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Experimental Study of Oil and Gas Pressure Vessel Welding Using The Shielded Metal Arc Welding Process

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ABSTRACT - Oil and gas pressure vessels operating at a pressure of 100 psi or higher generally use base materials with a minimum tensile strength of 400 N/mm². The fabrication of these vessels using welding methods must ensure that the weld joint achieves a minimum tensile strength equal to or greater than 400 N/mm² while maintaining good ductility. Experimental study is conducted to evaluate the effectiveness of the Shielded Metal Arc Welding (SMAW) process in meeting these requirements. The investigation aims to determine whether the selected welding parameters could produce weld joints with the necessary tensile strength and ductility. The base metal material specification used is SA 36 with a thickness of 8 mm. The weld joint uses a single V groove type, and the filler metal specification for the SMAW process is A5.1 with an AWS E7018 classification and a wire diameter of 3.2 mm. The welding machine is set with a current range of 90 A - 170 A and a voltage range of 16 volts - 25 volts. A total of six welding specimens were prepared for mechanical testing. Acceptance criteria for the test results are based on ASME Section IX standards. The tensile test results for two weld specimens showed ultimate tensile strengths of 495.98 N/mm² and 497.41 N/mm2. The root and face bend test results showed no open defects exceeding the criteria set by the ASME IX standard. The hardness test results show relatively uniform values. The microscopy examination showed a grain profile predominantly composed of ferrite structures. Based on these results, the SMAW process, when applied with the selected parameters, proves to be a suitable method for welding oil and gas pressure vessels.

Keywords: welding, pressure vessel, ASME, tension test.

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INTRODUCTION

Indonesia is a member of the G20, highlighting the significant impact of its Gross Domestic Product (GDP) on global economic growth. The country's economic growth target is heavily influenced by the development of industries, including the energy sector, which plays an important role in meeting the national energy needs. As an archipelago nation with densely populated regions, ensuring a stable supply of petroleum products is very important (Maizar 2010). To meet fuel demand, the Indonesian government, through PT Pertamina (Persero), has established the Refinery Development Master Plan (RDMP), which will increase the oil refinery capacity from the current 1 million barrels per day to 1.425 million barrels per day.

The oil refinery development project must meet installation and equipment feasibility aspects to ensure operational safety. The selection of materials for onshore natural gas refinery facilities is focused on using materials that can be manufactured by domestic industries (Djoko 2019). One of the mechanical constructions in the refinery development project is the design and fabrication of pressure vessels. An important aspect of the design and fabrication phase of pressure vessels is welding, which is one of the most widely used methods of metal joining (American Welding Society 2015).

The standard referenced in the design and qualification testing of welding procedures for pressure vessels used in the oil and gas industry is ASME Section IX. The design and qualification of welding procedures are essential steps to ensure that the welding quality meets the required standards (Singh 2020). Indah (2020) conducted an investigation on the application of welding procedure specifications (WPS) for ships. In this study, a weld quality test was carried out using the bending test method. The specimen used was a 3500 LTDW HN 309 tanker steel plate welded according to a WPS using a 300° bevel. The test results showed the highest load on specimen number 2 (root) at 3.42 kN, while the lowest load was found on specimen number 1 (face) at 3.07 kN. Visual inspection of the bending test results showed no open welding defects on the surface.

Satish (2016), conducted a study on the specification of welding procedures concerning the ASME Section IX standard. Qualification of the WPS was carried out by experimenting with welding the IS2062 Gr steel plate. B with a thickness of 16 mm, the dimensions of the specimen were made with dimensions of 150 x 300 mm. Two specimens are required for the tensile test, while four specimens are needed for the bending test. The welding process used is SMAW with electrode specifications using E7018. The diameter of the wire used is 3.15 mm and 4 mm current type and DCEP polarity. Current range 100 – 180 Ampere voltage range 22-28 volts. The tensile test results include 472 MPa, showing that the value is above the minimum value required by the ASME standard.

Sachin (2022), conducted experimental study on the qualification of the girth weld welding procedure on S355 tubular steel material with a diameter of 219.1 mm and a thickness of 8.18 mm. In this experiment, Sachin made 3 different distances on the weld toes of 5,10, and 15 mm, respectively. Each distance uses 2 different welding procedures. Mechanical tests on specimens were carried out according to the NORSOK M-101 standard. Although the results of the mechanical testing met the minimum criteria for the strength of the welds. The results of the Charpy, hardness, and microstructure morphology tests show different values.

