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Submerged Arc Welding Procedure For 5Cr-0.5Mo Steel For Low Temperature Application

Special Edition Presented at ASME 2026 by
Precision Equipments (Chennai) Private Limited, Chennai, India

ABSTRACT

The development and qualification of welding procedures for Cr–Mo pressure vessel steels require careful control of weld metal composition and microstructure to ensure adequate toughness at sub-zero service temperatures. Submerged Arc Welding (SAW) is widely employed in heavy-section fabrication due to its high deposition rate, deep penetration capability, and consistent weld quality. In a heat exchanger application, the design specified a minimum shell-side temperature of –15 °C and a maximum operating temperature of 380 °C, thereby imposing stringent low-temperature impact toughness requirements on both base material and weld metal.

SA387 Grade 5 steel was selected for shell construction primarily due to its established creep resistance and suitability for elevated-temperature service. However, achieving adequate low-temperature toughness at the design temperature of –15 °C posed a significant technical challenge, particularly for the weld metal produced using low-alloy SAW consumables of EB6 classification. Published data on the impact toughness of Cr–Mo weld metal at temperatures below 0 °C are limited, and the application of such consumables in sub-zero environments is relatively uncommon, raising concerns regarding weld metal integrity and fracture resistance.

This work describes the development and qualification of a SAW procedure for 5Cr–0.5Mo steel using EB6 consumables, with emphasis on achieving the specified –15 °C Charpy V-notch impact performance. The engineering approach included consumable selection based on chemistry matching, optimization of welding parameters and heat input, controlled fabrication of procedure qualification test coupons, and comprehensive mechanical testing. The qualified welds demonstrated compliance with the required –15 °C impact toughness criteria. Subsequent implementation in production welding confirmed repeatability and robustness of the developed procedure.

The study establishes that EB6-type SAW consumables can be successfully applied to 5Cr–0.5Mo steel for sub-zero service when appropriate welding procedures and controls are adopted, providing a validated solution for low-temperature pressure vessel fabrication.

Keywords: *5Cr-0.5Mo steels, SAW, EB-6, Pressure Vessels*

1. INTRODUCTION

The selection of suitable materials for petrochemical pressure vessels is a critical aspect of design and fabrication, particularly for applications involving high temperatures, high pressures, and aggressive service environments. Materials operating under such conditions must possess high mechanical strength, resistance to creep deformation, and microstructural stability during prolonged thermal exposure. In addition, adequate resistance to corrosion and hydrogen-related degradation mechanisms is essential to ensure long-term reliability and safe operation of pressure equipment.

Chromium–molybdenum (Cr–Mo) alloy steels are widely used in petrochemical and refining industries due to their excellent high-temperature strength and metallurgical stability. Among these, SA387 Grade 5 (SA387 Gr.5) is extensively employed in the fabrication of pressure vessels, reactors, and heat exchangers operating at elevated temperatures. This alloy steel typically contains approximately 5% chromium and 0.5% molybdenum, which significantly enhance its mechanical properties and environmental resistance. Chromium improves oxidation resistance and provides protection against corrosive environments encountered in hydrocarbon processing and sulfur-containing atmospheres. Molybdenum enhances creep strength and resistance to high-temperature deformation, enabling the material to perform reliably under long-term service conditions typically ranging between 400°C and 600°C.

In addition to its high-temperature strength, SA387 Gr.5 exhibits good resistance to high-temperature hydrogen attack (HTHA), which is a critical concern in hydrogen-rich refining environments. Exposure to high temperature and hydrogen can lead to decarburization and methane formation within the steel microstructure, resulting in internal fissuring and loss of mechanical strength. Cr–Mo steels such as SA387 Gr.5 offer improved resistance to such degradation mechanisms due to the stabilizing influence of chromium and molybdenum on carbide phases [1,2].

