IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Enhancing Saw Pipe Welding Quality Through Process Variables

Kuldeep Sharma[1] Ashok Kumar[2] Dipak K Banerjee[3] Randy Marvel[4]

[1] Dura-Bond Industries, Pittsburgh, USA

[2,3 and 4] Welspun Tubular LLC, Little Rock, USA

ABSTRACT

Abstract Welded pipes are particularly susceptible to rapid degradation. Cracks can be detected during regular inspections, either mandated by the welding-filling process or by employing more intrusive methods like cutting and replacing sections. Such small discontinuities can evolve into fatigue cracks or stress corrosion cracks during service. Welding process parameters significantly influence fabricated joint quality.

The characteristics of welding are crucial in the industrial sector, particularly in the manufacturing sector. One key process for ensuring the quality of welding is the post-welding non-destructive test (NDT), although it is both time-consuming and expensive. To minimize the occurrence of defects, online monitoring has been used to continuously measure certain welding parameters and forecast the quality of the weld. The objective of this study is to assess the dependability of non-destructive test (NDT) methods for examining pipeline welds used in the oil and gas industry. Techniques, includes ultrasonic methods manual and automatic, digital radiography, manual and automatic were utilized. Pipe discontinuities includes- lack of fusion, lack of penetration, porosity, slag, off-seam under cut, crack etc. The experiments were conducted on samples from pipelines that had been developed during the welding process. The findings indicate that automatic ultrasonic tests are more effective in detecting defects compared to manual ultrasonic and radiographic tests.

KEYWORDS: Welded Pipes, NDT, Ultrasonic testing, Digital Radiography, Weld Defects

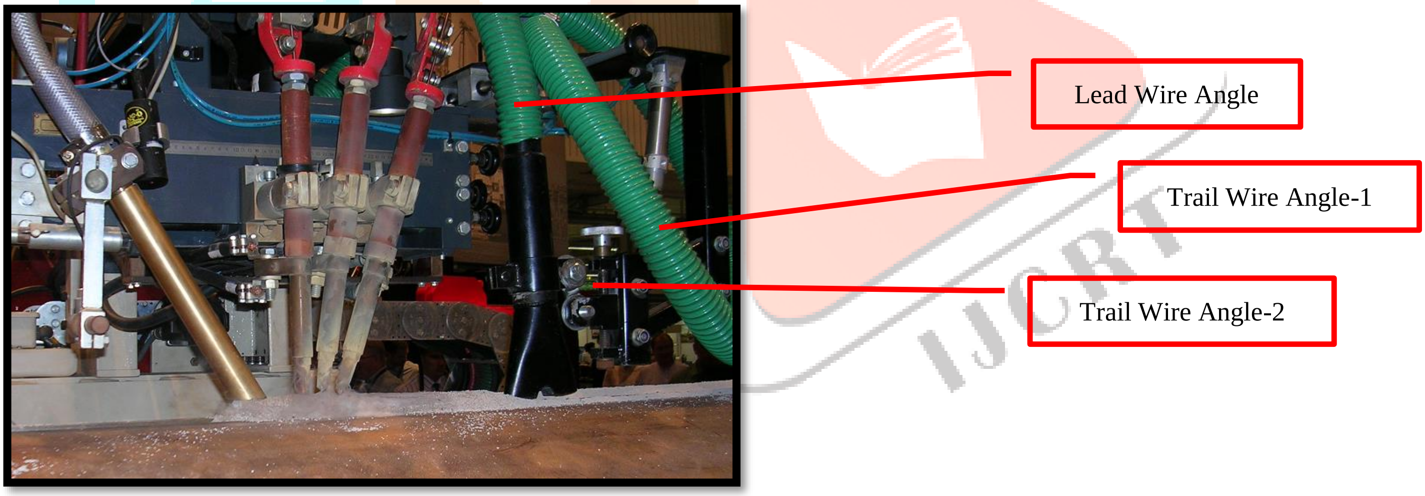
1. INTRODUCTION

[1] Submerged Arc Welding (SAW) is the preferred method in industries requiring long welds using thick steel sheets. This process creates a welded bond by submerging an electric arc beneath a granular flux blanket, forming a protective shield and slag over the weld zone. A continuously fed wire forms the arc, and arc voltage and welding current are crucial parameters. The welding speed decisively influences the depth of penetration and the width of the weld. Increased heat input can significantly reduce the mechanical properties of the weld, particularly its toughness, due to grain coarsening in the weld metal. While this increase in heat input enhances productivity, it comes with a detrimental impact on mechanical properties. For instance, bead geometry is vital for ensuring adequate penetration when welding into grooves. While a reduced wire diameter improves productivity, it can also weaken the bead's aspect ratio, potentially leading to hot cracking in certain steels. [1]

[2] Non-destructive testing (NDT) is a method used to assess materials without causing any damage. It involves inspecting and evaluating the quality of welded joints, components, and defects in welded parts, as well as comparing the characteristics of different materials without harming them. This means that the component, such as a casting, welded structure, or forged piece, can remain in use without being damaged by the NDT process. NDT is used to ensure the quality of materials at various stages, including raw material,

fabrication, and during in-service inspections. It helps determine whether the material meets reliability and durability standards, ensuring it won't fail within the expected timeframe. Non-destructive evaluation encompasses a range of terms to describe the processes involved, including non-destructive testing and non-destructive evaluation (NDE). This involves the examination and inspection to identify any irregularities, flaws, or defects in the material. NDT methods can help in selecting materials with fewer imperfections or defects, allowing for the study of the behaviour of newly produced materials. NDT can detect a variety of flaws, which can be accepted or rejected based on set standards. These flaws can range from cracks, incomplete penetration, incomplete fusion, porosity, inclusions, etc., and can vary in size, type, and location. These defects pose risks in service.