Brecken (2016), conducted a qualification for steel plate welding procedures with ASTM A 36 specifications using the GTAW and GMAW welding processes. The standard referenced in the testing process is AWS B1.1. One of the tests carried out is a tensile test and a bending test. The tensile test specimen has dimensions of 16 inches long by 2 inches wide and 0.38 inches thick. The bending test specimen uses dimensions of 16 inches long, 1.5 inches wide, and 0.38 inches thick. A buckling test was performed on 4 specimens to check that the welds were completely fused. The results of the bending test showed that no open defects were found on the surface of the weld specimen. Tensile tests were carried out on 2 specimens to ensure that the mechanical strength of the welds met the required values. The results of the tensile test showed that the values for both specimens were 66.2 and 65.65 ksi. This value shows above the minimum value of the tensile strength of the A36 material of 55.1 ksi.

Anna (2018), conducted a welding experiment using the specifications of the welding procedure applied to 5 (five) different factories. Ana observed the quality of the welds at 5 different factories. Although all five factories followed the same WPS, the welding results did not consistently ensure the same quality. Qualified WPS do not guarantee the same output.

Zhan (2016), conducted a qualification study of welding procedures based on the GBT25343.3-2010 standard using the SMAW welding process on steel plates that meet Q345R specifications. The test results show that the welding of the Q345R material produces good weld quality. These materials can be applied using SMAW, MIG, and SAW welding processes. The thickness of the Q345R steel plate is less than 30 mm, and no post-weld heat treatment (PWHT) is required.

Sirin (2016), studied the effect of the chemical composition of the welding wire on the mechanical properties of the pipe welded using the SAW welding process. In this experiment, the siring used two steel pipes that meet the API-X65 specifications which have different chemical compositions. Welding wire uses approximately 4 pieces with different chemical compositions. Therefore, this study aimed to analyze the effect of using different chemical compositions on the mechanical properties of API-X65 pipe welds. The types of tests carried out include the hardness test, Charpy test, and tension test. The results of the weld toughness test are below the base metal and HAZ. Welding wire containing Mn, B, and Ti will increase the value of weld toughness. The mechanical properties of welds vary depending on the type of welding wire used. This underscores the importance of selecting the appropriate welding wire composition to achieve optimal weld mechanical properties.

Bharwadj (2022) conducted welding procedure qualification, and the welding procedure qualification record (WPQR) was carried out on S355 grade tubular pipe girth welds, with weld toe proximity distances of 5 mm, 10 mm, and 15 mm. Two different welding processes were used, following a pre-qualified WPS. The WPQR was conducted in compliance with NORSOK M-101, which adheres to the EN 15,614–2017 standard, and all necessary mechanical tests were performed. Although all mechanical test results satisfied the minimum requirements specified in the NORSOK code, the study results showed a significant variation in Charpy impact and hardness values in the proximity region between adjacent welds.

WPS design

The design of a WPS depends on the standard referenced. Several standards regulate the design techniques for WPS, including ASME Section IX, AWS D1.1, API 1104, and others. ASME Section IX is used as a reference for designing WPS for pressure vessels. The requirements for designing WPS are outlined in Article II of ASME Section IX.

The design criteria that must be defined according to ASME Section IX standards include welding process, joints, base metal, filler metal, positions, preheat, PWHT, electrical characteristics, and technique. Defining these design criteria assists designers in selecting variables to be applied to the WPS document. Additionally, selecting the appropriate welding process is important to ensure it suits field conditions.

Pressure vessels are fabricated as process equipment in oil and gas refineries. In general, the selection of the welding process for pressure vessels depends on the specifications of the process equipment used in oil and gas refineries. The use of Shielded Metal Arc Welding (SMAW) for pressure vessel welding offers several advantages, including practicality and cost-effectiveness. The WPS for pressure vessels using the SMAW process, designed with various welding parameters, must be validated to ensure that the weld quality meets standard requirements. A WPS that has not undergone testing/validation is referred to as a pre-welding Procedure Specification (pre-WPS) document.

Testing of welded specimens

Testing of welded specimens based on ASME IX standards primarily includes mechanical testing using the tensile test method, which provides quantitative results. In addition to tensile testing, bend testing is also performed to qualitatively assess the weld ductility. Other tests, such as hardness, toughness, macro, and micro tests, may be included as supplementary. In various applications, supplementary tests are classified as additional requirements.

