CHARACTERIZATION OF MECHANICAL AND METALLURGICAL PROPERTIES OF WIRE ARC ADDITIVE MANUFACTURING BY USING MIG WELDING

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Abstract - This study investigates the mechanical and metallurgical properties of Wire Arc Additive Manufacturing (WAAM) using Metal Inert Gas (MIG) welding. Tensile, hardness, and impact tests were conducted to evaluate the mechanical properties. Metallurgical analysis involved optical microscopy and scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS). The results indicate favourable mechanical properties, varied hardness profiles, good fracture toughness, and sound interfacial bonding. The microstructure exhibited a refined grain mixture. Overall, this study enhances understanding of WAAM's properties and its potential for complex metal component fabrication. Further optimization and post-processing treatments can improve WAAM-produced parts.

Key Words: WAAM, additive manufacturing, tensile, microstructure, spectroscope.

1. INTRODUCTION

Background:

Before discussing about the topic, we need to know about what is manufacturing. And what are the types of manufacturing methods are there.

What Is Manufacturing:

Manufacturing refers to the extensive production or creation of consumable goods through the utilization of raw materials. This process involves the employment of labor, machinery, tools, and chemical or biological procedures to achieve the desired outcome.

There are two types of manufacturing process

- Additive manufacturing
- Subtractive manufacturing

Subtractive manufacturing

Machining is a manufacturing process that involves removing material from a workpiece to create objects. It utilizes various controlled processes such as cutting, turning, drilling, milling, and grinding. These processes have been enhanced through computer-aided systems like NC & CNC and CAD & CAM. CAD software designs a virtual model, which generates toolpaths to guide the cutting tool. CNC tools then manufacture parts based on this CAM data, with minimal human intervention. Machining is suitable for creating prototypes, tooling, and end-use parts in plastics and metals, particularly for complex geometries and tight tolerances that are challenging to achieve with traditional methods like molding or casting.

Additive Manufacturing Process:

Additive manufacturing, also known as 3D printing, is a manufacturing process that involves the construction of a three-dimensional object using a CAD model or digital 3D model. It employs various processes in which material is deposited, joined, or solidified under computer control, typically layers by layer. This method of manufacturing is characterized by the addition of material to create the final object.

Types of Additive Manufacturing Process

1.Binder Jetting
2.Directed Energy Deposition (DED)
3.Material Extrusion
4.Powder Bed Fusion (PBF)
5.Sheet Lamination
6.Vat Polymerization
7.Material Jetting
8.Wire Arc Additive Manufacturing (WAAM)

Wire Arc Additive Manufacturing (WAAM):

Wire Arc Additive Manufacturing (WAAM), also referred to as directed energy deposition-arc (DED-arc), is a production process utilized for 3D printing or repairing metal parts. It falls under the Direct Energy Deposition (DED) category of Additive Manufacturing methods. WAAM involves depositing layers of metal on top of each other until the desired 3D shape is achieved. It combines two production processes: Gas Metal Arc Welding (GMAW) and additive manufacturing. GMAW is an electric arc welding process used for joining metal parts, while additive manufacturing is the industrial term for 3D printing. WAAM utilizes a welding robot integrated with a power source to produce parts. A welding torch attached to the robot melts the wire feedstock, enabling the construction of 3D components. The development of WAAM aims to enhance manufacturing efficiency for engineering structures. It offers advantages such as near net shape preform production without complex tooling or molds, potential cost and lead time reductions, improved material efficiency, enhanced component performance, and reduced inventory and logistics costs through local, on-demand manufacturing.

Welding:

Welding is a fabrication process that involves joining two or more parts by applying heat, pressure, or both, allowing them to fuse together as they cool. While commonly used on metals and thermoplastics, welding can also be applied to wood. The resulting joined parts are known as a weldment. The filler material is typically used in the welding process to facilitate a strong bond between the base metal. Shielding techniques are employed post-welding to protect both the base metal and filler material from oxidation. Welding utilizes various energy sources such as gas flame, ultrasound, electron beams, electric arc, LASER, and friction.