From a fabrication standpoint, SA387 Gr.5 demonstrates acceptable weldability when appropriate welding procedures are followed. Controlled preheating, suitable interpass temperature control, and proper post weld heat treatment (PWHT) are essential to reduce cracking susceptibility and achieve the required microstructural stability in welded joints. The material is standardized under the ASME Boiler and Pressure Vessel Code, which specifies requirements for chemical composition, mechanical properties, and heat treatment to ensure consistent performance in pressure vessel applications [3].

Despite these advantages, achieving the required impact toughness in welded joints remains a significant challenge, particularly when employing high-productivity welding processes such as Submerged Arc Welding (SAW).

SAW is widely used in heavy fabrication due to its high deposition rates, deep penetration capability, and excellent productivity. However, the relatively high heat input associated with this process can adversely influence the toughness of both the weld metal and the heat-affected zone (HAZ).

One of the primary metallurgical concerns in SAW of Cr–Mo steels such as SA387 Gr.5 is the formation of coarse-grained microstructures in the HAZ resulting from prolonged thermal cycles. Coarse grain formation reduces resistance to brittle fracture and can significantly lower impact toughness. Furthermore, high heat input may promote the formation of undesirable microstructures such as bainite or martensite, depending on the cooling conditions, which may further degrade toughness properties [4].

The selection of welding consumables and flux composition also plays a crucial role in determining weld metal toughness. In SAW, flux composition significantly influences oxygen content and inclusion morphology in the weld metal. Improper flux–wire combinations may lead to higher oxygen levels and the formation of coarse inclusions, thereby reducing notch toughness. Therefore, controlling oxygen levels, impurity content, and alloy recovery is essential to achieve the desired weld metal properties [5].

Residual stresses and the effectiveness of post weld heat treatment (PWHT) further influence the final mechanical properties of welded joints. Inadequate PWHT may result in incomplete stress relief and insufficient tempering of hard microstructures, while excessive heat treatment may lead to over-tempering and strength reduction. Consequently, careful control of PWHT parameters is required to obtain a balanced combination of strength and toughness.

In addition, welding parameters such as heat input, interpass temperature, and travel speed must be carefully controlled to achieve the required mechanical properties. Achieving consistent toughness across thick sections remains challenging due to variations in cooling rates through the plate thickness.

This study focuses on the application of SA387 Gr.5 in petrochemical pressure vessels, with particular emphasis on the challenges associated with Submerged Arc Welding in achieving the required toughness properties. The work further examines the metallurgical factors affecting weld metal and HAZ toughness and discusses strategies for optimizing welding procedures for critical high-temperature service conditions.

2. MATERIALS AND METHODS

The welding experiments were carried out on SA387 Gr.5 Cl.2 plates of dimensions 1000 mm × 350 mm × 50 mm thickness using the Submerged Arc Welding (SAW) process. The objective was to evaluate the welding procedure and ensure that the welded joints met the required metallurgical and mechanical property requirements for high-temperature petrochemical service.

2.1 BASE MATERIAL AND JOINT PREPARATION

The base material used in this study was SA387 Gr.5 Cl.2 Cr–Mo alloy steel. The plates were prepared with a double V groove joint configuration to reduce weld metal volume and achieve balanced residual stresses during welding.

The groove angle on the first side was maintained at 60°, with a root face of 1.5 mm and a root gap of 2 mm. The groove depth on the first side was 30 mm. After completion of welding on the first side, back gouging was carried out to a depth of 26 mm to ensure complete penetration and removal of any potential root defects.

Prior to welding, the groove surfaces were thoroughly cleaned to remove contaminants such as oil, rust, scale, and moisture in order to prevent welding defects and ensure sound weld quality. Refer Fig.2 for the procedure qualification weld coupon

2.2 WELDING CONSUMABLES AND PREHEATING

Welding was performed using an EB6 electrode wire of 3 mm diameter in combination with F8P2 basic agglomerated flux. The flux was baked prior to use in accordance with recommended practice to remove absorbed moisture and minimize the risk of hydrogen-induced cracking.

