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EFFECT OF PREHEATING TEMPERATURE VARIATION ON MICROSTRUCTURE AND HARDNESS OF WELD OVERLAY CLADDING OF SS400 CARBON STEEL BY SMAW METHOD

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Abstract

SS400 carbon steel is a type of low carbon steel that has low surface hardness, wears easily, and is not resistant to impact. The application of cladding can reduce the risk of material failure due to the weakness of SS400 carbon steel. In this study, cladding was performed by SMAW method using HV-600 electrodes and a current of 115 A. This welding process causes heat to be concentrated in the melting area, resulting in uneven heating and cooling, so preheating is necessary. This study aims to evaluate the effect of preheating temperature variations of 200°C, 300°C, 400°C, and non-preheating on microstructure and hardness in the cladding process. Macro structural testing shows that the application of preheating can minimize the occurrence of welding defects, and an increase in preheating has an effect on increasing the depth of the HAZ in each specimen tested. Microstructure testing shows that the application of higher preheating will form more ductile phases in the base metal, diffusion layer, HAZ areas. The base metal area has pearlite and ferrite phases. The diffusion layer shows clear boundaries as a result of the diffusion process. The HAZ section forms a fine pearlite microstructure and coarse pearlite and ferrite phases. The weld metal layer is not affected by the preheating temperature used, there are martensite and ferrite phases. Hardness testing on 200°C preheating specimens has the highest hardness in the weld metal of 680.11 HV. Hardness in the diffusion layer, HAZ, and base metal which shows that an increase in preheating temperature affects the decrease in the hardness value of the specimen.

Key words: SS400 Carbon Steel, Cladding, Preheating, Microstructure, Hardness

INTRODUCTION

Steel is a metal alloy consisting of Iron (Fe) as the basic element and Carbon (C) as the main alloying element (Zainuri et al., 2021). Carbon steel classification is divided into three types, namely low carbon steel, medium carbon steel, and high carbon steel. Steel is often used in various applications, such as infrastructure development, manufacturing various transportation components, making weapons, and making tools (Arinda et al., 2022). This rapid development has increased the need for steel use, especially in low carbon steel. Materials classified as low carbon steel are 1020, ST 37, SS400, ASTM A36 these materials have a carbon content of less than 0.3%. Low carbon steel is one of the materials that is widely used as a construction material in industry because carbon steel is a material option that is considered economical as well as being malleable and has good machinability (Dwivedi et al., 2017).

One of the materials classified as low carbon steel is SS400 Steel, "SS" stands for Structural Steel and grade 400 which is similar to ASTM A36 (Sahrevy et al., 2021). SS400 steel is a type of carbon steel that has a low carbon content which is below 0.3%(Anggigi et al., 2019). Examples of applications using SS400 carbon steel are bridge structures, ship hulls, excavator booms, oil tanks. SS400 carbon steel has several weaknesses that can result in low service life. These weaknesses include low surface hardness, low wear resistance, and inability to withstand impact (Darmo et al., 2020). The weakness of carbon steel can cause indirect product or component failure, resulting in losses to the user or industry. In a company, if the equipment experiences repeated damage, the company must repair the equipment facility which has the potential to hamper the production process. Another alternative to overcome this problem is to replace the damaged unit but replacement requires high costs if the damage occurs repeatedly in a short time. Therefore, one solution to overcome this problem is to carry out the Cladding process on components that often experience damage.

The cladding process aims to inhibit material failure due to corrosion, impact load, wear or wear, and can increase the surface hardness value so that the process can extend the service life of the base material that has gone through the cladding process (Hutahaean et al., 2021). In addition, the fast and efficient processing process in saving time is one of the advantages of the cladding process. The cladding process that is often used is weld overlay cladding, which is a welding process by combining or adding a layer of metal between the parent metal and the coating material, usually the welding process used is Shielded Metal Arc Welding (SMAW) or other types of welding such as Gas Metal Arc Welding (GMAW) (Aryadi et al., 2022). Factors that can affect the welding results are preheating and the type of electrode that will determine the mechanical properties of the weld overlay cladding (Pratama et al., 2019).

According to the American Welding Society, the definition of preheating is the heat given to metal parts before the welding process is carried out to reduce the temperature difference of the specimen so that weld defects do not occur due to the heat generated during welding (Isworo et al., 2021). The preheating process needs to be done because when welding there will be heat in the welding area. High heat will be centered in the melting area. Uneven heating and cooling will cause various effects on the welding area such as microstructure, hardness and tensile strength (Akbar et al., 2020). Preheating will reduce the temperature difference from the parent material so that it will minimize problems that occur such as distortion and excessive residual stress (Rifaldi et al., 2021).