Joining processes are crucial in pipeline construction, with approximately 7000 miles of pipelines constructed annually. Various techniques are used, each with its own pros and cons for large-diameter welds. The choice of joining technique should consider ease of use, application importance, and economic impact. This process includes main connections, tie-in connections, repair of large-diameter welds, and fabrication welding. Inspections are essential due to stronger materials, environmental concerns, thinner pipe walls, high demand for pipelines, and technological advancements. Automated testing equipment, such as phased array technology, is utilized to assess weld quality efficiently by generating and receiving ultrasound signals through strategically placed elements.[2][3[When dealing with welds that are already in use, it is important to be able to assess how much the materials have degraded to ensure the weld's safety and quality. However, it's hard to remove samples from structures that are already in use. This is why it's necessary to use non-destructive methods, such as ultrasonic tests, to evaluate degradation. Ultrasonic non-destructive methods are already well-established for identifying and describing flaws in both metallic and non-metallic components, as well as in welds. However, more research is needed to determine if ultrasound could be used to assess material properties and degradation.[3]2. Machine / Materials & Methods (welding machine setting and observations)



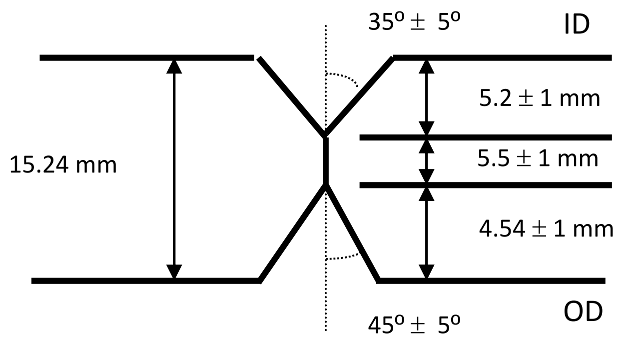
SAW Welding Setup of pipe-Fig (1)

Fig (1) this setup is commonly used for Submerged Arc welding and is specifically designed for welding API grade pipes that are intended for cross country pipelines. It is equipped with an automatic wire feeding system, a flux feeding system, and an online recovery system. The setup utilizes one main wire (DC) and two auxiliary wires (AC-1 & AC-2).

Process Variables for SAW: There are various factors that can affect the appearance and mechanical properties of the weld when altered.

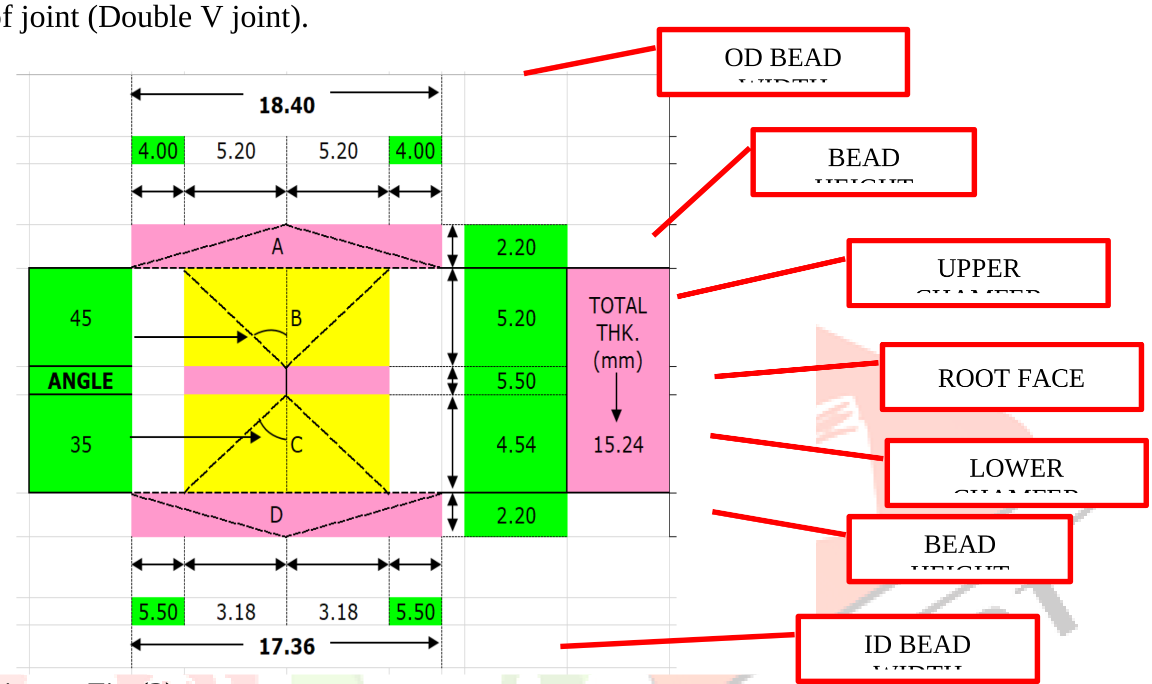
Bevel Geometry: The bevel design will differ depending on the type of joint being welded (butt joint, T-joint, corner joint, etc.). When selecting the joint configuration, take into account the strength and load-bearing capacity required for the joint.