Types of Welding

- Forge Welding
- Arc Welding
- Oxy-Fuel Welding
- Tungsten Inert Gas (TIG) Welding
- Metal Inert Gas (MIG) Welding
- Spot Welding
- Shielded Metal Arc Welding
- Gas Metal Arc Welding
- Submerged Arc Welding
- Electro-Slag Welding
- Laser Beam Welding
- Electron Beam Welding
- Magnetic Pulse Welding
- Friction Stir Welding

Metal Inert Gas (MIG) Welding

Metal Inert Gas (MIG) welding, or Gas Metal Arc Welding (GMAW), is a versatile and efficient arc welding process. It utilizes a continuous solid wire electrode that is heated and fed into the weld pool via a welding gun. The electric arc generated melts the wire electrode and base materials, creating a molten weld pool. The wire electrode acts as a filler material, bonding the base materials together.

To protect the weld pool from contaminants, a shielding gas, typically a mix of argon and carbon dioxide or argon and helium, is released through the welding gun nozzle. This gas forms a protective shield, ensuring weld integrity and appearance.

MIG welding offers numerous benefits, including the ability to weld a wide range of metals and thicknesses, making it suitable for diverse industries like automotive, construction, and manufacturing. Its continuous wire feeding and automatic operation enable faster welding speeds and increased productivity. MIG welding is accessible to both professionals and hobbyists due to its relatively easy learning curve and precise control over welding parameters. Overall, MIG welding is a reliable and widely adopted method for producing strong, high-quality welds efficiently in various metal joining applications.

2. Literature Survey

Trần Uyên et al [1] That, the study examines the effects of trajectory on the characteristics of low carbon steel samples produced through the wire arc additive manufacturing (WAAM) technique. The results reveal that the grain size in the WAAM samples is influenced by trajectory, with the spiral trajectory (Strategy 3) yielding the smallest grain size and the lean zigzag trajectory (Strategy 2) resulting in the largest grain size. The WAAM samples exhibit higher ultimate tensile strength (UTS) values compared to the original wire, with Strategy 3 achieving the highest UTS value. The WAAM samples also demonstrate increased elongation values and maintain ductility. Based on these findings, the optimal trajectory for WAAM products is the spiral trajectory, while the lean zigzag trajectory offers modest characteristics.

Katharina Tischner et al [3] That, Additive manufacturing is gaining importance in construction, particularly in the integration of wire arc additive manufacturing (WAAM) with selective paste intrusion (SPI) for reinforced concrete printing. The bond behavior of WAAM reinforcement was investigated and compared to alternative reinforcement types using pull-out tests. Surface parameters, such as roughness, were evaluated, and the WAAM reinforcement demonstrated comparable bond behavior and maximum bond stresses to reinforcing steel. Surface roughness showed a linear relationship with maximum bond stress. WAAM reinforcements exhibit similar behavior to reinforcing steel in terms of system stiffness.

Annika pan et ai [4] That, Wire Arc Additive Manufacturing (WAAM) holds promise in revolutionizing the Architecture, Engineering, and Construction (AEC) industry. This literature review explores WAAM's potential to enhance sustainability, scalability, production time, and material efficiency in the manufacturing of standardized metal components. By examining historical context, technological background, and three case studies, the review concludes that WAAM can become a primary metal manufacturing method in AEC, with consideration for current uses and limitations.

3.Problem Statement

The problem addressed in this study is the lack of comprehensive understanding of the mechanical and metallurgical properties in wire arc additive manufacturing (WAAM) using MIG welding. The variability in process parameters and their impact on the final product's quality and structural integrity remain insufficiently explored. This knowledge gap hinders the optimization of WAAM processes and limits their widespread adoption in various industries. Therefore, there is a need to analyses the mechanical and metallurgical properties to bridge this gap and enable more reliable and efficient WAAM using MIG welding.