The method to optimize the properties of SS400 material which has weaknesses including low surface hardness, low wear resistance, and inability to withstand impact is to perform a weld overlay cladding coating process. Research conducted by Prakoso, et al. (2023) aims to determine the effect of preheating variations on microstructure, macro hardness and micro hardness with the SMAW method. The research conducted shows the highest macro hardness value of 798.70 HV which occurs in the HAZ of specimens without preheating. The micro structure shows the formation of martensite phase with the highest micro hardness of 647.20 HV, ferrite phase with the highest micro hardness of 598.50 HV, fine pearlite phase with the highest micro hardness value of 384.96 HV and coarse pearlite phase with the highest micro hardness of 371.69 HV. The preheating temperature used produces a hardness value interval that is not far between the HAZ and base metal compared to no preheating, the higher the preheating temperature, the more dominant the coarse pearlite phase is seen in the HAZ and base metal (Prakoso, 2023).

Oktaviandy et al., (2023) conducted a study on variations in preheating temperature in the SMAW welding process with SS400 material. Before the SMAW welding process, the specimen underwent special treatment in the form of preheat at temperatures of 100°C, 150°C, and 200°C. The preheat process aims to improve the mechanical properties of the material. Impact tests, tensile tests, and microstructure analysis were carried out to evaluate the effects of these treatments. The results showed a significant increase in impact energy, tensile strength, yield strength, elastic modulus, and strain in specimens that underwent preheat and cooling treatments. These findings indicate that the use of preheat and cooling media can improve the mechanical performance of SS400 materials, which can provide positive benefits in construction applications that require higher strength and durability.

Based on the background and previous research, the preheating process greatly influences the SMAW welding process. This is the author's reference in the Cladding process carried out using the SMAW method. Determining the right temperature in the SMAW cladding preheating process is the key in this study. So further research is needed on the effect of preheating temperature variations on the macrostructure, microstructure and hardness of the SS400 carbon steel cladding overlay weld using the Shielded Metal Arc Welding (SMAW) method.

METHODS

This study uses SS400 carbon steel as the base metal, with the chemical composition shown in Table 1. The cladding method used is weld overlay cladding with Shielded Metal Arc Welding (SMAW) welding type. The welding process uses HV-600 electrodes and the welding current is 115 A. The preheating temperature variations used are 200°C, 300°C, 400°C and without using preheating. Figure 1 shows cladding process scheme.

Table 1. Chemical composition of SS400 carbon steel

Composition	SS400	HV-600 electrodes
Fe	Bal	Bal
C	0.17	0.06
Si	0.21	0.4
Mn	0.86	1
P	0.18	0.02

Figure 1 is a scheme of the cladding process with the SMAW method, starting from specimen preparation to the testing process of macro structure, micro structure and hardness. The process carried out after cladding is the preparation of test specimens, which includes the process of machining, mounting, grinding and polishing, as well as the etching process using a mixture of HNO_3 and Alcohol in accordance with ASTM E407-99 standards.

Macro testing aims to evaluate the macro structure of the material at the weld area in accordance with ASTM E3-01 standards. Macro testing in the welding process is very important because it provides an overview of the penetration depth and width of the HAZ (Heat-Affected Zone). In addition, this test is also able to identify defects in the weld (Racmatullah et al., 2020).

Microstructure testing is an in-depth analysis method that aims to identify and evaluate grain size and phases in materials that determine the mechanical properties of these materials. The optical microscope used in this research is the Carl Zeiss.

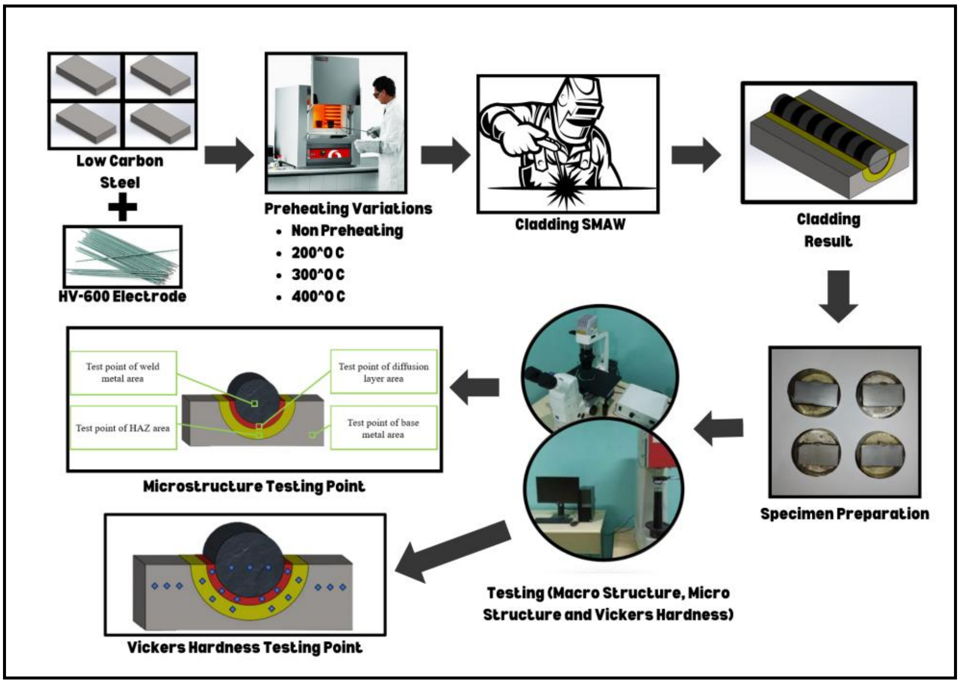


Figure 1. Cladding Process Scheme

Hardness testing in the study was carried out using the Vickers method in accordance with ISO 6506/ASTM E384. The tool used in hardness testing is a universal hardness tester type ZHU 25CL. Hardness testing aims to measure the material's resistance to harvesting deformation through indentation. Equation 1 is a formula that can be used to calculate the Vickers hardness value of the material (Sofyan, 2021).

