Investigation On Submerged Arc Welded 9%Cr 1%Mo (Grade 91) Steel

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***Abstract*—The present study investigates the mechanical, metallurgical, and microstructural characteristics of Submerged Arc Welded (SAW) 9Cr–1Mo (Grade 91/P91) steel, widely used in high-temperature and high-pressure applications such as power plants. Welding of P91 steel poses significant challenges due to its high hardenability and susceptibility to heat-affected zone (HAZ) degradation and cracking. In this work, SAW was performed on 20 mm thick P91 plates using Thermanit MTS-3 filler wire under controlled thermal conditions. The welded specimens were evaluated through chemical, mechanical, and microstructural analyses. Mechanical characterization included tensile, impact, hardness, and elevated temperature tensile testing. Microstructural evaluation was conducted using optical microscopy and SEM. The results revealed uniform hardness distribution without excessive hard zones, satisfactory tensile properties with fracture occurring in the base metal, and good high-temperature performance. However, impact toughness showed significant variation, particularly low values in the weld metal region. The study concludes that while SAW welded P91 joints exhibit adequate strength and high-temperature performance, optimization of post-weld heat treatment is necessary to improve toughness and ensure reliability in critical applications.**

***Index Terms*—P91 steel, Submerged Arc Welding, Heat Affected Zone, Mechanical Properties, Microstructure, High-temperature performance**

I. INTRODUCTION

P91 steel (9Cr–1Mo–V–Nb) is extensively used in thermal power plants due to its excellent creep strength, oxidation resistance, and thermal stability. These properties make it suitable for components operating at elevated temperatures (500–650°C) and high pressures.

However, welding of P91 steel is challenging due to:
- Formation of untempered martensite
- Susceptibility to hydrogen-induced cracking
- Heat-affected zone (HAZ) softening and Type IV failure

Submerged Arc Welding (SAW) is widely used for thick-section welding due to its high deposition rate and automation capability. Despite its advantages, strict control of welding parameters and post-weld heat treatment (PWHT) is essential to maintain the desired tempered martensitic microstructure.

This study aims to evaluate the effect of SAW on:
- Mechanical properties
- Microstructural evolution
- Structural integrity of P91 weldments

II. LITERATURE REVIEW

Satish Kumar et al (2022) This study explores the enhancement of mechanical properties of modified 9Cr–1Mo steel through the development of a bainitic microstructure via austempering. The steel was first austenitized at 1000 °C for 1 hour, followed by isothermal holding at 460 °C for varying durations, after which two cooling routes were applied: water quenching (Set-I) and air cooling (Set-II). Microstructural characterization using optical microscopy and SEM confirmed the successful formation of bainite. The heat-treated specimens exhibited significant improvements in mechanical performance, with Vickers hardness increasing to approximately 1.5–2 times that of the as-received tempered martensitic steel. Tensile strength dramatically increased from around 700 MPa to nearly 1300 MPa after austempering, while only a slight reduction in elongation was observed, maintaining reasonable ductility. Overall, the study demonstrates that controlled austempering treatment effectively transforms the microstructure and provides an excellent combination of high strength and adequate ductility in modified 9Cr–1Mo steel.

Tomotaka Hatakeyama et al (2023) This study investigates the influence of laser powder bed fusion (LPBF) parameters on the microstructure evolution of modified 9Cr–1Mo steel and its subsequent response to normalizing and tempering heat treatments using EBSD analysis. An optimal energy density range of 100–150 J/mm³ was identified for fabrication, producing an as-built microstructure consisting mainly of coarse columnar δ-ferrite and fine martensite, with a small amount of retained γ phase at their interfaces. δ-ferrite formed due to rapid solidification, while martensite developed within the heat-affected zones during LPBF. Higher energy density and a 67°-layer rotation scan strategy increased the martensite fraction, whereas a 90° rotation promoted strong <001> texture along the build and scan directions. Tempering reduced hardness through martensite recovery and enhanced M23C6 carbide precipitation, while normalizing eliminated the typical as-built morphology and produced a refined lath martensitic structure. In-situ EBSD observations revealed that martensite transformed into finer prior austenite grains compared to δ-ferrite, indicating that a higher initial martensite fraction Favors finer and more equiaxed prior austenite grain formation. Overall, the study demonstrates that LPBF processing parameters significantly affect both the as-built microstructure and subsequent heat-treatment responses of modified 9Cr–1Mo steel.

A.B. Zala et al 2022) This study evaluates the effect of aluminide coating on the weldability, microstructure, and mechanical properties of 9Cr–1Mo steel intended for fusion reactor blanket module applications. Since aluminium from the coating can adversely influence weld metallurgy, conventional TIG welding with a V-groove design was employed to mitigate coating-related effects. Comparative analysis between aluminide-coated and uncoated steel revealed the presence of undissolved alumina inclusions near the weld fusion line in coated specimens; however, defect-free weld joints were successfully produced. Mechanical testing showed that the tensile strength of coated weld joints (648 ± 16 MPa) was comparable to uncoated welds (667 ± 14 MPa) and base metal (643 ± 18 MPa). Impact toughness evaluated at 0 °C, −25 °C, and room temperature also met acceptable limits (~45 J), indicating no significant degradation due to coating. Microstructural characterization using microscopy, EDS, and XRD confirmed that the coating had minimal detrimental influence on overall joint performance. Overall, the study demonstrates that with appropriate joint design and welding practice, aluminide-coated 9Cr–1Mo steel can achieve satisfactory mechanical properties comparable to uncoated steel.

