NTU Journal of Engineering and Technology (2025) 4 (2) : 80-86
DOI: https://doi.org/10.56286/ntujet.v4i2

IRAQI Academic Scientific Journals

P-ISSN: 2788-9971 E-ISSN: 2788-998X
NTU Journal of Engineering and Technology
Available online at: https://journals.ntu.edu.iq/index.php/NTU-JET/index

The Effect of Preheating on Weld Defect Formation Using X-ray Radiography

Elaf Ahmed Ali[1], A. D. Younis[1]
[1] Department of Mechanical Engineering, College of Engineering, University of Mosul /Mosul 41002/ Iraq.
elaf.22enp68@student.uomosul.edu.iq, alaayonis@uomosul.edu.iq.

Article Informations

Received: 14-12-2024,
Revised: 25-03-2025,
Accepted: 11-04-2025,
Published online: 23-06-2025

Corresponding author:
Name: Elaf Ahmed Ali
Affiliation : University of Mosul
Email: elaf.22enp68@student.uomosul.edu.iq

Key Words:
welding process,
Crack,
Heat Input,
GTAW & SMAW,
radiography test.

A B S T R A C T

The manufacturing of long-section pipes is expensive and demands sophisticated procedures, requiring the assembly of smaller pipes by welding. Welding is essential in the oil and gas sectors and several other industries. A welding procedure was executed on two ASTM A106 grade B pipes utilizing GTAW and SMAW techniques for four layers. Testing identified a transverse crack in a welded joint (Test No-01A) at site 20, measuring 4 mm. A PMI test established the chemical composition of the weld joint. A key factor contributing to cracks is the temperature disparity between the weld zone and the base metal. To alleviate this, the joints were warmed prior to welding, The results showed that preheating the metal before the welding process reduces or prevents the occurrence of cracks by minimizing the temperature gradient between the base metal and the welding temperature. As the PMI test findings revealed discrepancies in the chemical composition of the welded joints prior to and subsequent to welding, attributable to chemical reactions throughout the operation. These findings underscore the influence of temperature and chemical alterations on weld integrity.

1. Introduction

Throughout history, various methods for metal joining have been employed, with forge welding by blacksmiths being the dominant technique for much of this period. Steel is a crucial engineering material with diverse uses across several domains. It is distinguished by providing an extensive array of mechanical and other features at a cost-effective rate.[1].However, it was not until the late 19th century that innovative welding methods began to develop. In the past, crafting tools and weapons involved various techniques like hammering and heating metals, which are recognized as some of the earliest welding forms. [2].

It is a manufacturing technique that has two or more elements joined by the action of heat and/or pressure to obtain a connection. This technique is widely used in a lot of industries and in construction too [3].

First, heating up the pieces reduces the metal to its molten stage, cools down, and thereby solidifies to form a strong, durable bond. This process plays a significant role in many industries, namely, the construction of huge structures ranging from bridges to skyscrapers, the manufacture of all types of transport-from automobiles to aircraft-and in making large machinery, as well as major electronic appliances. Successful welding, in fact, requires an optimum regulation of many parameters, like the temperature to be applied, heating time, and amount of pressure. Competent welders and engineers must efficiently handle these variables to achieve optimal weld quality. Furthermore, safeguarding the welding zone from air pollutants is essential. Exposure to air can induce oxidation and introduce contaminants that compromise the reliability of the weld. To avoid this, shielding gasses or alternative preventive measures are frequently utilized [4].

Temperature makes an essential contribution to determining the behavior of steel, which tends to become brittle at low temperatures[5].

The impact of temperature variations during the welding process on crack formation was examined through extensive literature research and experimental testing of many factors.

S. Odebiyi [6] and associates performed an extensive evaluation of carbon steel welding using arc-based methods, utilizing software tools to examine the influence of welding settings on microstructure and mechanical characteristics. Welding ability is greatly influenced by the carbon equivalent (CE), which determines preheat temperatures and ensures weld reliability; high carbon content diminishes welding ability and increases the danger of cold cracking. The findings demonstrated that enlarging heat input enhances weld quality by refining the microstructure and improving durability while concurrently reducing resistance in the heat-affected area.

Balram Y. [7] and team examined, in a research work, the impact of thermal input on weld imperfections in dissimilar joints of AISI 316 stainless steel and Monel 400. The team, using the Gas Tungsten Arc Welding process, examined 120, 130, and 140 A welding currents with the help of a 235X X-ray radiography machine manufactured by CEREM. The testing results of 130 and 140 A welding currents gave defectless joints, whereas, at 120 A, a line crack emerged due to the lack of enough heat input. At the end of the work, it could be concluded that the use of 130 and 140-A currents allows for excluding defects in the high-quality joining of dissimilar metals.