Preheating was uniformly applied to the joint area at 200°C using controlled heating methods. The temperature was continuously monitored throughout the welding process to ensure uniform heat distribution. During welding, the interpass temperature was maintained below 300°C to prevent excessive grain growth and maintain desirable metallurgical characteristics in the weld and heat-affected zone.

2.3 WELDING PROCEDURE AND PARAMETERS

The welding was performed using direct current electrode positive (DCEP) polarity. Multi-pass welding was adopted to fill the groove, consisting of root, fill, and capping passes. The welding parameters were maintained within the following ranges:

Current: 450–480 A
Voltage: 30–32 V
Travel Speed: 440–460 mm/min
Heat Input: ~2.09 kJ/mm

Careful slag removal and surface cleaning were carried out between passes to prevent slag inclusions and ensure proper fusion between layers. After completion of welding on the first side, back gouging was performed by grinding to remove any potential slag inclusions or unfused regions. The second side welding was then carried out using the same welding parameters and procedure to ensure consistency and uniform weld quality.

2.4 POST HEATING AND INSPECTION

Immediately after welding, post heating was performed at 350°C for a soaking period of 120 minutes. This step was carried out to facilitate hydrogen diffusion and reduce the risk of hydrogen-induced cracking. Prior to post-weld heat treatment (PWHT), the welded joint was subjected to a series of non destructive examinations (NDE) to verify weld quality.

Visual Examination (VT): To assess weld bead profile and identify visible surface defects such as cracks, undercuts, or overlaps as per ASME Sec IX.

Liquid Penetrant Testing (LPT): To detect surface-breaking discontinuities that may not be visible during visual inspection as per ASME Sec V with acceptance as per ASME Sec IX.

Radiographic Testing (RT): To evaluate internal weld integrity and identify volumetric defects such as porosity, slag inclusions, or lack of fusion as per ASME Sec V with acceptance as per ASME Sec IX

Only after satisfactory acceptance of these inspections was the welded joint approved for further heat treatment.

2.5 POST WELD HEAT TREATMENT (PWHT)

Post-weld heat treatment was performed in the temperature range of 710–730°C with a holding time of 540 minutes. Controlled heating and cooling rates were maintained throughout the heat treatment cycle to relieve residual stresses and temper the weld and heat-affected zone microstructures.

2.6 MECHANICAL AND METALLURGICAL TESTING

Following PWHT, the welded joint was subjected to a series of mechanical and metallurgical evaluations to assess weld quality and performance.

The tests carried out included:

Impact Toughness Testing
Hardness Measurement
Macro Examination
Microstructural Examination

These evaluations were conducted to verify that the welded joint met the required mechanical property and metallurgical criteria for high-temperature petrochemical service applications.

3. RESULTS AND DISCUSSION

The welded joints produced using the Submerged Arc Welding (SAW) process were subjected to a series of mechanical and metallurgical evaluations in order to assess the effectiveness of the developed welding procedure. The results obtained from tensile testing, bend testing, impact toughness testing, hardness measurements, and macro examination are discussed below.

3.1 TENSILE TEST

The tensile test results obtained from the welded joint of SA387 Gr.5 Cl.2 demonstrate that the developed welding procedure is capable of producing welds with mechanical properties comparable to the base material as shown in Table. 1. The ultimate tensile strength values recorded for the two specimens were 580.69 MPa (TT1) and 547.31 MPa (TT2). Both values fall within the specified tensile strength range for the base material, which is 515–690 MPa.

In both specimens, failure occurred in the base metal region with ductile fracture characteristics, rather than in the weld metal or heat-affected zone. This indicates that the weld metal and HAZ possess strength equal to or greater than that of the parent material. These results confirm that the welding procedure satisfies the Procedure Qualification Record (PQR) tensile property requirements.

