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Integration of Six Sigma, Fault Tree Analysis, and Design of Experiment in Welding Quality Improvement

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ABSTRACT

The quality of water wall welding in boiler fabrication remains a critical issue, as a high welding defect rate of 25–30% can lead to leakage, increased repair welding, and reduced reliability of welded joints. This study aims to systematically reduce welding defects and improve the quality of water wall welded joints by integrating Six Sigma, Fault Tree Analysis (FTA), and Taguchi Design of Experiments (DOE). Six Sigma with the DMAIC framework was applied to evaluate process performance and define critical quality characteristics, while FTA was used to identify the dominant root causes of welding defects. The analysis revealed that suboptimal GMAW welding parameters—specifically welding current, root gap, groove angle, and travel speed—were the main contributors to defect formation in water wall welded joints. Taguchi DOE was subsequently employed to determine an optimal and robust combination of welding parameters. The results show that the optimal parameter setting increased the tensile strength of the welded joint to 495.08 MPa and improved the signal-to-noise ratio by 1.36 dB, indicating enhanced welding quality and process stability.The optimized parameters were implemented through an updated Welding Procedure Specification (WPS), enabling the improvement results to be consistently applied in production. This study demonstrates that the integrated Six Sigma–FTA–DOE approach provides an effective and systematic solution for improving water wall welding quality in boiler manufacturing.
Keyword: Water Wall, Welding Quality, Six Sigma, Fault Tree Analysis, Design of Experiments, Tensile Strength

ABSTRAK

Kualitas pengelasan *water wall* pada fabrikasi *boiler* masih menjadi isu kritis, karena tingkat cacat pengelasan yang tinggi, yaitu sekitar 25–30%, dapat menyebabkan kebocoran, meningkatnya kebutuhan *repair welding*, serta menurunnya keandalan sambungan las. Penelitian ini bertujuan untuk menurunkan cacat pengelasan secara sistematis dan meningkatkan kualitas sambungan las *water wall* melalui integrasi metode *Six Sigma*, *Fault Tree Analysis* (FTA), dan *Taguchi Design of Experiments* (DOE). *Six Sigma* dengan kerangka kerja DMAIC diterapkan untuk mengevaluasi kinerja proses dan menetapkan karakteristik kualitas kritis, sementara FTA digunakan untuk mengidentifikasi akar penyebab dominan dari terjadinya cacat pengelasan. Hasil analisis menunjukkan bahwa parameter pengelasan GMAW yang tidak optimal—khususnya arus pengelasan, *root gap*, sudut alur (*groove angle*), dan kecepatan pengelasan—merupakan kontributor utama terbentuknya cacat pada sambungan las *water wall*. Selanjutnya, Taguchi DOE digunakan untuk menentukan kombinasi parameter pengelasan yang optimal dan robust. Hasil penelitian menunjukkan bahwa pengaturan parameter optimal mampu meningkatkan kekuatan tarik sambungan las hingga 495,08 MPa serta memperbaiki rasio *signal-to-noise* sebesar 1,36 dB, yang mengindikasikan peningkatan kualitas pengelasan dan stabilitas proses. Parameter yang telah dioptimalkan kemudian diimplementasikan melalui pembaruan *Welding Procedure Specification* (WPS), sehingga hasil perbaikan dapat diterapkan secara konsisten dalam proses produksi. Penelitian ini menunjukkan bahwa pendekatan terintegrasi *Six Sigma*–FTA–DOE memberikan solusi yang efektif dan sistematis untuk meningkatkan kualitas pengelasan *water wall* pada industri manufaktur *boiler*.

Keyword: Water Wall, Kualitas Pengelasan, Six Sigma, Fault Tree Analysis, Design of Experiments, Tensile Strength

1. Introduction

Over the past five years, the industrial sector in Indonesia has experienced significant development, contributing to the achievement of national economic development objectives, particularly in terms of Gross Domestic Product (GDP) and value added [1]. One of these sectors is the palm oil industry, which serves as a major contributor to Indonesia's economic growth by generating foreign exchange earnings and employment opportunities, with an annual production capacity of 237,600 tons [2]. The palm oil industry converts fresh fruit bunches into crude palm oil (CPO) through a series of processes, including weighing, grading, sterilization, nut separation, pressing, clarification, and storage [3]. The sterilization, pressing, and clarification processes require high-pressure steam. As the primary generator of high-pressure steam, the boiler system therefore constitutes a critical piece of equipment in this industry [4].

The boiler is one of the most critical machines in the palm oil industry for steam generation. Boiler manufacturing involves welding processes that play a vital role, as the steam produced is conveyed through water wall pipes that are interconnected by welded joints. This steam is subsequently distributed to major equipment, including power turbines, sterilizers, pressing stations, kernel recovery stations, and purification stations [5]. Welding that does not meet quality standards can potentially lead to leakage at the water wall weld joints, which represent weak areas prone to early failure. Such failures may result in reduced efficiency, unplanned operational shutdowns, and costly repair activities [6], [7]. This condition highlights the necessity for effective planning and control in boiler production, particularly in the welding stage, to ensure that no operational issues arise in the boiler during plant operation [8].

The palm oil industrial facility fabrication company manufactures boilers that are welded using the shielded metal arc welding (SMAW) process. This process utilizes electrical energy as the heat source to melt the base metal and filler metal, thereby joining two metal components [9]. The company faces challenges related to defects that arise during the welding of the boiler water wall, leading to high costs incurred to ensure welding quality. Welding defects observed in the boiler are classified as visible defects, including porosity, undercut, and cracks on the weld surface [10]. Porosity is a welding defect characterized by the presence of small holes within the weld metal, which may be located on the surface of the welded joint [11]. Cracks are welding defects in the form of fractures that develop in the welded joint. Undercut is a defect characterized by the formation of a groove along the edge of the weld metal or a condition in which the weld metal fails to completely fill the joint gap [12]. Inadequate welding current can lead to welding defects such as porosity, cracks, and undercut [13]. Hal ini dapat menyebabkan kebocoran pada saat hydrotest maupun saat boiler beroperasi pada area water wall. This condition may result in leakage during hydrostatic testing as well as during boiler operation in the water wall area. The impact of visible defects is the occurrence of leakage at water wall pipe joints, which is primarily caused by cracking at each welded connection.