$$HV = \frac{1,8544\,P}{d^2} \quad \text{.............................(1)}$$

Description:

HV = Hardness Vickers

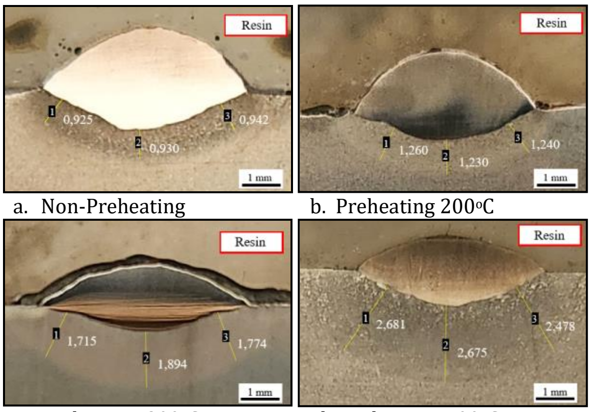
P = Force (Kg)

d = Diameter of indentation trace (mm)

RESULTS AND DISCUSSION

Macro Structure Testing

Macro structural photographs were taken with 7x magnification using a DSLR camera to observe the HAZ (Heat Affected Zone), base metal, and weld metal. Macro structure testing shows the areas formed during the welding process, such as the width of the HAZ on the specimen. In addition, the purpose of macro testing is to determine weld defects that may occur. Figure 2 shows a photo of the macro structure of each preheating specimen. Figure 3 shows the Comparison Chart of Preheating Against HAZ Width.



a. Non-Preheating b. Preheating 200°C

c. Preheating 300°C d. Preheating 400°C

Figure 2. Macro Structure

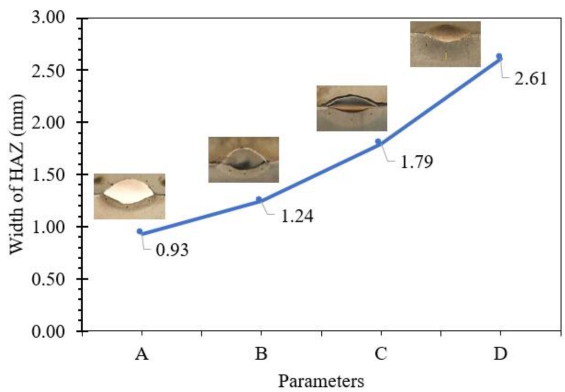


Figure 3. Comparison Chart of Preheating Against HAZ Width

Figure 2 shows that macro structure testing on all specimens is free from welding cracks, it shows the application of preheating can minimize the occurrence of welding defects by reducing the cooling rate of the material, the reduced cooling rate causes the material to be more ductile and has better crack resistance. Specimens without preheating have an average HAZ width of 0.93 mm. Specimens with 200°C preheating had an average HAZ width of 1.24 mm while specimens with 300°C preheating had an average HAZ width of 1.79 mm. The specimen with the highest preheating at 400°C shows an average HAZ of 2.61 mm. HAZ width data obtained from macro structure observations show differences in the width of the HAZ which correlates with the initial welding temperature, higher preheating temperatures produce a wider HAZ, while specimens without preheating have a smaller HAZ width. This happens because the preheating temperature accelerates the heating process of the parent material or base metal, preheating also serves to slow down the cooling rate, which ultimately widens the Heat Affected Zone (HAZ). These results support the research of Rachmatullah, et al (2020) where an increase in preheating temperature will increase the width of the HAZ area (Racmatullah et al., 2020).

Microstructure Testing

Microstructure testing was observed using an optical microscope. This test observed four different parts, namely the base metal layer, cladding or weld metal, diffusion layer, and Heat Affected Zone (HAZ) shown in Figure 1 The surface of the specimen must go through an etching process to improve optical visibility, making it easier to determine grain boundaries and phase identification. The etching process was carried out using ASTM E407-99 standards involving a mixture of 3% HNO_3 and 97% Alcohol with a duration of about 7 seconds.

1. Base Metal

Base metal is the base metal where in this study the base metal used is SS400 carbon steel which is classified as low carbon steel. Figure 4 shows the microstructure of the base metal region at 500X magnification.

