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Literature Review on Microstructure and Mechanical Properties of Ss400 Steel Due To Variations in PWHT Temperature in the GMAW Welding Process

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Abstract. Post-Weld Heat Treatment (PWHT) is a widely employed thermal method used to relieve residual stresses and enhance the mechanical properties of welded joints. This study investigates the effect of PWHT on the mechanical and microstructural properties of SS400 steel welded using the Gas Metal Arc Welding (GMAW) process. The research focuses on evaluating how variations in PWHT temperature influence tensile strength. impact toughness. hardness. and microstructural characteristics. Specimens were subjected to PWHT for 1 hour with a 15-minute holding time. followed by natural cooling at room temperature. The results indicate that PWHT significantly improves impact toughness and refines grain structure. especially in the Heat Affected Zone (HAZ). while leading to a reduction in tensile strength compared to untreated specimens. Higher PWHT temperatures promoted the formation of finer ferrite and bainitic phases. contributing to enhanced ductility and toughness but reduced hardness due to grain coarsening. Microstructural analysis confirmed a shift in phase composition. where an increased ferrite content resulted in lower hardness. while a dominant pearlite phase corresponded with higher hardness values. Overall. this study highlights the importance of optimizing PWHT parameters to achieve a desirable balance between strength. hardness. and toughness in SS400 welded joints. particularly for structural applications such as shipbuilding.

Keywords: Post-Weld Heat Treatment (PWHT); Gas Metal Arc Welding (GMAW); mechanical properties

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1. Introduction

SS400 material is a type of carbon steel with a carbon content of approximately 0.17%, classified as low-carbon steel. SS400 is commonly used in ship construction and general construction projects (1). In the shipbuilding industry, low-carbon steel is widely used, especially as the primary material for hull structures. One of the most frequently used types is SS400 steel plate, which contains less than 0.3% carbon. SS400 is favored due to its high ductility and toughness, with a Brinell hardness ranging from 95 BW to 145 HBW and a tensile strength between 320 MPa and 550 MPa, making it well-suited for ship body construction (2).

In the ship construction process, metal joining is a critical stage that determines the strength and reliability of the structure. Various metal joining methods are commonly used. such as mechanical joining using bolts and rivets, adhesive bonding, and thermal joining methods such as welding. Among these. welding is the preferred method because it produces strong, efficient, and permanent joints. Welding methods include Shielded Metal Arc Welding (SMAW), Gas Tungsten Arc Welding (GTAW). Gas Metal Arc Welding (GMAW), and Flux-Cored Arc Welding (FCAW). One of the most widely used welding processes in the industry is Gas Metal Arc Welding (GMAW) due to its efficiency

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good weld quality. and suitability for large-scale fabrication applications. such as ship hull manufacturing.

Gas Metal Arc Welding (GMAW) is a welding process in which the energy is generated from an electric arc (2). GMAW is typically operated semi-automatically, and with the rapid development of the industry, from light to heavy construction, there is a growing demand for fast and high-quality welding processes making GMAW a viable alternative (3). In ship construction, weld joint quality is highly critical. Incomplete fabrication or repair processes, as well as initial cracks, can lead to structural failure when exposed to cyclic loads, such as wave forces during ship operation. These cracks are generally caused by the microstructure or phases formed in the Heat-Affected Zone (HAZ), hydrogen diffusion in the weld area, and residual stresses around the HAZ.

The tensile strength of the weld metal is highly influenced by the heat input during welding. Therefore, Post Weld Heat Treatment (PWHT) is essential for reducing residual stress. Refining the microstructure. and improving mechanical properties such as tensile strength and toughness (4). Residual stresses are critical factors influencing the service performance, reliability, and durability of welded carbon steel joints. These stresses can affect the joint, susceptible to brittle fracture, fatigue failure, and stress corrosion cracking, particularly within the heat-affected zone (HAZ) (5). Another contributing factor to imperfections in welding outcomes is the presence of welding defects and residual stresses concentrated in the weld zone (6). To minimize such imperfections or reduce residual stresses, a PWHT process is typically applied. The primary objective of PWHT is to relieve the residual stresses that develop during the welding process. thereby enhancing the structural integrity and performance of the welded join (7).

Based on previous research, it has been observed that preheating and post-weld heat treatment (PWHT) significantly influence the amount of distortion that occurs in welded joints. The findings indicate that the primary factors contributing to welding distortion are the thermal treatments applied before and after welding. as well as the holding time following the welding process (8).

PWHT can reduce residual stresses and improve the microstructure of post- welding materials. The cooling medium used in the PWHT process plays a vital role in determining the welding results, especially in heat distribution and final mechanical properties of the material (9). The parameters of PWHT include heating, holding, and cooling. The appropriate temperature for conducting PWHT is above 300 °C, with a constant cooling rate not exceeding 260 °C/hour (10). PWHT affects the mechanical properties of dissimilar welding between austenitic stainless steel and carbon steel. The hardness value in the HAZ of the stainless steel increases. Tensile strength and yield strength of the weld joint improve at a temperature of 550 °C (11). PWHT is usually performed depending on the thickness or the alloy content of the component being repaired (12).