Double-V Butt Joint: Both edges of the workpieces are bevelled to create V-shaped grooves. This type of joint needs welding from both sides to ensure proper penetration and fusion.



Bevel Geometry for SAW – Fig (2)

Fig (2) - Fig (2) - For Submerged Arc Welding setup, the appropriate bevel geometry is required for a specified wall thickness (15.24 mm). Bevel Geometry defines the upper bevel angle, lower bevel angle, root face, and the type of joint (Double V joint).



For API pipes – Fig (3)

Fig (3) – For double V joints, the welding terminology includes specific joints for SAW, such as ID and OD welding bead height, upper and lower bevel, and root face with bevel angles.

AREA				LENGTH
A	B	C	D	
mm^2	mm^2	mm^2	mm^2	mm
20.24	27.04	14.43	19.09	1000

VOLUME					WEIGHT
A	B	C	D	TOTAL	
mm^3	mm^3	mm^3	mm^3	mm^3	KG
20240	27040	14432	19094	80806	0.63

Bevel Design Volumetric calculation – Fig (4)

Fig (4) – In a double V bevel design, it is important to calculate the area and volume of the ID OD weldment to establish the mechanical properties of submerged arc welding (SAW). The double V bevels, as shown in

Figure (3) sections A, B, C and D, define the area (mm2) and volume of the weldment (mm3), and the wire feed calculation provides specific results for the length per weight of welding electrodes during welding.

[4] Submerged arc welding is well-known for its ability to use high weld currents, thanks to the properties and functions of the flux. This allows for deep penetration and high deposition rates.

• Boosting the current results in increased penetration and a faster wire melt-off rate.

• Excessive current produces a deep, penetrating arc, leading to burning through, undercutting, or the formation of high, narrow beads that are prone to solidification cracking.

• Insufficient current may lead to an unstable arc, inadequate penetration, and potential lack of fusion.

ID WELDING PARAMETERS			
	AMP	VOLT	SPEED (CM/MIN)
DC	820	32	150
AC	765	34	
OD WELDING PARAMETERS			
	AMP	VOLT	SPEED (CM/MIN)
DC	1075	28	150
AC	750	30	
TOTAL HEAT INPUT		41.90 KJ/CM	

Welding Parameters (Before) - Fig (5)

Fig (5) – The welding process variables are defined as the lead (DC) and trail (AC) current, along with the voltages (DC and AC), welding speed, welding heat input, and wire feed speed, together with the actual running welding parameters. Figure 5 outlines the conditions before optimizing weld quality with welding variables.

The adjustment of arc voltage affects the arc length. If the arc voltage increases, the arc length also increases, and vice versa. The voltage mainly determines the shape of the weld bead cross-section and its external appearance. [4]

ID WELDING PARAMETERS			
	AMP	VOLT	SPEED (CM/MIN)
DC	825	34	150
AC	770	36	
OD WELDING PARAMETERS			
	AMP	VOLT	SPEED (CM/MIN)
DC	1100	30	150
AC	775	32	
TOTAL HEAT INPUT		45.42 KJ/CM	

Welding Parameters (After) – Fig (6)

Fig (6) – Optimizing welding parameters involves adjusting the internal welding settings. The lead current is set at 850A (DC) with 34V (DC), while the trail current is 770A (AC) with 36V (AC). The welding speed is kept constant at 150 cm/min, while the welding heat input is increased to 45.42 KJ/CM. This is done to achieve a wider Heat Affected Zone (HAZ) in a Double V bevel joint during welding.

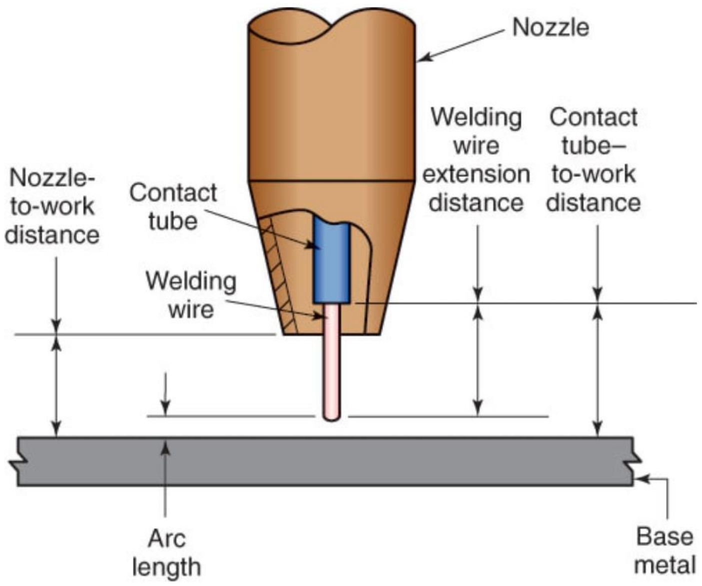
[5] Electrode Size-In Submerged Arc Welding (SAW), the size of the electrode plays a crucial role in determining the efficiency and quality of the welding process. SAW is a welding method that uses a continuous, consumable electrode and a flux blanket to shield the arc and the molten weld pool. The electrode

size refers to the diameter of the electrode wire used in the process.