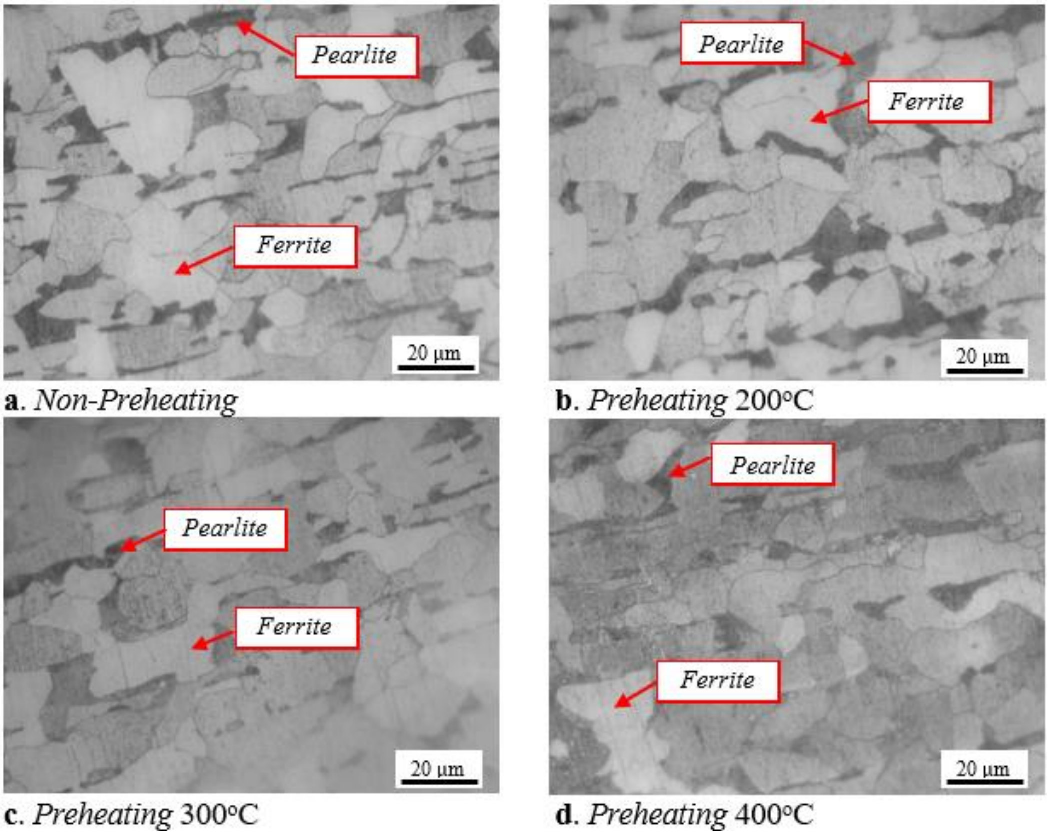


Figure 4. Microstructure of Base Metal

Figure 4 is the result of microstructure observations made on the base metal showing ferrite and pearlite phases. The microstructure of the base metal shows that there are two phases formed, namely the ferrite phase (white / light) is more dominant than the pearlite phase (black /

dark). The microstructure of the base metal can also be seen that the shape of the ferrite phase tends to be larger than the pearlite phase (Dikwan et al., 2019). The ferrite phase is more dominant because the solubility of carbon in this phase is relatively lower than the austenite phase. This phase has a fairly good mechanical ability, but it is less ductile and hard because of the pearlite phase. Observation of the microstructure of the base metal shows that the higher preheating temperature affects the grain size of the pearlite phase which is getting smaller. The grain size of a specimen will correlate with the better mechanical properties of the specimen. In the 400°C preheating variation, the pearlite phase grain size is smaller than other variations, provides a better strain value and shows more ductile material properties (Antaqiya et al., 2019).

2. Weld Metal

Weld metal is a filler metal above the base metal or base metal where the filler metal in this study uses HV-600 electrodes which have a carbon content of 0.6% and are classified as high carbon steel. Figure 5 shows the microstructure of the weld metal area with 500X magnification.

