EXPERIMENTAL INVESTIGATION OF PROCESS PARAMETERS ON THE QUALITY OF ALUMINIUM COMPONENTS MANUFACTURED THROUGH WIRE ARC ADDITIVE MANUFACTURING (WAAM)

A Synopsis submitted to Gujarat Technological University

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in

Mechanical Engineering

by

PATEL DHAVAL BHARATBHAI

189999919042

under supervision of

DR. PUJARA AKSHAY ASHVINKUMAR

GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

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DECLARATION

I declare that the synopsis of Ph.D. thesis entitled **"EXPERIMENTAL INVESTIGATION OF PROCESS PARAMETERS ON THE QUALITY OF ALUMINIUM COMPONENTS MANUFACTURED THROUGH WIRE ARC ADDITIVE MANUFACTURING (WAAM)"** has been carried out by me under the supervision of **DR. PUJARA AKSHAY ASHVINKUMAR** (Assistant Professor, Mechanical Engineering Department, Vishwakarma Government Engineering College, Chandkheda, Ahmedabad, Gujarat, India).

This is the presentation of original research work carried out by me and it has not been submitted in part or in full for the award of any other degree or diploma of any institute or university.

PATEL DHAVAL BHARATBHAI

(189999919042)

CERTIFICATE

This is to certify that the synopsis of the thesis entitled **EXPERIMENTAL INVESTIGATION OF PROCESS PARAMETERS ON THE QUALITY OF ALUMINIUM COMPONENTS MANUFACTURED THROUGH WIRE ARC ADDITIVE MANUFACTURING (WAAM)** submitted by **Mr. PATEL DHAVAL BHARATBHAI (189999919042)**, part time external candidate, in partial fulfillment for the award of the degree of "Doctor of Philosophy", in Mechanical Engineering Department at Gujarat Technological University Ahmedabad, Gujarat, India, is a record of his own work carried out under my supervision and guidance and have satisfactorily and successfully completed all eight DPCs along with three research weeks and pre-submission seminar.

Supervisor:

Dr. Pujara Akshay Ashvinkumar

Assistant Professor, Mechanical Engineering Department,

Vishwakarma Government Engineering College,

Chandkheda, Ahmedabad, Gujarat, India.

1. Title of thesis and abstract

Experimental Investigation of Process Parameters on The Quality of Aluminium Components Manufactured Through Wire Arc Additive Manufacturing (WAAM)

In order to reduce heat accumulation and its adverse effects on properties of the components in Wire+Arc additive manufacturing (WAAM), this study investigates the influence of a water-based active cooling technique on thermal management and heat accumulation mitigation for the deposition of ER5356 alloy. The application of this simple and cost-effective strategy directs towards the novel approach to improving deposition quality and thermal stability in aluminium additive manufacturing. With this method, the preform is partially submerged in a water-filled work tank in such a way that the welding surface remains above the water surface at a fixed distance, and more water is added to maintain this gap. As a heat sink, the water absorbs the heat produced during the deposition process, by which heat accumulation can be averted. Single-pass multi-layer linear walls of ER5356 were deposited using the standard Gas Metal Arc Welding (GMAW) process with different thermal control techniques. By measuring the process parameters and recording the thermal history of the preforms, the effects of water cooling on material properties are evaluated. For further improvement, a new approach, Tandem Immersion Active Cooling (TIAC), is developed in which A supplementary water nozzle was mounted with the welding torch at a horizontal offset of 50 mm in the torch travel direction, supplying a controlled water jet to the deposited layer immediately behind the arc. The water is supplied through this additional nozzle. Microstructural and SEM fractographic analyses were performed to evaluate the effect on impact strength and tensile strength. The results show that this technique successfully lowers heat accumulation by 80% to 88 % reduction in temperature. Surface waviness is reduced by 16%, layer height has increased by 50% and deposition efficiency has increased by 18%. Wall thickness is improved and remains nearly constant. Further, the anisotropy of the mechanical properties decreased, indicating an improvement in the quality of the preform. This approach provides an effective and scalable solution to mitigate key challenges that come with this rapidly growing additive manufacturing process by providing a cheap and effective way to manage heat in WAAM.

2. Brief description on the state of the art of the research topic

Wire arc additive manufacturing (WAAM) is transforming manufacturing in several industries. This approach of metal additive manufacturing allows to manufacture intricate metal items faster than other methods. It slowly melts metal wire with an electric arc, which makes it more flexible and cheaper than other methods of manufacturing items. (Vázquez and others, 2020) A robotic arm or other automated equipment transfers the metal line to the proper spot on a substrate by following a predefined path. (Xia and others, 2020). The metal starts to deposit and mix with the substrate when it melts, gently taking on the shape (B. Wu, Pan, Ding, Cuiuri, Li, et al., 2018) Additionally, its distinctive shape makes it simple to create complex designs that are difficult or impossible to create using conventional techniques. This is a fundamental benefit of all additive manufacturing techniques. WAAM enables the fabrication of lightweight, geometrically complex aerospace structures without altering fundamental airframe assembly protocols. This contributes to improved fuel efficiency of the aircraft and is good for the environment. (Rosli et al., 2021) In the automotive sector, WAAM offers a cost-effective route to near-net-shape fabrication of structurally complex components. (Singh & Khanna, 2021) WAAM facilitates rapid prototyping and low-volume production of energy sector components, including structural elements of wind turbines and energy storage systems. (Raut & Taiwade, 2021) Because of its many advantages, WAAM has emerged as a promising metal additive manufacturing technique, offering advantages in material efficiency and geometric flexibility compared to conventional subtractive processes. (Langelandsvik and others, 2021a) The aerospace (brackets, fittings, etc.), automotive (suspension components, body panels, etc.), shipbuilding (propellers, offshore platform components, etc.), medical, defence, and precision parts industries are all seeing an increase in the use of additive manufacturing of aluminium alloys. Recently, there has been an increase in the analysis and application of WAAM for the 5xxx series, particularly the aluminium alloys 5183 and 5356 (Wieczorowski et al., 2023; Prasanna Nagasai et al., 2022; Köhler et al., 2020). The 5356 Al-Mg alloy used in this investigation is notable for its exceptional strength and resistance to corrosion. The main alloying element in the aluminium alloys of the 5000 series is magnesium. Because of its composition, this alloy is especially well suited for coastal areas. (Langelandsvik and others, 2021b)

