Mechanical and metallurgical study of ER-4043 aluminum alloy using wire arc additive manufacturing

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Abstract— **Additive manufacturing, particularly wire arc additive manufacturing (WAAM), has gained significant attention in recent years as a promising technology for producing complex metal components. This study focuses on the investigation of the mechanical and metallurgical properties of components fabricated from ER-4043 aluminum alloy using WAAM. The research encompasses a comprehensive examination of the microstructure, mechanical performance, and metallurgical characteristics of WAAM-produced ER-4043 aluminum alloy samples. The WAAM process parameters, including wire feed rate, arc voltage, and deposition speed, are systematically optimized to achieve desirable material properties. Microstructural analysis reveals the presence of various phases and grain structures within the WAAM-fabricated ER-4043 aluminum alloy, and the impact of process parameters on these structures is assessed. Mechanical properties such as tensile strength, hardness, and fatigue behavior are investigated to evaluate the performance of the produced components. Furthermore, metallurgical characteristics, including intermetallic formation, porosity, and elemental composition, are thoroughly studied to understand the alloy's behavior during WAAM processing. This investigation sheds light on the effects of process parameters on microstructure and mechanical properties, providing valuable insights for optimizing ER-4043 aluminum alloy fabrication using WAAM. Ultimately, this research contributes to a deeper understanding of the mechanical and metallurgical aspects of ER-4043 aluminum alloy manufactured through WAAM, facilitating its application in various industries such as aerospace, automotive, and marine, where lightweight, high-strength aluminum components are in demand.**

Keywords—**WAAM; Additive Manufacturing; residual stress; distortion; simulation; FEA**

I. INTRODUCTION

The wire arc additive manufacturing (WAAM) process has become a production technology because it is economical to build large metal parts with somewhat high deposition rates. WAAM primarily uses an electric arc as a heat source to melt metal wire and produce three-dimensional metal objects layer by layer, in contrast to powder and other additive manufacturing techniques like laser and electron beam. . This may considerably reduce the fabrication costs. This article reviews WAAM processes and methods and gives an exhaustive overview of the residual stresses, microstructures, and material properties of the as-fabricated and post-fabrication treated WAAM components. Nowadays, WAAM turns into an optimistic manufacturing process for different materials like Titanium, Nickel-based superalloys, steel, and aluminum. Compared with traditional.

The advantages of AM over conventional subtractive manufacturing are numerous (such as CNC machining). First, in a CAD/CAM system, the entire AM process may be automated, from part design through production. By doing this, each new part requires less human interaction and production time. Although the CNC machining program can be generated automatically from CAD models as well, complex geometries require multiple re-fixtures, necessitating time-consuming and costly re-fixture and calibration procedures. Metal additive manufacturing (MAM) is a significant new manufacturing technique used now across the globe. In order to produce the component in a net-near shape, MAM offers aid. Parts for applications in aerospace, automotive, and biomedical engineering are often produced using this technique [1, 2].

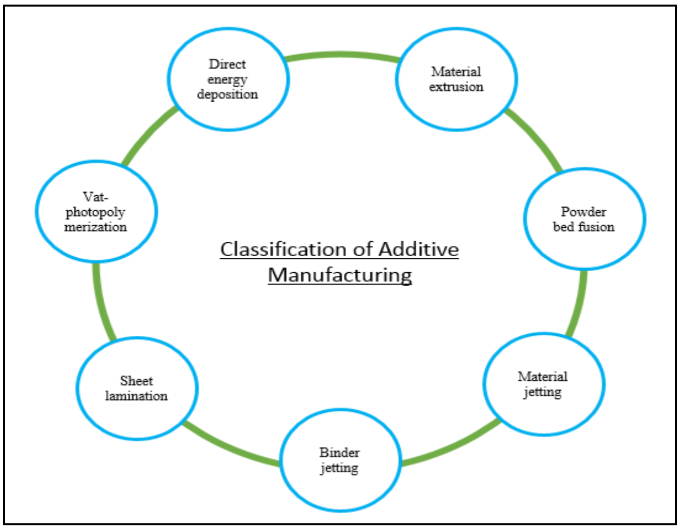


Fig. 1 Various metal AM technologies

II. CLASSIFICATION OF WAAM PROCESS

The WAAM procedures are divided into groups based on the heat source. Three types of WAAM are frequently used: plasma arc, tungsten inert gas (TIG), and metal inert gas (MIG). The deposition rate for the MIG based WAAM method is 2-3 times higher than that of the TIG and Plasma Arc based processes. The various WAAM techniques were outlined. The experimental setup for the WAAM approaches is shown in figure below.