The provisions regarding specimens and tensile test procedures refer to paragraphs QW151 and QW152 of the ASME IX standard, while the acceptance criteria for tensile test results are based on paragraph QW153. A tensile test specimen is considered to have passed if the tensile strength value of the specimen, based on the test results, is not less than the minimum specified tensile strength of the base metal.

The guidelines for specimens and bend test methods are outlined in paragraphs QW161 and QW162 of the ASME IX standard, with the acceptance criteria for bend test outcomes outlined in paragraph QW163. A bend test specimen is deemed successful if there is no open discontinuity in the weld or heat-affected zone greater than 3 mm, measured from any point on the convex surface after the test.

METHODOLOGY

Design and qualification of welding procedures

The design and Qualification of welding procedures follow these stages:

The design of welding procedures follows the following design criteria:

Welded joints

The welded joint used for qualifying welding procedures is a single bevel V groove with a root spacing of 2-4 mm, and the weld angle is 60^o. This connection is not equipped with backing material, as shown in Figure 2. The welding of the plate specimen is carried out in stages, forming 4 layers with an interpass temperature of 250°C, as shown in Figure 3.

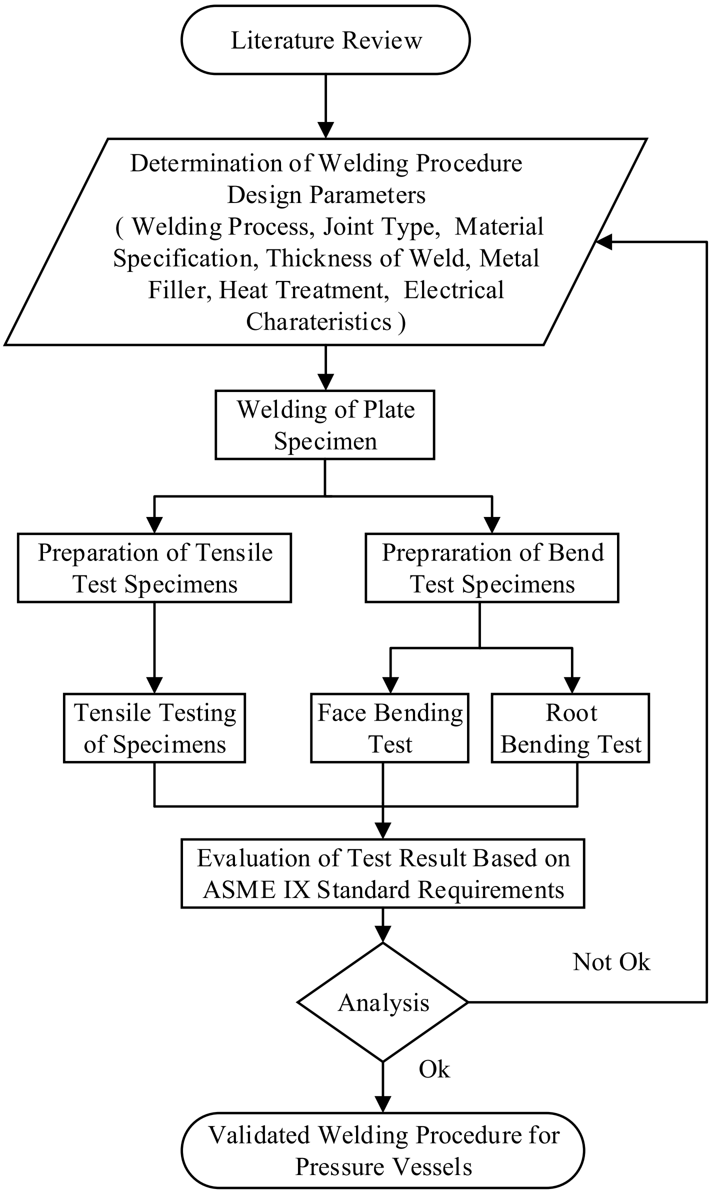


Figure 1. Flow chart of experiment

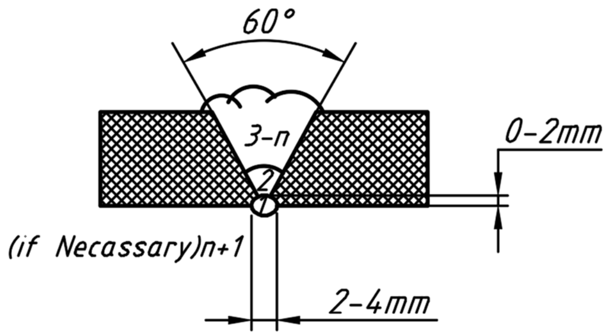


Figure 2. Example of a welded connection 1 (Bhardwaj et al. 2022)