There are two primary methods used to relieve residual stress: mechanical and thermal methods. Among these. the thermal method specifically PWHT is the most commonly applied. In addition to relieving residual stress. PWHT also serves to improve the toughness of the welded joint in the Heat Affected Zone (HAZ) and refine the grain structure of the material. The effectiveness of PWHT largely depends on parameters such as holding time, temperature, and cooling medium, all of which significantly influence the enhancement of the weld metal's mechanical properties, including tensile strength, ductility, toughness and more (13).

Heat treatment aims to increase ductility and eliminate internal stresses, refine crystal grains and increase tensile stress and hardness of the material. This can be achieved as desired if attention is paid to influencing factors such as heating temperature and cooling media. Several studies have shown that varying the temperature and duration of Post Weld Heat Treatment (PWHT) provides a very significant change in the strength and durability of the material (9).

As part of the quality evaluation of SS400 steel weld joints using the Gas Metal Arc Welding (GMAW) process. especially after being subjected to PWHT at varying temperatures, testing is required to observe changes in microstructure and mechanical properties. These tests include tensile testing, impact toughness testing, and hardness testing. Tensile testing is used to determine the material's strength under axial load; impact toughness testing measures the material's ability to absorb energy before fracturing; and hardness testing indicates the surface's resistance to deformation. These three tests are crucial to assess the extent to which PWHT affects the quality of SS400 steel welds in the context of ship construction.

2. Materials and Methode

The research methodology in this study consists of several stages. starting from the preparation of materials to the welding process and subsequent testing. The first step involves preparing the SS400 steel material. followed by the creation of a V-groove with a 45° angle. The next stage is the Gas Metal Arc Welding (GMAW) process, which is carried out in the 3G welding position using a 10 mm thick plate and ER-5356 filler metal. After welding. the SS400 specimens undergo Post Weld Heat Treatment (PWHT) at varying temperatures of 700°C. 800°C. and 900°C, each held for 1 hour with a holding time of 15 minutes. This is followed by a natural cooling process at room temperature (25°C) for 5 hours (14). The following is the SS400 chemical used as a material in this study.

Table 1. Chemical composition of SS 400 / mas. % (9)

Element	P	C	S	Mn	Cu	Si	Cr	Fe
Mas. %	0.0018	0.0337	0.0	0.288	0.013	0.0	0.0273	Balance

2.1 Specimen Preparation and Welding

a. Preparing the research material. SS400 steel.
b. Setting up the GMAW (Gas Metal Arc Welding) machine and ER70S-6 solid wire.
c. Preparing the welding groove (joint preparation).
d. Grinding the surface of the steel specimens to smoothen it and reduce the risk of welding defects.
e. Adjusting the welding parameters. including voltage. current (amperage). and wire feed speed.
f. Performing the welding process and allowing the weld to cool in an open-air environment.
g. Inspecting the welds for surface defects or irregularities.
h. Proceeding to the Post-Weld Heat Treatment (PWHT) process.

2.2 PWHT Process

The process begins with specimen preparation. where the material or sample is readied for the next steps. Following this. the post-weld heat treatment (PWHT) temperature and holding time are determined based on material specifications and welding conditions. Once these parameters are set. the PWHT heating process is carried out. gradually raising the temperature to the target level. After reaching the desired temperature. the specimen enters the PWHT holding stage. where it is maintained at that temperature for a specific duration to relieve stresses and improve mechanical properties. Finally. the specimen undergoes cooling and inspection to evaluate the results and ensure the treatment has achieved the desired effects.

2.3 Tensile Test Specimen

The tensile test specimens of the joints were prepared according to the DIN ISO 6892 standard. with dimensions of 380 mm in length. 37 mm in width. and 12 mm in thickness. as shown in Figure 1 (16).

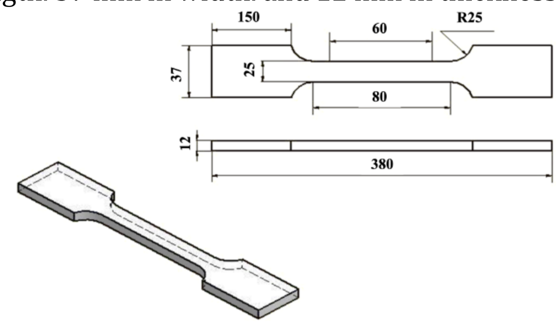

Figure 1. Tensile Test Specimen Design (16)

2.4 Toughness Test Specimen

The tensile test specimens of the joints were prepared according to the ASTM E23 standard. with dimensions of 55 mm in length. 10 mm in width. and 6 mm in thickness. as shown in Figure 2 (14).

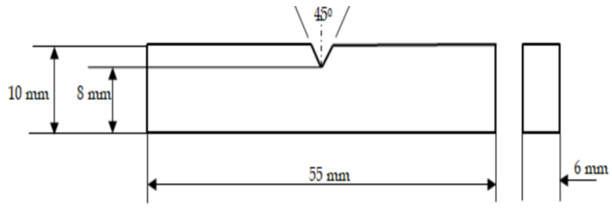

Figure 2. Toughness Test Specimen Design (14)

2.5 Hardness Test Specimen

The hardness test is intended to determine a material's ability to withstand a load when a specific force is applied to the test material (17). The hardness test was conducted at the half of the plate thickness, across the weld metal, and had a distance between 2 test points of 1 mm as shown in Figure 3.