WAAM has several benefits, but it also has certain drawbacks and difficulties. Excessive heat is the main problem. (Da Silva and others, 2020) The increased heat input causes temperature fluctuations, thermal cycling, and residual stresses, which lead to pore growth, distortions, and changes in the microstructural and material properties. Wu et al. (2017,2018) reported that to guarantee that the finished product has strong fusion, high precision, and good mechanical integrity, it is crucial to control and minimise this heat accumulation. (Cui et al., 2021) (Montevecchi et al., 2018) Further, inadequate heat dissipation may result in localized heat accumulation, residual strains, distortion, and porosity. This deteriorates the quality of the fusion and the precision of the dimensions. Real-time monitoring and optimization of cooling systems, gas flow, and deposition parameters enhance heat dissipation, stabilize the process, and improve components produced by WAAM. (B. Wu, Pan, Ding, Cuiuri, & Li, 2018) (da Silva et al., 2020) Another drawback of layer-by-layer deposition is residual tensions caused by rapid heating and cooling. Tensile and compressive stresses, deformation, and a reduction in structural stability are all caused by these temperature variations. Enhancing the performance and dependability of components requires efficient management through post-processing treatments, regulated cooling, and optimised process parameters. (Q. Wu et al., 2020) (Hönnige et al., 2017) To reduce deformation and guarantee the geometric integrity of components, effective control via cooling techniques, predictive modelling, and optimised process parameters is crucial. (Manurung et al., 2021) (Prajadhiama et al., 2019) Rapid heating and cooling during deposition cause changes in the microstructure, like grain refinement, phase changes, and heterogeneity. Strength, ductility, and toughness are all directly impacted by these modifications. (Su et al., 2019) (Klein & Schnall, 2020) Post-processing techniques such as hot isostatic pressing (HIP) and non-destructive evaluation (NDE) are essential for defect detection and quality assurance in WAAM components. (Biswal et al., 2019) (Yehorov et al., 2019) Optimised deposition strategies, real-time thermal monitoring, and precise process adjustments are essential to prevent overheating and maintain build quality and precise adjustments to process parameters. Serrati et al., 2023) Interlayer bonding is very important for the strength of the structure. If the layers don't fuse well, the structure can delaminate, crack, or lose strength. Strong bonding requires exact control over the deposition settings, adequate shielding gas flow, and ensuring that the layers fuse correctly and the components function dependably. (Zahidin et al., 2023) (Yaseer & Chen, 2021) Effective control involves optimised deposition procedures, preheating, stress relief treatments, and real-time inspection to reduce fracture formation and provide high-quality, long-lasting components. Heat exchanger-based cooling systems have been shown to be beneficial in thermal management during WAAM in order to alleviate the aforementioned problems and limitations (Seow et al., 2020; Huang et al., 2023). According to Lauren et al. (Heinrich et al., 2023), employing a copper plate as a heat exchanger during WAAM can greatly improve thermal management, which raises the rate of deposition. By using a cooling system with a network of passageways filled with coolant as the heat exchanger, Dash et al. (Dash et al., 2023a) increased cooling rates and reduced material flaws in WAAM ER70S-6 steel. Using a thermoelectric cooling technique, Li et al. (Li et al., 2018; Shi et al., 2019) reduced the production time by 60.9% and enhanced the grain refinement (reducing the average grain size from 7.96 to 5.97 μm) in tandem WAAM of AA2325.

Near-Immersion Active Cooling (NIAC) is a thermal management technique in which the deposited preform is partially submerged in a liquid coolant bath during WAAM, as illustrated schematically in Figure 1, eliminating the need for intricate cooling system designs, and effectively mitigating challenges such as inadequate deposition formation, elevated porosity, residual stress, deformation and substandard mechanical properties in the WAAM of aluminum alloy. Using water as a cooling medium, Scotti et al. (Scotti et al., 2020) carried out NIAC in WAAM of AlMg5, improving deposition morphology and accomplishing quick heat extraction without increasing porosity. Researchers ascribed the improved performance of WAAM Al to grain refining attained via NIAC (Sinha et al., 2023; Teixeira et al., 2021). Teixeira et al. (Teixeira et al., 2021) indicated that the layer edge to water distance (LEWD) exerts a little influence on the average grain size of aluminum alloy produced via WAAM with NIAC. Sinha et al. (Sinha et al., 2023) discovered that water-based NIAC imparts an ultimate tensile strength of 268 ± 5 MPa to WAAM-fabricated aluminum alloy. Silva et al. (da Silva et al., 2021) endeavoured to enhance the surface quality and relative density and of aluminum alloy by improving the deposition parameters of WAAM. Despite NIAC's proven advantages in enhancing WAAM performance, the influence of cooling media on the microstructural attributes and mechanical properties of NIAC WAAM of ER5356 has been infrequently examined. This work systematically examines the impact of cooling media on the deposition quality and mechanical performance of WAAM aluminum alloy, providing theoretical support for the optimization of cooling process design in industrial applications.