In addition, hidden welding defects may lead to reduced structural integrity, leakage, decreased machine efficiency, and an increased risk of severe failure. Hidden defects include cluster porosity, slag inclusion, and lack of fusion. Cluster porosity may be caused by poor welding practices during arc initiation or termination, inadequate shielding gas coverage, or defects in the welding electrode coating [14]. Slag inclusion is a condition in which molten material generated from the melting of the electrode coating becomes trapped within the solidified weld metal [15]. Lack of fusion can be caused by poor welding technique and excessively low welding voltage, resulting in inadequate wetting of the weld bead [16].

The average welding defect rate reaches 26.7% per month, with visible defects accounting for 65% and invisible defects for 35%. This high defect rate indicates serious quality issues and has a direct impact on productivity in the manufacturing process of water wall pipes within the company [17]. Welding defects constitute a primary source of product failure due to the inherent complexity of the welding process, which involves numerous interacting parameters and is highly sensitive to process variations. Therefore, a structured quality improvement framework and a systematic failure analysis method are required to effectively address these issues.

Six Sigma is employed as a quality improvement framework to reduce welding defects through a data-driven DMAIC cycle. The DMAIC approach focuses on defining critical welding defects, measuring process performance through defect rates and defects per million opportunities (DPMO), analyzing variations in process parameters, implementing appropriate improvements, and controlling process conditions to ensure that quality performance is sustainably maintained [18]. Various previous studies have demonstrated that Six Sigma is capable of significantly improving welding quality and process efficiency, as evidenced by reductions in defect rates and increases in sigma levels [19].

As a complementary approach, Fault Tree Analysis (FTA) is employed as a failure analysis tool to identify and map the root causes of welding defects that lead to product failure. In this context, welding defects are treated as basic events that contribute to the top event, namely the functional failure of the water wall. FTA logically represents cause–effect relationships among human, machine, material, method, and environmental factors, thereby providing a clear understanding of why welding defects occur and how they propagate into system-level failures [20]. Accordingly, Six Sigma (DMAIC) plays a role in improving and controlling process performance, while FTA functions as a tool for analyzing failure mechanisms.

In addition, Taguchi Design of Experiments (DOE) is applied not merely to reduce experimental costs or the number of trials, but primarily due to its capability to analyze the effects of multiple control factors in the presence of uncontrollable noise factors. The welding process requires high stability and consistency in quality, rather than solely achieving optimal conditions under ideal circumstances. Taguchi DOE emphasizes robust design through the use of orthogonal arrays and signal-to-noise ratios to generate process parameters that remain stable despite variations in operating conditions [21]. Therefore, Taguchi DOE is highly suitable for reducing welding defects in applications that require long-term process stability and reproducibility.

Based on the problem of high welding defect rates and the complexity of the welding process in water wall manufacturing, this study aims to systematically and sustainably reduce welding defects. Specifically, the study seeks to implement Six Sigma through the DMAIC cycle as a quality improvement framework to measure, analyze, improve, and control welding process performance. In addition, this study aims to identify and map the root causes of welding defects that contribute to product failure using FTA, thereby enabling a causal and structured understanding of failure mechanisms. Furthermore, Taguchi DOE is employed to determine optimal welding process parameter combinations that are robust against variations in operating conditions, with a particular focus on enhancing process stability and welding quality consistency. Through the integration of DMAIC, FTA, and Taguchi DOE, this study is expected to provide a comprehensive approach to reducing welding defects while simultaneously improving process reliability and the quality of water wall products.

2. Research Methodology

This study is an experimental investigation employing a quantitative approach, designed as a quality problem-solving framework for the welding process [22]. The research methodology integrates Six Sigma through the DMAIC cycle as the primary quality improvement framework, FTA as a root cause failure analysis tool, and Taguchi DOE to systematically optimize welding process parameters [23], [24], [25]. This approach enables the identification of cause–effect relationships between variations in process parameters and welding defect rates, while simultaneously generating measurable and sustainable improvement solutions. The overall research design is illustrated in Figure 3.

The research steps are structured based on the Six Sigma approach through the DMAIC cycle, which is specifically applied to address the high incidence of welding defects in water wall boiler fabrication. Each phase focuses on the actual conditions of the on-site welding process and is directed toward generating measurable technical solutions.

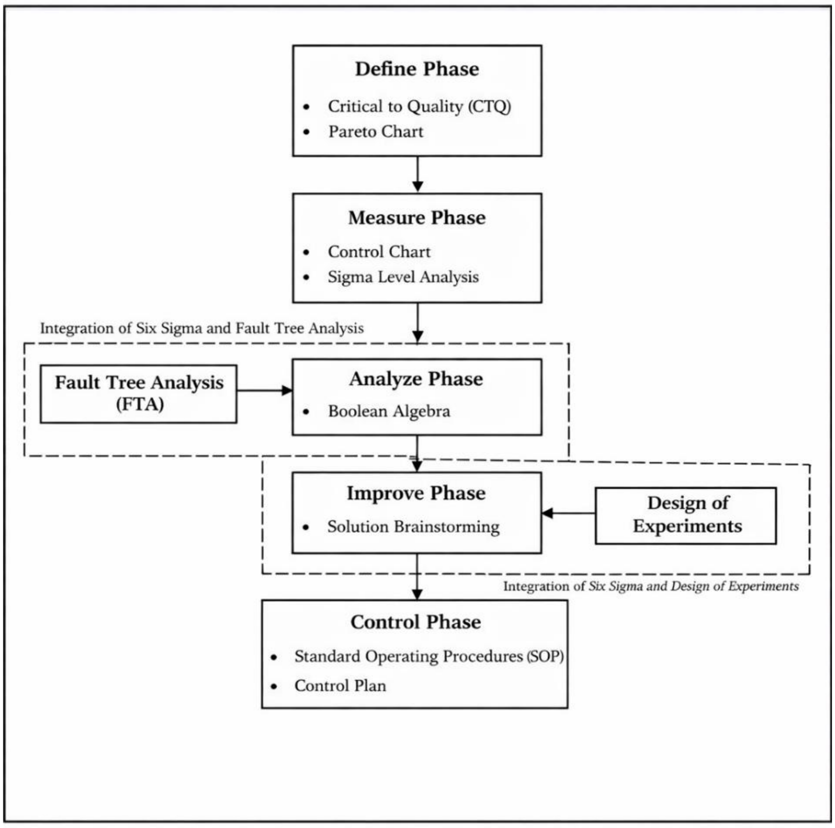


Figure 1. Research Design

In the Define phase, the main research problem is established based on the actual conditions of the water wall welding process, namely the high welding defect rate reaching 25–30%, which results in leakage, rework, and reduced boiler reliability. Critical to Quality (CTQ) characteristics are identified by referring to the most frequently occurring welding defects, including both visible defects (porosity, undercut, crack) and invisible defects (cluster porosity, slag inclusion, lack of fusion). A Pareto diagram is employed to identify dominant defect types, thereby directing improvement efforts toward the causes that contribute most significantly to weld joint failures [26], [27].