The choice of electrode size in SAW depends on several factors, including the material being welded, the joint configuration, the welding current, and the desired welding speed. In Fig (4) and Fig (5), the size of the electrodes for Lead wire (DC) and trail wire (AC) is kept constant at 4.0mm each in External Welding (OD) and Internal Welding (ID).[5]

[6] Electrode extension: also known as "stick-out" or "arc length," is the distance between the end of the welding gun or torch and the tip of the welding electrode (welding wire). This distance is a crucial parameter in SAW welding, as it influences the electrical characteristics of the welding arc, the heat input, and the overall weld quality.

The electrode extension refers to the distance that the continuous electrode sticks out beyond the contact tip. At high current densities, the resistance heating of the electrode between the contact tip and the arc will significantly increase the electrode melting rate by 25-50%. The longer the extension, the more heat is generated, resulting in a higher rate of melting. [6]

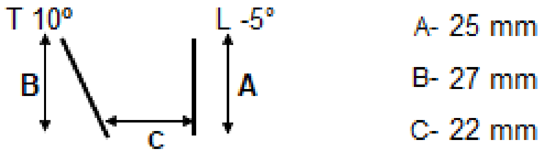


Electrode Extension – Fig (7)

Fig (7) –Reference of Electrode extension taken from CSWIP book TWI UK from SAW process chapter. For both external (OD) and internal (ID) welding, the Stick Out (Electrode Extension) with references in Figure 8 is A=25 mm and B=27 mm. The electrode extension is important for controlling the amount of heat applied to the weld joint. A longer extension typically results in higher heat input, which can impact the depth of penetration and fusion of the weld. The electrode extension affects the depth of penetration into the base material and the shape of the weld bead. A longer extension might lead to deeper penetration, while a shorter one could result in a shallower weld.

[7] The electrode extension affects the fusion between the base metals and the electrode wire. Improper electrode extension can result in incomplete fusion, inadequate sidewall fusion, and other defects. The ideal electrode extension in SAW welding is influenced by factors such as welding current, electrode diameter, base material thickness, joint design, and desired weld characteristics. Welding procedure specifications (WPS) provided by welding codes or manufacturers typically include guidelines on electrode extension for different welding scenarios.

It is crucial to maintain a consistent electrode extension to ensure consistent weld quality. Welders should adhere to recommended electrode extension guidelines and adjust them based on specific welding conditions and joint requirements. [7].



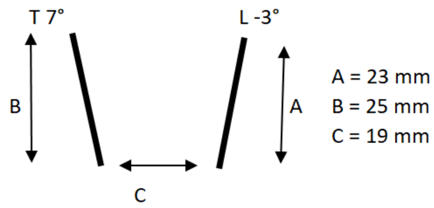
Electrode angle (leading, trailing) Before - Fig (8)

Fig (8) – Welding head settings with both electrodes (DC) and (AC) were adjusted before optimizing weld parameters. The lead wire (DC) stick out A was set to 25 mm, while the trail wire (AC) stick out B was set to 27 mm, with wire spacing C set to 22 mm. The setup included lead wire angle (DC) at -5° and trail wire angle (AC) at 10°.

[8]In SAW welding, the angle of the electrode significantly affects the weld quality, penetration, and overall performance. The electrode angle refers to the orientation of the welding electrode in relation to the joint being welded. Two primary angles should be considered.

Work Angle: The work angle, also known as the travel angle or drag angle, is the angle at which the electrode is inclined in relation to the direction of welding travel. It affects the direction of heat transfer and the shape of the weld bead. Typically, a slight leading or trailing angle (usually around 5–15 degrees) is used. A leading angle directs more heat toward the base metal, while a trailing angle directs more heat toward the deposited metal.

Tilt Angle: The angle refers to the tilt or incline of the electrode perpendicular to the joint being welded. It impacts the depth of penetration and the overall profile of the weld. A slight tilt of around 5–10 degrees is often used to control the depth of penetration and achieve the desired weld shape. [8]



Electrode angle (leading, trailing) After - Fig (9)

Fig (9) – In order to improve the weld bead shape and depth of penetration on both the internal (ID) and external (OD) sides, we adjusted the welding head settings for a Double V bevel joint according to Figure 2. We changed the lead wire (DC) stick out to A = 23 mm and the trail wire (AC) stick out to B = 25 mm, with a wire spacing of C = 19 mm. Additionally, we set the angles of the lead wire (DC) to -3° and the trail wire (AC) to 7°. These adjustments also helped us maintain the proper weld bead shape. The optimal electrode angles can vary depending on factors such as joint configuration, welding current, electrode diameter, base metal thickness, and specific welding procedure requirements. Welding parameters like voltage, current, travel speed, and electrode extension also interact with electrode angles to influence the final weld quality.

Polarity: Two types of polarities are commonly used in SAW welding: direct current electrode positive (DCEP) and direct current electrode negative (DCEN).

[9]In DCEP polarity, the electrode is connected to the positive terminal of the welding power source, and the workpiece is connected to the negative terminal.