A critical review of the existing literature reveals several significant research gaps that motivate the present study. These are outlined below:

- Existing mitigation techniques such as post-process heat treatment, inter-pass cold rolling, peening, and ultrasonic impact treatment are either material-specific or limited in applicability.

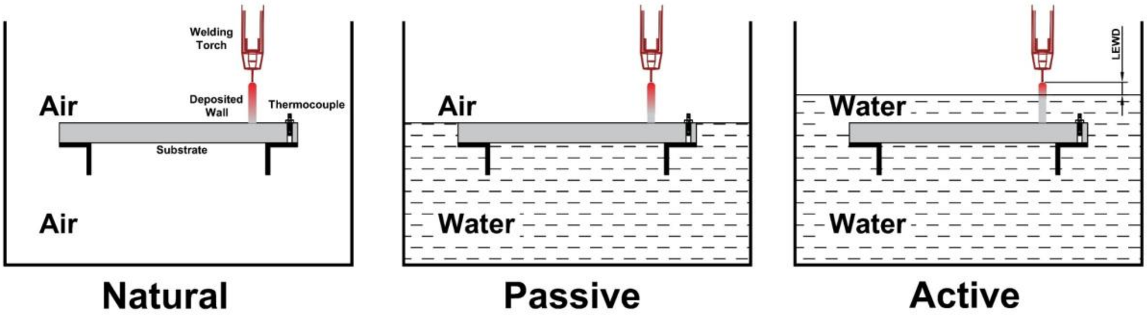

Fig. 1 Schematic representation of the various cooling approaches applied

- Inter-pass cold rolling is restricted to simple geometries and does not effectively address overall distortion.
- Promising results of active inter-pass cooling (e.g., CO_2 cooling) are mainly limited to titanium alloys (e.g., Ti6Al4V), with very limited studies on aluminium WAAM.
- Gas-based cooling (air/CO_2) suffers from low thermal conductivity and interferes with shielding gas in GMAW processes.
- Lack of research on liquid-based cooling approaches (water, cryogenic cooling) for efficient heat extraction in WAAM.
- Deposition strategy and cooling interaction is not well explored, especially in terms of path planning and thermal management.
- Limited understanding of the relationship between heat accumulation, residual stress evolution, and mechanical properties in aluminium WAAM.
- Environmental effects beyond shielding gas (such as controlled cooling environments) are largely unexplored.
- Difficulty in achieving wrought-like microstructure and isotropic properties in WAAM aluminium components through existing approaches.

3. Definition of the problem

WAAM of aluminium alloys is inherently prone to progressive heat accumulation, which leads to poor dimensional accuracy, undesirable microstructure, and inferior mechanical properties. Existing approaches to mitigate these issues are either insufficient, geometry-limited, or not suitable for aluminium WAAM processes. Moreover, current cooling strategies—particularly gas-based methods—are unable to provide the required heat extraction efficiency and may disrupt the welding environment. There is also a lack of systematic understanding of how inter-pass cooling, deposition strategy, and thermal history interact to influence material properties.

Therefore, based on the above limitations, a critical research gap exists and there is a critical need to:

Develop an effective, scalable, and process-compatible cooling strategy that can control heat accumulation during aluminium WAAM and enhance the deposition rate & efficiency and systematically evaluate its influence on microstructure, geometric quality and mechanical performance.

4. Objectives and scope of work

The objective of present research is to develop a process to mitigate heat accumulation in Aluminium WAAM components and identify the effect of it on the material properties. The major objectives of this research are listed as follows:

1. The objective is to design and develop a reliable WAAM system for experimentation by integrating key components such as a programmable welding power source, wire feeder mechanism, motion control system (CNC/robotic arm), shielding gas arrangement, and data acquisition system.
2. To fabricate vertical wall components by deposition of ER5356 aluminum alloy to build thin-wall vertical structures using the developed WAAM setup.
3. To investigate the effect of inter-layer (inter-pass) active cooling on the material properties using water as a coolant. Develop the new approach named TIAC (Tandem Immersion Active Cooling) and compare it to the existing NIAC (Near Immersion Active Cooling) Approach.
4. To investigate the effect of deposition strategy on the material properties along with active cooling.
5. To investigate the effect of inter-layer (inter-pass) active cooling on the material properties using liquid nitrogen as a coolant.

Building upon the stated objectives, the scope of this research is bounded as follows. The work includes the design, integration, and validation of a WAAM system comprising a programmable welding power source, wire feed unit, motion control system

(CNC/robotic), shielding gas delivery system, and data acquisition framework. The scope involves the deposition of ER5356 aluminium alloy to fabricate thin-wall vertical structures. Process parameters such as current, voltage, travel speed, and wire feed rate will be monitored and the fabricated samples will serve as baseline specimens for further comparative studies.

A key aspect of the research is the development of an innovative cooling strategy termed Tandem Immersion Active Cooling (TIAC), and its comparison with the conventional Near Immersion Active Cooling (NIAC) method. The scope includes the design and integration of a water-based cooling system to control inter-layer temperature. The effectiveness of both cooling approaches will be evaluated in terms of thermal regulation, layer thickness, deposition efficiency, surface waviness and microstructural refinement. The study will examine the influence of different deposition strategies (such as travel path) on heat accumulation and material behaviour. The interaction between deposition strategy and active cooling techniques will be analysed to identify optimal combinations that enhance build quality and mechanical performance. The research extends to the development of a liquid nitrogen-based inter-pass cooling system to enable rapid heat extraction. Comparative analysis will be performed against water-based cooling and non-cooled conditions. Comprehensive characterization of fabricated components will be carried out, including microstructural analysis (optical microscopy, SEM), mechanical testing (hardness, tensile strength), and evaluation of defects and anisotropy. Thermal history and cooling rates will also be analysed to correlate process parameters with material behaviour.

