

Effect of GMAW Preheating Temperature Variation on Metallography and Mechanical Properties of S355J2 Steel in Container Flat Top Wagon 50 Feet

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Abstract— This research was motivated by observations of the production process of 50-foot Container Flat Top Wagons at PT INKA (Persero) prior to GMAW welding of the material, where preheating was identified as a problem. The research problem is that the uncertain preheating temperature parameters cause distortion in the material, thereby affecting its mechanical properties. The solution to this problem involves conducting research to determine the most suitable preheating temperature parameters for the Process Instruction (PI). This study aims to analyze and determine the appropriate preheating temperature for the production of 50-foot Container Flat Top Wagons at PT INKA (Persero). The research method used is a quantitative experimental method, with the research object being S355J2 steel material subjected to preheating at varying temperatures of 200-225°C, 300-325°C, and non-preheating, followed by GMAW welding. The research results indicate that preheating at 300-325°C yields the highest tensile strength and hardness values. The conclusion of this study is that increasing the preheating temperature results in increased tensile strength and hardness, as the percentage of pearlite phase increases.

Keywords— S355J2 steel, preheating, GMAW welding, mechanical properties, temperature.

I. INTRODUCTION

PT INKA (Persero) manufactures container flat top wagon 50 feet that are exported to New Zealand. The production process experienced delays due to cracks in the underframe weld joints caused by the GMAW welding method, which is prone to cracking. To overcome this, preheating was carried out to increase the base metal temperature and microstructure as needed, thereby reducing excessive distortion and residual stress [1]. The main material of the underframe is S355J2 steel, which has high tensile strength, but preheating production is not yet stable, thus affecting the mechanical properties of the material.

Variations in preheat temperature for S355J2 steel in the manufacture of manufactures container flat top wagon 50 feet were first conducted at PT INKA (Persero). The use of preheat with GMAW welding in this area has not been widely practiced, making this study a recent review of preheat optimization [2].

There are no precise preheat temperature parameters for the underframe production process, so the maximum effective preheat temperature limit is not yet known. In addition, the use of the brander preheat method on S355J2 steel material has not been fully explained and requires further research.

Preheating is part of heat treatment that serves to heat the material before welding to reduce the temperature gradient and reduce distortion [3]. Preheating also affects the mechanical properties and microstructure of the material [4]. S355J2 steel has superior structural characteristics, but the preheating temperature needs to be controlled in order to achieve optimal mechanical properties.

This study investigated the effect of preheating temperature variations applied using the brander method on S355J2 steel welded with the GMAW process, with a primary emphasis on metallographic examinations. Macrostructural analysis was carried out to evaluate the shape, continuity, and width of the weld fusion zone and to detect possible discontinuities, while microstructural analysis was performed to examine grain morphology and phase distribution in the weld metal, heat-affected zone, and base metal. These metallographic observations were the main basis for assessing how preheating influences weld quality and microstructural transformations. To complement these findings, tensile and vickers hardness tests were also conducted, serving as supporting evaluations that helped link the observed microstructural changes to the overall mechanical performance of the material [5].

The novelty of this research lies in testing variations in preheat temperature on S355J2 steel, specifically on container flat top wagon 50 feet using the brander method, which was conducted for the first time at PT INKA (Persero). This research developed preheat temperature recommendations based on test results for the railway industry production process.

II. LITERATURE REVIEW

A. Container Flat Top Wagon 50 Feet

The underframe container flat top wagon 50 feet product of PT INKA (Persero) exported to Australia and ordered by Kiwi Rail, which was produced from November 2022 to April 2023 [2]. The container flat top wagon 50 feet uses S355J2 steel as the main material in the construction of the train's underframe. The underframe is the main structural part of the train that functions to support the load from the bearings. The underframe receives static and dynamic loads that arise due to irregularities in the track.



Fig. 1. Container Flat Top Wagon 50 Feet Intermediate Goods (a) dan Finished Goods (b)

B. S355J2 steel

S355J2 steel is a type of structural steel marked with the letter “S” in S355J2 and produced in accordance with the EN ISO 10025-2 standard [6]. Structural steel consists of iron and carbon. S355J2 steel has the mechanical properties shown in the table 1.

TABLE I. Mechanical Properties of S355J2 Steel

Grade	Yield Strength min (MPa)	Ultimate Tensile Strength (MPa)	Elongation min (%)	Hardness (HV)
S355J2	355	470-630	17	155±5

C. Gas Metal Arc Welding (GMAW)

GMAW welding is a metal joining technique that utilizes heat energy converted from electrical energy as a heat source [7]. In this process, welding wire in the form of a roll is used as an electrode, while shielding gas is supplied to protect the molten metal from contamination during the welding process. The GMAW welding process occurs due to the transfer of ions between the anode and cathode in the base metal and filler metal, which triggers the formation of high heat until the two metals melt [8].