A. Gas Metal Arc Welding (GMAW) Based WAAM

An arc welding procedure is gas metal arc welding. The metal and the consumable electrode form the arc. The GMAW process consists of the movable and rotatable flat work table, and the computer controls the passive visons sensor. The passive vision control sensor controls \sthe movement of a nozzle to the top surface distance. This controller helps to obtain apparent bead deposition. In GMAW based WAAM method. The molten pool overflowed as a result of the layer by layer accumulation of metal. The component develops a flaw as a result of the overflow. Maintaining the ideal travel speed, wire feed, and inclination angle between the workpiece and nozzle will help manage this overflow. In the GMAW process, the deposition rate can be increased by employing a double electrode.

B. Cold Metal Transfer (CMT) Based WAAM

On a modernised GMAW system, the CMT is built. Fronius developed this technology in the year 2004. It is a modified form of the GMAW technology that correlates both the droplet detachment and wire movement, managing the base material's heat. During each short circuit interval, itintervenes in the power input and supervises the filler wire's withdrawal, which results in spatter-free welding with a low heat supply. This process has a high deposition rate and little heat inputFig.4 (a) and (b) show the experimental configuration of CMT-based WAAM equipment (b). The basis of CMT is that while arcing, melted filler travels forwards to the weld pool. When the filler begins to dip inside the weld pool, the arc is put out. The filler wire then begins to move backward, which encourages the droplet to disengage. This inveterate the mechanical kind of transfer that different from the GMAW process.

C. Gas Tungsten Arc Welding (GTAW) Based WAAM

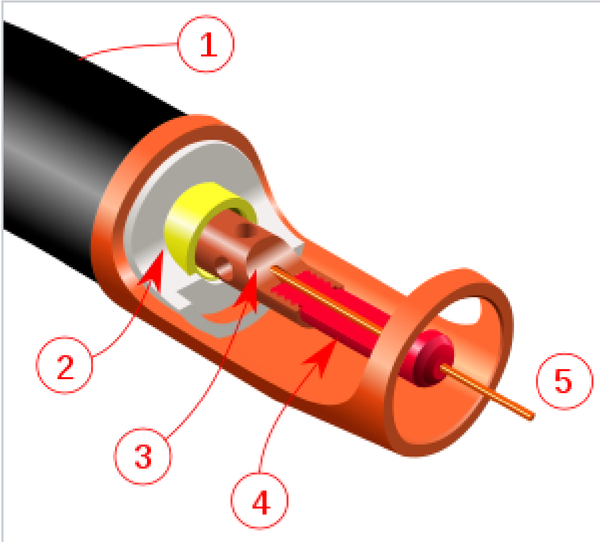
A separate wire feeder is utilized for the deposition in the GTAW arc welding process, which is carried out with a non-consumable tungsten electrode and a TIG torch. The wire feed orientation attributes the deposition process and impacts the bead's material transfer and quality. The filler wire is deposited externally from the side; the deposition's accuracy is not good in GTAW. To increase deposition accuracy, the mathematical model and simulation development must progress. The coaxial feeding of wire during TIG technology increases the rate of deposition and enhances the surface quality of the layersThe main process parameter is the temperature difference between each layer. The difference in the thermal gradient influences the mechanical characteristics and microstructure of the component. The droplet dispassion size and deposition rate have increased with the use of hot-wire GTAW with vibration. However, there was little to no variation in the size and shape of the beads. To create intermetals and functionally graded materials, a double wire feeder additive layer manufacturing system based on GTAW has been established.