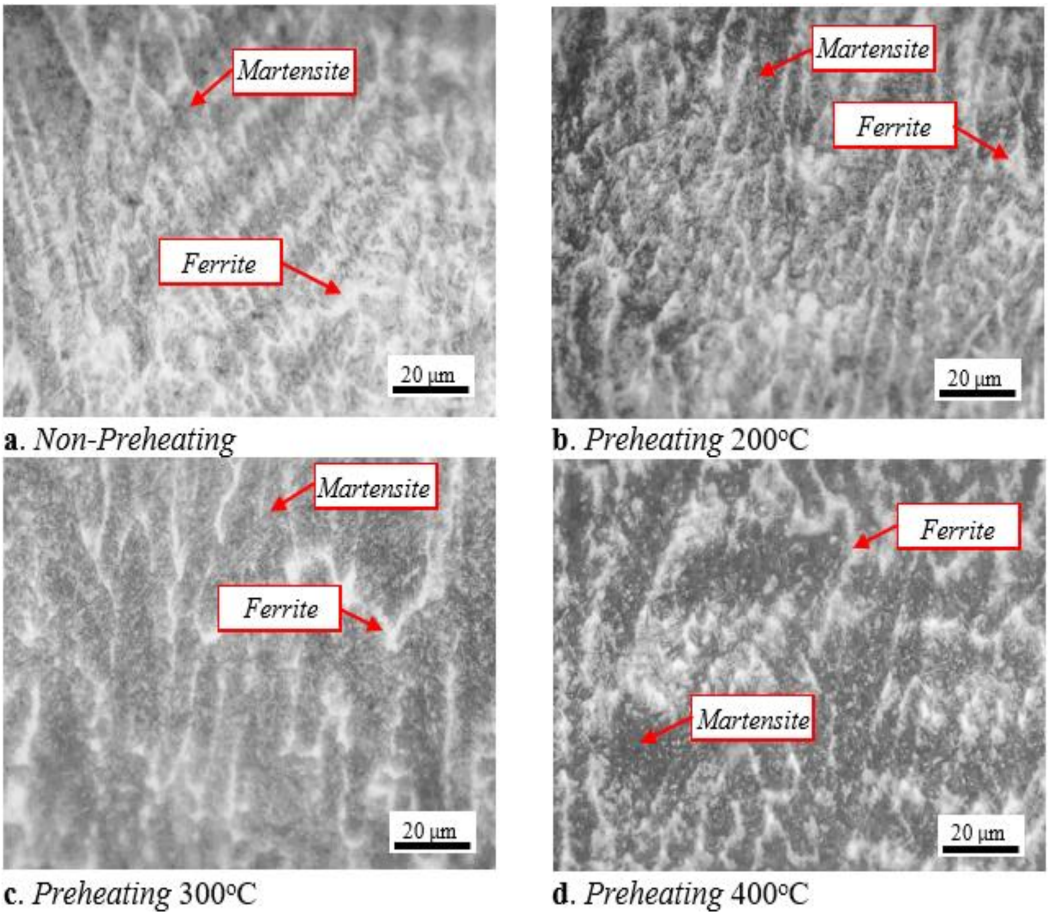


Figure 5. Microstructure of Weld Metal

Figure 5 shows the phases formed in the weld metal after the cladding process, namely martensite and ferrite. Martensite is a phase formed from the transformation of austenite without diffusion, which occurs when the iron-carbon alloy austenite is rapidly cooled to a relatively low temperature. Martensite is the hardest phase in steel but brittle, this transformation process is caused by trapping carbon atoms in the crystal structure when a change from FCC to BCC occurs (Douglas, 2014). Referring to chemical composition of the HV-600 electrode, there are elements such as carbon (C) and manganese (Mn). Carbon and manganese elements act as phase formers in the formation of the austenite phase, this austenite will then transform into martensite (Azisqi, 2022). The manganese content of 1% in the HV-600 electrode produces a solid solution in ferrite. Silicon with a content of 0.4% plays a similar role to manganese as a ferrite shaper (Black, 2008). Figure 5 shows that the microstructure produced in the weld metal is not affected by the preheating temperature used, both without preheating and with preheating the martensite and ferrite phases are still formed with similar characteristics. The microstructure shows that the main factor affecting the formation of martensite and ferrite phases is the chemical composition used in the electrode.

3. Diffusion Layer

Diffusion layer includes the area around the welding point where the base metal melts completely (William, 2018). Figure 6 shows the microstructure of the diffusion layer region at 500X magnification.