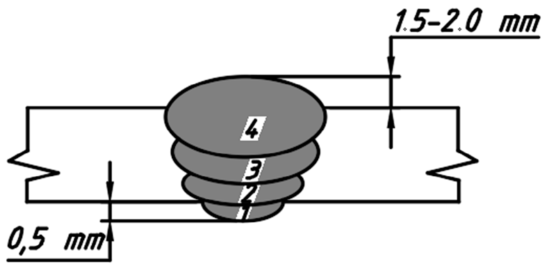


Figure 3. Example of a welded connection 2 (Bhardwaj et al. 2022)

Metal base

The base metal in this design uses SA36 material specification with a thickness of 8 mm. This material specification is included in the material category P number 1 Group number 1. The qualification range for base metal thickness is 5 - 16 mm.

Metal fillers

Welding procedure qualification using SMAW processes with filler metal data as follows:

SMAW process

Specification number A5.1, AWS Class number E7018, F number 4, A number 1, diameter 3.2 mm.

Welding position

Welding positions are designed to apply to flat positions. In the specimen preparation stage, a flat position during welding is carried out.

Heat treatment

Heat treatment consists of preheating. Preheat temperature applies at a minimum temperature of 30°C with an interpass temperature of 250°C. On the planned base metal thickness, PWHT is not carried out.

Electrical characteristics.

The electrical characteristics of each welding process follow the following quantities in Table 1.

Technique

The welding technique on the plate specimen uses a combination method, with the stringer technique applied at the root and the weave bead

Table 1. Electrical characteristics (Satish et al. 2016)

Welding Parameters										
Specimen No.	Weld Pass	Weld Process	Filler Metal		Current			Travel Speed (mm/min)	Heat Input (KJ/mm)	Preheat/ Interpass temp (°C)
			Class	Size (mm)	Polarity	Ampere Range (A)	Voltage Range (V)			
P1	1	SMAW	E7018	3.2	DC-EP	90-170	16-25	70-140	1.04-3.24	250
	2	SMAW	E7018	3.2	DC-EP	90-170	16-25	70-140	1.04-3.24	250
	3	SMAW	E7018	3.2	DC-EP	90-170	16-25	70-140	1.04-3.24	250
	4	SMAW	E7018	3.2	DC-EP	90-170	16-25	70-140	1.04-3.24	250

technique used during the fill and cap passes.

After establishing the welding design parameters, the next step is to apply the welding process based on these parameters on a plate specimen measuring 250 mm x 300 mm. Once the welding on the plate specimen is complete, the specimen is cut according to the illustration shown in Figure 4 for testing.

Testing of welded specimens

Testing of the welded specimens follows the requirements specified in ASME Section IX. A total of six (6) welded specimens must be tested, with the breakdown as follows: 2 specimens for tensile testing, two specimens for face bend testing, and two specimens for root bend testing. The preparation of test specimens in this experiment is done in accordance with the ASME IX standard requirements

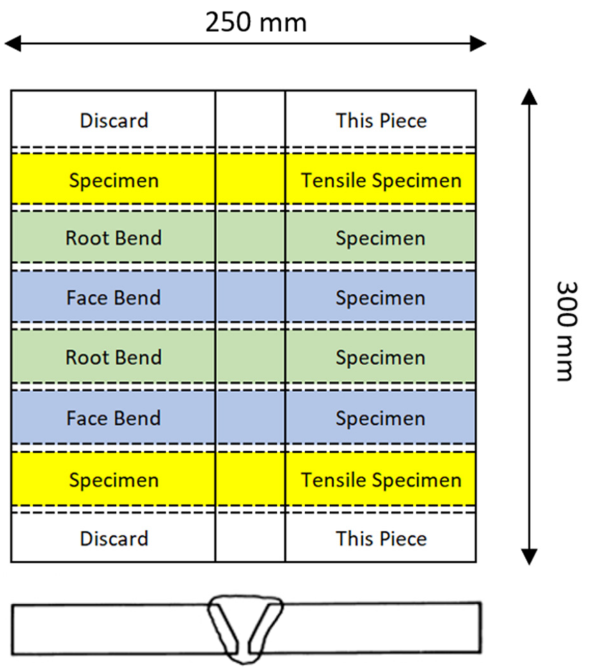


Figure 4. Sectioning of welded base material for test specimen preparation (ASME 2019)

and follows the specified cuts.