D. Plasma Arc Welding (PAW) Based WAAM

PAW is a method of arc welding. In PAW, the electrode and ionised shielding gas workpiece are connected by molten metal wires with an arc acting as a heat vent. Figures 5a–c show a schematic illustration of different WAAM strategies. When compared to parts that are deposited utilising the WAAM-based GMAW process, PAW-produced components have a longer fatigue life. This fact is also connected to PAW's smaller, broader bead geometry, which results in a slower rate of stress start. To forecast the size and shape of the deposited weld bead produced by the PAW process, Bai et al. reported models and experiments. Continuous heat input and wire feeding result in an increase in the deposited bead diameter; an increase in the number of layers results in a drop in layer height. The layer's width and height decreased by 30% from the first layer to the second layer and by 3% from the second layer to the twenty-first layer. The arc energy density in PAW is significantly higher than in GTAW, resulting in less welding distortion and correct weld beads with faster welding.

III. EXPERIMENTAL WORK

A. Performance and Process Parameters Control in WAAM



GMAW torch nozzle cutaway image:

1. Torch handle
2. Molded phenolic dielectric (shown in white) and threaded metal nut insert (yellow)
3. Shielding gas diffuser
4. Contact tip
5. Nozzle output face

Each technique has a different set of process parameters based on how various WAAM processes are categorized. The bead trail on different methods needs to be conducted to obtain a proper process parameter. The WAAM procedure makes use of filler wires and a heat source to create metal components. The filler wires are produced in the welding industry and can be purchased in rolled form. No unique wires need to be created for the WAAM approach. Metals are deposited using WAAM, which combines a wire feeding system and an arc as the heat source. The components are created, and the filler wire from the wire feed system is melted to complete the repair process. The interpass temperature between each layer as the metal part is being deposited is rising. It is because of the development of higher heat deposition. During the fabrication of the metal part, the process parameters are most important in the WAAM technique to obtain defect-free fabricated components. The following are the crucial process variables that must be maintained throughout the deposition process.

- *Effect of Travel Speed (TS) in WAAM*: One important process parameter taken into account during the WAAM process for fabricating metal parts is travel speed. Due to heat conduction, the travel speed and power affect the component during fabrication. By conducting the bead on trial, the travel speed and power are optimized. The increase in travel speed is accelerated by the metal part's surface roughness. Figure6 shows the appearance of bead geometry with different TS and power. Also, the higher TS reduces the height of the deposited bead. Increasing TS causes discontinuous bead geometry and insufficient material deposition in the GMAW process. An intermittent bead geometry forms with a high TS, as shown in Fig.3.

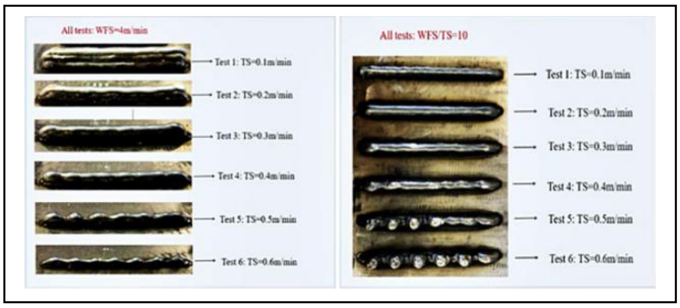


Fig. 3. Single bead deposition with different torch speed.

- *Influence of Wire Feed Speed (WFS) in WAAM*: WFS is one of the crucial process variables taken into account in the creation of the WAAM system. The wire feed rate is the main input parameter; it is a significant parameter on the weld bead width of deposited layers followed by voltage and weld speed. The complicated shapes with the circular and square track were deposited by GTAW based AM process. It demonstrates that a consistent bead deposit may be obtained using a greater wire feeding angel.

- *Effect of Torch Angle and Weld Current During WAAM*: In WAAM, the flame is maintained with its orientation parallel to the path of wall building. Due to the different force model, if the angle varies, the deposit geometry can differ. The experimental findings indicate that the molten metal sags less in the solidification phase with a smaller torch angle—meaning a stronger bead geometry created with a small torch angle between 45˚ to 90˚.