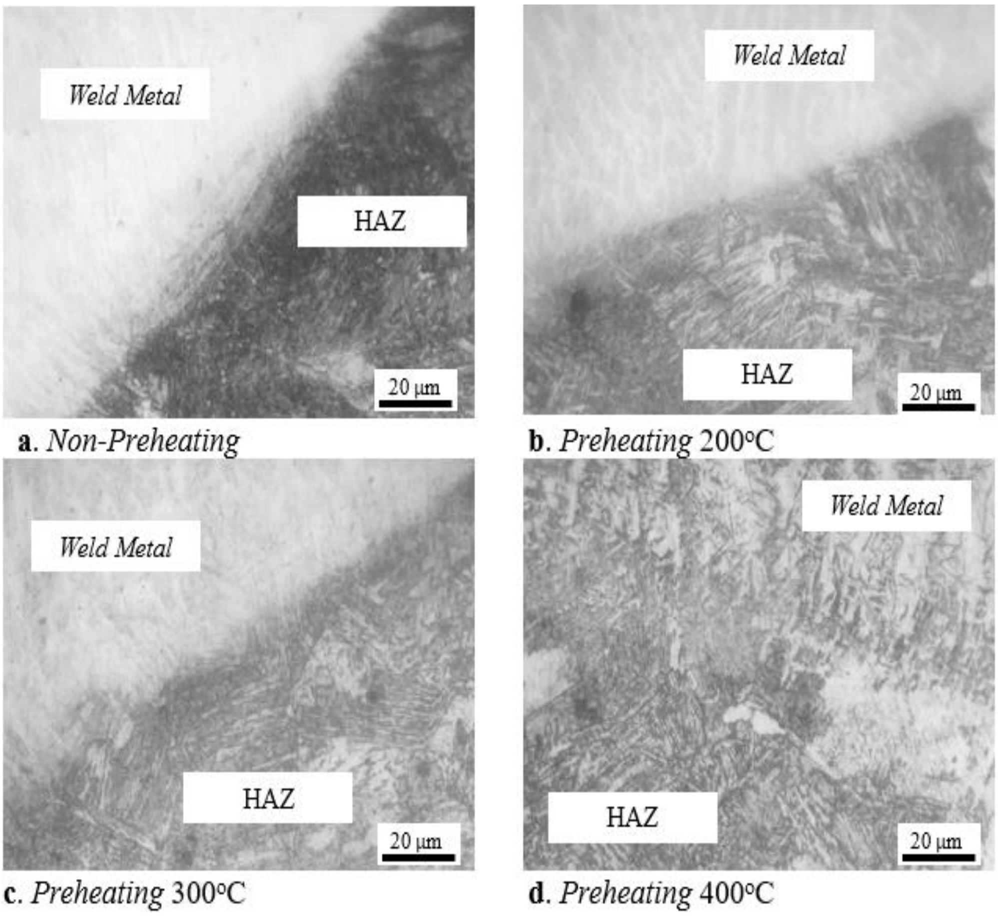


Figure 6. Microstructure of Diffusion Layer

Figure 6 shows microstructure observations made on the diffusion layer which is the boundary between the weld metal and the Heat Affected Zone (HAZ) in specimens without preheating and specimens with variations in preheating temperature. Diffusion is the mechanism of moving atoms or molecules through the material. Diffusion itself occurs through substitutional diffusion, where atoms fill vacancies in metals and alloys to achieve atomic balance, and interstitial diffusion, where atoms move from one side to fill the other without changing the main constituent atoms (Smith et al., 2019). Figure 6a shows the specimen without preheating, the boundary line between the weld metal and HAZ is flatter. The boundary line or thin band occurs due to localized melting in the grain during the welding process and the relatively fast cooling rate makes the boundary line clearer, indicating the chemical composition of the diffusion layer area is identical to the base metal. The diffusion layer in the preheated specimens, as shown in Figure 6b, Figure 6c, and Figure 6d, shows that the boundary line or thin band has widened due to the relatively slower cooling rate resulting from the preheating treatment used. Diffusion layer shows interstitial diffusion with widened boundary lines or thin bands at the boundary of weld metal and Heat Affected Zone (HAZ) of specimens with preheating, especially in specimens with 400°C preheating shown in Figure 6d. The increase in preheating temperature provides more space and heat energy, which increases the diffusion rate of atoms, causing better melting so that the mixing of weld metal and base metal accumulates in the diffusion layer region. This phenomenon indicates that preheating affects the intensity and characteristics of atomic diffusion, which has implications for changes in the microstructure and chemical composition of the diffusion layer (Kalpakjian et al., 2010).

4. Heat Affected Zone (HAZ)

The Heat Affected Zone or HAZ involves regions that undergo thermal changes but are not fully melted. The data obtained from these observations is critical to understanding the effect of preheating on the properties of the Heat Affected Zone (HAZ), including grain distribution and size, which directly affect the strength and durability of the material. Figure 7 shows the microstructure of the heat affected zone with 500X magnification.