M. Taghipour [8]and colleagues investigated the cause of failure in a flange-pipe weld joint within a steam line at an ammonia plant, using SYSWELD software to simulate residual stress distribution. The results showed a coarse microstructure in the weld root area, including Widmanstätten ferrite, with lower hardness due to large grain size. The simulation revealed high residual tensile stress that contributed to crack initiation. The failure was attributed to improper welding parameters, which led to a weakened root structure. Li Liying [9] and colleagues studied the microstructure and mechanical properties of welded joints in L415/316L bimetal composite pipes to reduce costs and improve quality. They conducted various tests such as tensile, bending, and hardness tests using in-depth analysis techniques. Results indicated that mechanical properties met standards, with bending test cracks attributed to martensite formation. Moreover, the study found that ER309MoL welding wire is unsuitable for 316L, supporting the post-internal welding process.

Pushp Kumar Baghel [10] research focused on the investigation of parameters of Shielded Metal Arc Welding (SMAW) and its effect on stainless steel and dissimilar base materials weld quality. Different types of electrical electrodes were used to conduct practical experiments on copper and stainless steel, 304 samples. Researchers observed that choosing the proper electrodes (for example, Inconel ENiCrMo3) massively improves the quality of the weld and minimizes the chances of defects occurring. For example, this can be accomplished through optimal weld parameter design to create resilient, defect-free welds.

The focus of this research is to evaluate the correlation and relationship of the temperature difference between the input temperature and a comparatively variant temperature during the bin-aiding and solidifying copper pathology process on the onset and upsurge of fractures in the steel characters pipes. The objective of the research is to study the thermal variations and chemical analysis before and after the welding process using specialized welding techniques and to analyze the impact of these variations on the occurrence of defects in the weld zone through X-ray inspection.

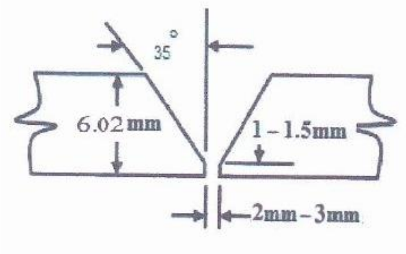
2. EXPERIMENT

2.1 Materials and Welding Procedure

Several samples were prepared for welding carbon steel pipes, each with a diameter of 4 inches and a thickness of 6.02 mm, by creating grooves between the joints for welding in a V-shape at a 70°-degree angle with a root face value of 1.5 mm and a root opening of 3 mm as illustrated in Fig.1 The welding process was performed in four stages to ensure high-quality welds, as shown in Fig.2, where the ER70S filler wire was selected due to its compatibility with the chemical composition of the base metal for the welded joints using the GTAW welding method in which the tungsten electrode is negative, and the base metal is positive. The chemical composition of the base metal is shown in Table 1. As a shielding gas, Argon gas was used at a flow rate of 8 to 16 liters per minute to prevent oxidation in the base metal for the root and hot layers. All the details above fall under the GTAW welding method.
Subsequently, the electrodes were changed to the E7018 filler wire, with the tungsten electrode being positive and the base metal harmful, to fill the final weld layers, which are the fill and cap, using the SMAW arc welding method. To complete the welding process, Table 2 includes the mechanical properties of the metal used in the welding process. The heat input to the base metals was calculated using Equation 1 [14].

$$\text{Heat input (HI)} = \frac{V*I*60}{S*1000} \quad (1)$$

This equation considers the welding voltage (V), current (I), and welding speed (S), as shown in Table 5. Heat input is expressed in kilojoules per millimeter (kJ/mm) and serves as a key indicator of the thermal energy transferred to the weld zone. It directly influences the microstructure and mechanical properties of the welded joint. The calculated values were based on the standards defined in the Welding Procedure Specification (WPS) according to ASME codes.