In the Measure phase, the actual performance of the water wall welding process is evaluated. Historical welding defect data are collected and analyzed using Defects Per Million Opportunities (DPMO) and sigma level calculations to determine the initial process capability. In addition, control charts (P-charts) are applied to monitor welding process stability and identify periods with significant defect variation. These measurement results provide a quantitative basis for assessing the extent to which the welding process deviates from the desired quality targets [27], [28].

In the Analyze phase, cause–effect relationships between welding defects and process-related factors are systematically examined using FTA. Welding defects are treated as the top event and are decomposed into various basic events encompassing human, method, material, machine, and welding parameter factors. This analysis focuses on identifying dominant causal factors contributing to defect occurrence, particularly those related to GMAW parameter settings. The FTA results indicate that improper process parameter settings and the absence of optimal welding standards are the primary causes of defects in water wall pipe joints [29], [30].

In the Improve phase, efforts are focused on resolving the root causes identified through FTA. At this stage, Taguchi DOE is employed as the primary tool to determine optimal and robust combinations of GMAW welding parameters. Welding parameters such as welding current, root gap, groove angle, and travel speed are evaluated using Taguchi orthogonal arrays to assess the influence of each factor on weld joint tensile strength. Signal-to-noise (S/N) ratio analysis is applied to select parameter combinations that not only produce the highest tensile strength but also remain stable under variations in operating conditions. Accordingly, Taguchi DOE directly serves as a technical solution for reducing welding defects and improving the quality of water wall joints.

In the Control phase, actions are taken to ensure that the improvements achieved can be sustained over time. The optimal welding parameters obtained from the Improve phase are implemented in the form of a Welding Procedure Specification (WPS) in accordance with ISO and ASME standards. Control is maintained through the application of standard operating procedures and periodic monitoring of welding quality to ensure consistency in welding outcomes and to prevent the recurrence of similar defects [26].

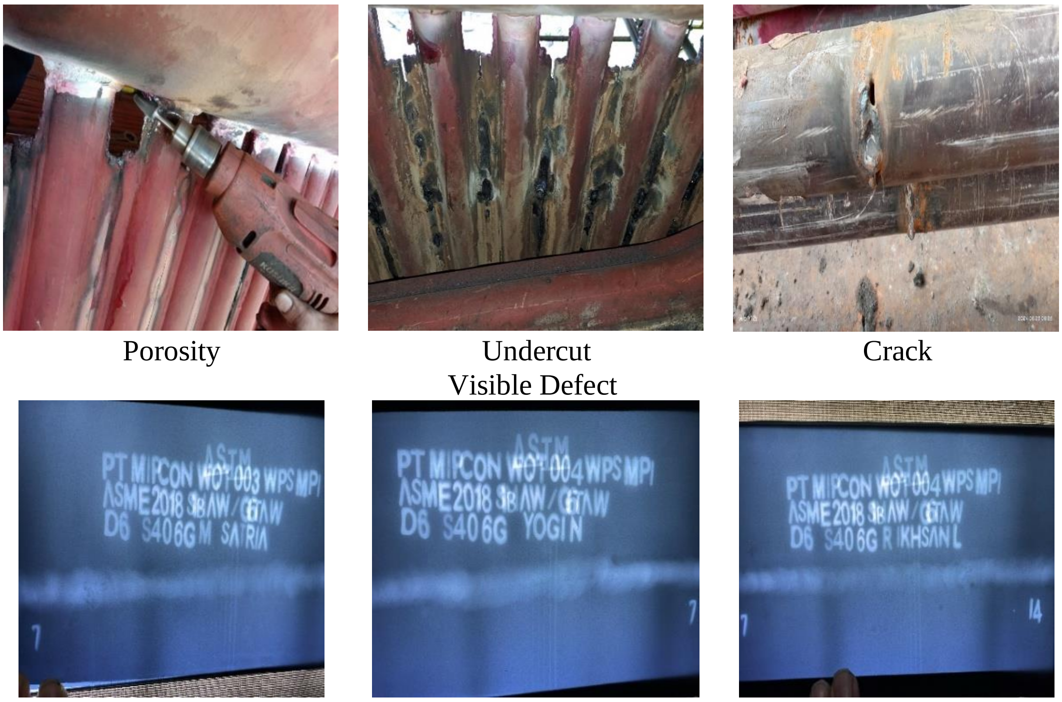
3. Result and Discussion

The high welding defect rate in water wall boilers indicates that quality issues cannot be resolved solely through final inspection, but instead require a structured and data-driven improvement approach. Therefore, this study proposes the integration of Six Sigma, FTA, and Taguchi DOE as a comprehensive solution to reduce welding defects and enhance process reliability. Six Sigma serves as a systematic framework for measuring and controlling process performance, FTA plays a role in identifying cause–effect mechanisms of failure, while Taguchi DOE is used to generate optimal and robust welding parameters. The implementation of this solution is carried out progressively through the DMAIC cycle, ensuring that each improvement decision is grounded in the results of the preceding analysis stage. This results and discussion section presents the sequential application of the proposed approach, from the Define stage to the Control stage, based on the actual conditions of the water wall welding process within the company.

3.1. Define Phase

The Define phase serves to screen the main problems that warrant further analysis and to determine the direction of solutions to be developed in subsequent stages [26]. The primary focus at this stage is to ensure that the selected quality characteristics are relevant to the actual failures occurring in water wall boiler pipe joints.

Based on observation results and welding inspection data, the number of welding defects recorded in water wall pipe joints remains relatively high. These defects consist of visible defects such as porosity, undercut, and pinholes, as well as invisible defects such as cluster porosity, slag inclusion, and lack of fusion. The presence of these defects directly affects weld joint quality, potentially leading to leakage in water wall pipe joints, increased rework activities (repair welding), and reduced structural reliability in the water wall area. This condition does not indicate a failure of the boiler system as a whole, but rather localized failures at welded joints that may evolve into functional failures if not properly controlled. The visible and invisible defects in water wall boiler pipe can be seen in Figure 2.