B. Different WAAM Processed Materials

Ni-Based Superalloys

Aluminum Alloys

Titanium Alloys (Ti6Al4V)

Steel [45, 50, 56]

C. FEA Simulation in WAAM Process

FEA simulation of the WAAM process can provide important new insights into the temperature distribution and residual stresses that emerge during the manufacturing of metal components. A substance endures various re-heating and re-cooling cycles while being deposited layer by layer. This transient thermal behavior affects the component's performance. Numerous numerical modelling techniques are addressed in this work. Simufact Welding is designed for modeling and simulation of a wide range of thermal joining processes by means of structural welding simulation including usual arc and beam welding processes as well as brazing. Additionally, Simufact Welding provides possibilities to model heat treatment processes, variations of cooling and unclamping setups as well as mechanical loading of welded structures.

- *Thermo-Mechanical Analysis* Using FEM, the general procedure of thermomechanical analysis is depicted in Figs 4 for simulating temperature distribution and assessing residual stress and distortion. transient thermal analysis was performed to acquire the temperature fields. The material properties of the deposited components can be extracted thanks to this temperature distribution. studied the thermoelastic-plastic model and the nonlinear thermal model for WAAM temperature and stress simulation [3]. The top and bottom layers have been found to have the highest transient stress. From the bottom to the middle layer, the peak temperature was raised until it reached a stable range in the top layers. Because of the reheating and cooling processes that take place when a new layer is being deposited on the top surface, a higher magnitude of residual stress is noticed during this process.

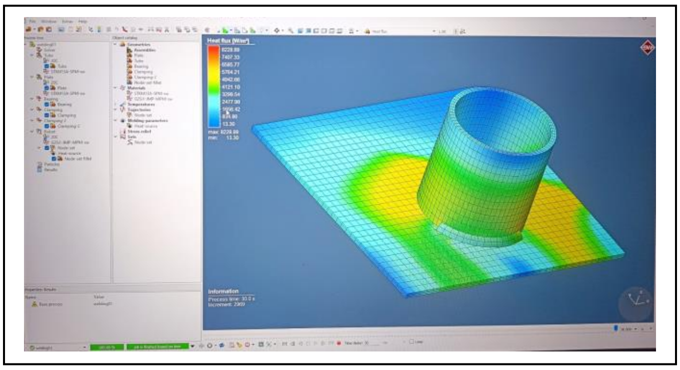


Fig. 4. Thermo-Mechanical Analysis (Heat flux)

D. Residual Stress Measurement Methods in Metal Components

Since residual stresses have a significant impact on the lifespan and functionality of a component, their precise estimation is crucial. Residual stresses are categories on different \scales. i.e., Type I, Type II, and Type III. I developed in several grains where the microlevel stresses in Type were obtained [4].

The Type II and Type III developed in stress measurements were used to get the microscale and nanoscale measurements, which are categorised into destructive, semi-destructive, and non-destructive measurements and are displayed in Fig. with single grains and various atomic distances. stress measurements are classified into destructive, semi destructive, and non-destructive, shown in Fig.5.

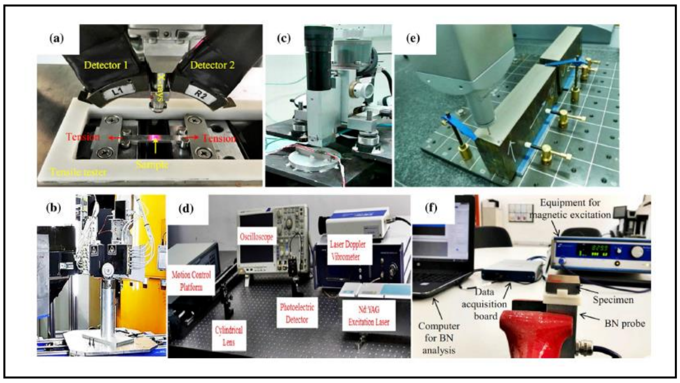


Fig. 5. Digital photographs of residual stress measurement setup: [a] experimental set-up for XRD stress measurements assisted with uniaxial tensile tester, [b] Neutron diffractometer and samples, [c] typical RS measurement setup on MTS 3000-hole drilling machine, [d] laser ultrasonic system, [e] contour measurement after the first cut of the flat specimen, [f] experimental arrangement for the Barkhausen Noise evaluation. Reproduced with permission from Elsevier

E. Post and in Process Treatments

Post-processing treatments are essentially required to improve the material characteristics and manage residual stresses for particular application needs. Metal components use postprocessing treatments to lessen residual stresses and enhance the material behaviour of the deposited metal pieces. They are detailed below in a manner similar to how various post-fabrication methods enhance the strength and material characteristics of superalloys, titanium alloys, and aluminium alloys, respectively. The post-processing techniques have a big impact on how refined grains are. In order to meet the requirements for WAAM parts, the post-fabrication treatments' capabilities are given below [5].