5. Original contribution by the thesis

The major original contributions of this research to the field of wire arc additive manufacturing of aluminium are summarized as follows:

1. Design and development of a fully functional WAAM experimental setup with provision for integrating advanced cooling systems.
2. Development and validation of Tandem Immersion Active Cooling (TIAC) as an effective thermal management technique. Implementation of water-based and cryogenic inter-pass cooling systems compatible with WAAM processes.
3. Detailed investigation of the effect of inter-pass cooling on thermal history,

geometric quality and deposition stability. Quantitative analysis of microstructure refinement, grain size variation, and phase evolution under different cooling conditions.

4. Demonstration of process effects on hardness, tensile strength, and structural integrity of WAAM-fabricated aluminium components through controlled cooling.
5. Establishment of a comparative methodology to evaluate multiple cooling techniques under identical processing conditions.
6. Development of a scalable and industry-relevant solution for mitigating heat accumulation in WAAM.

6. Research Methodology

The experimental setup developed for the gas metal arc welding-based WAAM system is shown in Figure 2. The system primarily consists of a direct current (DC) welding power source (LORCH S5 RoboMIG XT W) along with argon gas bottle attached to 6-axis robot (Kuka KR8 R2100 HW). The wire spool is mounted on robot arm and the wire is passed via feeder up to welding torch.

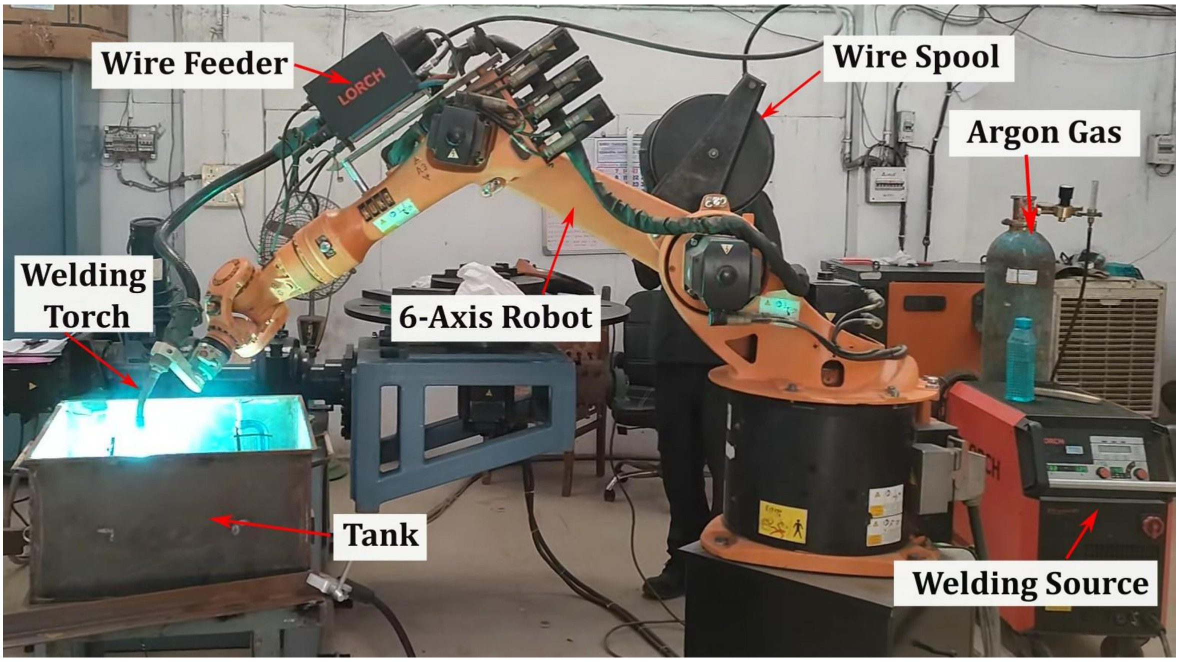

Fig. 2 Experimental Setup depicting various equipment used for this investigation

The welding torch of the GMAW was mounted as an end effector of the robot for the deposition process. A commercial aluminum substrate with dimensions 300 x 300 x 25 mm^3 (length × breadth × height) was used as a base plate for deposition and clamped on support inside the tank which is shown in Figure 3. The tank is filled with ordinary tap water, which acts as a coolant and provides the necessary cooling during the different manufacturing techniques. A pump is attached to supply the water for immersion during TIAC approach via flexible pipe. Its output is connected to the welding nozzle in tandem. A K-type thermocouple is attached at midpoint of deposition path to monitor temperature and another K-type thermocouple is attached to the tank wall to measure the temperature of the water. Both the thermocouples are attached to a MAX6675 analogue to digital converter for conversion and amplification of electric signal provide by thermocouples. The output is attached to datalogger to record the temperature every second. The datalogger is developed using an Arduino Uno micro controller development board and SD card shield. An LCD display is also attached for the live monitoring of the data. Chemical composition of the aluminum wire (ER5356) used for deposition is shown in Table 1. The ER5356 wire was selected due to its wide applications, including aerospace, automobiles, and pipelines. The deposition strategy includes a 200 mm linear path with zigzag torch travel pattern in to the torch travel direction. The deposition parameters used to construct the wall are shown in Table 2. After deposition of the wall, each wall is separated from substrate using machining, and then both ends were removed using hacksaw to analyse cross section of the wall, the surface of both the front and back faces were finished using vertical machining centre and thickness of wall is reduced to 5 mm to extract the specimen.