3.2 SIDE BEND TEST

The side bend test results further validate the integrity and ductility of the welded joint. All four specimens (SB1–SB4) successfully passed the test without exhibiting any open discontinuities after bending.

The absence of surface-breaking defects such as cracks or tearing indicates good ductility and proper fusion throughout the weld cross-section. The results also confirm the absence of internal defects such as lack of penetration, lack of fusion, or slag inclusions, demonstrating the effectiveness of the welding parameters and joint preparation used in the study.

3.3 IMPACT TOUGHNESS TEST

Impact toughness testing was carried out at –15°C in order to evaluate the resistance of the weldment to brittle fracture under low-temperature service conditions as shown in Table. 2

The acceptance requirement of a minimum average value of 54 J was satisfied in all tested regions, including the weld metal and heat-affected zones. The weld metal exhibited average impact toughness values of 101 J at the top weld location and 120 J at the 3/4t location, both significantly higher than the minimum specified requirement.

Even higher toughness values were observed in the HAZ regions, with average values of 254.6 J and 267.33 J at different notch locations. The corresponding lateral expansion values and percentage shear fracture indicate predominantly ductile fracture behavior, confirming strong resistance to brittle failure even under sub-zero conditions as shown in Table. 3

To simulate actual production conditions, Production Test Coupon (PTC) testing was also conducted. The coupon was subjected to the minimum PWHT cycle of 120 minutes at 710 730°C, representing the actual job condition. To evaluate the metallurgical stability of the weldment under prolonged thermal exposure, the coupon was further subjected to an extended PWHT cycle of 360 minutes, equivalent to three times the job holding duration. Refer Table 4 and Table 5 for the toughness results.

The results indicate that the weld metal and HAZ maintained excellent toughness even after the extended PWHT cycle. Average toughness values ranged between 173–186 J, demonstrating that the weldment retained its toughness after prolonged tempering exposure.

The consistency of toughness values in both PQR and PTC results highlights the robustness of the developed welding procedure. The low-temperature impact properties obtained in the present study are strongly influenced by the metallurgical behavior of 5Cr–0.5Mo steel during the SAW process. The use of basic agglomerated F8P2 flux played a significant role in controlling weld metal oxygen content and inclusion morphology, thereby contributing to improved notch toughness. Controlled heat input (~2.09 kJ/mm) and interpass temperature helped minimize excessive grain coarsening in the heat-affected zone and promoted the formation of tempered bainitic microstructures with improved toughness characteristics. This performance can be attributed to Controlled heat input during welding, Proper weld bead sequencing resulting in effective tempering of previous passes, Strict control of interpass temperature and Accurate execution of PWHT within the specified temperature range

These factors collectively contribute to maintaining a refined microstructure and achieving stable toughness properties suitable for sub-zero service environments.

3.4 HARDNESS TEST

Hardness measurements were performed in accordance with NACE MR0175 requirements to evaluate the susceptibility of the weldment to hydrogen-induced cracking and sulfide stress cracking.

The results indicate that hardness values across all regions— including base metal, weld metal, and heat-affected zones—are well below the maximum allowable limit of 235 HV10 specified for sour service applications as shown in Table 6.

The measured hardness values were approximately:

Base metal: 161–175 HV10
HAZ: 168–177 HV10
Weld metal: 188–196 HV10

These values indicate that the welding procedure and PWHT cycle successfully produced a tempered microstructure with controlled hardness, thereby reducing susceptibility to hydrogen assisted cracking mechanisms.

3.5 MACRO EXAMINATION

Macro examination was conducted to evaluate weld penetration, fusion characteristics, and overall weld quality. The polished specimen was etched using 50% nitric acid, followed by examination under a stereo microscope at 10× magnification.

The macrostructure revealed complete fusion between the weld metal and base metal across the joint interface (Fig.2). No welding defects such as lack of fusion, porosity, or slag inclusions were observed in the examined section. The weld bead profile and fusion boundaries were found to be uniform, confirming the soundness of the welding procedure and proper control of welding parameters.