In DCEN, the electrode is connected to the negative terminal of the welding power source, and the workpiece is connected to the positive terminal. [9]

[10]The choice of polarity depends on factors such as welding speed, penetration, and the material being welded. Different applications and materials may benefit from one polarity over the other. Manufacturer's welding procedure specifications and guidelines for specific setups and materials. With when it comes to SAW welding, you can choose between single-wire, double-wire, and multi-wire systems, each offering specific advantages and applications.

In single wire SAW, one electrode wire creates the welding arc and feeds filler metal into the joint. It's commonly used for straightforward welding of thicker materials with less strict requirements for speed and efficiency.

The double-wire submerged arc welding (SAW) system involves feeding two electrode wires simultaneously into the weld pool. This setup boosts the deposition rate, enabling higher welding speeds. The double-wire SAW is commonly used for higher productivity and can be especially effective for welding thicker materials. [10]

[11]The multi-wire submerged arc welding (SAW) process involves using more than two electrode wires, often arranged in a circular or semi-circular configuration around the joint. This system offers even higher deposition rates and welding speeds compared to single- or double-wire systems. Multi-wire SAW is suitable for heavy-duty welding applications where maximum efficiency and productivity are essential. It is often used in industries such as shipbuilding, structural steel fabrication, and the construction of large-scale infrastructure.

The selection of wire-system configurations depends on factors such as the material to be welded, joint design, welding speed, deposition rate, and project specifications. Multi-wire systems can improve productivity, but they necessitate more complex equipment and setup, and ensuring weld quality is still essential maintained. [11]

[12] **Off canter (In case of Spiral pipe):** Before welding, the pipes need to be properly prepared. This includes cleaning the surfaces to be welded to remove any dirt, rust, or contaminants. Joint configuration, fit-up, and alignment are crucial for a successful weld. [12]

[13] Welding Machine: Set up the SAW welding machine with the appropriate power settings, electrode feed rate, and voltage based on the pipe's material thickness and diameter.

Rotating Fixture: The pipe is mounted on a rotating fixture or positioned, which can be manually controlled or automated. The rotation speed should be adjusted to ensure even and consistent welding.

When using the off-centre technique in spiral pipe welding, the welding torch or electrode is intentionally positioned slightly off-centre from the joint. This method helps prevent excessive overlap and undercut at the edges of the joint, thus improving the overall weld quality and reducing the likelihood of defects. Additionally, off-centre welding helps control the heat input into the joint, which is crucial in pipe welding to avoid distortion and maintain structural integrity. By adjusting the torch position, we can achieve a more controlled and consistent weld.[13]

[14] Avoiding Burn-Through: In situations where the base metal is relatively thin, off-centre welding can prevent burn-through. This occurs when too much heat is applied to the material, causing it to melt. By focusing the heat slightly away from the centre of the joint, you can help prevent this issue.

Penetration: Proper penetration is crucial for creating a strong and durable weld. Off-canter welding can help ensure that the weld penetrates fully into the joint, creating a solid bond between the two pieces of metal. [14]

Non-Destructive Testing (NDT)

[15] Non-destructive testing (NDT) is essential for assessing the quality of pipes used to transport oil and gas. In this study, we employed automated ultrasonic testing (UT), phased array manual UT, and digital X-ray techniques to evaluate weld quality after modifying welding parameters. Although NDT techniques are widely used for various types of inspections, this study focuses specifically on weld quality.

Non-Destructive Testing (NDT) in SAW Pipe Welding: Importance and Techniques

NDT plays a pivotal role in ensuring the integrity and reliability of welds in Submerged Arc Welding (SAW) pipes, which are widely used in the oil and gas industry. The significance of NDT lies in its ability to detect potential defects without damaging the welded components, ensuring that the welded pipes meet stringent quality standards. [15]

Importance of NDT in Welding

[16] Welded pipes are prone to various defects during fabrication, such as cracks, porosity, and lack of fusion, which can compromise their performance under operational stress. NDT methods are crucial for identifying these defects early in the manufacturing process. Detecting and rectifying flaws before the pipes are deployed ensures long-term durability and safety, reducing the likelihood of failures that could lead to costly repairs or catastrophic accidents. [16]

Ultrasonic Testing (UT)

[17] Ultrasonic Testing is one of the most effective NDT methods for inspecting welds in SAW pipes. It involves the use of high-frequency sound waves to detect internal flaws within the welded joints. UT is particularly effective for identifying subsurface defects, such as lack of fusion, slag inclusions, and cracks, which may not be visible on the surface.

In this study, automated UT with a probe configuration of I+X+I+X was employed. This setup allowed for comprehensive coverage of the weld area, enabling the detection of both longitudinal and transverse defects. Manual Phased Array UT was also used, providing a detailed sectorial scan (S-scan) image of the weld. This method allows for precise localization and characterization of defects, making it a valuable tool for ensuring the weld's structural integrity. [17]

Digital X-Ray (Radiography)

[18] Digital X-ray radiography is another advanced NDT technique used in this study. Unlike traditional radiography, digital X-ray provides high-resolution images with enhanced contrast, enabling the detection of fine defects such as porosity and slag inclusions. The process involves passing X-rays through the weld and capturing the image on a digital flat panel detector, which is then analyzed for defects.