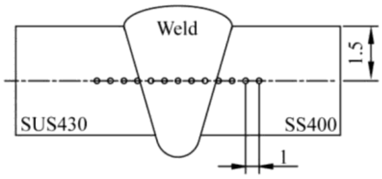

Figure 3. Hardness test specimen design (18)

The Vickers method is one of the most sensitive techniques for hardness testing. It features a single continuous scale applicable to all materials. with the Vickers hardness number (VHN) depending on the applied load. Due to the possibility of using very light loads. this method is particularly suitable for testing the hardness of thin materials. down to a thickness of 0.005 inches. The hardness value can be expressed as follows (19):

$$HV=\frac{[2P\sin\left(\frac{\alpha}{2}\right)]}{d^2}$$

$$HV= 1.854\ P/d^2$$

Where:
P : specified load (Kg)
d : average diagonal length
α : angle between opposite diamond faces

Specimen preparation for hardness test (19):

a. Prepare the polished specimen until smooth on the part to be checked
b. Install the one to be used on the Vickers hardness tester machine. the indenter used in the test is a pyramid-shaped diamond indenter
c. Place the material to be tested on the test object surface perpendicular to the indenter axis
d. Adjust the height of the test table and adjust the focus level between the microscope and the test object
e. Press the start button. the indenter will slowly descend
f. Pay attention to the monitor which will show the pressure force value which continues to increase until it reaches the predetermined force limit
g. After that. measure the area that was pressed earlier
h. Then enlarge the layer display using the magnifying control button on the Vickers hardness tester machine to measure the curvature angle by making a line so that the diagonal length can be easily determined.
i. The Vickers hardness measurement results will be calculated automatically using the software in it.

2.6 Microstructure Preparation

The microstructure of an alloy is influenced by various factors. including the type and concentration of alloying elements. as well as the heat treatment applied. Microstructural examination is conducted using an optical microscope. which operates with varying magnification levels and specific methodologies. Prior to microscopic observation. a series of preparatory steps must be performed to ensure the accuracy and clarity of the microstructural features. These steps include sectioning the specimen to the required dimensions. mounting it in a stable medium. followed by sequential polishing to produce a smooth surface. The surface is then etched using a suitable chemical reagent to reveal the grain boundaries and phase distributions. Finally. micrographs are captured for analysis and documentation.

3. Result and Discussion

3.1 Tensile Test Result

The study shows a clear increase in impact toughness of SS400 steel welded joints after undergoing post-weld heat treatment (PWHT). Without PWHT, the material recorded an average toughness value of 0.446 J/mm^2. This value increased to 0.514 J/mm^2 after PWHT at 800°C, and further to 0.691 J/mm^2 when the temperature was raised to 850°C (14). These findings indicate that higher PWHT temperatures significantly enhance the material's resistance to impact, likely due to stress relief and microstructural refinement.

Specifically. the specimen without PWHT had an average tensile strength of 456.45 MPa and an elongation of 26.78%. For the 800°C PWHT. the average tensile strength was 427.60 MPa with 30% elongation. and for the 850°C PWHT. it was 411.68 MPa with 28.54% elongation. These results indicate that temperature variation in PWHT affects tensile strength.

The variation in tensile strength is related to changes in hardness and ductility due to PWHT. as PWHT increases hardness but reduces ductility. Materials without PWHT tend to have higher tensile strength because they retain more ductility. As hardness increases. ductility decreases. making the material more brittle. Therefore. the highest tensile strength is observed without PWHT. and the lowest at 850°C PWHT. This aligns with the findings of Randhiko et al.. which confirm that PWHT temperature variations significantly influence the mechanical properties of welded joints (20).

A similar result is also reported in another study, which found that the highest average ultimate tensile strength was obtained from the FCAW (Flux-Cored Arc Welding) welded joint without any post-weld heat treatment, reaching 467.404 MPa. In contrast, the lowest tensile strength was recorded in the specimen subjected to normalizing at 975°C, with a value of 377.01 MPa. Another specimen treated with normalizing at 875°C showed an intermediate tensile strength of 410.025 MPa (21). Although the study used ST 40 steel. this material is equivalent to SS 400 in terms of mechanical properties, as they differ only in standard classification.

The results of the tensile strength test on FCAW welded joints with PWHT indicate a clear decrease in tensile strength as the heat treatment temperature increases (22). This behavior contrasts with the trend observed in impact toughness, where PWHT typically enhances performance. The reduction in tensile strength after PWHT can be attributed to microstructural changes, particularly the increase in ferrite phase and decrease in dislocation density, which reduce the material's resistance to tensile loading.

This inverse relationship between tensile strength and toughness is also reflected in data from specimens welded using the GMAW (Gas Metal Arc Welding) process. Despite differences in the welding method, the application of PWHT similarly results in lower tensile strength values. These consistent findings across both FCAW and GMAW processes further confirm that while PWHT improves ductility and toughness by relieving residual stresses and refining the microstructure, it simultaneously reduces tensile strength due to the loss of strain hardening and decreased dislocation density.

Based on the data presented tensile tests was conducted using the GMAW method, the specimen exhibiting the highest average tensile strength was the untreated (RAW) material, reaching 801.3 MPa. In contrast, the lowest tensile strength was recorded in the specimen subjected to PWHT for 2 hours, with an average of 577 MPa. The specimen treated with PWHT for 1 hour showed a slightly higher tensile strength of 627 MPa, outperforming both the untreated welded specimen (620 MPa) and the specimen treated with PWHT for 3 hours (592 MPa) (12).