Root opening: 2mm to 3mm
Thickness: 6.02 mm
Root face: 1mm to 1.5 mm
Groove angle: 70 degree

Fig. 1. Schematic diagram of weld groove design

Table 1. Weld chemical composition: before the welding process

Alloy Elements (w/%) of base metal chemical composition before the welding process.					
Elements and their %	C	p	Ni	Cu	Others
	0.14	0.02	0.3	0.35	S=0.003, Mo=0.15, Al=0.06, N=0.012, B=0.0005, Ti=0.04 Ca=0.006, Nb=0.01
	Mn	Si	V	Cr	
	1.35	0.4	0.01	0.03	

The design of the weld groove plays a critical role in weld quality and defect formation. Parameters such as groove angle, root face, and root opening affect heat input, melting characteristics, and stress distribution during the welding process. Selecting an inappropriate groove angle may lead to excessive heat input or insufficient fusion, increasing the likelihood of defects such as porosity, lack of fusion, or edge defects. Therefore, choosing the optimal groove geometry is essential to minimize defects and improve the performance of the welded joint.

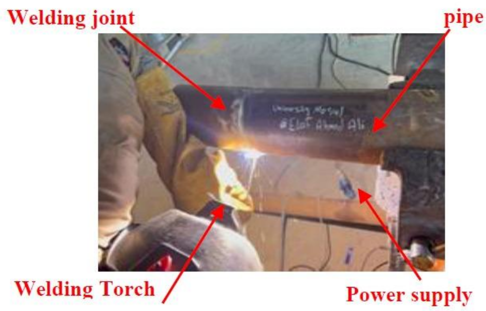


Fig. 2. Welding process

2.2 Positive Material Identification (PMI)

The SciAps Z902 C+ Premium uses Laser-Induced Breakdown Spectroscopy (LIBS) to determine chemical elements by generating plasma through a laser pulse on the sample, which give us the opportunity to have precise and efficient analysis of both metallic and non-metallic materials. The SciAps X200, on the other hand, relies on X-ray fluorescence (XRF) technology to determine composition of the elements through exhilarating atoms and emitting photons at characteristic wavelengths, making it suitable for field analysis of metals soils and raw materials.

Table 2. Mechanical properties of carbon steel

Materials	Tensile Strength (MPa)	Yield Strength 0.2 % (MPa)	Elong-ation (%)	Microhar-dness (HRB)
ASTM A106	445	310	49	144

These portable devices provide high accuracy and are widely used in research and industry for material composition analysis.[11] Both devices were used to perform Positive Material Identification (PMI) testing, with measurements taken before and after welding. The numerical results of the PMI test are presented in Tables 1, 3, and 4, showing the changes in chemical composition and highlighting the impact of the welding process on the sample constituents. As shown in Fig. 3.

Fig. 3. PMI equipment used: a) SCIAps x200 b) SciAps Z902 C+ Premium

2.3 X-Ray Radiography Test

The X-ray flaw detector from ZHONG YI NDT CO. LTD, operating at 300kV and 5mA, equipped with a control panel and serial number 42357, is manufactured in China, as shown in Fig.4. This device is used to detect internal flaws in metallic materials by allowing X-rays to penetrate the material and identify any hidden cracks or voids. It is suitable for industrial inspection applications such as pipe inspection. It is an essential part of non-destructive inspection (NDT) techniques that help assess the integrity of materials without causing any physical damage to the material. X-ray inspection of samples was used to detect weld flaws[12].

Fig. 4. a) X-Ray Flaw Detector b) Control Panel

2.4 Microstructure Analysis

The microstructure of 0.24% carbon steel mostly comprises a combination of ferrite and pearlite phases. At this carbon concentration, ferrite—a malleable and ductile phase—dominates, but pearlite, consisting of alternating layers of ferrite and cementite, is present in lesser quantities. This amalgamation yields a balanced framework that offers moderate strength along with commendable ductility. The ferritic portions boost the steel's malleability, while the pearlitic sections improve its hardness and wear resistance. This microstructure is optimal for applications necessitating a blend of toughness and moderate strength. The figure below shows the companion of the specimen microstructures shown in Fig.5.

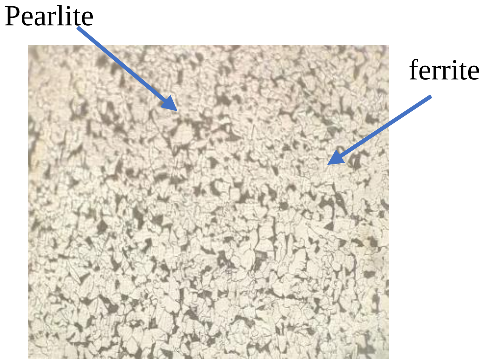


Fig. 5. Description of the microstructure of 0.24% carbon steel

The presence of ferrite provides ductility that helps absorb the thermal stresses generated during the welding process, thereby reducing the likelihood of crack formation. As for pearlite, its hardness and strength enhance the mechanical integrity of the welded joint. Therefore, the balance between ferrite and pearlite is a crucial factor in achieving strong welds that are resistant to common defects.

