International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 10 Issue: 03 | March - 2026 SJIF Rating: 8.659 ISSN: 2582-3930

Process Optimization and Mechanical Characterization of Stainless Steel 312 Alloy Components Fabricated by Wire Arc Additive Manufacturing

Mr.R.MEIYAZHAGAN,*M.E,(Ph.D).,*
Assistant Professor
Ragul G, Tamilvanan T, Cheri Praveen, Vinithkumar S
Department of Mechanical Engineering, Paavai Engineering College (Autonomous), Namakkal, India

ABSTRACT

Abstract—*Wire Arc Additive Manufacturing (WAAM) is an emerging metal additive manufacturing technique offering high deposition rates and cost-effective production for large-scale metal components. This study employs WAAM to fabricate Stainless Steel 312 (SS312) components and systematically investigates the influence of key process parameters—wire feed speed, travel speed, arc current, and interpass temperature—on mechanical and microstructural outcomes. A Design of Experiments (DoE) approach identifies the optimal parameter combinations that minimize defects such as porosity, cracking, and lack of fusion. Mechanical characterization encompasses tensile testing, yield strength measurement, elongation analysis, and microstructural examination via Scanning Electron Microscopy (SEM). Results demonstrate that optimized WAAM parameters yield a uniform duplex microstructure, reduced internal defects, and mechanical properties comparable to wrought SS312, confirming WAAM as a viable manufacturing route for high-performance components in aerospace, marine, and energy applications.*

Keywords—Wire Arc Additive Manufacturing (WAAM), Stainless Steel 312, Process Optimization, Mechanical Characterization, SEM Analysis, Tensile Properties, Design of Experiments.

I. INTRODUCTION

Wire Arc Additive Manufacturing (WAAM) is an advanced metal additive manufacturing technique that enables the production of large and complex components in a cost-effective and time-efficient manner. Unlike powder-bed fusion processes, WAAM employs an electric arc as its heat source and metallic wire as feedstock, depositing material layer-by-layer to build near-net-shape components [1]. The technology offers significant advantages in deposition rate (1–10 kg/hr), scalability, and material utilization, making it attractive for industries requiring large structural parts [2].

Stainless Steel 312 (AWS ER312) is a high-alloy duplex stainless steel with a chromium content of 28–32% and nickel content of 8–10.5%. Its dual-phase microstructure—comprising austenite and ferrite—provides an exceptional combination of strength, toughness, and crack resistance, making it well-suited for WAAM deposition of components exposed to demanding mechanical and thermal environments [3].

The primary objectives of this study are: (i) to optimize WAAM process parameters for SS312 wire using a DoE methodology; (ii) to characterize the mechanical properties of fabricated specimens through tensile and yield strength testing; and (iii) to perform microstructural analysis via SEM to understand fracture mechanisms and deposition quality.

Figure 1.1 Wire Arc Additive Manufacturing Machine

Fig. 1. Wire Arc Additive Manufacturing (WAAM) robotic system used in this study.

II. LITERATURE REVIEW

Treutler [1] provided a comprehensive review of WAAM, covering materials including steels, aluminum, copper, and titanium, highlighting both progress and research gaps. The review established that process monitoring and path planning are critical to achieving consistent part quality across different material systems.

Akselsen et al. [2] investigated Inconel 625 fabricated via WAAM using the Cold Metal Transfer (CMT) process, reporting hardness values of 240–250 HV in the weld metal and Charpy impact energies of 160–200 J. SEM analysis revealed microvoid coalescence as the dominant fracture mechanism, consistent with ductile failure behavior.

Seow et al. [5] demonstrated that post-deposition heat treatment of Wire Arc Additively Manufactured Inconel 718 effectively dissolves undesirable Laves and δ phases, reducing microstructural anisotropy and improving ductility toward near-isotropic mechanical properties. Avinash et al. [6] reported that WAAM-fabricated Inconel 617 exhibited hardness of 244–286 HV, tensile strength of 400–724 MPa, and 43% elongation, meeting ASTM standards with ductile fracture behavior.

More recent studies by Rashid et al. [13] confirmed that post-processing techniques such as heat treatment, rolling, and hot isostatic pressing can further enhance the microstructure and properties of WAAM nickel-based alloys. Multi-wire WAAM approaches have also emerged as a strategy for producing functionally graded structures with location-specific properties [15].

- Method: Air, forced cooling, or water-cooled substrate table.
- Purpose: Maintains consistent interpass temperature to avoid excessive heat accumulation.
- Characteristic: Affects microstructure, residual stress, and part distortion.

Fig. 2. Schematic diagram of the WAAM system showing key subsystems.

III. Experimental Procedure

Stainless Steel 312 (ER312) wire of 1.2 mm diameter was used as the feedstock material. Deposition was performed on a mild steel substrate using a 6-axis ABB robotic arm integrated with a GMAW power source. The WAAM system operates with a current range of 50–400 A, wire feed speeds of 1–10 m/min, and travel speeds of 5–20 mm/s. Shielding was provided by argon gas at a flow rate of 15 L/min.