Table 1. Chemical compositions of the ER5356 welding wire

Element	%
Al	94.327
Si	0.110
Mn	0.157
Cr	0.180
Pb	0.000
Mg	4.830
Fe	0.285

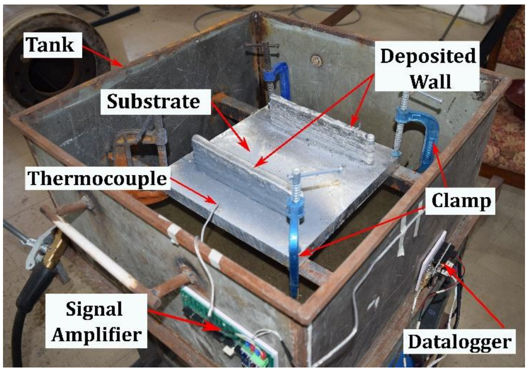

Fig. 3 Closeup view of the deposition area

The specimen for tensile testing and Charpy impact testing were extracted from this 5 mm thick plate using wire cut electro discharge machining process. For investigating tensile strength three orientation were chosen namely vertical, horizontal and inclined to analyse the anisotropy and layer adhesion of the process. As this technique involves the immersion of component partially in the water, some portion of the deposited wall will be under the water while remaining one will be outside the water which will introduce different cooling rate for both region of the deposited wall. To investigate this effect horizontal specimen were extracted from top and horizontal region of the deposited wall. The specimen size is decided as per ASTM B557M standard for tensile testing and ASTM E23-16b for impact testing.

Table 2. Process equipment and parameters

Deposition Equipment	S-RoboMIG XT
Voltage & Current	22.1 V, 123A
Deposition Material	ER5356 Wire, 1.2 mm in diameter
Substrate	Commercial Al (300 x 300 x 25 mm)
Wire feed speed	7600 mm/min
Deposition Speed	12.5 mm/sec
CTWD	10 mm
LEWD	0-20 mm
Shielding gas	Argon, 20 L/min
Cooling Liquid	Tap water at ambient temperature (~25°C)
Volume of tank	47 liters
Deposition geometry	Single wall with varying layers, length of 200 mm and height of approx. 65 mm
Deposition strategy	Unidirectional, Single pass, Zigzag pattern (for N, P, A20, A10, TIAC, LN2) Bidirectional, Single pass, Zigzag pattern (for TIAC-BD)

7. Result and Discussion

7.1 Thermal analysis

Thermal analysis shows that active cooling effectively suppresses heat accumulation during the WAAM process. Under natural cooling conditions, a continuous rise in temperature is observed with increasing deposition time, reaching peak values close to ~190°C, indicating severe heat accumulation and poor thermal dissipation. In contrast, passive cooling shows moderate temperature control, stabilizing in the range of ~60–80°C, while active cooling (Active cooling with a layer-edge-to-water distance (LEWD) of 20 mm (Active 20) and 10 mm (Active 10)) effectively reduces both peak temperature and thermal fluctuations, maintaining lower and more stable thermal cycles. The second set of results, with thermocouples immersed in water, further confirms that active cooling significantly suppresses temperature build-up, with Active 10 showing the lowest and most stable temperature profile (~15–20°C), followed by Active 20 and Passive conditions. The advanced cooling approaches, including TIAC/TIAC-BD and LN2, highlight distinct thermal behaviors, where liquid-based cooling methods maintain relatively stable and lower temperatures, whereas LN2 exhibits sharp thermal gradients and cyclic peaks, indicating rapid but less uniform cooling. Among all cooling approaches evaluated, TIAC-BD achieved the most significant reduction in peak substrate temperature (≈88%), leading to improved thermal stability, which is critical for controlling microstructure, reducing residual stress, and enhancing the mechanical performance of WAAM-fabricated components.

7.2. Geometric quality

The geometric quality of the WAAM-fabricated samples clearly reflects the influence of different cooling strategies on bead uniformity and dimensional stability. Under natural (N) and passive (P) conditions, the walls exhibit relatively smoother profiles but show noticeable widening and slight irregularities due to heat accumulation and molten pool instability. With active cooling (A20 and A10), an improvement in layer definition is observed; however, At a LEWD of 10 mm (A10), rapid localised heat extraction may lead to premature solidification and pool instability, resulting in increased surface waviness compared to A20. The TIAC approach results in better height control but introduces surface irregularities and occasional defects, likely due to rapid localized cooling. In contrast, TIAC-BD demonstrates comparatively improved uniformity and reduced distortion, suggesting better thermal balance during deposition. The LN2-cooled sample shows the most uniform and straight geometry with minimal distortion, highlighting the effectiveness of rapid heat extraction in controlling bead shape and preventing excessive spreading. The results indicate that controlled active cooling significantly enhances geometric accuracy, while improper or uneven cooling can lead to surface irregularities despite reducing heat accumulation.