The observed decline in tensile strength following PWHT is primarily attributed to the relief of residual stresses induced during welding. The thermal exposure during PWHT facilitates microstructural relaxation and a reduction in dislocation density, ultimately leading to decreased tensile strength.

These findings align with previous research on AISI 1045 steel, which also reported a consistent decrease in tensile strength with increasing PWHT holding time. In that study, the tensile strength values dropped from 469.13 MPa (no PWHT) to 444.56 MPa (15 minutes), 432.47 MPa (30 minutes), and finally to 421.87 MPa (45 minutes). A similar trend was observed in research involving SS400 low-carbon steel subjected to PWHT at varying temperatures, where the maximum tensile strength decreased from 456 MPa (no PWHT) to 427 MPa (800°C) and further to 411 MPa (850°C). These results further confirm the inverse relationship between PWHT duration or temperature and the tensile strength of welded steel joints (23).

Heat treatment at temperatures ranging from 400°C to 550°C results in the transformation of the ferrite microstructure into coarse-grained ferrite. The presence of coarse grains leads to a reduction in material hardness due to a lower dislocation density, which is associated with larger grain sizes. Consequently. the hardness values decrease compared to specimens that did not undergo heat treatment. In addition. coarse microstructures reduce tensile strength. as the narrower grain boundaries are less effective at impeding dislocation movement (24).

In contrast. heat treatment in the range of 550°C to 700°C leads to the formation of finer ferrite structures, which are inherently harder, At these higher temperatures, the microstructure evolves into a mixed phase consisting of bainite, Martensite, and spheroidized particles. As the grain size becomes finer, the dislocation density increases, contributing to higher hardness values. Furthermore, the yield strength improves significantly compared to the specimens treated at lower temperatures. Fine-grained microstructures enhance tensile strength by providing broader grain boundaries, which are more effective in restricting dislocation motion (24).

These findings are in agreement with previous studies, which also reported that specimens without PWHT, exhibited higher hardness values compared to those subjected to PWHT. The explanation lies, in the fact that PWHT tends to relieve internal stresses and promote microstructural recovery. which. while beneficial for toughness, often results in reduced hardness and strength due to grain coarsening and reduced dislocation density.

In addition to variations in PWHT temperature, holding time also plays a significant role. This is evidenced by the discussion in a previous study, where tensile test results indicated that the values changed with increasing PWHT holding time. The longer the holding time, the more the tensile strength decreased. This demonstrates a direct correlation between extended PWHT holding time and the reduction in tensile strength. Both PWHT and its holding time contribute to the relief of residual stress and the refinement of the microstructure within the material after the welding process. which ultimately leads to a decrease in tensile strength as the holding time increases (25).

3.2 Toughness Test Result

The study shows a clear increase in impact toughness of SS400 steel welded joints after undergoing post-weld heat treatment (PWHT). Without PWHT, the material recorded an average toughness value of 0.446 J/mm^2. This value increased to 0.514 J/mm^2 after PWHT at 800°C, and further to 0.691 J/mm^2 when the temperature was raised to 850°C (24). These findings indicate that higher PWHT temperatures significantly enhance the material's resistance to impact, likely due to stress relief and microstructural refinement.

Variations in temperature can affect the tensile strength of a material due to changes in hardness and ductility after the PWHT process. The hardness of a metal tends to increase after PWHT normalizing, while its ductility tends to decrease. In general, both impact energy and impact strength increase with higher PWHT temperatures. As the heating temperature rises, the material becomes tougher and the residual stresses are reduced (24).

The improvement in toughness is attributed to the increased homogeneity of the material's mechanical properties after PWHT, resulting in a more consistent response under loading or impact testing. Therefore, the highest impact strength was observed in the specimen treated at 850°C PWHT, while the lowest was found in the specimen without PWHT.

This indicates that PWHT contributes significantly to improving a material's toughness compared to those without any heat treatment. Higher PWHT temperatures tend to further increase toughness while reducing residual stresses in the material. In contrast, materials without PWHT are more prone to crack formation after welding due to unrelieved residual stresses. The primary purpose of PWHT is to minimize these stresses, and without it, they remain uncontrolled and may compromise the integrity of the welded structure

Based on the analysis of the obtained data, it can be observed that the results of the tensile and impact tests show opposite trends. In the tensile test. the specimen without PWHT exhibited higher tensile strength compared to those that underwent PWHT. Conversely, the impact test results showed that specimens treated with PWHT had higher impact strength than those without heat treatment. This difference occurs because post-weld heat treatment at various temperatures affects the material's mechanical properties by altering its hardness and ductility. After the PWHT normalizing process, the hardness of the material tends to increase, while its ductility decreases. This increase in hardness contributes to higher strength, but at the expense of ductility (24).

As a result, specimens that underwent PWHT tend to have lower tensile strength but higher impact resistance compared to untreated specimens. Increasing the PWHT temperature further enhances the material's toughness and helps reduce residual stresses formed during the welding process. The primary purpose of PWHT is to relieve these residual stresses, which if left unaddressed, can make the material more susceptible to cracking and compromise the overall performance of the welded joint.