The use of digital radiography offers several advantages, including real-time imaging, faster inspection times, and the ability to archive and enhance images for detailed analysis. This method is particularly useful for inspecting the internal structure of welds, providing a clear picture of any imperfections that may compromise the pipe's quality [18].

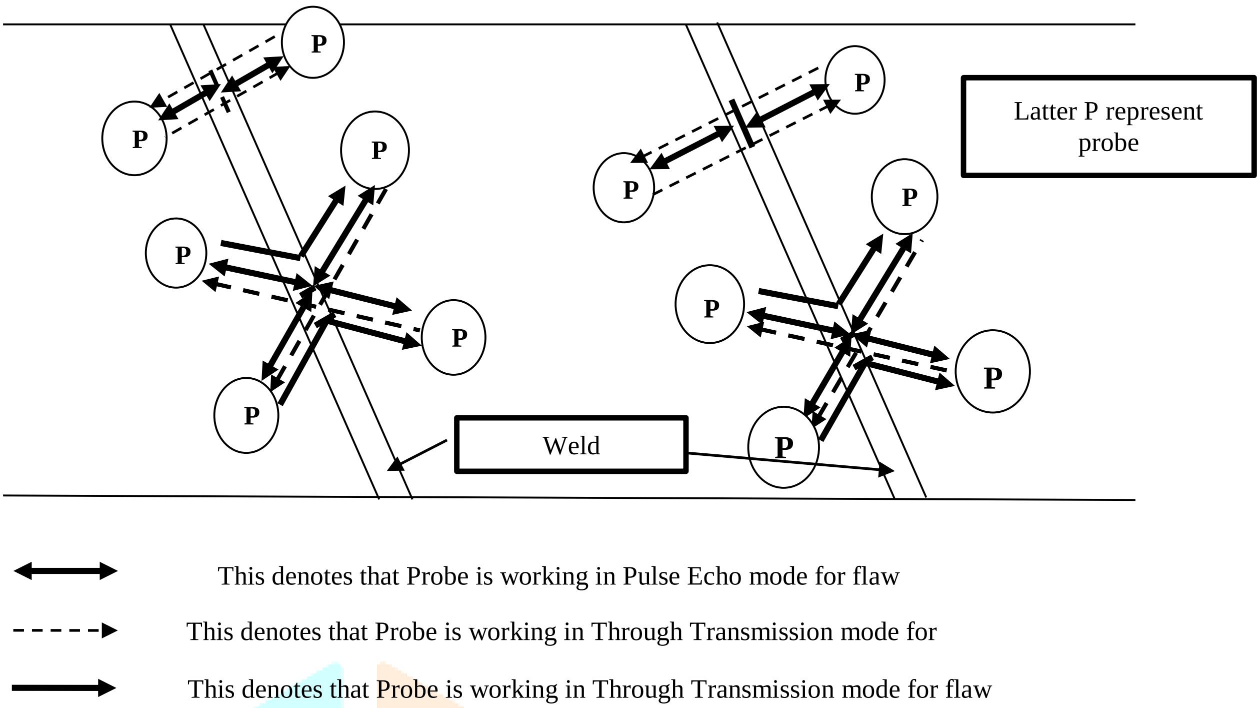
EQUIPMENT'S USE

AUTOMATED WELD UT

BRAND NAME : GE INSPECTION TECHNOLOGIES

TYPE OF MACHINE : SNUP-SP/LO-OFF

Mode of testing : PROBE CONFIGURATION (I+X+I+X mode)



Probe configuration (I+X+1+X) – Fig (10)

Fig (10) - Automatic weld machine setup consisting of 12 transducers and installed with I+X+1+X configuration to detect longitudinal and transverse defects.

Calibrated with N5 notches on weld tows on ID and OD & 1.6 mm TDH on weld centre line.

PHASED ARRAY MANUAL UT

The ultrasonic phased array instrument—Olympus made Omni scan pulse-echo type—is equipped with a calibrated dB gain or attenuation control stepped in increments of 2 dB or less. The Omni Scan contains 16 independent pulser/receiver channels. The system can generate and display Sectorial scan (also called S-scan) images and is calibrated with 1.6 mm through drilled hole for sensitivity.