Porosity | Undercut | Crack
Visible Defect

Cluster Porosity | Slag Inclusion | Lack of fusion
Invisible Defect

Figure 2. Visible and Invisible Defect in Water Wall Boiler Pipe

These findings are consistent with previous studies indicating that welding defects in boiler pipe joints are among the primary causes of leakage and reduced component service life, particularly when such defects are not detected during the fabrication stage [31]. Other studies have also shown that the dominance of certain defects, such as porosity and lack of fusion, is often associated with improper process parameter settings and the lack of controlled welding procedure standards [32]. Therefore, early identification of defect types and quantities becomes a critical step to ensure that improvement efforts are directed toward the causes that contribute most significantly to joint failure.

In the Define phase, Critical to Quality (CTQ) characteristics are established to represent the key requirements that must be satisfied by water wall weld joints. The CTQs focus on minimizing both visible and invisible defects, as well as achieving joint strength that meets the specified technical standards. The determination of these CTQs serves as the foundation for all subsequent DMAIC stages, as all analyses, measurements, and improvements are directed toward fulfilling the defined quality characteristics. The CTQs applied in this study are presented in Table 1.

Table 1. Critical to Quality (CTQ)

CTQ (Critiqal to Quality)	Measurement parameters	Expectation
1. Free from visible defects	Visual inspection	
2. Free from invisible defects.	Radiographic testing	Optimal strength of water wall pipe weld joints and freedom from leakage at welded connections
3. Reduced number of defects	Compliance with WPS and ASME/ISO standards	
4. Weld joint strength	Compliance with WPS and tensile testing	

The most dominant welding defect in water wall pipe joints is porosity, contributing 29% of the total recorded defects, followed by undercut at 20% and cracks at 17%. This defect dominance pattern indicates that porosity represents the primary issue in the welding process, which is consistent with previous studies reporting that porosity is often the most common defect in carbon steel welding due to improper process parameter settings and inadequate shielding gas protection. [33].

The Pareto diagram is used to visualize the distribution of defects based on the 80/20 principle, which states that the majority of quality problems are typically caused by a small number of key factors. The Pareto approach has been widely applied in welding defect analysis to prioritize defect types that contribute most significantly to weld joint failures [34]. By identifying the percentage contribution of each defect type, quality improvement efforts can be directed in a more focused and data-driven manner, thereby concentrating control actions on defects that have the greatest impact on joint quality degradation. The visualization of the Pareto analysis results is presented in Figure 3.

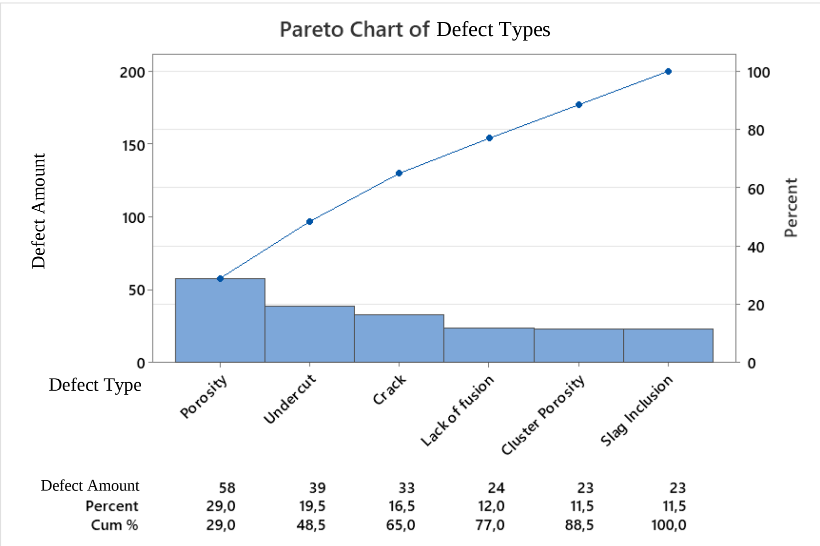


Figure 3. Pareto chart of welding defects

The Pareto diagram analysis indicates that three major defect types—porosity, undercut, and cracks—collectively account for 65% of the total weld joint defects in water wall pipes. The dominance of these three defects suggests that the degradation of weld joint quality is not caused by a wide range of dispersed factors, but rather is concentrated in a small number of recurring defect types. This condition is significant because porosity, undercut, and cracks are directly associated with reduced weld joint integrity and an increased risk of leakage in water wall pipes.

By controlling these three dominant defect types, a significant reduction in the overall number of defects can be achieved without addressing all existing defect variations. Therefore, the Pareto results provide a basis for setting improvement priorities in subsequent stages, where the analysis focuses on process-related factors that trigger the occurrence of porosity, undercut, and cracks through FTA, and are subsequently optimized by adjusting welding parameters in the Improve phase using DOE.

3.2. Measure Phase

The Measure phase is conducted to evaluate the actual performance of the water wall welding process based on the measurement of operationally defined quality variables [35]. The measurement object in this study is the welded joints of water wall pipes, with the primary variables comprising the number of joints inspected, the number of defective joints, and the types of welding defects identified. Welding defects are classified into visible defects such as porosity, undercut, and cracks, as well as invisible defects such as cluster porosity, slag inclusion, and lack of fusion.

Each weld joint has a defined number of defect opportunities based on the CTQs, allowing the Defects Per Million Opportunities (DPMO) to be calculated consistently. In addition, the proportion of defects per production period is used to evaluate process stability through control charts. The DPMO values and sigma levels are then used as indicators of the water wall welding process capability prior to improvement [26]. The results of the quality variable measurements are presented in Table 2.

Table 2. DPMO Results and Sigma Levels

Period	Total Weld	Number of defects	CTQ	DPU	TOP	DPO	DPMO	Sigma Level
Januari	64	18	4	0.281	256	0.0703	70312.50	2.97
Februari	51	14	4	0.275	204	0.0686	68627.45	2.99
Maret	60	17	4	0.283	240	0.0708	70833.33	2.97
April	55	14	4	0.255	220	0.0636	63636.36	3.02
Mei	87	23	4	0.264	348	0.0661	66091.95	3.01
Juni	55	18	4	0.327	220	0.0818	81818.18	2.89
Juli	75	21	4	0.280	300	0.0700	70000.00	2.98
Agustus	77	23	4	0.299	308	0.0747	74675.32	2.94
September	75	19	4	0.253	300	0.0633	63333.33	3.03
Oktober	87	26	4	0.299	348	0.0747	74712.64	2.94
November	57	7	4	0.123	228	0.0307	30701.75	3.37
Total	743	200	4	0.269	2972	0.0673	67294.75	3.00

Based on the measurement results in Table 2, the quality parameters of the water wall welding process are evaluated using the indicators DPU, DPO, DPMO, and sigma level. The measurement object is the welded joints of water wall pipes, while the number of defect opportunities is determined based on four CTQs: porosity, undercut, crack, and lack of fusion.