The results of the toughness test on FCAW welded joints with PWHT clearly demonstrate an increase in impact strength with higher heat treatment temperatures. This trend is consistent with findings from similar studies using different welding methods. For instance. data obtained from GMAW (Gas Metal Arc Welding) specimens exhibit a comparable pattern. where post-weld heat treatment also leads to improved toughness. Although the welding processes differ. the influence of PWHT on enhancing the mechanical properties—particularly impact resistance—remains evident. These consistent results across both FCAW and GMAW processes reinforce the conclusion that PWHT contributes significantly to improving the toughness of welded joints through microstructural refinement and reduction of residual stresses (23).

This finding is consistent with the results reported by Santoso, Amiruddin, and Kiryanto (2024), who investigated the effect of PWHT annealing duration on GMAW-welded ST60 steel. Although the welding method and material differ, their study similarly confirmed that PWHT enhances impact resistance by relieving internal stresses and improving structural uniformity. The alignment between these studies reinforces the conclusion that PWHT is effective in increasing the toughness of welded joints, regardless of the welding technique used (23).

Based on the results of the impact tests among specimens subjected to different PWHT (Post-Weld Heat Treatment) durations. The data indicate that longer PWHT durations correlate with increased absorbed energy values. Specifically, the specimen treated with PWHT for 1 hour exhibited an impact toughness of 1.03 J/mm^2, while the specimens treated for 2 hours and 3 hours reached 1.15 J/mm^2 and 1.21 J/mm^2, respectively. In contrast. the specimen without PWHT recorded a lower value of 0.95 J/mm^2, and the raw material demonstrated the lowest impact toughness at 0.42 J/mm^2 (23).

These findings are consistent with previous research on S45C steel subjected to PWHT with varied holding times of 30, 60, and 90 minutes. The results showed a direct relationship between longer holding times and improved impact toughness. with values of 0.685 J/mm^2, 0.791 J/mm^2. and 0.897 J/mm^2, respectively. In comparison, the specimen without heat treatment showed a significantly lower impact value of 0.355 J/mm^2 (23).

A similar trend was also observed in a separate study involving low-carbon ST42 steel subjected to PWHT at different temperatures. The specimen without PWHT had an impact value of 0.99 J/mm^2, while those treated at 600°C and 650°C exhibited higher values of 1.16 J/mm^2 and 1.42 J/mm^2, respectively. These findings further support the conclusion that both increased PWHT duration and temperature positively influence the toughness of carbon steel materials (23).

3.3 Hardness Test Result

Based on the data presented, post-weld heat treatment (PWHT) significantly reduced the hardness of SS400 steel across all regions base metal, HAZ, and weld metal compared to the raw material. The raw material consistently showed higher hardness values, with peak measurements reaching 353.46

HV in the HAZ, while PWHT specimens recorded lower values, generally ranging from 203 HV to 257 HV across all regions (19).

These findings indicate that the application of stress relieving annealing significantly affects the hardness properties of the material, leading to reduced hardness in the weld zone, HAZ, and base metal (26). This reduction is associated with the relaxation of residual stresses and changes in the microstructure induced by the heat treatment process (19).

The results of the heat treatment experiments reveal notable variations in hardness across the base metal regions, particularly between specimens that underwent preheating and those that did not. These differences are primarily attributed to changes in grain size induced by the thermal cycles. In the heat-affected zone (HAZ), a general reduction in hardness was observed for specimens that received both preheating prior to welding and post-weld heat treatment (PWHT). A similar trend was identified in the weld metal region, where PWHT contributed to a decrease in hardness. When correlated with the microstructural characteristics, it was evident that an increased presence of the pearlite phase led to higher hardness values. This finding suggests that the proportion of pearlite relative to ferrite plays a significant role in determining the overall hardness of the material. In terms of brittleness. the progression of phases from least to most brittle can be classified as ferrite. pearlite. bainite. and martensite (13).

3.4 Microstructure Analysis Result

Although the temperature variations used in this study differ from those applied in the tensile and toughness tests, the microstructural analysis presented here provides clear evidence of the differences between specimens subjected to PWHT and those without heat treatment. This contrasts with previous studies that did not incorporate microstructural examination. thereby highlighting the significance of PWHT temperature variations in influencing the internal structure of the material.

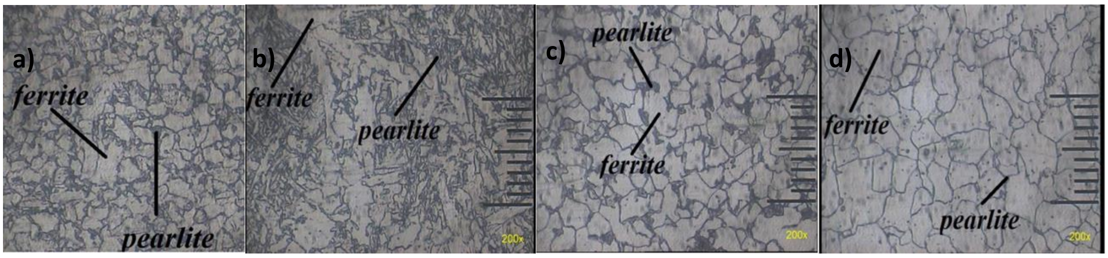

Figure 4. Microstructure of the a) Raw Material HAZ, b) Raw Material Weld Metal, c) PWHT 875°C Material HAZ, d) PWHT 875°C Material Weld Metal (21)

The microstructural phases observed in the four micrographs are ferrite, which appears white. and pearlite, which appears dark. Ferrite is a phase characterized by low strength but good ductility, while pearlite is known for its higher strength and relatively high hardness (21) The high strength and ductility were achieved by the mechanism of coordinated deformation between the ferriteand the austenite (2).