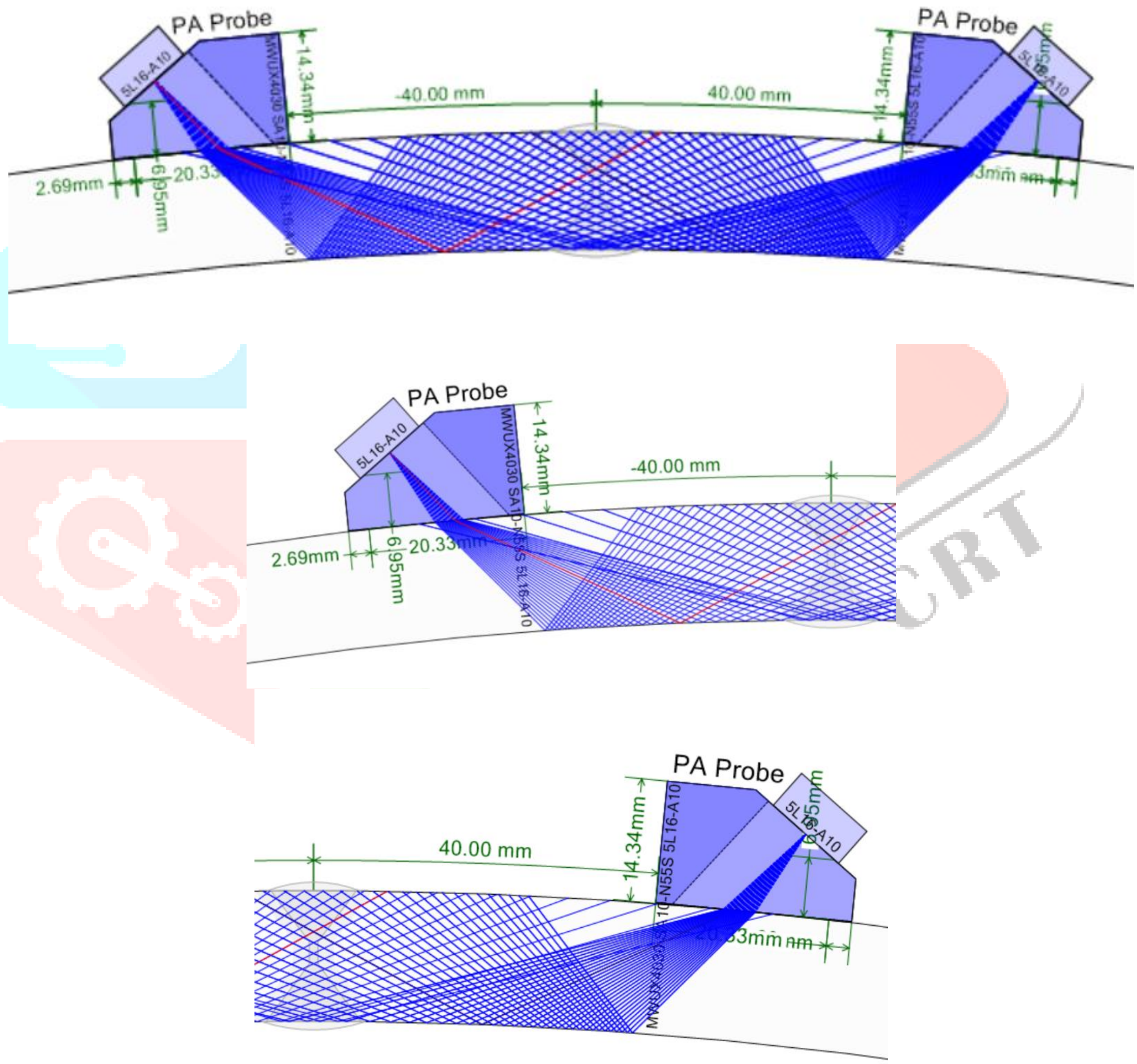
Search Unit:

PROBE	Frequency	Number of elements	pitch	Active Aperture	Elevation
5L 16 A10	5 MHz	16	0.60 mm	9.6 mm	10 mm

Wedge:

Wedge	Probe type	Nominal Refracted Beam Angle (in steel)
SA10-N55S	A10	55 degree

Scan Plan (ES Beam scan plan to show full weld coverage with above Phased Array transducer and wedge):



Digital Radiography

X-ray Equipment:

Instrument type – Constant Potential Unit, Model- MG 226, 225 kV, 7 mA
Make – Y xlon International, Denmark
X-ray Tube – Metal –Ceramic, Cone beam, Focal spot -0.4mm & 1.0mm
Cooling Unit – Water cooling unit

Digital Flat Panel Detector:

Make – PerkinElmer
Model - XRD 0822
Receptor Type – Amorphous Silicon Detector
Pixel Area – 204.8 x 204.8 mm²
Pixel matrix Total – 1024(h)x1024(v)
Resolution – 3.94 lp/mm

Image Enhancement & Archiving System:

Model & Make – Y xlon Image 3500 System

It was designed for inspection systems using a digital flat panel detector to create, enhance, and archive 8-bit and 16-bit X-ray images with a very high dynamic contrast range..

Y xlon Multi-Axis CNC Controller:

The Y xlon Multi-Axis CNC Controller is a programmable, high performance servo motion capable of commanding 32 axes of motion simultaneously. CNC controller can be set-up with several different programs which can control following:

a) Speed, start & end position of wagon in automatic mode.
b) X-ray tube & flat panel position.
c) X-ray voltage, current and focal spot selection.
d) Door and carriage safety interlocks.

Sensitivity: 1.5% or better with wire type IQI

Result Before and after applying all modification/points/standard setting explained above (Sample size 100 pipes)

Before Modification (Sample size 100 pipes each before and after modification)

Result Table

	UT result before standard setting (no. of pipes with defect)	UT result after standard setting (no. of pipes with defect)	Digital X-ray result standard setting (no. of pipes with defect)	Digital X-ray result after standard setting (no. of pipes with defect)
Lack of fusion	3	0	2	0
Lack of penetration	1	0	1	0
porosity	6	2	7	2
slag	5	2	6	2
Off-seam/undercut	1	0	1	0
Crack	0	0	0	0
Other	5	1	4	1

Note: all pipes are tested through both methods (UT and Digital X-ray), and most defects are found by both methods.