Previous studies have highlighted the importance of microstructure in determining the performance of P91 steel welds.

- Austempering improves strength significantly by forming bainitic structures.
- Welding processes such as GTAW and SMAW show strong dependence on PWHT for toughness improvement.
- Type IV cracking in HAZ is identified as the most common failure mode.
- Modified PWHT techniques enhance creep life and microstructural uniformity.
- Additive manufacturing and advanced welding methods influence martensite formation and carbide precipitation.

These studies emphasize that microstructural control and heat treatment are critical for ensuring weld performance.

III. EXPERIMENTAL METHODOLOGY

Basic understanding of Welding.
Literature review
Material selection
Submerged Arc Welding of Plates
Microstructural Characterization
Hardness Testing
Impact Testing
Tensile Testing

Analysis and interpretation of results obtained from above tests.

IV. WELDING PROCESS AND PARAMETERS

Submerged Arc Welding (SAW) of 20 mm thick P91 (9Cr-1Mo-V-Nb) steel plate using Thermanit MTS 3 filler wire requires strict control of heat input and thermal cycles to maintain mechanical properties. The joint was typically prepared with a single or double V-groove and welded using multi-pass technique under DC electrode positive polarity, maintaining a preheat temperature of 200–250 °C and interpass temperature between 200–300 °C to prevent hydrogen-induced cracking and excessive hardness. A basic low-hydrogen flux is used in the SAW process, and welding parameters were selected to ensure adequate penetration without overheating the heat-affected zone. Proper inspection and mechanical testing such as hardness, tensile, and impact tests are performed to confirm that the weld meets the required standards for high-temperature service applications.

V. RESULTS AND DISCUSSION

1. VICKERS HARDNESS TEST

The test is based on the principle that when a standard load is applied through a diamond indenter onto a material surface, it produces a square-shaped indentation

Base Metal (BM)
Recorded values (HV10):
200, 210, 206, 212, 213, 212, 212, 216

- Range: 200 – 216 HV
- Average: ≈ 210 HV

Heat Affected Zone (HAZ)
Recorded values (HV10):
244, 256, 258, 249, 204, 221, 207, 212

- Range: 204 – 258 HV
- Average: ≈ 231 HV

Weld Metal (WM)
Recorded values (HV10):
234, 243, 259, 246, 237, 246, 259, 253

- Range: 234 – 259 HV
- Average: ≈ 247 HV

2. TENSILE TEST

SAW welded joint evaluated for their mechanical characteristics through transverse tensile testing. A tensile test done to determine tensile properties such as tensile strength, yield strength, percentage of elongation, and percentage of reduction in area and modulus of elasticity. The welding parameters were randomly chosen within the range available in the machine. The joint was made with random parameters and evaluate tensile strength and burn off. Then the joint was made and evaluated the mechanical and metallurgical characteristics. The Submerged Arc welded specimens were prepared as per the ASTM standards. The test was carried out in a Universal Testing Machine (UTM) 600 KN (Servo hydraulic Universal Testing Machine) make.

RESULTS OBTAINED ON TENSILE TEST

Property	Value
Upper Yield Strength (ReH)	551 MPa
Lower Yield Strength (ReL)	529 MPa
Ultimate Tensile Strength (UTS)	662 MPa
% Elongation	30.72 %
% Reduction in Area	72.58 %
Fracture Location	Base Metal

3. IMPACT TEST

The Impact Test is used to determine the toughness of a material that is, its ability to absorb energy and resist fracture under sudden or shock loading. Unlike tensile testing (slow loading), impact testing measures behaviour under high strain rate conditions.

TOUGHNESS VALUES OF IMPACT TEST

Location	Specimen	Impact Energy (J)
Weld Metal	W1	7 J
Weld Metal	W2	5 J
HAZ	H1	153 J
HAZ	H2	8 J
Base Metal	B1	118 J
Base Metal	B2	90 J

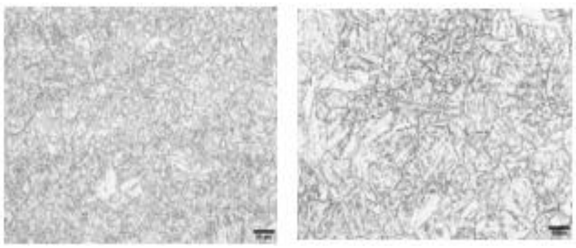
4. HOT TENSILE TEST

The Hot Tensile Test is performed to determine the mechanical properties of materials at elevated temperatures. It is especially important for materials used in high-temperature environments such as boilers, turbines, and power plant components (e.g., P91 steel)