In the microstructure of the HAZ (Heat-Affected Zone) of the specimen without any post-weld heat treatment, a significant amount of dark region identified as pearlite can be seen. This indicates a higher tensile strength. However, as tensile strength increases, the material's tensile strain capacity tends to decrease, which also affects the elastic modulus.

The ST40 steel specimen subjected to PWHT at 875°C exhibits greater ductility and toughness compared to the as-welded condition. This improvement is associated with microstructural refinement and increased ferrite content resulting from the heat treatment process (21).

Based on the microstructural analysis, it can be concluded that the welded joint of ST40 steel using FCAW (Flux-Cored Arc Welding) without any heat treatment exhibits the highest hardness. This is supported by the micrograph showing a more dominant pearlite phase. which contributes to the higher tensile strength of the specimen compared to those treated with normalizing at elevated temperatures.

The microstructural analysis conducted on both FCAW and GMAW welded joints reveals a consistent trend in phase distribution and structural transformation due to post-weld heat treatment

(PWHT). Despite the differences in welding techniques, the effects of PWHT on refining grain boundaries, promoting ferrite formation. and reducing pearlite concentration were similarly observed in both processes. This parallel outcome suggests that PWHT has a comparable influence on the metallurgical characteristics of welded carbon steel, regardless of the welding method used. Such consistency reinforces the conclusion that the thermal cycle of PWHT plays a critical role in enhancing microstructural uniformity and improving the overall mechanical behavior of the material.

The following presents a detailed overview of the microstructural characteristics observed in the GMAW specimens with and without PWHT treatment.

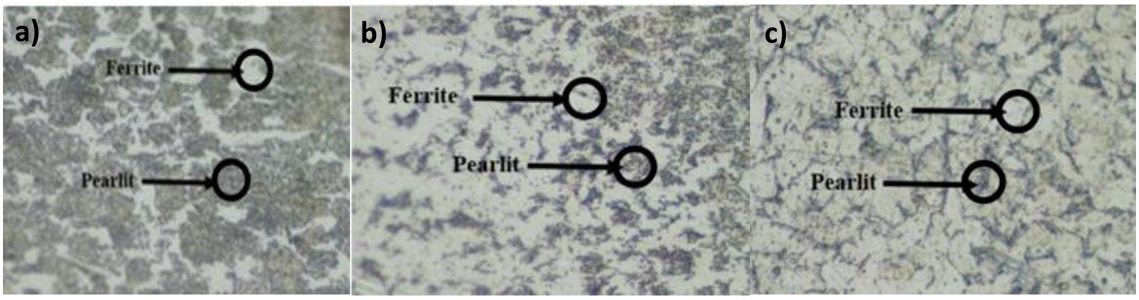

Figure 5. Microstructure of the a) Base Metal PWHT 3, b) HAZ PWHT 3 Hours, c) Weld Metal PWHT 3 Hours (23)

These images indicate noticeable changes in the microstructure after the application of PWHT in the base metal, heat-affected zone (HAZ), and weld metal regions. Across all three regions, it was observed that increasing the PWHT duration led to a more refined and uniform grain structure. In particular, the specimen subjected to PWHT for 3 hours exhibited the most compact and orderly distribution of ferrite and pearlite phases. indicating improved microstructural homogeneity with longer heat treatment duration (23).

This happens because when PWHT is carried out with temperatures above the critical temperature namely 723 °C, there is a change in the ferrite phase to become larger and the dominance of the pearlite phase decreases, causing the phase that was previously pearlite to turn into ferrite. This is supported by research which states that when heating reaches a critical temperature slow cooling causes carbon in the pearlite phase to decrease and has an impact on the former pearlite phase turning into ferrite (28).

In the percentage results, with the increase in PWHT temperature, the percentage of pearlite value decreases, and the ferrite phase increases. As the PWHT temperature increases, the increase and decrease in the percentage of ferrite and pearlite has an effect and this result is linear with the hardness value of a material. The higher the percentage of pearlite. the higher the hardness value, and vice versa when the ferrite percentage is higher, the material has softer properties. From the results of the micro-Vickers hardness test and micro examination, the hardness value is directly proportional to the composition of the pearlite and ferrite phases formed according to the PWHT temperature variations carried out after welding (29). The higher the density and dominance of the pearlite phase which is characterized by a dark color or tends to be black, the higher the hardness value of the material or specimen test area, and vice versa, the higher the density and dominance of the ferrite phase, the hardness value of a material or area tested, the lower the hardness value. This is because the pearlite phase has hard and strong properties (30).

4. Conclusions

The results of this study demonstrate that post-weld heat treatment (PWHT) significantly influences the mechanical and microstructural properties of welded SS400 steel. While tensile strength was found to be higher in specimens without PWHT, those treated with PWHT exhibited greater impact strength and improved toughness. This contrast is attributed to the stress-relief and microstructural changes induced by PWHT. which reduce residual stresses and enhance ductility, albeit at the cost of reduced tensile strength.