The dimensions of the test specimens for bend testing are in accordance with the ASME IX standard requirements and follow Figure 5.

The dimensions of the test specimens for tensile testing follow the ASME IX standard requirements and follow Figure 6.

Tensile test specimens must be taken only from the designated section, as showed in Figure 4. After this section is cut from the plate specimen, the specimen is then shaped according to the dimensions and diagram as shown in Figure 6.

In addition to conducting tensile and bend tests as required by ASME IX to verify the quality of welds, hardness testing, and microstructure testing were also performed. The hardness test was conducted using the Brinell method to determine the hardness in the base metal, heat-affected zone, and weld metal. The microstructure test was carried out to examine the microstructure of the welded area. The

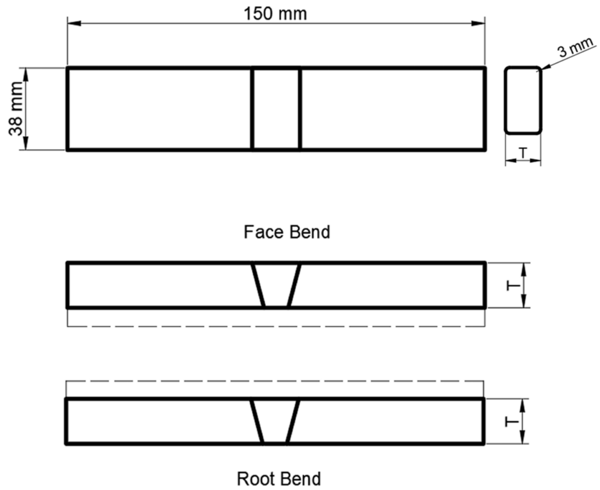


Figure 5
Bend test specimen

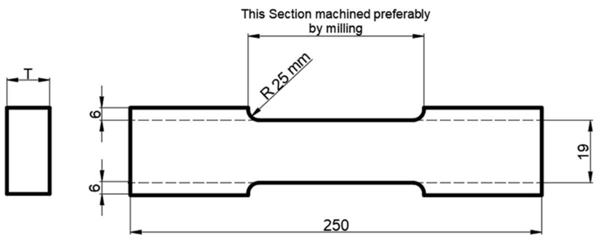


Figure 6. Tensile test specimen (ASME 2019)

microstructure test was performed at a magnification of 100x, 200x, and 400x.

RESULT AND DISCUSSION

The welding application on the plate specimen was carried out based on the design parameters established, as explained in experimental methodology section. The welding results visually appear satisfac-

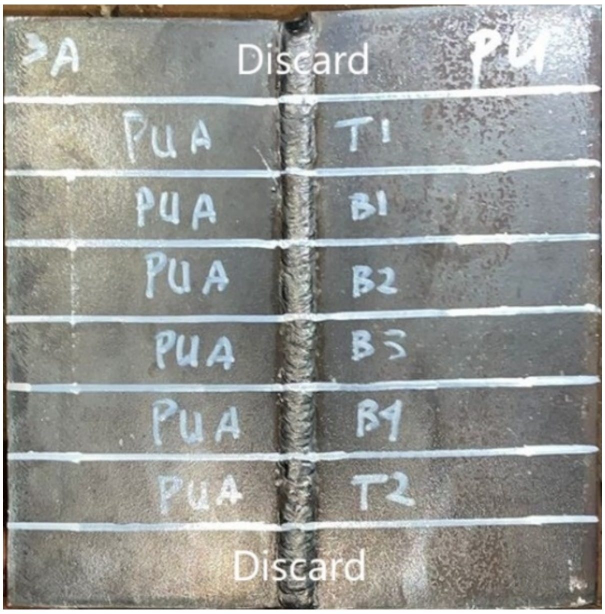


Figure 7. The welded plate specimen.

tory, as shown in Figure 7.

One of the factors affecting the welding results is the application of heat treatment. Preheating is a widely used technique in welding high-strength steels as it helps lower the risk of cracking in the heat-affected zone (Kou 2021). The selection of an interpass temperature at 250°C shows satisfactory welding results.