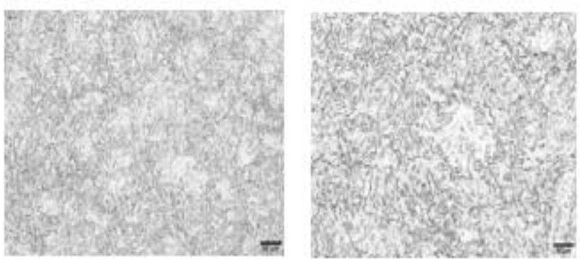
RESULTS OBTAINED ON HOT TENSILE TEST

Temperature	Yield Strength (MPa)	Tensile Strength (MPa)	% Elongation	% Reduction in Area
550 °C	355	380	16	83
600 °C	279	303	15	90

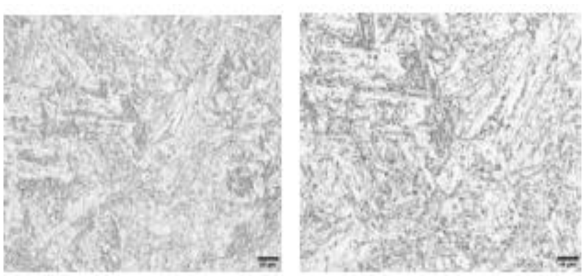
5. ANALYSIS OF MICROSTRUCTURES



MICROSTRUCTURES OF BASE METAL (P91) (500x & 1000x)



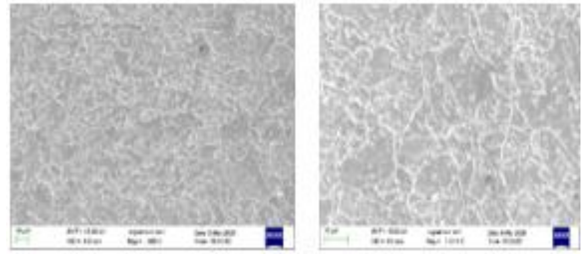
MICROSTRUCTURES OF HAZ (500x & 1000x)



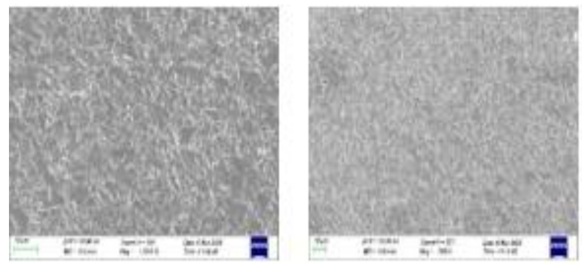
MICROSTRUCTURES OF WELD METAL (500x & 1000x)

Base Metal: Tempered martensite
HAZ: Mixed microstructure (coarse + fine grains)
Weld Metal: Martensitic structure
Observations:
Grain refinement in some regions
Evidence of martensite formation
Microstructural heterogeneity in HAZ

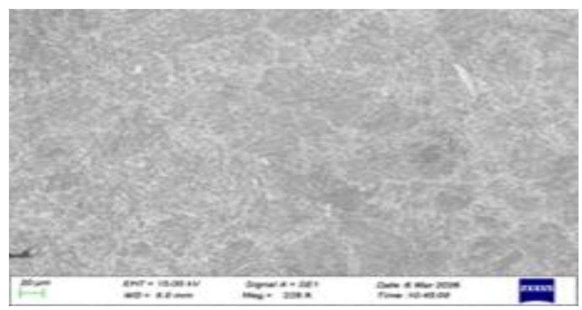
6. ANALYSIA OF SEM



SEM IMAGE OF BASE METAL (500x & 1000x)



SEM IMAGE OF WELD METAL (500x & 1000x)



SEM IMAGE OF HAZ

Grain Structure: Compared to your "Base Metal" image, the grains here appear more irregular and "fragmented." You can still see the tempered martensite laths, but the Prior Austenite Grain Boundaries (PAGBs) were less uniform.
Phase Transformation: This region likely reached temperatures just below or near the Ac_1 or Ac_3 critical points during welding. This causes partial or full transformation of the original martensitic structure, often resulting in a "Fine-Grained HAZ" (FGHAZ).

VI. CONCLUSION

The investigation confirmed that Submerged Arc Welding is a suitable welding process for Grade 91 (9Cr–1Mo) steel, producing weld joints with high strength, acceptable hardness, and stable high-temperature performance. However, careful control of welding parameters and proper post-weld heat treatment are essential to improve impact toughness and minimized microstructural inconsistencies, particularly in the weld metal and heat affected zone.

Overall, the SAW welded P91 steel joint demonstrates good mechanical integrity and suitable for high-temperature applications, such as power plant piping, boilers, and pressure vessel components, provided appropriate heat treatment and quality control procedures were followed.

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