D. Preheat

Preheating is the process of heating the parent metal before welding. The purpose of preheating is to reduce the temperature difference between the weld area and the surrounding area, thereby reducing the risk of cracking and improving the quality of the welded joint. In arc welding, the high temperature of the heat source causes a temperature difference between the hot weld area and the parent material with a lower temperature, resulting in expansion around the welding area. The preheat process helps reduce temperature differences, thereby reducing the potential for defects such as distortion and excessive residual stress [9].

E. Macro Examination

Macro examination is a test used to evaluate the physical characteristics of a welded sample that are visible to the naked

eye or under low magnification (less than 50×). In this study, the examination was conducted in accordance with ISO 17639 using a digital microscope with magnification up to 50×.

The measurable indicators obtained were the thickness and width of the heat-affected zone (HAZ) resulting from the preheating process at different temperature variations, observed primarily at 10x magnification. This evaluation provides an initial overview of weld quality, fusion characteristics, and the extent of thermal influence, which are essential for correlating preheating parameters with subsequent microstructural changes and mechanical performance [10].

F. Micro Examination

Micro examination is a metallographic test that aims to identify the grain structure of metals using a microscope. The observed regions are divided into three areas, namely the parent metal, the weld metal, and the heat-affected zone (HAZ). In this study, the examination was conducted in accordance with ISO 17639 using a digital microscope with 500× magnification. The measurable indicators obtained were the identification of microstructural features, analysis of grain morphology, and estimation of the type and percentage of phase distribution in the material after the GMAW welding process with preheating variations [11].

G. Mechanical Test

Mechanical testing in this study consisted of tensile testing and Vickers hardness testing. The tensile test, conducted in accordance with ISO 4136, was performed by pulling the specimen until failure to determine the mechanical properties of the material, including ultimate tensile strength (MPa), yield strength (MPa), and elongation (%) [12]. Meanwhile, the Vickers hardness test, carried out based on ISO 6507, was used to evaluate the resistance of the material to indentation using a small pyramid-shaped indenter under a specific load, producing a vickers hardness (HV) value [13].

III. RESEARCH METHOD

This research was conducted at the Materials Testing Laboratory of the Madiun State Polytechnic with consultation support from mentors in the Welding Technology Division of PT INKA (Persero).

The testing process macro examinations, micro examinations, and mechanical test aimed at obtaining measurable data on the effect of preheat temperature variations on the metallographic and mechanical properties of S355J2 steel in container flat top wagon 50 feet. The stage of this research can be seen in Figure 1 below.

Prior to conducting the experiment, a literature study and field observation were carried out to identify problems and research variables based on journal references, book articles, and related industry surveys. S355J2 steel material was prepared and cut to a size of 250 mm x 125 mm x 12 mm, then preheated using a burner method with non-preheat temperature variations of 200–225°C and 300–325°C. The Gas Metal Arc Welding (GMAW) process was carried out on specimens with a 30° V groove joint.

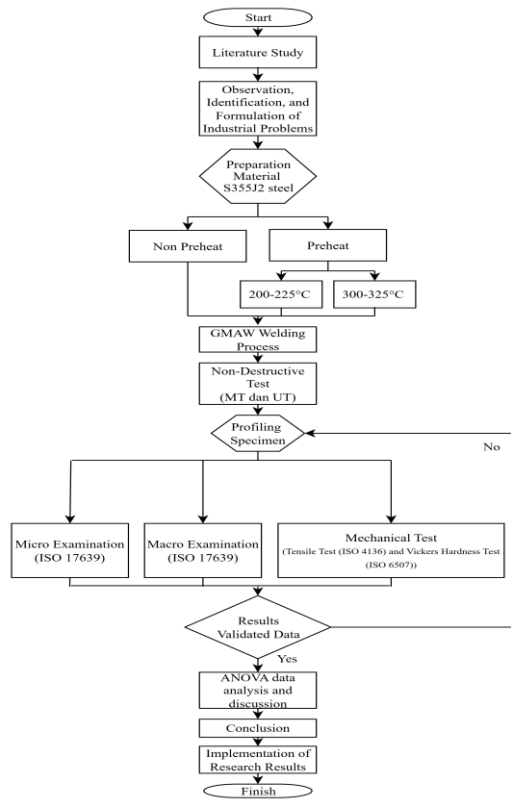


Fig. 2. Research Stages

After welding, the specimens were tested using Non-Destructive Testing (visual test, ultrasonic test, magnetic particle test) to ensure the quality of the welded joints met the standards. Specimens that passed then underwent, macro examination, micro examination, and mechanical test to measure mechanical and metallographic properties. The primary analysis in this study focused on metallographic examinations. Macro examination was carried out to evaluate the shape and width of the weld fusion zone, while microstructural analysis was conducted at 500× magnification after etching with 4% nital solution to determine the phase distribution and percentage of ferrite and pearlite in different regions of the weld. These observations provided detailed insights into how preheat temperature variations influenced the fusion characteristics and microstructural transformations of the material. In addition to metallographic tests, tensile testing (ISO 6892:2009) and Vickers hardness testing (0.98 N, 15 indentations) were performed to support the microstructural findings by correlating changes in phase composition with mechanical performance.