PWHT at higher temperatures (550°C–700°C) promotes the formation of finer ferrite and bainitic structures, improving toughness and yielding a refined, uniform grain structure. However, these microstructural evolutions also reduce hardness and strength due to grain coarsening and decreased dislocation density. The holding time of PWHT further influences these outcomes, with longer durations leading to more pronounced reductions in tensile strength.

Microstructural analysis confirmed that increased PWHT duration and temperature lead to changes in the ferrite–pearlite balance. A higher percentage of ferrite corresponds to lower hardness, while a greater pearlite fraction results in increased hardness due to its inherently stronger characteristics. These findings align with previous studies and underline the importance of optimizing PWHT parameters to achieve a desired balance between strength. toughness. and hardness in welded components.

References

1. Oktaviandy. N. R.. Kardiman. K.. & Hanifi. R. "Effect of Preheat Temperature Variation with Cooling Media on Mechanical Properties in Welding SS400 Steel". SINTEK JURNAL: Jurnal Ilmiah Teknik Mesin. 17(2). pp. 130–142. 2023. Retieved from : https://doi.org/10.24853/sintek.17.2.130-142S.
2. A. Farhan. U. Budiarto. and A. W. B. Santosa. "Analisa Perbandingan Kekuatan Tarik. Tekuk. dan Mikrografi Pada Sambungan Las Baja SS 400 Akibat Pengelasan FCAW (Flux-Cored Arc Welding) dengan Variasi Jenis Kampuh dan Posisi Pengelasan." Jurnal Teknik Perkapalan. vol. 7. no. 4. pp. 323–333. 2019. [Online]. Retrieved from : https://ejournal3.undip.ac.id/index.php/naval
3. L. P. Ketaren. U. Budiarto. and A. W. B. Santosa. "Analisa Pengaruh Variasi Kampuh Las dan Arus Listrik Terhadap Kekuatan Tarik Dan Struktur Mikro Sambungan Las GMAW (Gas Metal ARC Welding) Pada Aluminium 6061." Jurnal Teknik Perkapalan. vol. 7. no. 4. pp. 345–354. 2019. [Online]. Retrieved from : https://ejournal3.undip.ac.id/index.php/naval
4. C. Wahyunanta. N. S. Drastiawati. "Pengaruh Variasi Media Pendingin dalam Proses PWHT Pengelasan SMAW untuk Material Baja SS400 terhadap Nilai Kekerasan dan Kekuatan Tarik". JTM: Jurnal Teknik Mesin UNESA. vol. 11. no. 1. pp. 13–18. 2023. [Online]. Retrieved from: https://ejournal.unesa.ac.id/index.php/jtm-unesa/article/view/50698
5. O. Falodun, S. Oke, and M. Bodunrin, "A comprehensive review of residual stresses in carbon steel welding: formation mechanisms, mitigation strategies, and advanced post-weld heat treatment techniques," *Int. J. Adv. Manuf. Technol.*, vol. 136, pp. 4107–4140, 2025, doi: 10.1007/s00170-025-15088-8. [Online]. Retrieved from: https://www.researchgate.net/publication/388528409_A_comprehensive_review_of_residual_stresses_in_carbon_steel_welding_formation_mechanisms_mitigation_strategies_and_advanced_post-weld_heat_treatment_techniques
6. J. Xiong, T. Li, X. Yuan, G. Mao, J. Yang, L. Yang, and J. Xu, "Improvement in weldment of dissimilar 9% Cr heat-resistant steels by post-weld heat treatment," *Metals*, vol. 10, pp. 1-10. 1321, 2020. [Online]. Available: https://doi.org/10.3390/met10101321
7. S. Sunardi. "Analisis Kekerasan dan Kuat Impak Hasil Pengelasan Baja SS400 dengan Variasi Arus Listrik Las SMAW".. j. inov. ilmu pengetah. dan teknologi. vol. 2. no. 1. pp. 6–10. Dec. 2020. [Online]. Retrieved from : https://openjournal.unpam.ac.id/index.php/JIPT/article/view/8655S
8. eno. H. R.. & Rosidi. "Analisis Pengelasan GMAW Pada Pelat Baja SS400 Untuk Mengurangi Distorsi Studi Kasus Sheeting Roof E-Inobus". Prosiding Seminar Nasional Teknik Mesin. vol. 12. no.1. pp. 46–55. 2022. [Online]. Retrieved from https://prosiding.pnj.ac.id/sntm/article/view/10
9. M. P. S. Paskel. M. Ariyon. Fitrianti. Ira Herawati. A. Sebayang. E. Tarigan. et a;.. "Study of the Effect of Post Weld Heat Treatment on the Bending Strength of Weld Joints in SMAW and GMAW Methods in Root Bend Areas and Face Bend on ASTM A106 Grade B" International Journal of Engineering. Science and Information Technology. Vol. 5. No.2. pp. 368–371. 2025. [Online]. Retrieved from: https://ijesty.org/index.php/ijesty/%20article/view/850
10. W. Naziful Akhyar, E. Afrizal, and W. Fatra, "Pengaruh Temperatur Post Weld Heat Treatment (PWHT) terhadap Sifat Mekanis Material Baja A36 yang mengalami Pengelasan Shielded Metal