3. RESULTS AND DISCUSSIONS

After the welding process was carried out for the used models, an X-ray examination of the welding was performed. The results (Test No-01A) showed the presence of an apparent crack, as shown in Figure 6, where it was shown that the reason for the appearance of this crack is attributed to the difference in temperatures between the welding area and the metal. A welding (Test 3) was conducted, considering the preheating process of the welded joint. The X-ray inspection results showed no cracks within the weld layers. This is attributed to the minimal difference between the weld zone and the base metal, as the base metal was heated to a temperature of 80°C, as shown in Figure 7. While the sample (Test No 01) showed some defects due to considering the effect of the current on the welding process, a current of 100 amperes was used for welding the sample (Test No 01). It was found that this current value was insufficient to avoid defects resulting from the welding process due to inadequate heat during the operation, as shown in Figure 8.

These results align with a study conducted by researcher [13] Abdel Hayy and others examined the effect of preheating in welding on the mechanical properties of SA.106 Gr. B pipe. The findings showed that preheating improves tensile strength and hardness while reducing defects and cracks in the heat-affected zone.

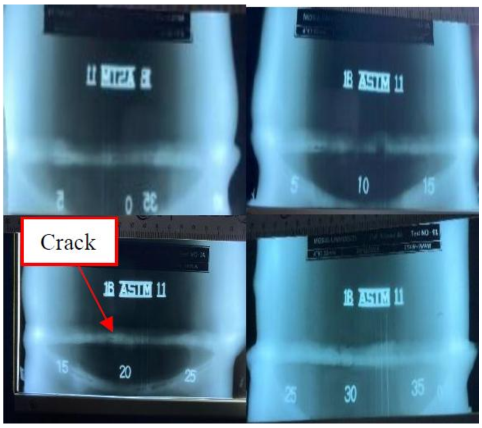


Fig. 6. X-ray photograph involved crack defect.

Fig. 7. X-ray photographs after preheating for the welding zone.

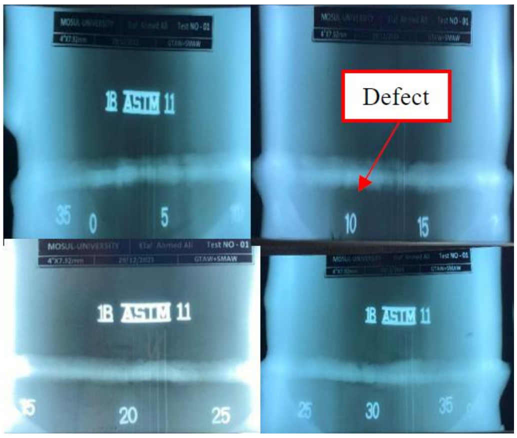


Fig. 8. X-ray photograph after preheating for welding zone at a current of 100 Amperes.

SMAW and GTAW welding techniques were used, and the same methods were applied in this working paper, where the X-ray examination results in the research revealed no cracks in the weld after preheating. This agreement with the researchers' findings confirms that preheating significantly enhances weld quality and reduces defects, especially cracks. This alignment between the two studies indicates that preheating leads to fewer weld defects, depending on the type of welding and the conditions used.

The output results in this investigation are supported by Balram Y. [7], who was mentioned. In this context, the CEREM 235 X-ray apparatus and GTAW methodology were utilized to analyze the weld currents at 120, 130, and 140 A. The results showed that defect-free welds were obtained with 130 and 140 A welding currents, while linear cracks occurred due to insufficient heat input with a welding current of 120 A. Based on this observation, the application of 130 and 140 A current values was adopted in this work to obtain defect-free, quality welds in dissimilar metals.

Arc welding quality directly depends on the depth of penetration, fusion, and joint strength, which, besides current and voltage, is controlled by groove angle, root face, and root opening. An adequate angle means deeper penetration; it is the root face that balances joint strength with ease of fusion. Similarly, it is with root opening: it regulates the amount of fusion; too large an opening may cause excessive melting, and too small an opening result in less adequate fusion. Voltage controls arc width and heat-affected zone: when the voltage is higher, wider arcs and larger heat-affected zones result in weakened joints and more defects along weld lines. On the contrary, low voltage imposes heat on the targeted areas, supporting solid, controlled welding within approved limits. The increased current generates more heat and allows for deeper fusion, thereby enhancing joint quality; however, an excessively high current may induce cracking. Therefore, precise control of these variables, groove angle, root gap, amperage, and voltage, is essential to achieving robust, fully penetrative welds and improving the integrity of welded joints.