The welded plate specimen was then cut according to the procedure explained in Figure 4.

Figure 8. The results of the plate specimen cutting for testing purposes

The results of the plate specimen cutting for tensile and bend testing are shown in Figure 8.

The tensile test specimens T1 and T2 were then tested using a Universal Testing Machine with a testing load capacity of 150 kN. The bend test

Figure 9. The tensile test process for the test specimen.

Figure 10. The bending test process for the test specimen

Figure 11. The tensile test results for the specimen

specimens B1, B2, B3, and B4 were tested using a Universal Testing Machine.

The tensile test results for the two specimens are as follows.

The stress-strain graph profiles for the two tensile test specimens are shown in the following Figures 12 and 13.

The ultimate test load testing shows a value higher than the tensile strength of the base metal material SA 36, where, based on data from ASME Section II, the minimum tensile strength of SA 36 material is 400 N/mm². The fracture location was found to be in the base metal. The failure mechanism follows a ductile pattern. The test results show that the selected design parameters produced weld quality that meets the requirements of the ASME IX standard.

One of the key factors affecting the success of the test results in this experiment is the selection of welding wire specifications for the joint design. The selection of welding wire with the E7018 classification showed tensile test results exceeding the minimum tensile strength value of SA36 base metal. The tensile strength test results show values not much different from experimental results carried out by (Alhassan 2021). Through tensile testing experiments, Alhassan aimed to compare the tensile strength values of specimens using E6013 and E7018 welding wire specifications. Experimental results showed that low-carbon steel welded specimens using E7018 welding wire produced a tensile strength of 443 N/mm², while those using E6013 welding wire produced a tensile strength of 392.8 N/mm², with the fracture locations on both specimens occurring in the weld zone.

In the tensile test experiment, the fracture location was found in the base metal SA36, which shows that the tensile strength value obtained represents the tensile strength of the SA36 material. Therefore, the tensile strength in the weld zone is greater than that of the SA36 material.

The range of current and voltage determined in this experiment showed good weld penetration depth. In the current range of 90-170 Amperes and voltage of 16-25 Volts, complete weld penetration and fusion were achieved. This result is also supported by (Singh's 2022) investigation, which conducted welding experiments on low-carbon steel SA36 within a current range of 100-140 Amperes, resulting in improved penetration depth. Ogbunnaoffor's (2016) investigation showed the effect of electric current on the tensile strength properties of welded specimens.

The risk of brittleness in the weld zone can be anticipated by determining the appropriate current range during welding. In this experiment, using a current range of 100-140 Amperes with E7018 welding wire resulted in a metal hardness within a moderate range. This is supported by (Syukran's 2022) study, which conducted welding experiments on SA36 material using E7018 welding wire with

Table 2. Tensile test results

Specimen No.	Width (mm)	Thickness (mm)	Area (mm2)	Ultamate Total Load (KN)	Ultimate Tensile Load (N/mm2)	Yield Stregth (N/mm2)	Type of Failure and Location
TI	19,26	7,86	151,38	150	426,69	275,05	Ductile and failure at base metal
T2	19.20	7,85	150,72	150	435,28	264,66	Ductile and failure at base metal

a current range of 80-120A, resulting in a metal hardness of 35.7 – 42.3 HRC.

The tensile test results show that the weld metal has good hardness. The influence of welding parameter selection on the mechanical properties of the weld metal is also supported by the study of (Sumardiyanto 2019), where welding low-carbon API5L steel using 7018 welding wire produced a tensile strength of more than 500 MPa.

resulting in ductile welds. In the case of microstructural dissimilarities in the three weld regions, namely the base metal, heat-affected zone, and weld area, there is a potential for preferential weld corrosion (Nofrizal 2019). The use of an electric current in the range of 90 amperes shows good ductility, as supported by Oktavian's study on welding SS400 carbon steel using the SMAW process, which producetd a bending stress of 1.23 N/mm² with surface quality from the bending results without any open discontinuities found.

