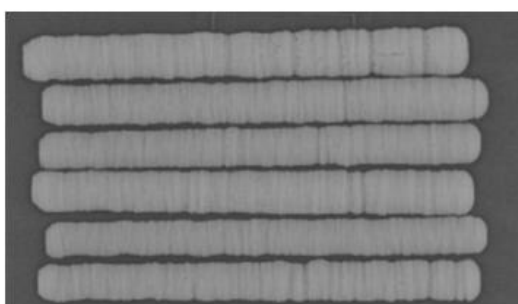


Figure 2. Various columns manufactured by WAAM. These columns are removed from the substrate for geometric and mechanical analysis. A total of nine columns are manufactured of the CMT synergetic mode for CMM, macro, and SEM inspection, as well as tensile and hardness test



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Figure 3. Horizontal X-ray comparison images showing internal voids in CMT vs. solid structure in PMC and Tensile test graphs or SEM images demonstrating porosity differences

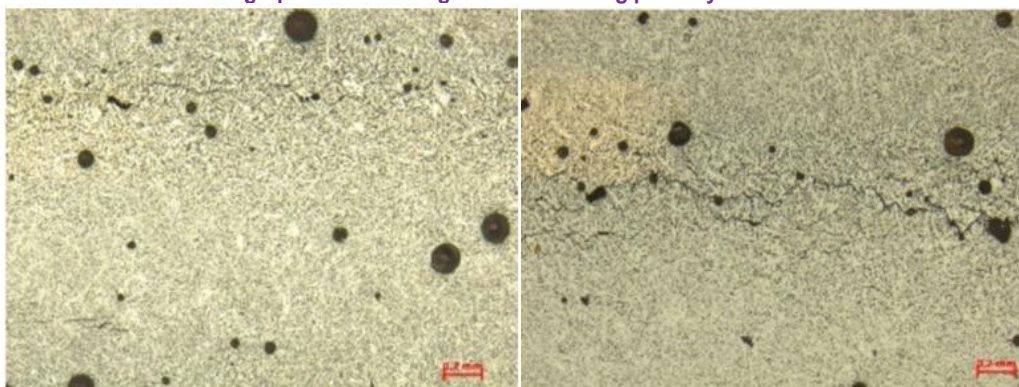


Figure 4. Macro image of the cut product. Layers are clearly visible in the macro images



Figure 5. CMM scan geometry for a rod manufactured via WAAM. A uniform cylinder is used as a reference to compare the manufactured part, and the deviation from the uniform cylinder is shown

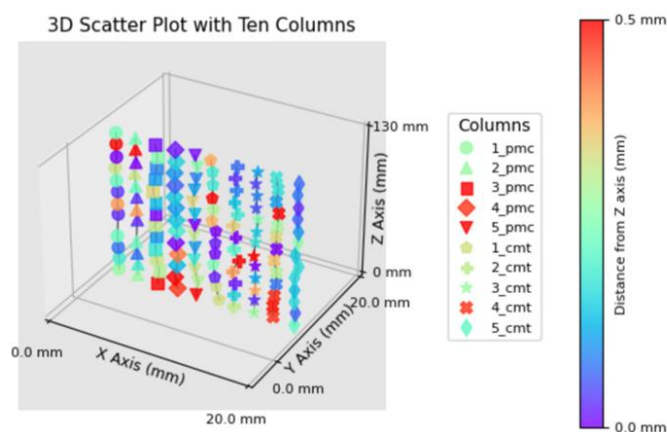


Figure 6. 3D scatter plot of CMM results of the rods. The points are color-coded according to their deviation from the column centreline. The plot is made with Cartesian coordinates: X and Y on the horizontal axes and Z on the vertical axis, with each axis in millimetres

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Figure 7. Image capturing the moment of spot-welding operation using PMC process. Image of the wire-arc additively manufactured load-bearing rod using the PMC process

Technical challenge

- How do advanced low-heat input (CMT) and pulse-controlled (PMC) welding methods compare in terms of heat input, and how does this affect the dimensional accuracy, straightness, and mechanical properties (tensile strength and elongation) of dot-by-dot aluminium deposition?
- Considering the high susceptibility of aluminium to hydrogen-induced porosity, what are the most appropriate Non-Destructive Testing (NDT) methods to detect internal discontinuities in such thin, cylindrical structures?
- How can established aerospace standards, such as the AWS D21.1 Acceptance Criteria, be applied to evaluate the structural integrity and qualify these WAAM-produced wireframe components?
- Which approach ultimately yields a better balance of dimensional fidelity, mechanical performance, and internal structural quality, and why?