The crack appeared on the sample after A PMI examination was carried. It was shown that there was a difference in the proportions of the chemical compositions of the metal ASTM A 106 after the welding process in the area. The chemical composition of the weld and the Heat-Affected Zone (HAZ) were analyzed to assess the changes resulting from the procedure. Table 3 shows the chemical composition of the weld after the process, while Table 4 presents the chemical composition of the HAZ, allowing us to compare the chemical effects on both the welded area and the surrounding zone. The chemical changes resulting from the welding process revealed noticeable variations in the chemical composition of the metal, such as a decrease in sulfur and phosphorus levels due to evaporation, and an increase in manganese content in the heat-affected zone as a result of thermal redistribution. Additionally, changes were observed in the composition of the weld zone, reflecting the influence of the filler metal used, which has a chemical composition different from that of the base metal.

This difference is the result of chemical reactions during the welding process between the filler used, the electrode, and the metal, as well as the high temperature during the welding process. This increase leads to the loss or absorption of some elements due to melting and evaporation.

Weld chemical composition after the welding process and HAZ chemical composition after the welding process.

Table 3. Weld chemical composition after the welding process.

Alloy Elements (w/%) of Weld metal chemical composition					
Elements and their %	C	p	Ni	Cu	Others
	0.24	0.013	0.165	0.025	P=0.013, S=0.023, Mo=0.006
	Mn	Si	V	Cr	
	0.949	0.55	0.015	0.029	

The amount of heat introduced into the welding area depends directly on equation No. 1, as the current voltage and welding speed significantly affect the amount of heat introduced due to thermal gradients and thus affect the appearance of defects, including cracks, porosity, and others. Table 5 shows the amount of heat introduced during the welding process for four stages: root and hot using the GTAW method and fill and cap using the SMAW method according to the approved WPS (Welding Procedure Specification) and ASME standards.

Table 4. Heat-affected zone HAZ chemical composition after the welding process

Alloy Elements (w/%) of (HAZ) chemical composition					
Elements and their %	C	p	Ni	Cu	Others
	0.242	0.003	0.163	0.049	P=0.003, S=0.015, Pb=0.033, Mo=0.016
	Mn	Si	V	Cr	
	1.07	0.354	0.041	0.056	

Although Table 5 presents the welding parameters for each stage, the relationship between these parameters and defect formation was observed experimentally. It was found that using a low current (such as 100 A) resulted in insufficient heat input (0.96 kJ/mm), which contributed to the appearance of porosity and lack of fusion, as confirmed by the X-ray inspection results. In contrast, using a higher current (such as 140 A with a heat input of 1.3 kJ/mm) improved fusion and reduced the number of defects. These results confirm that variations in current and heat input have a direct impact on defect formation.

Table 5. Process parameters for GTAW and SMAW processes

SQ	Weld Layer	Process	Inert Gas	Filler Metal		Current		Arc Volts (v)	Gas Flow L/min	Travel Speed mm/min	Heat Input KJ/mm
				Class	Dia (mm)	Polarity	AMP. (A)				
1	ROOT	GTAW	Argon	ER70S-3	2.4	DCEN	100-140	8-14	8-16	50-90	0.96-1.3
2	HOT	GTAW	Argon	ER70S-3	2.4	DCEN	110-150	8-14	8-16	50-90	1.05-1.4
3	FILL	SMAW	N/A	E7018	2.5	DCEP	65-130	20-30	N/A	70-101	1.1-2.3
4	CAP	SMAW	N/A	E7018	2.5	DCEP	80-120	20-30	N/A	80-100	1.2-2.5

4. CONCLUSIONS

Welding is the most common process in engineering and industrial processes. Cracks are one of the most important problems facing welding processes. It was concluded through the welding of the models that cracks occur because of a temperature difference between the heat-affected weld zone and the base metal. These cracks occur as a result of a difference in temperatures between the welding area heat-affected zone (HAZ). And the base metal. To avoid cracks, several factors must be taken into consideration, including the main factors, which are preheating, the speed of welding, and proper electrode handling, in addition to secondary factors, including the skill of the welder and the cleanliness of the welded joints. The welding process also has a significant impact on the chemical composition of the welded joint through the chemical reactions that occur, which lead to a change in the chemical composition of the welded joints according to the PMI results previously.