Table 3. Bending test results

Type	Width	Thickness	Bending Angle	Defect	Result
Face Bend 1	38,30 mm	7,85 mm	135	none	Accepted
Face Bend 2	37,72 mm	7,88 mm	135	Open discontinuitis 2 mm	Accepted
Root Bend 1	38,22 mm	7,84 mm	135	Open discontinuitis 2 mm	Accepted
Root Bend 2	38.32 mm	7,92 mm	135	Open discontinuitis 3 mm	Accepted

The bending test results for the four welded specimens are as follows:

The results of the bending test on 2 (two) face bend specimens showed that 1 (one) specimen had an open discontinuity with a size of 2mm. This open discontinuity is still below the value required by the ASME Section IX standard, which is not more than 3 mm. Therefore, the face bend test results meet the ASME IX standard requirements. The results of the root bend test on both welded specimens showed open discontinuities with lengths of 2 mm and 3 mm, respectively. According to ASME IX criteria, these open discontinuities do not exceed 3 mm. Therefore, the test results still meet the ASME IX requirements.

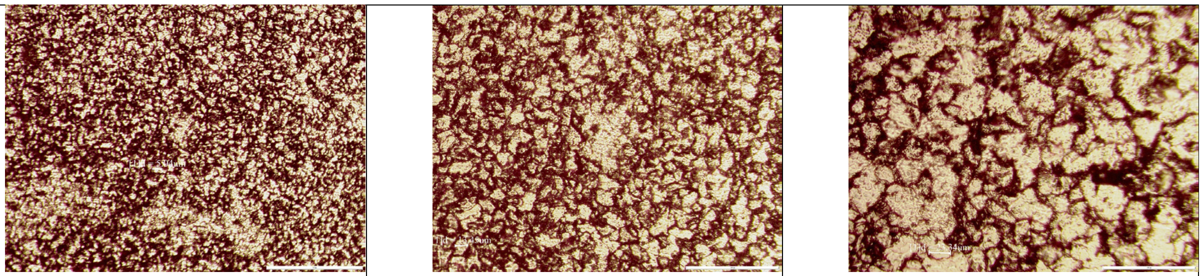
Figure 14. Face bend and root bend test result

The results of the bend test show that the welded specimens tend to have a uniform microstructure,

The hardness test was carried out using the Brinell method with the HBS-3000 Brinell Hardness Tester, applying a test load of 2.5 / 187.5 Kgf. The hardness test locations included the base metal, heat-affected zone (HAZ), and weld metal, as shown in Figure 15.

The hardness test results showed values of 142.5 HB in the base metal, 144.1 HB in the heat-affected zone, and 146.9 HB in the weld metal. Based on these test results, the hardness values show a range typical of low-carbon steel. The deviation in hardness values among the three test locations is not significant. The hardness values suggest a carbon content of approximately 0.2 wt%, with the grain structure predominantly composed of ferrite.

Microstructural observations of the weld metal at 100x, 200x, and 400x magnifications provide sufficient evidence that the grain structure is dominated by ferrite. The microstructure shows variations in grain size, which may be influenced by different heat exposure levels during the welding process. The higher hardness value in the weld metal is supported by microscopic test results, which show larger grain sizes in this area. The bright areas in



100X 200X 400X

Figure 16. Micro test result

the image are likely ferrite (Feα), which is soft and ductile, while the dark areas dispersed among the ferrite are likely pearlite, a mixture of ferrite and the harder cementite phase.

CONCLUSION

Based on the design and qualification of WPS, several conclusions can be drawn. First, tensile testing on two specimens resulted in tensile strength values of 426.69 N/mm² and 435.28 N/mm², with fractures occurring in the SA36 base metal. These tensile strength values are higher than the minimum tensile strength of SA36 set by ASME II, which is 400 N/mm². Second, bend testing on two face bend specimens and two root bend specimens showed open discontinuities but still under minimum criteria. Third, the selection of design parameters in the WPS for oil and gas pressure vessels has been applied to the SA36 steel plate specimens, producing welded specimens that passed the tensile and bend tests according to ASME IX standard requirements.

GLOSSARY OF TERMS

Unit	Definition	Symbol
API	American Petroleum institute	
ASME	American Society of Material Engineering	
ASTM	American Standard Testing Material	
AWS	American Welding Standard	
B1	Bending Test Specimen 1	
B2	Bending Test Specimen 2	
B3	Bending Test Specimen 3	
B4	Bending Test Specimen 4	
DCEP	Direct Current Electrode Positive	
GMAW	Gas Metal Arc Welding	
GTAW	Gas Tungsten Arc Welding	
HAZ	Heat Affected Zone	
SAW	Submerged arc welding	
SMAW	Shield Metal Arc Welding	
T1	Tensile Test Specimen 1	
T2	Tensile Test Specimen 2	
WPS	Welding Procedure Specification	

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