The quantitative geometric analysis further highlights the impact of cooling strategies on wall formation and deposition characteristics in WAAM. The layer height (LH) increases significantly with advanced cooling methods, with TIAC (2.60 mm) and TIAC-BD (2.83 mm) showing the highest values, indicating improved material build-up per layer due to controlled solidification. In contrast, natural and passive conditions maintain lower layer heights (~1.72–1.73 mm). The total wall width (TWW) decreases with active cooling, from 18.82 mm (Natural) to 12.95 mm (TIAC-BD), suggesting reduced heat input and better confinement of the molten pool. A similar trend is observed in effective wall width (EWW), where passive cooling shows the highest value (15.26 mm), while TIAC-based approaches result in narrower but more controlled deposition. The surface waviness (SW) is lowest for TIAC-BD (0.57 mm) and Active 10 (0.58 mm), indicating improved surface finish and stability, whereas LN2 and natural cooling exhibit relatively higher waviness. Notably, deposition efficiency (DE) is maximized for TIAC-BD (0.88) and Active 10 (0.86), reflecting better material utilization and reduced over-deposition. Experimental observations indicate that advanced cooling strategies, particularly TIAC-BD, significantly enhance geometric precision, surface quality, and deposition efficiency, while effectively controlling excessive material spread associated with heat accumulation.

Table 3. Comparison of various geometric parameter obtained by various approaches

Approach	LH (mm)	TWW (mm)	EWW (mm)	SW (mm)	DE
	Layer Height	Total Wall Width	Effective Wall Width	Surface Waviness	Deposition Efficiency
Natural	1.73	18.82	13.85	0.68	0.74
Passive	1.72	18.68	15.26	0.60	0.82
Active 20	1.90	16.25	12.57	0.65	0.77
Active 10	1.84	16.28	14.04	0.58	0.86
TIAC	2.60	14.66	11.40	0.64	0.78
TIAC-BD	2.83	12.95	11.38	0.57	0.88
LN2	2.30	15.89	11.98	0.66	0.75

7.3. Tensile strength

The tensile test results reveal a significant influence of cooling strategy and build orientation on the ultimate tensile strength (UTS) of WAAM-fabricated ER5356 aluminium components. In the vertical orientation, Active 20 exhibits the highest UTS (~277 MPa), followed closely by Passive (~267 MPa) and Natural (~264 MPa), while Active 10 shows a noticeable reduction (~228 MPa), indicating inadequate thermal control at lower cooling intensity. TIAC (~264 MPa) maintains comparable strength to Natural, whereas TIAC-BD (~238 MPa) and LN2 (~247 MPa) show moderate performance. In the inclined orientation, Natural condition achieves the highest UTS (~284 MPa), with LN2 (~258 MPa) and TIAC-BD (~249 MPa) showing relatively improved strength compared to other active cooling methods, while Active 20 drops significantly (~231 MPa). For the horizontal (bottom) samples, Natural again shows the highest UTS (~296 MPa), with LN2 (~268 MPa) and Passive (~276 MPa) performing well, whereas TIAC-BD records the lowest (~235 MPa). In the horizontal (top) condition, Natural (~285 MPa) and LN2 (~269 MPa) demonstrate superior strength, followed by Passive (~272 MPa) and TIAC (~251 MPa). The results indicate that while natural and passive cooling often retain higher tensile strength, advanced cooling methods like TIAC and LN2 provide competitive performance with potential benefits in microstructural control, and the variation across orientations highlights the role of thermal history and anisotropy in determining mechanical properties.

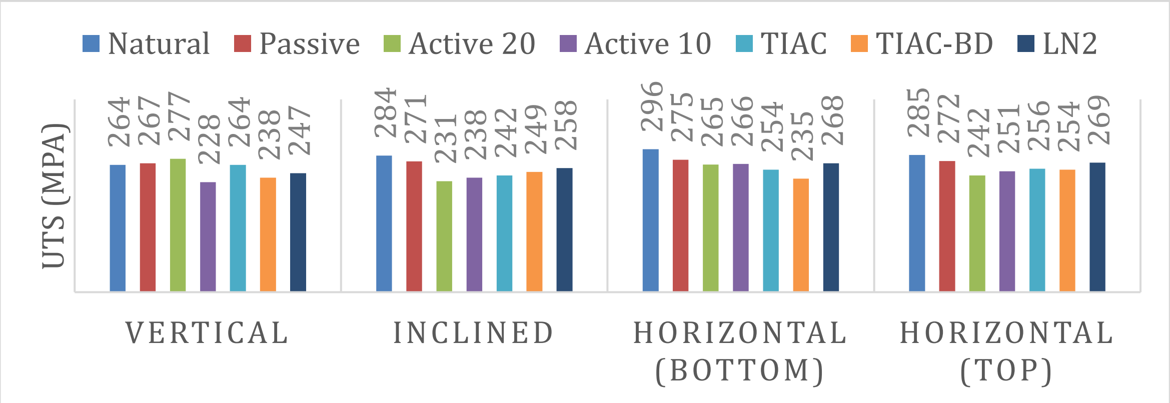

Fig.4 Tensile strength (MPa) of specimen manufactured under various cooling approaches in vertical (build, Z-axis), Inclined (45^{O}) and horizontal (transverse)

The fractographic analysis of the WAAM-fabricated ER5356 samples reveals a predominantly ductile mode of failure under both tensile and impact loading conditions across all orientations. The fracture surfaces are characterized by well-defined equiaxed and elongated dimples, indicating plastic deformation and void nucleation, growth, and coalescence as the primary failure mechanism. In tensile-tested specimens, the presence of uniformly distributed dimples surrounding larger gas pores and shrinkage cavities suggests that these internal defects act as stress concentrators and crack initiation sites, leading to a typical cup-and-cone fracture morphology associated with ductile overload. For impact-tested samples, a similar dimpled structure is observed, although with relatively finer dimples due to the higher strain rate involved in impact loading. Additionally, some regions show non-uniform porosity distribution, reflecting process-induced defects inherent to WAAM. The fractography confirms that despite the presence of porosity, the material retains significant ductility, and the failure behavior is governed by micro void coalescence mechanisms, consistent with aluminium alloy additive manufacturing characteristics.