3.6 OVERALL ASSESSMENT OF THE WELDING PROCEDURE

The combined results from mechanical testing and metallurgical examination demonstrate that the SAW welding procedure using EB6 electrode and F8P2 flux produces high quality weld joints in SA387 Gr.5 Cl.2 plates.

The weldments exhibited:

Adequate tensile strength exceeding base metal requirements
Excellent ductility and weld integrity confirmed by bend tests
High impact toughness at sub-zero temperatures
Hardness values compliant with NACE MR0175 requirements
Defect-free weld structure confirmed by macro examination

These results confirm that the developed Procedure Qualification Record (PQR) meets all applicable acceptance criteria and is suitable for high-temperature pressure vessel applications, including service environments involving sour conditions and hydrogen exposure.

TABLE 1: TENSILE STRENGTH OF THE WELD

Identification	UTS (MPa)	Type of fracture & location
TT1	580.69	Ductile at Base metal
TT2	547.31	Ductile at Base metal

TABLE 2: TOUGHNESS OF THE WELD (-15 DEG C)

Notch Location	Joules	Avg Joules
Top SAW weld	92, 100, 112	101
3/4T SAW weld	120, 116, 124	120
SAW HAZ - 1/4T to 1/2T	248, 280, 236	254
SAW HAZ Fusion line +2mm	230, 288, 284	267

TABLE 3: LATERL EXPANSION (-15 DEG C).

Notch Location	Lateral Expansion	% Shear
Top SAW weld	0.96, 1.24, 1,52	65, 67, 69
3/4T SAW weld	1.41, 1.17, 1.41	69, 67, 69
SAW HAZ - 1/4T to 1/2T	2.27, 2.42, 2.58	67, 69, 69
SAW HAZ Fusion line +2mm	2.52, 2.87, 2.73	63, 69, 72

TABLE 4: TOUGHNESS OF THE WELD (-15 DEG C) PWHT CYCLE: 710–730°C X 120 MINUTES

Notch Location	Joules	Avg Joules
Top SAW weld	162,168, 154	161
3/4T SAW weld	160,148, 162	156
SAW HAZ - 1/4T to 1/2T	180, 186, 182	182
SAW HAZ Fusion line +2mm	180,180, 186	182

TABLE 5: TOUGHNESS OF THE WELD (-15 DEG C) PWHT CYCLE: 710–730°C X 360 MINUTES

Notch Location	Joules	Avg Joules
Top SAW weld	172, 168, 178	173
3/4T SAW weld	182, 180, 186	182
SAW HAZ - 1/4T to 1/2T	186, 188, 186	186
SAW HAZ Fusion line +2mm	188, 186, 182	185

TABLE 6: HARDNESS TEST AS PER MR0175 - HV10

Location	Hardness (HV10)
Base metal	165, 163, 161, 166
HAZ - Right	171,172,169, 170, 175
Weldmetal	193, 192, 195, 196, 188, 190
HAZ - Left	175, 173, 172, 170, 176, 177