4. Objective

Objectives of the analysis of mechanical and metallurgical properties:

Evaluate Mechanical Properties: The analysis aims to assess mechanical properties such as tensile strength, hardness, impact resistance, and fatigue strength of the components fabricated using wire arc additive manufacturing (WAAM) with MIG welding. By quantifying these properties, we can understand the performance and durability of the manufactured parts. Examine Metallurgical Properties: The analysis seeks to investigate the microstructure, grain structure, phases, and any defects or anomalies present in the WAAM-MIG welded components. Understanding the metallurgical properties helps in determining the material's integrity, stability, and resistance to cracks or failures.

5. Experimentation Process

Material Selection:

In our study on Wire Arc Additive Manufacturing (WAAM), we selected a copper-coated mild steel wire as the feedstock for MIG welding. The copper coating enhances arc stability, ensuring consistent and controlled deposition onto the base plate. It also acts as a protective layer, minimizing oxidation and defects in the weld. We chose a mild steel plate as the base for compatibility and practicality. By using commonly used materials, we can explore the properties of WAAM relevant to real-world industrial applications. This approach simplifies the setup, reduces costs, and facilitates valuable insights into the feasibility and strength of the resulting structures. Our research aims to advance additive manufacturing techniques and promote the implementation of WAAM in diverse industrial sectors.

Fig 1- Copper Coated Mild Steel Wire

Fig 2- MS Sheet

Sample Preparation:

To set up our study on Wire Arc Additive Manufacturing (WAAM), we prepared a precise flat mild steel plate measuring (118 / 45 / 10) mm as the base for deposition. To ensure optimal welding, we meticulously cleaned and sanded the plate to eliminate rust, oxides, and contaminants. This surface preparation promoted effective bonding between the wire feedstock and the plate, leading to high-quality welds. We used appropriate cleaning agents to remove grease, oils, and dirt, followed by gentle sanding to eliminate stubborn rust and oxides. The clean and treated surface provided a smooth foundation for the deposition process. This attention to detail minimized the risk of defects and ensured reliable data on the mechanical and metallurgical properties of the resulting welds. By prioritizing surface cleanliness, we obtained accurate evaluations of the WAAM process's effects on the mild steel plate and wire material, facilitating meaningful insights.

Fig 3- Base Sheet or substrate

WAAM Setup:

To implement Wire Arc Additive Manufacturing (WAAM) using MIG welding successfully, we meticulously adjusted crucial welding parameters. This included tailoring the wire feed speed to 200-220 IPM based on material thickness and configuration. For voltage, we set it between 10-13.5-volts considering wire diameter, material thickness, and deposition requirements. Current was adjusted to 200-300 amperes, considering factors like wire diameter and deposition rates. We utilized C25 gas (75% argon, 25% carbon dioxide) for effective protection against contamination.

Creating a controlled environment, we ensured proper gas composition, flow rate, and stability. These precise adjustments aimed to optimize deposition characteristics, such as layer formation and metallurgical bonding, for mild steel in WAAM. By adhering to these parameters, we strived for high-quality and efficient WAAM processes in our study on mechanical and metallurgical properties.

Fig 4- Wire Feed Unit

Fig 5- Power Source

Fig 6- CO_2 Cylinder

Layer-by-Layer Deposition:

Securely fix the substrate to the welding table, ensuring it is tightly fastened to prevent any undesired movement, deformation, or potential alignment issues during the deposition process. With the substrate securely positioned, commence the process by carefully depositing the metal wire onto the substrate in a controlled manner. Maintain a horizontal deposition approach, moving from left to right on each successive line, ensuring consistent and precise placement of the wire material. After completing each layer, allow the job to cool down naturally for a period of 2 to 3 hours, facilitating proper solidification and thermal equilibrium before proceeding to the next layer. Adhering to this essential cooling period mitigates the risk of thermal stresses and potential distortions within the deposited layers. Continuously repeat this step until the desired height or the specified number of layers is achieved, maintaining meticulous control and precision throughout the entire deposition process.