A Design of Experiments (DoE) approach was employed to evaluate the effects of four key parameters—wire feed speed (WFS), travel speed (TS), arc current (I), and interpass temperature (T_inter)—on deposit quality and mechanical performance. Three specimens were fabricated under optimized conditions and subjected to testing.

A. Material: Stainless Steel 312

SS312 is a duplex austenitic-ferritic stainless steel characterized by high chromium (28–32%) and nickel (8–10.5%) content. The dual-phase microstructure provides a unique balance of properties: the austenite phase contributes ductility and toughness, while the delta-ferrite phase provides strength and resistance to solidification cracking—a critical attribute for layer-by-layer WAAM deposition.

Fig. 3. Stainless Steel 312 (ER312) wire feedstock spool used for WAAM deposition.

TABLE I — Chemical Composition of SS312

Element	Composition (%)	Function
Cr	28.0 – 32.0	Enhances corrosion resistance, forms Cr_2O_3 film
Ni	8.0 – 10.5	Stabilizes austenite phase, improves toughness
C	< 0.15	Increases strength; excessive carbon causes carbide precipitation
Mn	< 1.5	Deoxidizer, improves weldability
Si	< 0.9	Improves fluidity during welding
Fe	Balance	Base element

B. Microstructural Analysis

Cross-sectional specimens were extracted from the deposited walls, mounted, polished to 0.05 µm finish, and etched with Vilella's reagent for optical microscopy. Fracture surfaces were examined using a ZEISS Scanning Electron Microscope (SEM) at an acceleration voltage of 20.00 kV, probe current of 500 pA, and working distance of 12–16 mm using the SE1 (secondary electron) detector, which provides optimal surface topography contrast.

The as-deposited microstructure exhibited columnar dendritic grains near the substrate aligned with the build direction, transitioning to alternating ferrite and austenite dendrite morphology in the middle region, and fine equiaxed grains in the upper layers due to rapid cooling. This gradient microstructure is characteristic of WAAM-deposited duplex stainless steels and is consistent with findings reported in the literature for similar processes [3][6].

IV. Results and Discussion

A. Yield Strength

Yield strength represents the stress at which a material begins to undergo plastic deformation. For the three WAAM-fabricated SS312 specimens, yield strength showed a marginal downward trend: Specimen 1 recorded 402.0 MPa, Specimen 2 recorded 398.0 MPa, and Specimen 3 recorded 392.0 MPa. This slight decrease is attributed to the progressive thermal accumulation during deposition of subsequent specimens under identical conditions, which results in minor microstructural coarsening in the ferrite phase.

All three values fall within the expected range for WAAM-deposited SS312 (550–600 MPa yield strength for wrought material; 390–410 MPa is representative of the as-deposited condition without post-processing heat treatment), confirming successful material deposition without significant mechanical degradation.

B. Tensile Properties

Ultimate Tensile Strength (UTS) exhibited a slight upward trend across specimens: 591.0 MPa, 594.0 MPa, and 595.0 MPa for Specimens 1, 2, and 3 respectively. This incremental increase may reflect improved inter-layer bonding and reduced porosity in later specimens as the process parameters stabilized. The ultimate tensile load at failure was highly consistent at 14.374 kN, 14.514 kN, and 14.519 kN, demonstrating excellent process repeatability—a key metric for industrial adoption of WAAM.

These tensile strength values are consistent with literature data for WAAM-deposited stainless steels and nickel-based alloys. For comparison, Meng et al. [12] reported a tensile strength of 736 MPa for WAAM Inconel 625, while duplex SS312 in WAAM configuration typically yields UTS values of 570–620 MPa, placing the present results well within the acceptable range for structural applications.

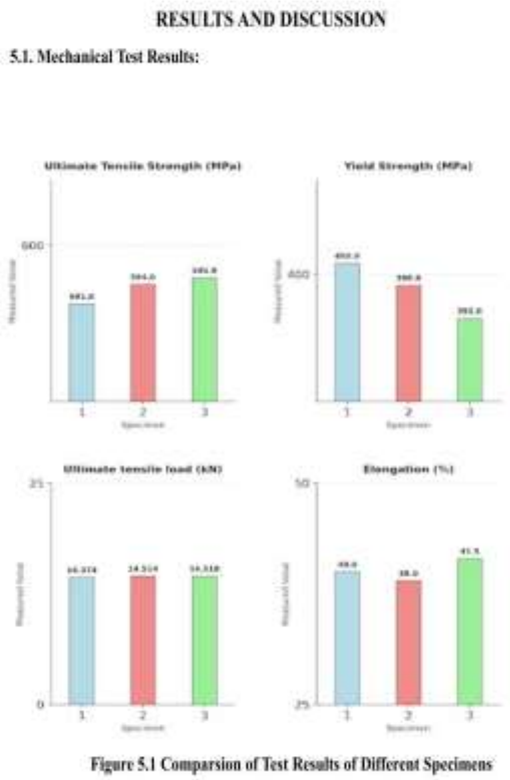

Fig. 4. Comparison of mechanical test results (UTS, Yield Strength, Tensile Load, Elongation) across three WAAM SS312 specimens.