Figure 1 ProcedureQualification Test Coupon

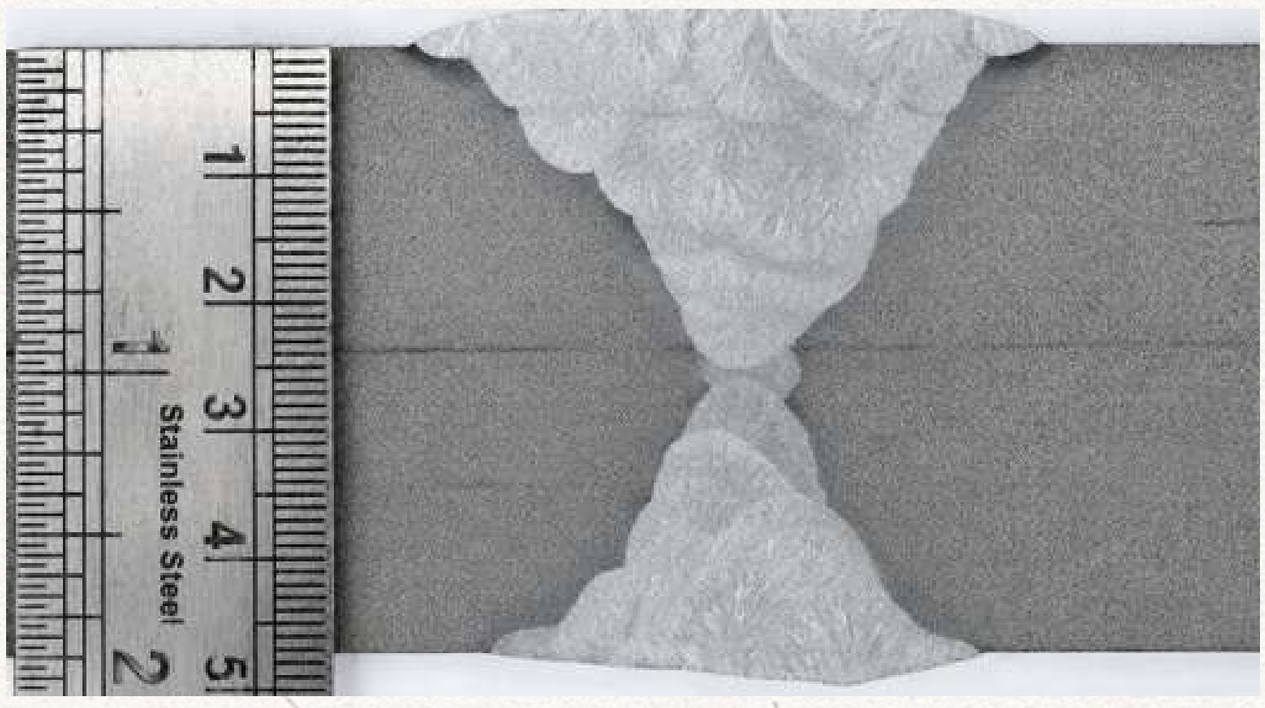


Figure 2 Macro Examination of 5Cr-0.5Mo steel weld

4. EXECUTION ASPECTS

All necessary precautions during welding execution were carefully followed to ensure the production of high-quality weld joints. Proper joint preparation with accurate groove geometry and thorough cleaning of groove surfaces was carried out prior to welding to prevent contamination and welding defects. Uniform preheating was applied and continuously monitored to maintain the specified temperature, while interpass temperature was strictly controlled to avoid excessive grain growth in the heat-affected zone. Welding parameters such as current, voltage, travel speed, and heat input were maintained within the qualified limits, and proper slag removal was ensured between passes.

Additionally, correct bead placement and sequencing were followed to facilitate effective tempering of previously deposited weld runs. Post heating and subsequent PWHT were also performed under controlled conditions, ensuring the development of stable microstructure. Refer Fig.3 and Fig.4.



Figure 3 Vessel manufactured with 5Cr-0.5Mo steel



Figure 4 SAW welding in Progress

5. CONCLUSION

This study demonstrates the successful qualification of SA387 Gr.5 Cl.2 welds using EB6 consumables through the SAW process for –15 °C service conditions. The welded joints satisfied all mechanical property requirements, with tensile failure occurring in the base metal and impact toughness values significantly exceeding the minimum requirement. Consistent toughness was maintained even after extended PWHT at 710 730 °C, confirming good metallurgical stability. Controlled heat input, interpass temperature, and proper bead sequencing ensured refined microstructure and acceptable hardness within NACE MR0175 limits. Overall, the developed welding procedure is suitable for reliable application in high-temperature petrochemical pressure vessel service.

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