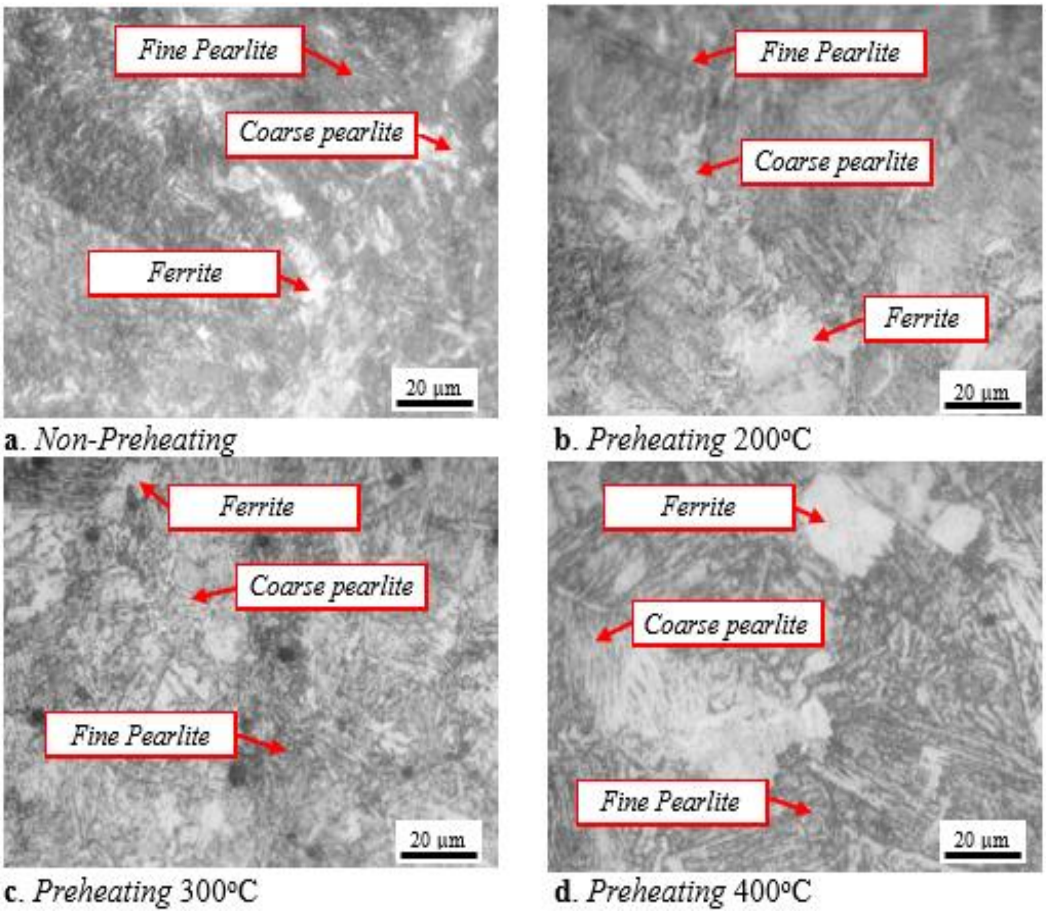


Figure 7. Microstructure of HAZ

Observations made in the HAZ area with specimens without preheating or with preheating show the presence of ferrite phase and pearlite phase. The pearlite phase is more dominating than the ferrite phase, the pearlite phase consists of fine pearlite for darker areas and coarse pearlite for lighter areas (Kalpakjian et al., 2010). Variations without preheating and with preheating provide differences in the HAZ microstructure. Specimens without preheating show that the fine pearlite phase is more dominant than the coarse pearlite phase, and the pearlite phase is more dominant than the ferrite phase. Specimens with 200°C preheating show that the coarse pearlite phase is slightly more dominant than the fine pearlite phase, and the ferrite phase tends to have a larger grain size when compared to specimens without preheating. In the 300°C specimen, the coarse pearlite phase is slightly more dominant than the fine pearlite phase, and the ferrite phase tends to have a larger grain size when compared to specimens without preheating and with 200°C preheating. In specimens with 400°C preheating, the coarse pearlite phase becomes the most dominant of the fine pearlite phase when compared to specimens at smaller preheating or without preheating, and the grain size of the ferrite phase is enlarged compared to smaller preheating. The use of higher preheating temperatures on SS400 carbon steel specimens before the cladding process affects the microstructure of the HAZ section which will produce coarser pearlite (Douglas, 2014). Coarse pearlite results from a slower cooling rate, while fine pearlite results from a relatively faster cooling rate (Kalpakjian et al., 2010). The fine pearlite phase is harder and stronger than coarse pearlite, but coarse pearlite has good ductility than fine pearlite (William, 2018).

Hardness Testing

Hardness testing in this study was carried out on SS400 carbon steel specimens that had been cladding, using the Vickers hardness testing method in accordance with ISO 6506/ASTM E384. The hardness tester used is a universal hardness tester type ZHU 25CL with a loading of 5 kgf using a camera magnification of 100X and an indentation time of 10 seconds. Figure 8 shows the graph of the Vickers hardness test results. Hardness testing aims to measure the material's resistance to deformation due to heating through indentation. The hardness test area is divided into four parts, namely base metal (BM), weld metal (WM), diffusion layer (DF), and heat affected zone (HAZ). Parameters A, B, C, D refer to the preheating temperature variations carried out A (non-preheating), B (200°C), C (300°C), D (400°C).

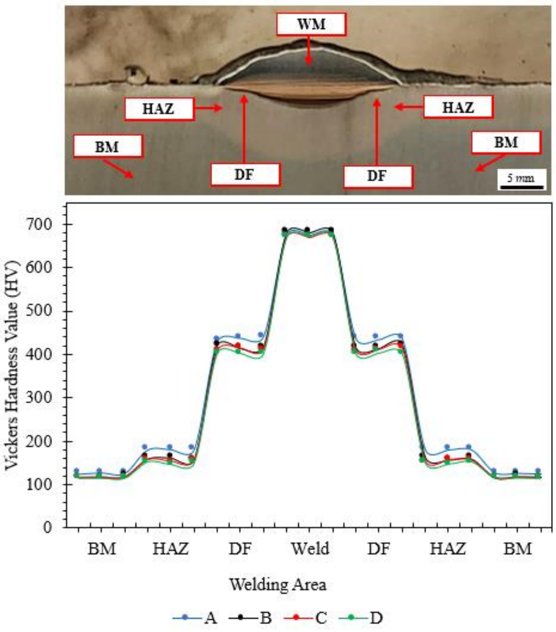


Figure 8. Graph of Hardness Value against Welding Area at Each Preheating Temperature

The base metal test area in the specimen without preheating shows the highest average hardness value in the base metal of 126.36 HV (Nurcholis et al., 2022). In specimens with 200°C preheating, the average value of base metal hardness is 117.66 HV. Specimens with 300°C preheating produced an average value of base metal hardness of 116.97 HV and specimens with 400°C preheating produced an average value of base metal hardness of 115.63 HV. The hardness test data on the base metal shows that increasing the preheating temperature will cause a decrease in the hardness value of the base metal. This is in accordance with the grain size of the pearlite phase formed in the base metal as shown in Figure 8, where an increase in preheating temperature will make the size of the pearlite phase in the microstructure smaller (Antaqiya et al., 2019).