The results table presents a comparison of defects detected in pipes before and after the implementation of standard settings using both Ultrasonic Testing (UT) and Digital X-ray techniques. A significant reduction in the number of defects is observed after the standard settings were applied. For instance, lack of fusion and lack of penetration defects were eliminated, as no defects were detected post-standard setting for both UT and Digital X-ray methods. Similarly, the occurrence of porosity, slag, and other defects decreased considerably, though not eliminated. The reduction in defects indicates the effectiveness of the standard setting in improving the detection and quality control process. The consistent results between UT and Digital X-ray methods after the implementation further highlight the robustness of these non-destructive testing techniques in enhancing inspection reliability. For Result 100 Pipes tested before and after standardizing setting

CONCLUSION

When choosing the right NDT technique and testing pipes at the appropriate stage of production, benefits include standard, high-quality zero-defect products, real-time production quality monitoring, and reduced production costs. This paper aims to explore the current state of non-destructive automatic ultrasonic control techniques and their potential applications.. Ultrasonic and digital radiography is the advanced preferred mode of testing as an alternative when needed. The advanced testing mechanism adopted has yielded almost 200% accuracy. It is important to note that there is a strong correlation between the type of defect and its location, whether it is on the surface or subsurface. Subsurface discontinuities generally require more time and cost to detect compared to surface defects. Subsurface defects take longer to be detected, and they are usually identified using recommended speed Radiography. If this is not possible, Ultrasonic testing can be used for detection, and the results should be validated using a Digital x-ray.This study demonstrates that optimizing welding parameters can significantly improve the quality of welded joints. By applying the discussed modifications, we successfully reduced common weld defects, as verified through NDT methods. Future research should explore further refinements in process variables to achieve even better outcomes.

REFERENCES

1. Joseph Sekyi-Ansah, Isaac Dadadzogbor,Stephen Edukul,Justine Justice Apegase Atarah, Julius CaesarPuoza, Adams Morro5Investigations of Weldment Joints of Exhaust Pipes Using NonDestructive Testing (NDT)
2. Mehmet Cagirici-NON-DESTRUCTIVE INSPECTION OF GIRTH WELDS BY PHASED ARRAY AND TOFD METHODS-MATTER VOLUME 2 ISSUE1,2015
3. B.VargasArista,A.Balvantin,A.Baltazar,F.García-Vázquez-On the use of ultrasonic spectral analysis for the characterization of artificially degraded API 5L X52 steel pipeline welded joints-Materials Science and Engineering:A-Volume 550,30 July 2012, Pages 227-234
4. R.S.Chandel,H.P.Seow,F.L.Cheong -Effect of increasing deposition rate on the bead geometry of submerged arc welds-.
5. CSWIP 3.1 & 3.2 Training and Examination Services Granta Park, Great Abington Cambridge CB21 6AL, United Kingdom.
6. Sharma, K. (2023). Analysis of Non-destructive Testing for Improved Inspection and Maintenance Strategies. e-Journal of Nondestructive Testing. https://doi.org/10.58286/28287
7. Dutta, R., & Ray, A. (2019). Advances in Submerged Arc Welding for Pipeline Applications. *Journal of Materials Processing Technology*, 273, 116244
8. Yang, J., Zhang, Y., & Li, M. (2020). Effect of Welding Parameters on the Microstructure and Mechanical Properties of Submerged Arc Welds. *Welding Journal*, 99(5), 146S-153S.
9. García-Martín, J., Gómez-Gil, J., & Vázquez-Sánchez, E. (2018). Non-Destructive Techniques Based on Eddy Current Testing. *Sensors*, 18(2), 383.
10. Hassan, M., & Abdellatif, A. (2019). Digital Radiography in Non-Destructive Testing: Techniques and Applications. *International Journal of Advanced Manufacturing Technology*, 104(9), 3981-3995.
11. Venugopal, T., & Venkataraman, G. (2017). Non-Destructive Testing in the Oil and Gas Industry: Challenges and Opportunities. *Journal of Petroleum Technology*, 69(8), 1083-1092.

12. Zhou, Zhi, et al. "Ultrasonic Testing Techniques for Inspecting Steel Pipes in Industrial Applications." Journal of Nondestructive Evaluation 39.3 (2020): 1-14.
13. *Koch, Andreas. "Digital Radiography in Non-Destructive Testing: Introduction and Methodology." Insight-Non-Destructive Testing and Condition Monitoring* 54.11 (2012): 617-621.
14. *Peters, Albert M., and Hugh McConnell. "Digital Radiography: Advantages and Challenges in Nondestructive Testing." Materials Evaluation* 78.7 (2020): 905-910.
15. *Brown, C., & Smith, R. (2021). Integrating Non-Destructive Testing with Advanced Welding Techniques. Welding in the World, 65(4), 633-641.*
16. *Krautkrämer, Josef, and Herbert Krautkrämer. "Ultrasonic Testing of Materials." Springer Science & Business Media, 2013.*
17. *Schmerr Jr, Lester W. "Fundamentals of Ultrasonic Nondestructive Evaluation: A Modeling Approach." Springer Science & Business Media, 2013.*
18. *Erhard, Andreas, et al. "Digital Radiography: Technology, Methods, and Applications." Nondestructive Testing Handbook, Third Edition: Volume 4 Radiographic Testing. ASNT, 2016.*