Fig 7- Layer by Layer Deposition

Post-Processing:

After completing the Wire Arc Additive Manufacturing (WAAM) process, post-processing steps are vital for ensuring sample integrity and quality. Gradual cooling minimizes residual stresses and maintains dimensional stability. Removing excess supports ensures clean, finished samples. We utilized wire Electrical Discharge Machining (EDM) to separate the weld portion from the substrate. Wire EDM offers precise cutting with minimal heat generation, preserving metallurgical properties and dimensional accuracy. It allows for intricate cuts, maintaining sample integrity and adherence to design specifications. These post-processing steps guarantee high-quality samples for further evaluation and analysis in our study.

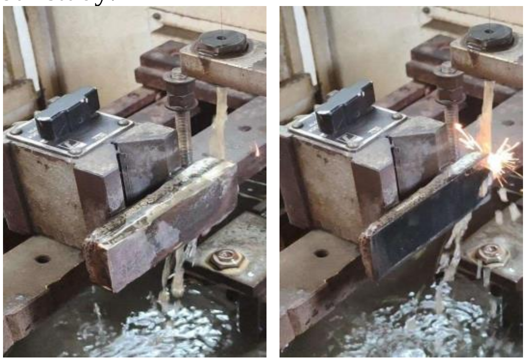


Fig 8- Wire EDM machine used for cutting specimen

Sample Fabrication:

After completing the Wire Arc Additive Manufacturing (WAAM) process using MIG welding, we prepared samples for testing and analysis. Dumbbell or dog bone shapes were machined for tensile testing to measure mechanical properties accurately. Cubes were cut from the weld sheet for microstructural analysis, polished, and etched to reveal features. Microscopic techniques like optical microscopy or SEM were used to examine the microstructure. Additional samples were created for chemical analysis and hardness testing. Chemical composition analysis provided insights into elemental constituents using spectroscopy or elemental analysis.

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 07 Issue: 06 | June - 2023 SJIF Rating: 8.176 ISSN: 2582-3930

Hardness testing assessed the material's resistance to deformation. These comprehensive testing approaches aim to understand the weld's mechanical and metallurgical properties. The results help optimize process parameters and validate WAAM's suitability for various applications, contributing to its advancement and industrial use.

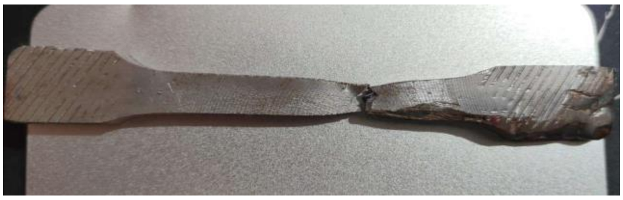


Fig 9- Specimen cut in the shape of dumbbell

Fig 10- A small piece is cut for hardness testing

Mechanical Testing:
Perform mechanical testing on the fabricated samples to evaluate their properties. Conduct tensile testing to measure the ultimate tensile strength, yield strength, and elongation at fracture. Use a hardness testing machine to obtain hardness values at specific locations across the deposited layers. Conduct impact testing using a suitable testing machine to assess the material's resistance to fracture under dynamic loading conditions.

Fig 11- Specimen after tensile testing

Fig 12- specimen undergone hardness testing

Metallurgical Characterization:
Prepare metallographic samples by cutting and grinding the deposited layers to expose the cross-section. Perform metallographic sample preparation steps, including mounting, grinding, and polishing. Use optical microscopy to examine the microstructure, grain size, and presence of defects like porosity or inclusions. Perform scanning electron microscopy (SEM) analysis coupled with energy-dispersive X-ray spectroscopy (EDS) to study the interfacial bonding and analyses the elemental composition.