The weld metal region shows fluctuating hardness values with the highest average hardness value in the 200°C preheating specimen, where in the specimen without preheating the average hardness value was recorded at 675.50 HV. Specimens with preheating at 200°C showed an increase in the highest average hardness value of 680.11 HV. In the specimen with 300°C preheating, the average hardness value decreased to 669.02 HV, while in the specimen with 400°C preheating, the average hardness value increased again to 672.25 HV. The resulting hardness value is higher than the base metal hardness value, which is influenced by the HV-600 electrode alloy and the hardness value is in accordance with the nature of the martensite phase where the phase has a very high hardness value, but the material will be increasingly brittle. The composition of the HV-600 electrode consists of 0.6%C, 1%Mn, 0.4%Si, 0.02%S, 0.02%P, 4%Cr, and Fe balance, where the elements C, Cr, and Mn are dominant enough to affect the mechanical properties of the weld metal layer. The 0.6%C composition of the HV-600 electrode is categorized as high carbon steel (Sofyan, 2021). The carbon element provides high hardness and strength and resistance to friction. The Cr element at 4% increases wear resistance, heat resistance, and corrosion. The content of 1% Mn increases the hardness and hardenability values (Black, 2008).

The diffusion layer test area on specimens without preheating produces an average hardness value of 435.58 HV then specimens with preheating 200°C produce an average value of diffusion layer hardness of 417.62 HV, while specimens with preheating 300°C produce an average value of hardness of 411.26 HV. Specimens with 400°C preheating showed an average diffusion layer hardness value of 402.65 HV. Testing of the diffusion layer shows that the preheating temperature affects the hardness value of the specimen. The resulting data shows that the specimen without preheating has the highest average hardness value in the diffusion layer, which is 435.58 HV. The higher the preheating temperature used, the average hardness value of the diffusion layer decreased from 417.62 HV at

200°C preheating, to 411.26 HV at 300°C preheating and 402.65 HV at 400°C preheating. This is because increasing the preheating temperature can reduce the cooling rate during the diffusion process providing more space and heat energy which makes an increase in the proportion of softer microstructure (Smith et al., 2019).

Specimens without preheating produced the highest average value of hardness in the HAZ of 180.47 HV. Specimens with 200°C preheating showed an average HAZ hardness value of 159.87 HV. Specimens with 300°C preheating showed an average HAZ hardness value of 155.17 HV, and specimens with 400°C preheating produced an average HAZ hardness value of 149.92 HV. Data on the Heat Affected Zone (HAZ) shows that the preheating temperature affects the average HAZ hardness value. An increase in preheating temperature causes a decrease in the hardness value in the HAZ section. The highest value of HAZ in specimens without preheating is caused by the formation of fine pearlite phase which is more dominant than coarse pearlite phase due to faster cooling rate compared to specimens treated with preheating. The fine pearlite phase is harder and stronger than the coarse pearlite phase, but fine pearlite is not as ductile as coarse pearlite William, 2018).

CONCLUSIONS

Based on the results of the discussion, the following conclusions are drawn:

1. Macro structure testing on all specimens is free from welding cracks, this indicates the application of preheating can minimize the occurrence of welding defects by reducing the cooling rate of the parent material, the reduced cooling rate causes the material to be more ductile and has better crack resistance. The application of preheating to the macro structure shows differences in the width of the HAZ which correlates with the initial welding temperature, the higher the preheating temperature used results in a wider HAZ area.
2. Microstructure testing shows that increasing the preheating temperature results in the formation of more ductile phases in the base metal, diffusion layer and Heat Affected Zone (HAZ) areas. The base metal region shows that the phases formed are pearlite and ferrite, the higher preheating temperature has an effect on the grain size of the pearlite phase getting smaller so that it makes the material have a better strain value at higher preheating applications. The diffusion layer area shows a clear boundary as a result of the diffusion process, where melting in the diffusion layer area makes the material more ductile. The HAZ section forms fine pearlite microstructure and also coarse pearlite and ferrite phases, where the higher the preheating temperature, the dominant coarse pearlite phase will be produced, the phase of ferrite and also coarse pearlite will produce more ductile material properties. The phases formed in the weld metal are not affected by the preheating temperature where the phases formed are martensite and ferrite, resulting in properties in the weld metal area that are hard but brittle due to the dominant martensite structure.
3. Hardness testing showed that increasing the preheating temperature resulted in a decrease in hardness values at the base metal, diffusion layer, and HAZ. Specimens without preheating had the highest hardness values at base metal (126.36 HV), diffusion layer (435.58 HV), and HAZ (180.47 HV). The decrease in hardness is due to the formation of a softer proportion of the microstructure due to the slower cooling rate at higher preheating temperatures. The weld metal hardness shows fluctuating values, with the highest hardness value at 200°C preheating of 680.11 HV.

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