Detailed solution/ process

To determine the superior technological approach for dot-by-dot aluminium WAAM, a systematic evaluation methodology combining destructive and non-destructive testing is executed:

1. Process Optimization and Comparison (CMT vs. PMC)

The dot-by-dot WAAM process relies heavily on controlling the heat input to maintain the stability of thin cylindrical columns. A Design of Experiments (DoE) methodology is utilized to optimize the parameters (e.g., wire feed speed, pause times) for both methods.

- Reasoning: CMT offers a highly controlled, lower heat input which theoretically minimizes thermal distortion for thin 4-7 mm structures. However, evaluation reveals that CMT's low heat input causes insufficient melting at the center of the columns, leading to severe voids and unacceptable porosity levels. PMC, alternatively, increases the heat input sufficiently to ensure stable arc dynamics, proper penetration, and a significant reduction in microporosity.



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2. Dimensional and Mechanical Evaluation

- Dimensional Measurement: A Coordinate Measuring Machine (CMM) is used to assess the geometric fidelity. The straightness of the rods produced with PMC is more homogeneous compared to CMT due to consistent heat input and reduced thermal distortion.
- Mechanical Performance: Destructive tensile testing is performed directly on the fabricated columns. The results prove PMC superior: PMC rods exhibit ultimate tensile strength values up to 187 MPa and elongation percentages reaching 4.9%, comfortably exceeding the 150 MPa and 2% aerospace requirements. CMT parts fail to perform reliably due to random porosity.

3. Non-Destructive Testing (NDT) and Quality Assurance

Radiographic Testing (RT) is selected as the primary NDT method because X-rays effectively penetrate the thin, complex structures to reveal internal volumetric discontinuities. The RT defect maps are cross-referenced with aerospace acceptance criteria. X-ray results clearly demonstrate that the centerline of PMC columns shows great homogeneity with low voids, whereas CMT columns exhibit hollow centers.

By analyzing the RT results alongside tensile data, it is concluded that the PMC method is the most suitable approach for producing aerospace-grade internal structures in dot-by-dot WAAM.

The Purpose of the elaborated CaseStudies

Case studies are structured examinations of real-world situations or challenges designed to bridge theory and practice. They are developed both as a research method and as a learning tool to strengthen analytical and problem-solving skills. By engaging with authentic industrial scenarios, students gain practical insight into complex professional environments.

The purpose of this case studies is to encourage active, learner-centred engagement. They support approaches such as problem-based learning by enabling students to work independently or collaboratively, with or without instructor guidance. Through analysing theoretical concepts within realistic contexts, students learn to interpret data and test results, evaluate alternative courses of action, and develop well-reasoned, creative solutions.

This approach is particularly valuable in sectors such as aerospace, defence, and advanced manufacturing, where challenges are multifaceted and solutions are rarely singular. Because multiple valid solutions often exist, guided facilitation is frequently beneficial to help students structure their reasoning, assess trade-offs, and justify their decisions effectively.



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Competence unit coverage:

AILEEN competence units		Covered CU
AW_01	Welding: Advanced Metallic Materials in Aerospace and Defence Sectors	X
AW_02	Welding: Advanced Welding Processes and Equipment in Aerospace and Defence Sectors	X
AW_03	Welding: Advanced Welding Applications in Aerospace and Defence Sectors	X
AW_04	Welding: Introduction to brazing technology Knowledge for quality brazed joints	
AW_05	Welding: Fundamentals of Industrial Brazing: Main Processes, Quality Standards & Applications	
AI_01	Inspection: Non-Destructive Testing (NDT) in Additive Manufacturing for metals and polymers	X
AI_02	Inspection: Metrology in Additive Manufacturing for metals and polymers	X
AI_03	Inspection: Inspection of AM parts. Material Quality	X
AAM_01	AM: Qualification, Certification and Standards for AM in A&D	X
AAM_02	AM: Quality Assurance & Quality Control for AM in Aerospace & Defence	X
AAM_02/3	AM: Design of AM parts for A&D (2 courses - for DED & PBF)	X
AD_01	Digital: Introduction to Digital Technologies in Advanced Manufacturing	
AD_02	Digital: Data Acquisition and Analysis	
AD_03	Digital: Industrial Internet of Things (IIoT) and Advantages in Advanced	
AD_04	Digital: Artificial Intelligence and Advantages in Advanced	
AD_05	Digital: Automation and Advantages in Advanced Manufacturing	
AD_06	Digital: Potentials of Advanced Simulation and Modelling in Advanced	
AD_07	Digital: Potentials of Digital Twins and Smart Factory Automation in Advanced Manufacturing	
AD_08	Digital: Unlocking the Potential of 3D Models Beyond Technical Drawings in the Aerospace and Defence Sector	X
AG_02	Green: Sustainable Design and Environmental Compliance in Aerospace and Defence	