A total DPMO value of 67,294.75 corresponds to a sigma level of 3.00, indicating that the welding process capability is at a moderate level [35]. This condition suggests that although the process remains within statistical control limits, the defect rate is still significant and has the potential to cause rework and reduce the reliability of water wall pipe weld joints.

To monitor the stability of the ongoing welding process, a proportion control chart (P-chart) is used. The P-chart is selected because the analyzed data consist of the proportion of water wall pipe weld joints exhibiting defects in each inspection period [36]. This control chart is used to identify whether the observed defect variation remains within natural process variation (common cause variation) or indicates the presence of process deviations (special cause variation). [37]. The overall welding defect control chart results are presented in Figure 4.

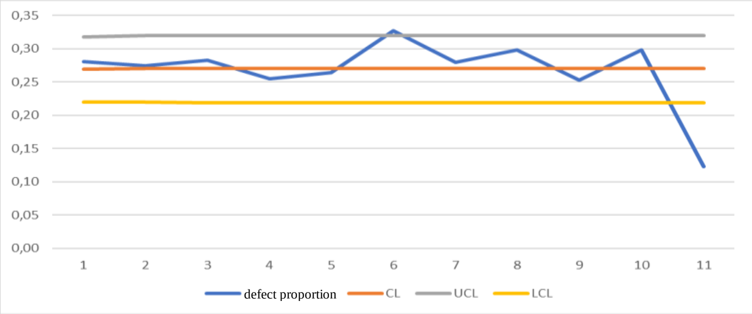


Figure 4. Welding Defect Control Chart

Based on Figure 4, it can be observed that the proportion of defects in water wall pipe weld joints during the sixth period (June) exceeds the Upper Control Limit (UCL). This condition indicates a significant process deviation in that period compared to the others. Statistically, a data point exceeding the control limit signifies that the observed variation is no longer attributable to natural process variation, but rather to special causes affecting welding process performance. This finding is critical, as the increase in defects during this period has the potential to escalate rework activities (repair welding), reduce productivity, and increase the risk of localized failure in water wall pipe weld joints. Therefore, this period is treated as an initial indication of the need for special cause analysis in the Analyze phase. To obtain a more specific understanding, the control chart is subsequently disaggregated by defect type, beginning with visible welding defects. The control chart for visible defects is presented in Figure 5.

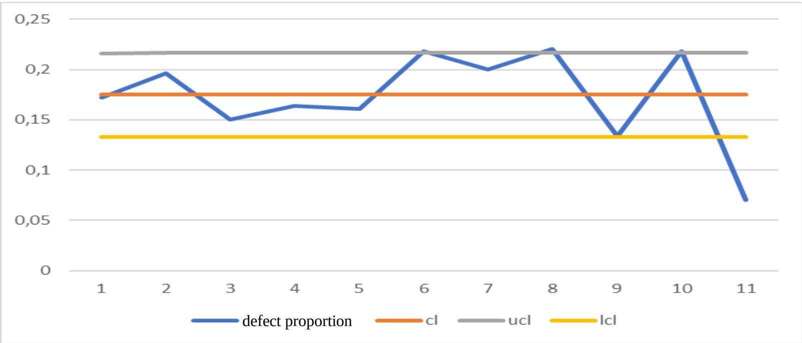


Figure 5. Control Chart of Visible Welding Defects

The analysis results indicate that all visible defect proportion values remain within the control limits, signifying that the welding process for visible defects is statistically under control. Nevertheless, several periods—namely June, August, and October—exhibit defect proportions approaching the upper control limit. This condition suggests the potential for process deviation if further control is not implemented. Although the process is still considered stable, these fluctuations indicate that certain welding parameters may be contributing to increased visible defects during those periods. Subsequently, the control chart for invisible welding defects is presented in Figure 6.

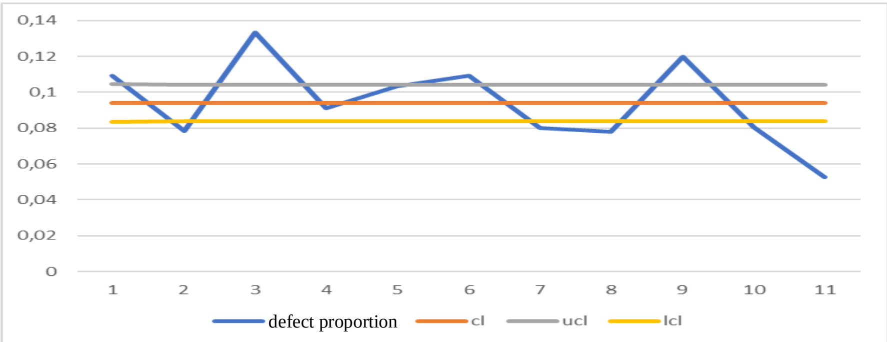


Figure 6. Control Chart of Invisible Welding Defect

Based on the analysis results, all proportions of invisible defects remain within the control limits, indicating that the welding process related to invisible defects is statistically stable. There are fluctuations with relatively high defect proportions in March and September; however, these variations can still be categorized as natural process variation and do not indicate significant process deviation. Nevertheless, the presence of invisible defects requires particular attention due to their difficulty to detect visually and their potential to reduce weld joint reliability if not properly controlled.

Overall, the control chart analysis indicates that although most of the water wall pipe welding process is statistically under control, there are indications of process deviations in certain periods as well as fluctuations in defect proportions approaching the control limits. Therefore, the decision in the Measure phase is to proceed to the Analyze phase to identify special cause factors influencing welding defect variation. This further analysis is conducted to ensure that uncontrolled process parameters can be identified and managed, thereby consistently achieving the defined CTQs.