The PMI analysis also revealed significant changes in the chemical composition of both the weld zone and the heat-affected zone (HAZ). The carbon content decreased by 0.1% in the weld zone compared to the base metal due to the use of low-carbon welding electrodes. Similarly, phosphorus content decreased by 35% in the weld zone and by 85% in the HAZ, while sulfur increased from 0.003

to 0.013, indicating the effects of evaporation, chemical reactions, or the transfer of impurities from the filler materials. In addition, slight variations were observed in the percentages of other elements such as manganese, nickel, and copper, which can be attributed to thermal redistribution and the conditions associated with the welding process. These combined changes reflect the complex impact of welding on the chemical composition and its direct influence on the joint quality and mechanical properties.

Acknowledgments

This work was financially supported by the Mechanical Engineer Department at Engineer College / Mosul University.

Reference

[1] S. I. Talabi, O. B. Owolabi, J. A. Adebisi, and T. Yahaya, "Effect of welding variables on mechanical properties of low carbon steel welded joint," Adv. Prod. Eng. Manag., vol. 9, no. 4, pp. 181–186, 2014.

[2] K. Weman, Welding Processes Handbook, 2nd ed., Boca Raton, London, New York, Washington, DC, 2012. [Online]. Available: https://pdfcoffee.com/welding-processes

[3] D. K. Pratiwi, A. Arifin, Gunawan, A. Mardhi, and Afriansyah, "Investigation of welding parameters of dissimilar weld of SS316 and ASTM A36 joint using a grey-based Taguchi optimization approach," J. Manuf. Mater. Process., vol. 7, no. 1, p. 39, 2023.

[4] R. Kovacevic, "Welding Processes," in InTech Handbook, Southern Methodist University, United States of America, 2012. [Online]. Available: https://www.intechopen.com/books/2504

[5] G. Gunawan and A. Arifin, "Intergranular corrosion and ductile-brittle transition behaviour in martensitic stainless steel," Ind. J. Eng. Sci., vol. 2, no. 3, pp. 031–041, 2021.

[6] O. S. Odebiyi, S. M. Adedayo, L. A. Tunji, and M. O. Onuorah, "A review of weldability of carbon steel in arc-based welding processes," Cogent Eng., vol. 6, no. 1, 2019.

[7] Y. Balram, T. V. Vardhan, G. V. Ramana, and B. S. Babu, "Effect of heat input on weld defects using X-ray radiography," 2019.

[8] M. Taghipour, A. Bahrami, H. Mohammadi, and V. Esmaeili, "Root cause analysis of a failure in a flange-pipe welded joint in a steam line in an ammonia plant: Experimental investigation and simulation assessment," Eng. Fail. Anal., vol. 129, 2021.

[9] L. Liying, X. Jun, H. Bin, and W. Xiaolei, "Microstructure and mechanical properties of welded joints of L415/316L bimetal composite pipe using post-internal-welding process," Int. J. Press. Vessels Pip., vol. 179, 2020.

[10] P. K. Baghel, "Effect of SMAW process parameters on similar and dissimilar metal welds: An overview," Heliyon, vol. 8, no. 12, 2022.

[11] S. Gunasekaran, P. Kuppuraj, and K. Priya, "Determine the chemistry of selected steel by NDE technique of Positive Material Identification (PMI)," Int. J. Sci. Res., vol. 3, no. 9, 2012.

[12] U. Caligulu, M. Yalcinoz, M. Turkmen, and S. Mercan, "X-ray radiography of AISI 4340-2205 steels welded by friction welding," Mater. Tehnol., vol. 50, no. 1, pp. 39–45, 2016.

[13] Hasanuddin University, J. Leonard, and Harfan, "The effect of welding pre-heating of SMAW and GTAW on mechanical properties of SA 106 Gr. B pipe of Energi Sengkang Co. Ltd," Int. J. Sci. Mech. Manuf., vol. 4, no. 1, pp. 273–277, 2017.

[14] L. O. Osoba, W. A. Ayoola, Q. A. Adegbuji, and O. A. Ajibade, "Influence of heat inputs on weld profiles and mechanical properties of carbon and stainless steel," Niger. J. Technol. Dev., vol. 18, no. 2, 2021.