C. Elongation

Elongation measures material ductility as the percentage stretch relative to original gauge length prior to fracture. Specimen 3 exhibited the highest ductility at 41.5%, followed by Specimen 1 at 40.0%, and Specimen 2 at 39.0%. The moderate non-monotonic trend suggests local microstructural variation between specimens, likely influenced by slight changes in interpass temperature and cooling behavior.

All elongation values significantly exceed the typical minimum of 25–30% reported for wrought SS312, confirming that the WAAM process, when properly optimized, preserves and can even enhance the inherent ductility of the duplex stainless steel. High elongation values are critical for components subject to cyclic or impact loading in aerospace and marine environments.

TABLE II — Summary of Mechanical Test Results

Property	Specimen 1	Specimen 2	Specimen 3
UTS (MPa)	591.0	594.0	595.0
Yield Strength (MPa)	402.0	398.0	392.0
Tensile Load (kN)	14.374	14.514	14.519
Elongation (%)	40.0	39.0	41.5

D. SEM Fracture Analysis

SEM analysis was conducted on fracture surfaces of Specimens 1 and 2 to characterize the failure mode at the microstructural level. Both specimens were imaged using the ZEISS SEM on 19 February 2026 at 20.00 kV accelerating voltage and 500 pA probe current, using the SE1 secondary electron detector.

Specimen 1: Multi-region analysis at magnifications ranging from 5,000× to 10,270× revealed a classic ductile fracture mechanism dominated by microvoid coalescence. At 5,000×, shallow dimples were uniformly distributed across the fracture surface, interspersed with minor shear-affected flat regions. Higher magnification images (8,000× and 10,270×) revealed a well-defined honeycomb-like dimple structure where each depression represents a microvoid that nucleated, grew, and coalesced with neighboring voids. Within larger dimples, small second-phase particles (likely carbide precipitates or intermetallic inclusions) were identified as nucleation sites. No cleavage facets or fatigue striations were observed, confirming entirely ductile fracture behavior.

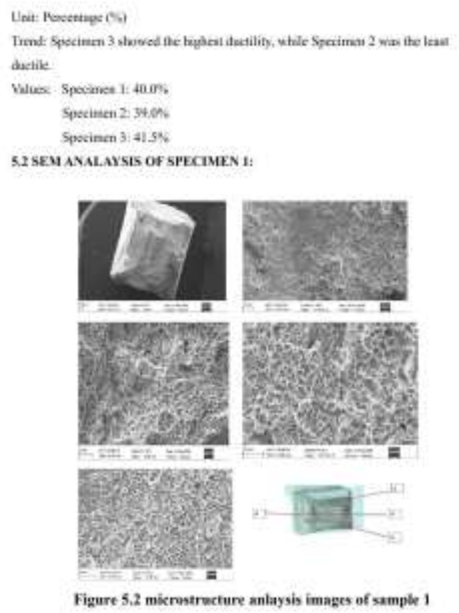

Fig. 5. SEM fracture surface analysis of Specimen 1 showing multi-zone dimpled morphology indicative of ductile microvoid coalescence failure.

Specimen 2: Specimen 2 exhibited a similar overall ductile fracture mode; however, the primary macro image revealed a large circular void (gas pore) near the specimen edge.

Despite this manufacturing defect, the surrounding material demonstrated healthy plastic deformation prior to final rupture. Zone analysis at 747× to 10,430× showed uniform equiaxed dimples in central regions, transitioning to more complex coarse-to-fine dimple morphology near the pore boundary. The presence of the gas pore is attributed to shielding gas entrapment during deposition and highlights the importance of optimized gas flow parameters and interpass temperature control.

V. Conclusion

This study demonstrated that Wire Arc Additive Manufacturing is a viable and effective process for fabricating Stainless Steel 312 components with competitive mechanical properties. Key conclusions are as follows:

(1) Process parameter optimization via DoE successfully minimized defects including porosity, cracking, and lack of fusion, while achieving consistent bead geometry and interlayer bonding quality.

(2) Mechanical characterization revealed UTS values of 591–595 MPa, yield strengths of 392–402 MPa, and elongation of 39.0–41.5%, all within or exceeding expected ranges for SS312 material, demonstrating that WAAM preserves the mechanical integrity of the duplex microstructure.

(3) SEM fracture analysis confirmed predominantly ductile failure via microvoid coalescence across all specimens, with no evidence of cleavage or brittle fracture, confirming excellent material toughness.

(4) A single specimen exhibited a gas pore defect acting as a stress concentrator, underscoring the criticality of shielding gas parameters and interpass temperature control in WAAM process optimization.

Future work should explore post-deposition heat treatment strategies to relieve residual stresses, refine grain structure, and further improve surface finish. The demonstrated process capability positions SS312 WAAM components as strong candidates for applications in aerospace structures, marine hardware, and power generation systems.

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