7.4. Impact Strength

The impact testing results demonstrate a clear influence of cooling strategy and deposition approach on the toughness of WAAM-fabricated aluminium components. In the vertical orientation, the highest impact energy (~10 J) is observed for Natural, Active 20, and TIAC conditions, indicating superior energy absorption capability, while Active 10 shows a significant reduction (~6.6 J), suggesting insufficient thermal control at lower cooling intensity. Passive cooling yields moderately high toughness (~9.1 J), whereas LN2 and TIAC-BD exhibit intermediate values (~6.8–7.0 J). In contrast, for the horizontal orientation, impact energies are lower, with TIAC-BD showing the highest value (~9.0 J), followed by TIAC (~8.3 J), indicating improved performance due to controlled heat dissipation and possibly refined microstructure. Natural and Active cooling conditions show moderate performance (~6.4–7.2 J), while Passive cooling remains relatively lower. These results suggest that active cooling strategies, particularly TIAC and its variants, enhance impact toughness, and that build orientation plays a significant role, with vertical samples generally exhibiting higher toughness due to favourable layer bonding and thermal history.

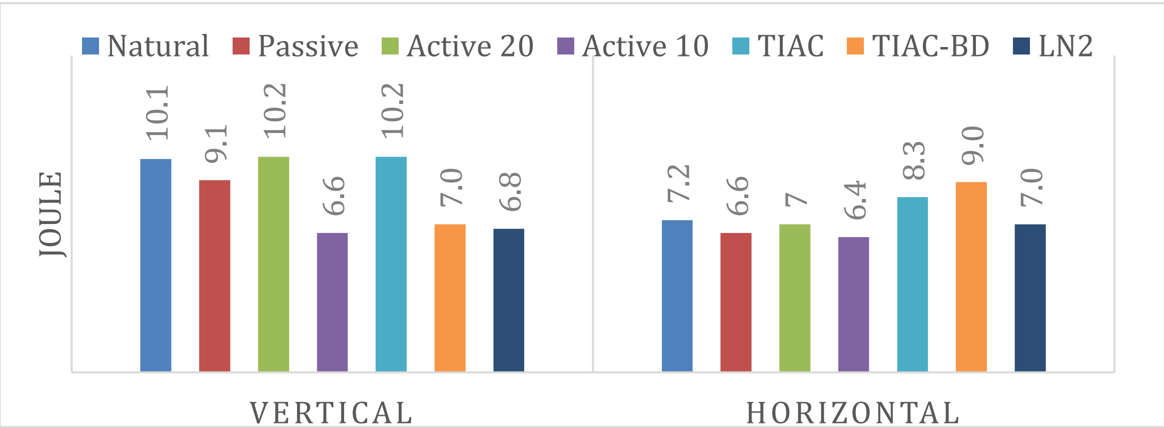

Fig.5 Charpy impact energy (J) absorbed by specimens manufactured under various cooling approaches in vertical (build, Z-axis) and horizontal (transverse) orientations.

7.5. Microstructural characterization

The microstructural characterization reveals a strong dependence of grain morphology and solidification behaviour on the applied cooling strategy during WAAM. Under natural and passive cooling, the microstructure is predominantly coarse with clear columnar dendritic growth, indicating slower cooling rates and significant heat accumulation, which promotes directional solidification along the thermal gradient. With active cooling (A20 and A10), a noticeable refinement in dendritic structure is observed, although some directional features persist, suggesting partial control over thermal gradients. In contrast, advanced cooling approaches such as TIAC and TIAC-BD exhibit a much finer and more uniform cellular/near-equiaxed α-Al microstructure, indicating higher cooling rates and improved thermal stability. Particularly, TIAC-BD shows reduced columnar alignment, suggesting a transition toward more isotropic solidification behaviour, which is beneficial for mechanical performance. The LN2-cooled samples also demonstrate fine cellular structures due to rapid solidification; however, they retain some directional features aligned with melt pool boundaries, reflecting steep thermal gradients. Across all conditions, the presence of spherical gas porosity is observed, likely due to entrapped shielding gas or hydrogen. The results confirm that enhanced inter-pass cooling significantly refines microstructure, reduces anisotropy, and improves solidification uniformity, with TIAC-based approaches showing the most balanced and desirable microstructural characteristics.

The XRD analysis confirms that all WAAM-fabricated ER5356 samples, irrespective of the cooling strategy, exhibit a predominant FCC aluminium (α-Al) phase, as evidenced by the characteristic diffraction peaks corresponding to the (111), (200), (220), (311), and (222) planes. The absence of additional peaks indicates that no secondary phases or undesirable intermetallic formations occur during the deposition process, highlighting the metallurgical stability of the alloy under different cooling conditions. However, noticeable variations in peak intensities between top and bottom layers suggest microstructural heterogeneity along the build height, primarily due to differences in thermal gradients, cooling rates, and grain orientation during layer-by-layer deposition. The sharper and more defined peaks observed in the top layers, particularly under active cooling conditions, indicate improved crystallinity, reduced residual stresses, and better lattice ordering. This can be attributed to lower heat accumulation and more stable thermal conditions in the later stages of deposition. The XRD results demonstrate that while cooling strategies do not alter phase composition, they significantly influence crystallographic texture and structural uniformity in WAAM components.