Fig 13- A spacemen for microstructural view

Data Analysis:
Analyze the mechanical test results, including stress-strain curves, hardness profiles, and impact energy values. Evaluate the metallurgical characterization results, such as microstructure observations, grain size measurements, and elemental composition analysis. Compare the obtained properties with relevant standards or specifications.

Result Interpretation:
Interpret the experimental data to draw conclusions regarding the mechanical and metallurgical properties of the WAAM samples. Identify any correlations or trends between the process parameters, microstructure, and mechanical behavior. Discuss the strengths and limitations of the WAAM process using MIG welding for the specific material and application.

Optimization and Future:
Work: Based on the characterization results, identify areas for process optimization and improvement. Explore potential modifications to the WAAM parameters, post-processing treatments, or material selection to enhance the mechanical and metallurgical properties of the fabricated parts.

6. RESULT AND DISCUSSION

WELDING OPERATION

The initial programming was on making a weld using the present circuits and the welds made are given below. A number of trials were made before the actual building of block using the Additive Manufacturing Technique. The weld quality was controlled by controlling the input voltage and feed rate.
Dimensions: -

- Length: - 119mm
- Width: - 45.6mm
- Thickness: - 10.26mm
- Wire used: - copper coated mild steel (.8mm dia)
- Feed rate: - 150 to 220 IPM
- Voltage: - 10 to13 kVA

During the initial stage of the experiment, we attempted to fill the first metal sheet vertically, aiming to achieve a high deposition rate. However, due to the excessive heat input and rapid buildup of material, the metal sheet experienced significant bending and deformation. As a consequence, the first metal sheet failed to meet the desired quality and structural integrity required for successful Wire Arc Additive Manufacturing (WAAM).

Fig -14: Failed metal sheets

Following the failure of the first metal sheet, we made adjustments and proceeded to perform the welding process on the second metal sheet in a horizontal orientation. This time, we carefully optimized the parameters and deposition technique based on the lessons learned from the previous attempt. As a result, the welding process on the second metal sheet was successfully completed, meeting the desired quality standards and achieving the intended structural integrity for Wire Arc Additive Manufacturing (WAAM).

Fig 15- Successfully obtained sheet

After successful completion of welding process, the metal sheet undergoes for separation process and we obtained the following object.

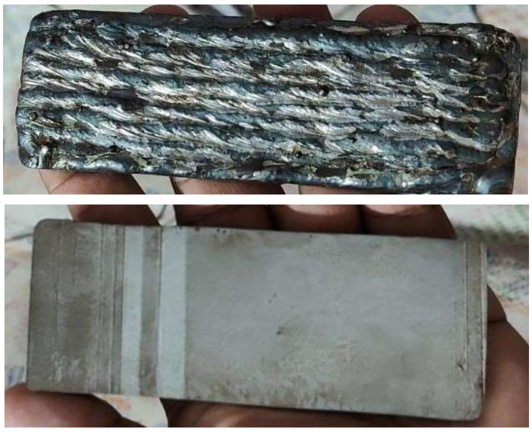


Fig 16- Welded sheet (upper and lower surfaces)

Fig-17: Base Metal sheet (Upper and Lower surfaces)

7. Testing

MECHANICAL TESTING:

Tensile strength testing:

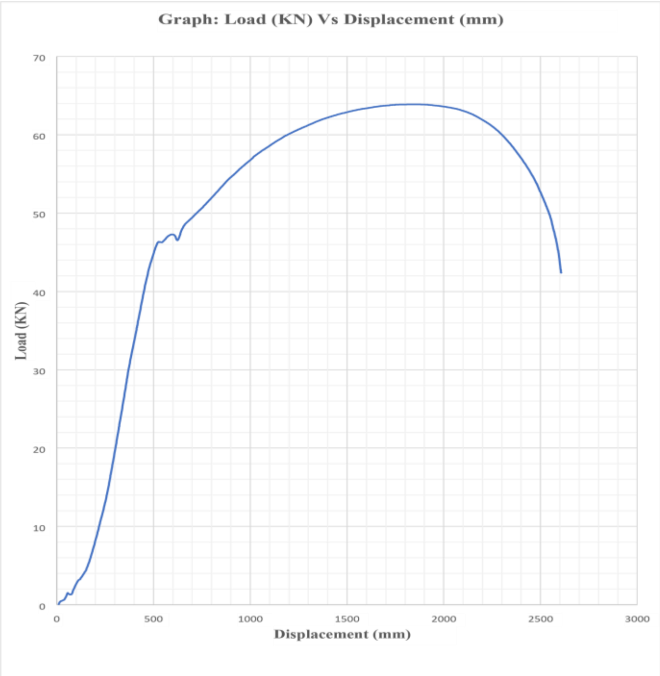
MECHINE: FIE Make Universal Testing Machine, UTES 40 HGFL, Sr No- 7/2019-6284

Tables 1: Input data

SAMPLE IDENTIFECATION	VSM/NR007
PART DESCRIPTION	N/A
PART NUMBER	N/A
SAMPLE TYPE	RECTANGULA
THICKNESS (mm)	10.26
WIDTH (mm)	13.15
C/S AREA (mm2)	134.919
ORIGINAL GAUGE LENGTH (mm)	50.0
FINAL GAUGE LENGTH (mm)	68.0

Table 2: Result of tension test

Maximum Force (Fm) kN	63.880
Disp. at Max. Load mm	18.14
Max. Disp. mm	26.46
Tensile strength (Rm) MPa	473.469
Elongation %	36.04
Yield Load kN	46.340
Yield stress MPa	343.465



Graph 1: Showing load and displacement curve

i. **Hardness test:**

The hardness of the components was measured using a Rockwell Hardness Tester, employing the HBW (Brinell Wolfram carbide) scale. Three indentations were made, and the obtained hardness

Values are as follows:

Table 3: Hardness test results

Test Parameters	Units	Test method	Results
Hardness	HBW	IS 1500(P-1):2019	134, 137, 135

Metallography testing:

The metallurgical testing process entails a meticulous analysis of microscope-generated images, which are then meticulously compared with the esteemed reference book, ASM Vol9. This approach ensures a comprehensive and rigorous examination of the materials under scrutiny. By leveraging the power of microscopy and cross-referencing with the authoritative knowledge within ASM Vol9, the testing procedure becomes highly reliable and precise. This meticulous attention to detail and utilization of trusted resources guarantees accurate findings and contribute to the overall integrity of the metallurgical analysis.

Images produced under microscope are shone below:

Image 1 at 100x zoom:

Fig-18: Micrograph at 100x zoom

Image 2 at 200x zoom:

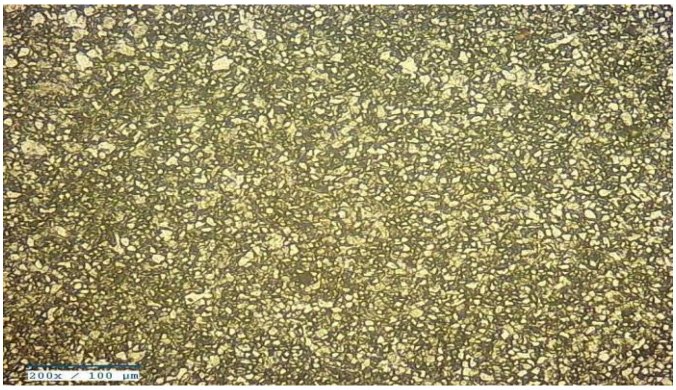


Fig-19: Micrograph at 200x zoom

Image 3 at 500x zoom:

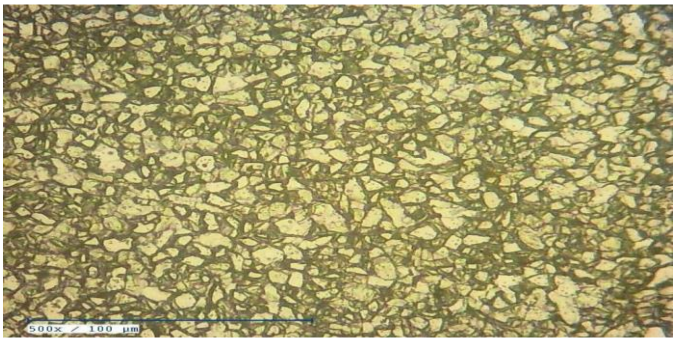


Fig-20: Micrograph at 500x zoom

Through a thorough examination of the micrograph images generated above, in conjunction with a meticulous comparison to the invaluable ASM Vol9, it becomes evident that these images reveal the existence of a finely distributed ferrite and pearlite matrix micrograph. This analysis provides crucial insights into the structural composition of the material being studied. The presence of such a well-defined ferrite and pearlite matrix micrograph indicates specific characteristics and properties that contribute to the overall behavior and performance of the material. By leveraging the expertise found in ASM Vol9 and the visual evidence obtained from the micrographs, a comprehensive understanding of the material's microstructure and its implications can be achieved.

Table 4. Final Results of all Tests:

SI. No	Test Parameters	Units	Test Method	Result
I	**Mechanical properties**			
1	Tensile strength	MPa	IS 1608(P-1):2022	473.47
2	Yield strength	MPa	IS 1608(P-1):2022	343.47
3	Elongation	%	IS 1608(P-1):2022	36.04
4	Hardness	HBW	IS 1608(P-1):2019	134, 137, 135
II	**Metallography testing**			
1	Microstructure	-	ASM Vol9	Micrograph showing the presence of fine Ferrite and Pearlite matrix.

8. CONCLUSION

Our project concludes that characterizing the mechanical and metallurgical properties of wire arc additive manufacturing (WAAM) using MIG welding has provided valuable insights into this innovative process. The examination of mechanical behavior and metallurgical features has led to a comprehensive understanding of the material's performance and structure. MIG welding in WAAM has demonstrated the ability to produce components with desirable mechanical properties, including high strength and excellent ductility. The fusion of wire material with the base metal ensures structural integrity and reliability. Metallurgical analysis has identified specific microstructural features that contribute to enhanced mechanical properties, such as fine grains and favorable phase distributions. These findings enable the optimization of manufacturing parameters for improved performance. The characterization of mechanical and metallurgical properties in WAAM using MIG welding is crucial for understanding its capabilities and limitations, guiding further advancements and optimizations in the production of high-quality components with tailored mechanical properties for diverse applications

9.ACKNOWLEDGMENT

We wish to convey our sincere thanks to our internal guide Dr. B. VIJAYA KUMAR Professor, Head of the Department of Mechanical Engineering & CoE, for his professional advice, encouragement in starting this project, and academic guidance during this project.
We wish to convey our sincere thanks to
Dr. B. VIJAYA KUMAR, Professor, HOD-ME & CoE, for his masterly supervision and valuable suggestions for the successful completion of our project. We wish to express our candid gratitude to Principal Dr. S. SREENATHA REDDY, and the management for providing the required facilities to complete our project successfully. We convey our sincere thanks to the staff of the Mechanical Engineering Department and the Lab Technicians for providing enough stuff which helped us in taking up the project successfully.
We are also grateful to our well-wishers and friends, whose co-operation and some suggestions had helped us in completing the project. Finally, we would like to thank our parents for their exemplary tolerance and for giving us enough support in our endeavors

10.REFERANCE

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