- Heat Treatments
- Work Hardening
- Interpass Rolling
- Interpass Cooling

During welding, the welded materials are exposed to very high temperatures that can cause micro-structural changes in them. Also, residual stresses build up in welded materials when they are allowed to cool naturally. If left unaddressed, these stresses and structural changes can severely compromise the mechanical properties of a material and can lead to failure during use. To prevent this, PWHT is required for welded parts.

F. Residual stresses and distortions

One of the main issues is the control of residual stresses and distortions, particularly for the large-scale WAAM process, since it can lead to early failure in addition to having an impact on part tolerances. Thermally induced strains during the non-uniform expansion and contraction of the material result in thermally induced stresses during welding. A material or structure will respond by warping in response to the produced strain. reported the residual stress and deformation on the fixed-end thin wall. The free end has undergone the most stress and distortion [6]. The updated inherent strain approach, which predicts accurate findings more quickly, was also used to calculate the stress distortion. In the build component, a larger longitudinal stress was noted. After unclamping, a decrease in longitudinal stress was noticed. Due to constraints in the clamped region, the maximum tensile residual stress was reported in the transverse and longitudinal directions, and the

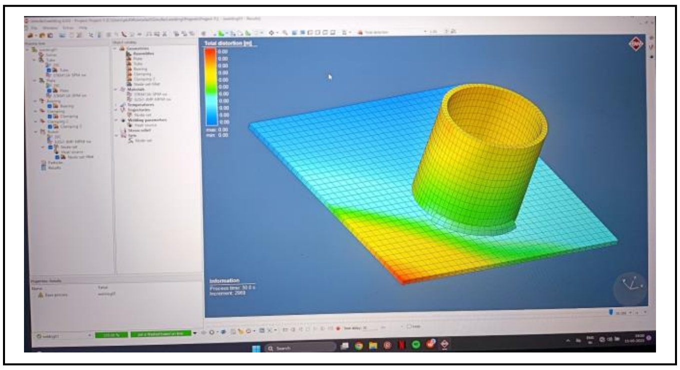


Fig. 6. Total distortion in the model

maximum compressive residual stress was reported in the thickness direction (z) according to the transient and steady-state thermal analysis of clamped and unclamped models. Additionally, by reducing layer thickness and tripling the heat input, stress can be decreased by 30%. The distribution of the simulated residual stresses seen in different directions [7].

IV. Results and Discussion

The fundamental problems in WAAM are relative stresses and deformation caused on by increased heat input. It is also the main concern, especially for a large-scale WAAM method. methods for improving material qualities, ways to lessen residual stresses, and the effects of post-fabrication treatments on component quality. Wire-feed AM is a viable technique for producing larger features with intermediate complexity, such as flanges or reinforced panels, because it has higher deposition rates and better material quality than powder-feed/bed AM technology. To fight the remaining tension and distortion, we apply a range of strategies.

V. Conclusion and Future Scope of Work

A. Conclusion

This article has reviewed recent technological advancements in the WAAM process. Techniques, process parameters, microstructures, and residual stress of the as-fabricated and post-fabrication treated WAAM components are all covered in detail in the WAAM procedures and methods. Additionally, compared to powder-based processes, WAAM is less expensive and can create large-scale metal components. On WAAM parts, rolling can lessen residual stresses and distortions, especially in the vicinity of the baseplate.

B. Future research interests

Research on WAAM of metal components is interdisciplinary and integrates materials science, thermo-mechanical engineering, and process design, as discussed in the current article. Process control and optimization control of residual stresses and distortions require extensive study and greater comprehension. Only a small number of operations have been completed, however interpass rolling on the WAAM component offers superior mechanical qualities to the same degree of wrought alloy. It would be helpful to conduct more research on interpass rolling on WAAM-deposited material. Additionally, for specific application needs, experimental studies on WAAM interpass rolled component residual stress and mechanical behavior comparison to wrought component may be helpful.

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