8. Achievements with respect to objectives

The achievements of the present research in relation to the stated objectives are as follows:

- A fully functional WAAM experimental setup was successfully designed and developed by integrating a programmable GMAW system, robotic manipulator, wire feeding system, shielding gas arrangement, and real-time data acquisition system, enabling controlled experimentation and thermal monitoring.
- Thin-wall vertical structures of ER5356 aluminium alloy were successfully fabricated using the developed WAAM setup, establishing stable deposition parameters and producing defect-minimized components suitable for further analysis.
- A novel Tandem Immersion Active Cooling (TIAC) technique was successfully developed and implemented, and its performance was systematically compared with conventional Near Immersion Active Cooling (NIAC) and other cooling strategies. The developed approach demonstrated a significant reduction in heat accumulation (≈80–88%), validating its effectiveness.
- The influence of inter-pass cooling using water as a coolant was thoroughly investigated, showing improvements in thermal stability, reduction in surface waviness (~16%), increase in layer height (~50%), and enhancement in deposition efficiency (~18%), thereby achieving better geometric control.
- The effect of deposition strategy in combination with active cooling was analysed, revealing improved wall uniformity, reduced distortion, and better control over molten pool behaviour, particularly in the TIAC-BD approach.
- A cryogenic cooling approach using liquid nitrogen (LN2) was successfully implemented and evaluated, demonstrating effective heat extraction and improved geometric stability, though with varying influence on mechanical properties.
- Comprehensive characterization established the relationship between cooling strategy, thermal history, microstructure, and mechanical properties, showing that active cooling leads to grain refinement, reduced anisotropy, and improved structural integrity.
- Mechanical testing confirmed that active cooling enhances impact toughness and reduces anisotropy, while maintaining competitive tensile strength compared to

conventional cooling methods.

9. Conclusion

Based on the experimental investigation and analysis carried out in this study, the following conclusions are drawn:

- The mechanical performance of WAAM-fabricated ER5356 aluminium components is strongly governed by cooling strategy and build orientation, significantly influencing tensile strength, impact energy, and microstructural characteristics.
- Natural cooling results in severe heat accumulation, leading to higher substrate temperatures and unstable thermal cycles, whereas passive cooling provides moderate improvement. In contrast, active cooling techniques effectively control heat input, achieving up to 80–88% reduction in peak temperature, thereby stabilizing the process.
- Geometric evaluation indicates that active cooling significantly improves deposition quality, resulting in enhanced wall uniformity, reduced surface waviness, controlled wall width, and higher deposition efficiency. Among all approaches, TIAC-BD demonstrated superior geometric performance.
- Tensile testing reveals orientation-dependent behaviour, with lower strength observed in the build (Z) direction due to weaker interlayer bonding. However, active cooling reduces anisotropy and provides more consistent mechanical properties across orientations.
- Impact testing highlights that vertical specimens exhibit higher toughness than horizontal specimens, and advanced cooling strategies such as TIAC improve energy absorption capability due to refined microstructure and improved interlayer bonding.
- Microstructural analysis confirms that active cooling promotes grain refinement and transition from columnar to near-equiaxed structures, leading to improved isotropy and mechanical performance. However, spherical gas porosity remains present across all conditions.
- XRD analysis indicates that all samples retain a stable FCC α-Al phase, confirming that cooling strategies do not alter phase composition but significantly influence crystallographic texture and lattice stability.

- Fractographic studies reveal a ductile failure mechanism dominated by micro void coalescence, with process-induced porosity acting as crack initiation sites.
- The developed TIAC and TIAC-BD approaches provide an effective, economical, and scalable solution for mitigating heat accumulation in aluminium WAAM, leading to improved thermal control, geometric accuracy, microstructural uniformity, and mechanical reliability.

The present research successfully demonstrates that effective thermal management through advanced inter-pass cooling strategies, particularly the developed TIAC approach, significantly mitigates heat accumulation in aluminium WAAM, leading to improved geometric accuracy, refined microstructure, reduced anisotropy, and enhanced mechanical performance, thereby establishing a practical and scalable pathway for high-quality industrial application of WAAM.

The study can be further extended and explored as per follows.

- Advanced thermal control and optimization by developing closed-loop temperature control systems using real-time feedback (thermal cameras/IR sensors) to dynamically adjust cooling rate, deposition speed, and arc parameters for precise thermal management.
- The proposed TIAC approach can be extended to complex geometries and multi-axis deposition, where thermal gradients are more challenging, to validate its applicability in real industrial components.
- The effectiveness of the developed cooling strategies can be explored for other aluminium alloys (2xxx, 6xxx, 7xxx series) and multi-material WAAM, to understand material-specific thermal behaviour and compatibility.
- Integration of active cooling with other techniques such as inter-pass rolling, ultrasonic vibration, or low heat-input arc modes (e.g., CMT) can be explored for enhanced microstructural control.
- Study of corrosion behaviour and environmental durability, especially due to water-based cooling and possible hydrogen absorption, is essential for long-term applications.

10. List of all publications arising from the thesis

1. Patel, D. B., & Pujara, A. A. (2026). Influence of active cooling on microstructure and mechanical properties of wire arc additively manufactured 5356 aluminium alloy. Engineering Research Express. https://doi.org/10.1088/2631-8695/AE35E4
2. Patel, D. B., Pujara, A. A., (2025). A review of various heat mitigation techniques in Aluminium alloy fabricated by wire arc additive manufacturing. International Journal of Advanced Research in Science, Engineering and Technology, 12. www.ijarset.com

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