3.3. Analyze Phase

The primary objective of the Analyze phase is to identify the cause–effect relationships that explain why welding defects occur in water wall pipe joints, based on the quantitative findings from the Measure phase [38]. At this stage, FTA is employed as the primary analytical tool to model weld joint failures in the form of a hierarchical and systematic logical structure. FTA enables the mapping of failure causes from the level of final consequences (top event) down to the underlying factors that contribute to defect occurrence [39].

In this study, the FTA top event is defined as local failure of water wall pipe weld joints that has the potential to cause leakage. To provide a clearer understanding of the failure mechanisms, the FTA is divided into two complementary diagrams, as shown in Figures 7 and 8. The first diagram focuses on weld joint failures that directly lead to leakage (failure due to leak), while the second diagram focuses on the hydrogen diffusion mechanism during welding that contributes to the degradation of joint mechanical properties and increases the risk of cracking (diffused hydrogen through welding).

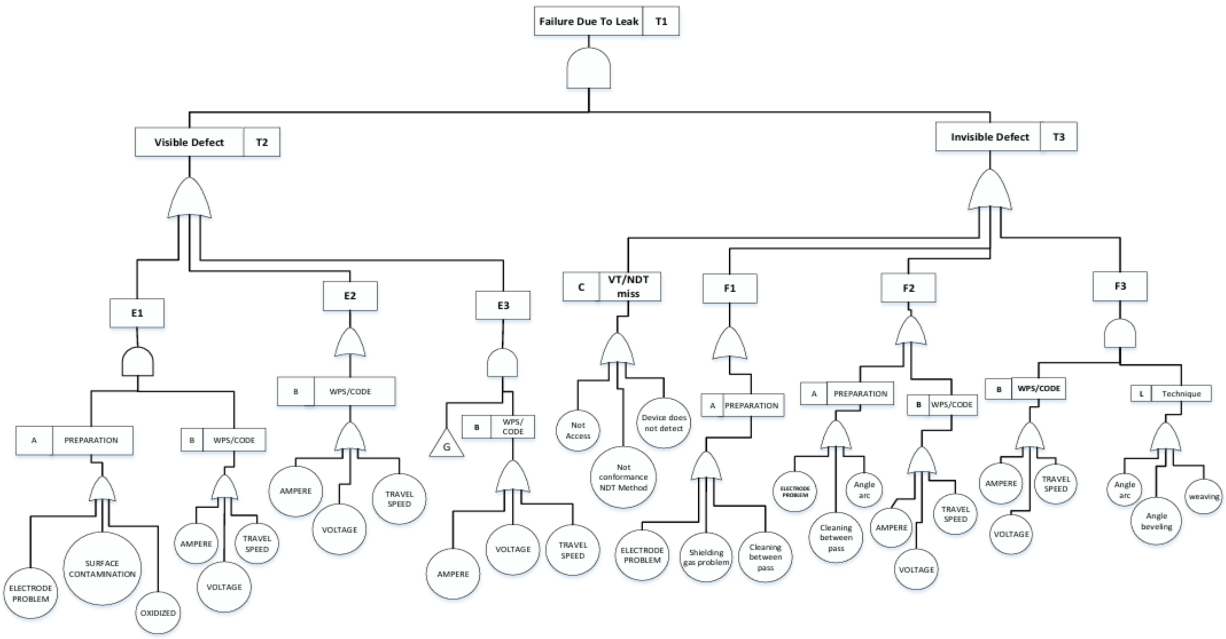


Figure 7. FTA of Leakage Failure in Water Wall Welded Joints

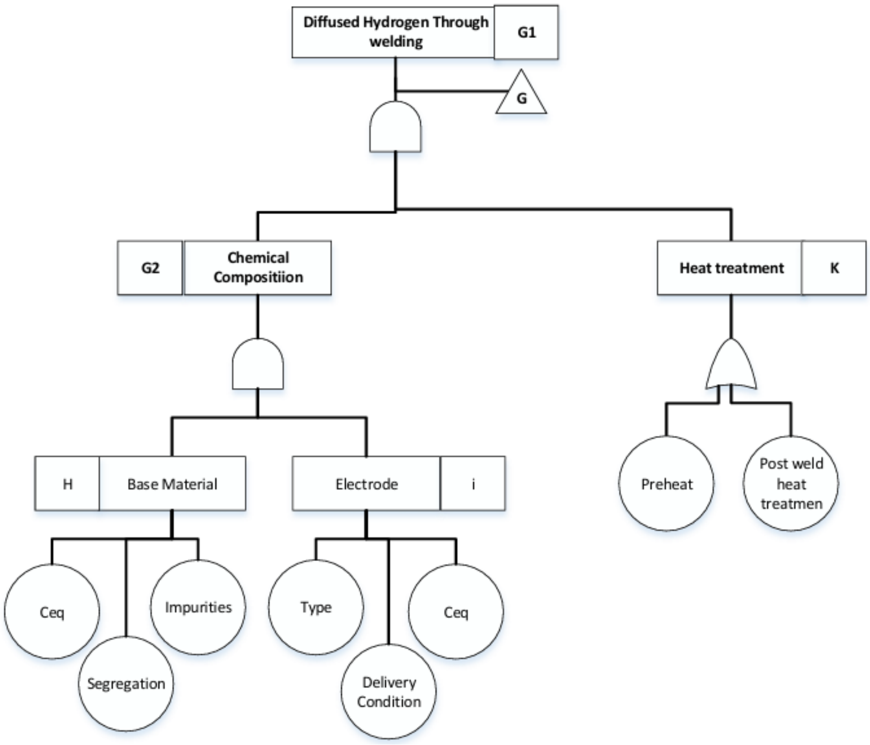


Figure 8. FTA of Hydrogen-Induced Weld Defects in Water Wall Pipes

Based on Figure 7, leakage failure is analyzed as a consequence of welding defects such as porosity, undercut, and cracks, which are directly associated with improper welding process parameters and material preparation. This diagram highlights the direct relationship between visible defects and functional failure of weld joints in water wall pipes. Meanwhile, Figure 8 examines indirect failure mechanisms, in which hydrogen diffusion during welding can trigger hidden defects such as cluster porosity, slag inclusion, and lack of fusion, potentially reducing joint toughness without early visual indications.

The FTA results indicate that both visible and invisible defects are strongly associated with process-related factors, particularly welding parameter settings, material preparation, and the absence of consistent welding procedure standards. To simplify the logical relationships among causal factors, the FTA structure is translated into Boolean algebra. Through the application of logical rules such as the commutative rule and absorption rule, combinations of causal factors are reduced to identify the dominant factors that most significantly influence the occurrence of welding defects [40].