IV. RESULTS AND DISCUSSION

The results and discussion of this research explain the results of experiments on the effect of preheat temperature variations (non-preheat, 200–225°C, 300–325°C) on S355J2 steel with GMAW welding on metallographic and mechanical properties. The tests included macro examinations, micro examinations, and mechanical test. The data obtained from these tests were then processed and evaluated. The analysis used One Way ANOVA to determine the effect of preheat temperature and to find the optimal temperature for the

production of container flat top wagon 50 feet at PT INKA (Persero).

A. Macro Examination

TABLE II. Macro Examination Result

Temperature Variation (°C)	Macro Examination Result	Description
Non Preheat		The fusion weld width of the preheated welded specimen was 25,96 mm and there were no discontinuities in the fusion weld.
200 - 225		The fusion weld width of the preheated welded specimen was 30,01 mm and there were no discontinuities in the fusion weld.
300 - 325		The fusion weld width of the preheated welded specimen was 32,5 mm and there were no discontinuities in the fusion weld.

All welding specimens showed good results with no defects in the fusion weld. The increase in preheat temperature was linearly related to the increase in fusion weld width, expanding the mixing area of the weld metal and the parent metal [14]. This phenomenon was in line with the increase in tensile strength due to a more stable heat distribution from preheating [5].

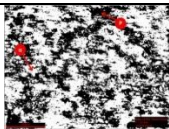
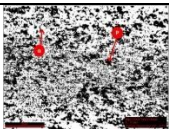
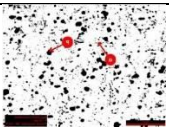
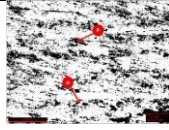
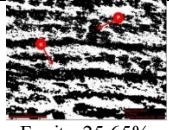

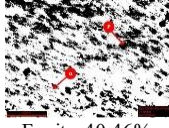

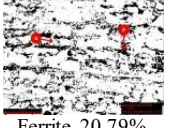
Based on the macro examination results, the fusion weld width without preheating was measured at 25.96 mm, while specimens preheated at 200–225 °C and 300–325 °C exhibited wider fusion zones of 30.01 mm and 32.5 mm, respectively. The macro images confirmed that higher preheat temperatures produced a broader and more homogeneous fusion area, with a smoother transition between the base metal and the weld metal, and no evidence of discontinuities [9]. These findings demonstrate that preheating enhances the melting and mixing process during welding, which improves metallurgical bonding and reduces the risk of localized defects. Consequently, the broader fusion width obtained at higher preheating temperatures supports the improvement in tensile strength, as a result of a more uniform heat input and refined microstructural characteristics in the weld region [15].

B. Micro Examination

The results of the observation show that an increase in preheat temperature changes the proportion of these phases in the welding area. In specimens without preheat, the microstructure shows a relatively balanced distribution between ferrite and pearlite, with ferrite around 37–40% and pearlite 60–62% in both the weld zone and heat-affected zone (HAZ) [4]. However, at a preheat temperature of 300–325 °C, pearlite becomes the dominant phase, reaching up to 88.31% in the weld zone and 79.21% in the base metal. This shift in phase composition directly influences the mechanical properties of the welded joint. Since pearlite exhibits higher hardness and strength compared to ferrite, its increased

proportion explains the higher hardness and tensile strength observed in the preheated specimens [16].

TABLE III. Micro Examination Result

	Non Preheat	200–225°C	300–325°C
Weld Zone	 Ferrite 37,47% Pearlite 62,53%	 Ferrite 31,28% Pearlite 75,35%	 Ferrite 11,69% Pearlite 88,31%
HAZ	 Ferrite 37,06% Pearlite 62,40%	 Ferrite 25,65% Pearlite 75,35%	 Ferrite 29,00% Pearlite 71,00%
Base Metal	 Ferrite 40,46% Pearlite 60,64%	 Ferrite 41,13% Pearlite 69,97%	 Ferrite 20,79% Pearlite 79,21%

Moreover, the microstructural refinement observed in the HAZ suggests that preheating promotes a more uniform transformation during the welding thermal cycle. The reduction in ferrite percentage, particularly at elevated preheat temperatures, indicates slower cooling rates that favor pearlite formation [13]. This phenomenon not only enhances hardness but also improves the overall homogeneity of the welded joint, reducing the likelihood of localized weak points. Therefore, variations in preheat temperature not only affect mechanical resistance but also significantly alter the microstructural composition, contributing to improved weld performance and long-term service reliability [17].

C. Mechanical Test

Mechanical testing was carried out to evaluate the effect of preheat temperature variations on the strength and hardness of S355J2 steel welds. Tensile testing was performed in accordance with ISO 4136 standards by pulling specimens until fracture to obtain yield strength, ultimate tensile strength (UTS), and elongation values.

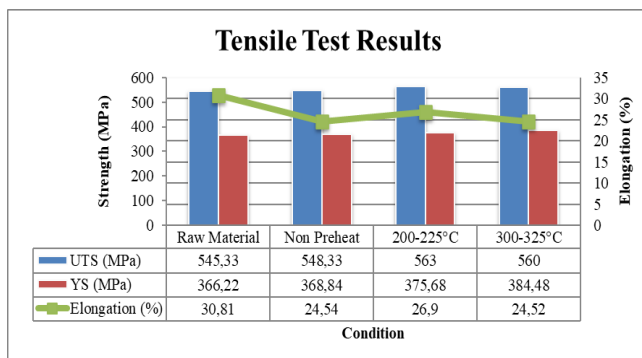


Fig. 3 Tensile Test Result Graph

The results demonstrated that the preheat process significantly increased tensile strength and resistance to plastic deformation. More uniform heat control during preheating

produced stronger and more stable welded joints, with a noticeable reduction in weld defects and residual stress in the fusion area [17]. Although a slight decrease in ductility was observed, the overall joint quality improved, which is particularly beneficial for structural applications requiring optimal weld stability and strength [18]. These findings confirm that preheat temperature variation plays a critical role in enhancing the mechanical performance of welded joints in S355J2 steel.

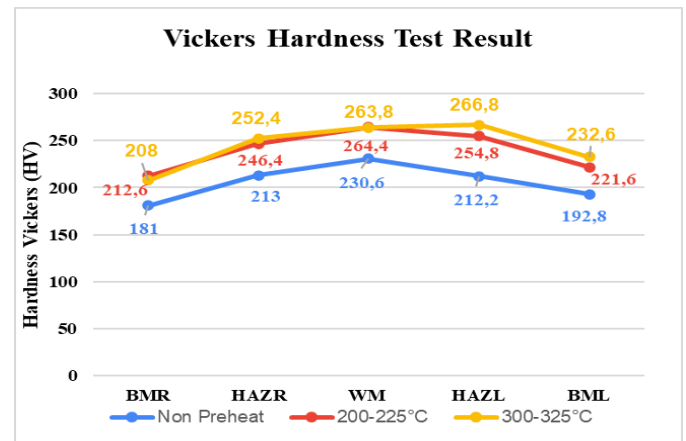


Fig. 3. Vickers Hardness Test Result Graph

In addition to tensile testing, hardness distribution across different weld regions was evaluated using the Vickers method in accordance with ISO 6507, with a load of 0.98 N applied at 15 indentation points in five main areas of the specimen. The results showed that the highest hardness values were consistently found in the weld metal zone, and these values increased with higher preheat temperatures due to filler metal fusion and rapid cooling that promoted harder microstructural phases [19]. The heat-affected zone (HAZ) also exhibited a significant increase in hardness, reflecting microstructural transformations induced by the welding thermal cycle [7]. Meanwhile, the base metal retained the lowest hardness, since it did not undergo direct fusion or substantial structural changes. Overall, the hardness test results confirmed that effective preheating not only improved tensile strength but also enhanced hardness distribution across the weldment, leading to better performance and reliability of the welded joints [20].

The results of both tensile and hardness tests were analyzed using statistical calculations (ANOVA) to see whether the differences between preheat temperatures were meaningful or just random. The analysis showed that changes in preheat temperature clearly affected the strength of the welds, as seen in the tensile test results, where the values of strength and elongation were different for each group. The hardness test also showed the same trend, with noticeable differences in hardness across the weld metal, HAZ, and base metal. These findings confirm that preheating has a real and measurable effect on improving both the strength and hardness of welded joints.

V. CONCLUSION

The metallographic examinations clearly demonstrated the

influence of preheating on weld quality. Macrostructural observations showed that higher preheat temperatures produced a wider and defect-free fusion zone, while microstructural analysis revealed a shift toward pearlite phase dominance in the weld metal and HAZ, resulting in a harder and more refined structure. These findings confirm that preheating plays a central role in altering weld morphology and microstructural balance. The tensile and hardness test results support these observations, showing increased strength and hardness values consistent with the microstructural transformations, even though a slight reduction in ductility was recorded. This alignment between metallographic and mechanical results underscores that the improvements in strength and hardness originate from the macro- and microstructural changes induced by preheating.

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