The logical simplification results indicate that the absence of a standardized Welding Procedure Specification (WPS) and inconsistent implementation of welding standard codes are the dominant factors triggering process parameter variations, which ultimately lead to welding defects in water wall pipe joints. This finding forms the basis for decision-making in the Improve phase, where improvements are focused on establishing optimal and standardized welding parameters through the DOE approach.

3.4. Improve Phase

In the Improve phase, the study focuses on determining the process changes to be investigated based on the collected data and the analysis results derived from variability observed in the welding process [41]. The analysis results are directed toward identifying specific changes that can be implemented to improve process quality. The primary focus of the Improve phase is the development of solutions to address issues classified as Critical to Quality (CTQ). The proposed solutions are subsequently tested, evaluated, and systematically documented to ensure that the implemented improvements achieve the intended quality enhancement objectives and accurately represent actual process conditions.

The Taguchi method is applied at this stage because it integrates the concept of robustness by considering the influence of noise factors through the signal-to-noise (S/N) ratio approach. Noise factors are defined as variables that cannot be directly controlled and have the potential to cause significant variability in the process or product. By applying the Taguchi method based on DOE, an experimental design is obtained that is oriented not only toward achieving optimal performance but also toward maintaining quality stability against process variations [42], [43]. This approach is combined with ISO/ASME standards to ensure that the optimization results remain aligned with industrial welding quality requirements.

The welding parameter variations employed in this study include welding current, root gap, groove angle, and travel speed, each tested at three levels as presented in Table 3. These four parameters are selected because they have a direct influence on fusion formation, penetration, and weld joint strength. The combinations of parameter variations are subsequently designed using a Taguchi orthogonal array to achieve an efficient number of experiments while remaining representative of the overall factor combinations under investigation.

Table 3. Welding Parameter Variation Data

Code Factor	Control Factor	Units	Level 1	Level 2	Level 3
A	Welding Current	A	110	110	117
B	Root gap	mm	2	3	4
C	Groove angle	Drajat	60	65	70
D	Travel speed	mm/min	62	91	72

The orthogonal array design used is L9 (3^4), as shown in Table 4, which consists of nine experimental combinations with four factor columns. Each column represents one welding parameter with predefined level variations. This design enables systematic analysis of the influence of each parameter on the welding response without requiring all possible experimental combinations.

Table 4. Taguchi Orthogonal Array

Experiment Number	Column			
	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The parameter variations based on the orthogonal array, along with the tensile strength test results and signal-to-noise (S/N) ratio values, are presented in Table 5. The tensile strength values, expressed in MPa, represent the strength of the weld joints produced by each parameter combination, while the S/N ratio is used to evaluate the stability of welding quality. Based on these test results, an average S/N value of 53.64 dB is obtained, reflecting the overall performance of the water wall welding process across the tested parameter combinations.

Table 5. Variasi Parameter *Orthogonal Array*

Exp.	Coded Matrix				Control Factor				TS (Mpa)	S/N Ratio (dB)
	A	B	C	D	Welding Current	Root Gap	Groove Angle	Travel Speed		
1	1	1	1	1	110	2	60	62	473	53,50
2	1	2	2	2	110	3	65	91	482	53,66
3	1	3	3	3	110	4	70	72	469	53,42
4	2	1	2	3	110	2	65	72	468	53,40
5	2	2	3	1	110	3	70	62	479	53,61
6	2	3	1	2	110	4	60	91	478	53,59
7	3	1	3	2	117	2	70	91	522	54,35
8	3	2	1	3	117	3	60	72	516	54,25
9	3	3	2	1	117	4	65	62	445	52,97
									AVG	53,64

The comparison between the predicted results and existing conditions based on S/N values is presented in Table 6. The analysis results show that the average S/N value under existing conditions is 53.09 dB, while under optimal design conditions it increases to 54.44 dB. This improvement yields a gain of 1.36 dB, indicating a significant enhancement in welding quality following the optimization of control parameters.

Table 6. Comparison of Prediction Result and Existing

S/N Prediction		S/N Existing	
Parameter	S/N (dB)	Parameter	S/N (dB)
Average S/N	53,64	Average S/N	53,64
A1/A2/A3	53,86	A1/A2/A3	53,53
B1/B2/B3	53,84	B1/B2/B3	53,33
C1/C2/C3	53,79	C1/C2/C3	53,79
D1/D2/D3	53,87	D1/D2/D3	53,36
Popt	54,44	Popt	53,09
Prediction			
Existing design	53,09		
Optimum design	54,44		
Gain	1,36		
Conclusion	Good improvement		

The optimization results indicate that the highest S/N value is achieved at a welding current of 117 A, a root gap of 2 mm, a groove angle of 70°, and a travel speed of 91 mm/min. The optimization plot of average S/N values for each control factor is shown in Figure 9, illustrating the trend of improved quality stability with the selection of optimal parameter levels.

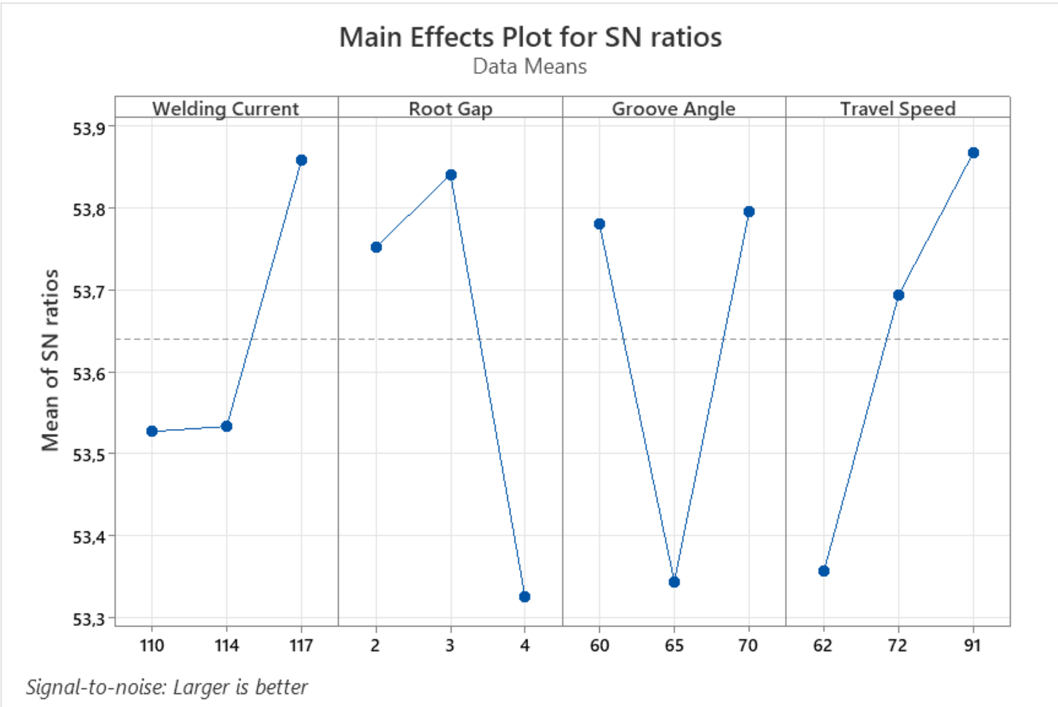


Figure 9. Optimization Plot of Average S/N Control Factors

In addition to the S/N-based evaluation, an analysis of weld joint tensile strength is also conducted. The tensile strength test results for each welding parameter indicate that the highest tensile strength is obtained at a welding current of 117 A, a root gap of 2 mm, a groove angle of 70°, and a travel speed of 91 mm/min. The tensile strength results are illustrated in Figure 10, which shows a trend of increasing weld joint strength at specific parameter levels. This improvement in tensile strength indicates enhanced weld fusion and penetration, thereby contributing to a reduced risk of leakage in the water wall boiler.

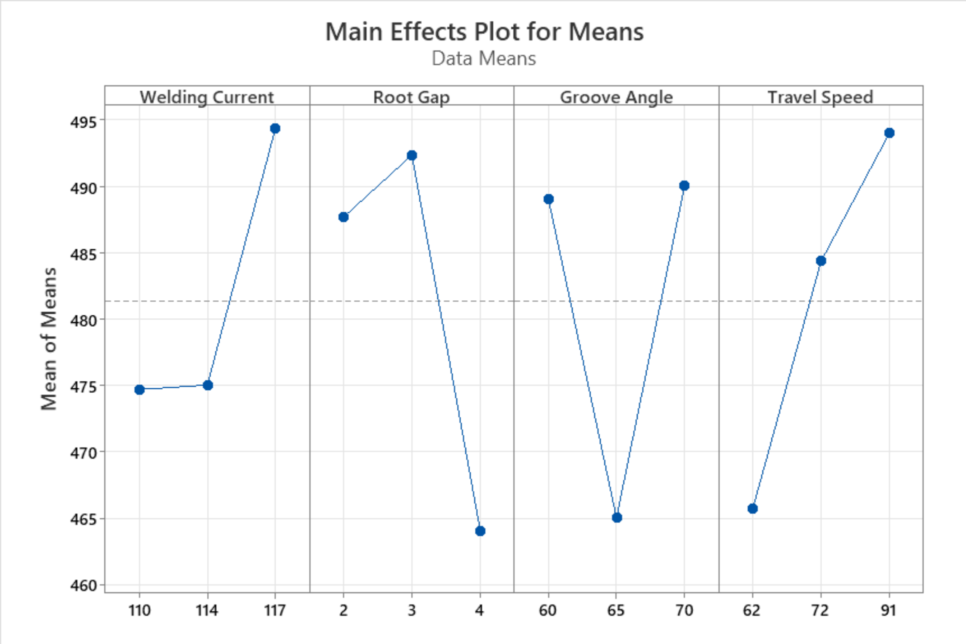


Figure 10. Optimization Plot of Means Tensile Strength

Based on the optimization results using the Taguchi-based DOE method, the optimal welding quality parameters are summarized in Table 7.

Table 7. Optimal Welding Quality Parameters

Parameter		Tensile Strength Value
Welding Current	117 A	476,00 Mpa
Root gap	2 mm	492,33 Mpa
Groove angle	70 Derajat	490,00 Mpa
Travel speed	91 mm/min	522,00 Mpa
	AVG Tensile Strength	495,08 Mpa

The optimal parameter combination yields an average tensile strength of 495.08 MPa. These results indicate that the implementation of the optimal parameter combination significantly improves the quality of water wall boiler weld joints, both in terms of mechanical strength and process stability against uncontrolled variations.

3.5. Control Phase

The Control phase aims to ensure that the quality improvements achieved in the Improve phase can be consistently sustained during water wall welding operations [44]. Although welding standards and work procedures based on ISO and ASME are already in place, the findings of this study are used to refine and tailor the Welding Procedure Specification (WPS) implemented at the company, particularly with regard to GMAW welding parameter settings.

The optimal parameters obtained from the Taguchi DOE results, such as welding current, root gap, groove angle, and travel speed, are established as standard parameters in the updated WPS. Accordingly, the Control phase functions not merely as the implementation of existing standards, but as a mechanism for integrating data-driven analysis results into operational procedures that are specific to the water wall welding case.

Control is implemented through the application of the updated WPS, monitoring compliance with welding parameters, and periodic evaluation of weld joint quality. This approach ensures that process variation is minimized, weld joint quality remains consistent, and the risk of recurrence of dominant defects is sustainably controlled within the limits of applicable international standards.

4. Conclusion

This study concludes that the high incidence of welding defects in water wall pipe joints is primarily caused by improper welding process parameter settings. Through the application of FTA in the Analyze phase within the Six Sigma framework, the dominant causal factors affecting weld joint quality are systematically identified, namely welding current, root gap, groove angle, and travel speed, which were not previously set at optimal conditions.

The integration of Six Sigma, FTA, and Taguchi DOE is proven to be effective in generating data-driven improvement solutions. The optimization results indicate that the welding parameter combination of a welding current of 117 A, a root gap of 2 mm, a groove angle of 70°, and a travel speed of 91 mm/min significantly improves weld joint quality, as evidenced by an increase in tensile strength to 495.08 MPa and an improvement in the signal-to-noise ratio of 1.36 dB.

The implementation of these optimal parameters into the Welding Procedure Specification (WPS) enables the achieved quality improvements to be locked into operational practice, thereby controlling process variation and minimizing the recurrence of dominant defects. Accordingly, this study provides a practical contribution in the form of an integrated approach that can serve as a reference for systematic and sustainable quality improvement in water wall welding.

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