Arc Welding (SMAW)," *JOM FTEKNIK*, vol. 8, no. 2, pp. 1–6, 2021. [Online]. Retrieved from: https://jom.unri.ac.id/index.php/JOMFTEKNIK/article/download/31677/30490
11. M. A. Jaya, S. M. B. Respati, and H. Purwanto, "Pengaruh suhu tempering terhadap kekuatan tarik, kekerasan dan mikrostruktur pada sambungan las Shielded Metal Arc Welding (SMAW) baja pegas daun," *Jurnal Ilmiah Momentum*, vol. 14, no. 1, pp. 16–22, 2018. [Online]. Retrieved from: https://www.researchgate.net/publication/337396675_PENGARUH_SUHU_TEMPERING_TERHADAP_KEKUATAN_TARIK_KEKERASAN_DAN_MIKROSTRUKTUR_PADA_SAMBUNGAN_LAS_SHIELDED_METAL_ARC_WELDING_SMAW_BAJA_PEGAS_DAUN
12. S. Joshi, J. Price, and K. Alawadhi, "Hardness, Microstructure, and Residual Stresses in Low Carbon Steel Welding with Post-weld Heat Treatment and Temper Bead Welding," *Metall. Mater. Trans. A*, vol. 45, pp. 1–12, 2014. [Onliine]. Retrieved from: https://www.researchgate.net/publication/261141354_Hardness_Microstructure_and_Residual_Stresses_in_Low_Carbon_Steel_Welding_with_Post-weld_Heat_Treatment_and_Temper_Bead_Welding
13. M. K. Al Amin. A. M. Zakaria. Bachtiar. E. R. Widodo. Arif Rachman. Muhammad Fauzi "Preheat and PWHT analysis of FCAW A573 grade 70 welds results of HT and NHT materials on hardness and microstructure". Journal of Welding Technology. Vol. 6. No.1. pp. 27–37. 2024. [Online]. Retrieved from : https://e-jurnal.pnl.ac.id/Welding_Technology/article/view/5239
14. F. W. Pribadi. N. S. Drastiawati. "Pengaruh Variasi Temperatur dalam Proses PWHT Pengelasan SMAW Untuk Material Baja SS400 Terhadap Nilai Kekuatan Tarik dan Kekuatan Impak" JTM: Jurnal Teknik Mesin UNESA. vol. 12. no. 2. pp. 17–22. 2024. [Online]. Retrieved from : https://ejournal.unesa.ac.id/index.php/jtm-unesa/article/view/58272
15. N. Muhayat. S. Yasinta. A.R. Prabowo. Y.C.N. Saputro and Triyono. "Effect of the post weld heat treatment on the microstructure of the underwater wet welding SS400 steel". Metalurgija. vol.64. no. 1-2. pp. 20-22. 2025. [Online]. Retrieved from: https://hrcak.srce.hr/319796
16. P. H. Saputra. I. S. Aisyah. D. Kurniawati. "Pengaruh Variasi Arus Terhadap Kekuatan Tarik dan Hasil Pengamatan Non-Destructive Test MT. UT pada Pengelasan GMAW Material Baja SS400"Prosiding Seminar Nasional Teknologi Industri Berkelanjutan IV (SENASTITAN IV). pp. 1–8. 2024. [Online]. Retrieved from : https://ejournal.itats.ac.id/senastitan/article/download/5772/3791
17. A. A. Prabowo, "Struktur Mikro dan Kekuatan Bending Baja AISI 1010," *Journal of Mechanical Engineering Learning*, vol. 9, no. 1, pp. 1–6, 2020. [Online]. Retrieved from: https://journal.unnes.ac.id/sju/jmel/article/view/40310/16696
18. Poonnayom. P.. Chantasri. S.. Kaewwichit. J.. Roybang. W.. & Kimapong. K. (2015). *Microstructure and tensile properties of SS400 carbon steel and SUS430 stainless steel butt joint by gas metal arc welding*. The International Journal of Advanced Culture Technology. 3(1). 61–67. https://doi.org/10.17703/IJACT.2015.3.1.61 [Online]. Retrieved from: https://www.researchgate.net/publication/283202290_Microstructure_and_Tensile_Properties_of_SS400_Carbon_Steel_and_SUS430_Stainless_Steel_Butt_Joint_by_Gas_Metal_Arc_Welding
19. A. Rudiyanto. R. Anjani. and V. Naubnome. "Analisis Proses Stress Relieving Annealing Terhadap Sambungan Las Gas Metal Arc Welding (GMAW) Material Baja SS 400". Jurnal Ilmiah Wahana Pendidikan (JIWP). vol. 8. no. 22. pp. 84-93. Nov. 2022. [Online]. Retrieved from: https://jurnal.peneliti.net/index.php/JIWP/article/view/2874
20. A. Randhiko. G. D. Haryadi. and Y. Umardani. "Pengaruh Post Weld Heat Treatment (PWHT) T6 Pada Aluminium Alloy 6061-O dan Pengelasan Longitudinal Tungsten Inert Gas terhadap Sifat Mekanik dan Struktur Mikro." JURNAL TEKNIK MESIN. vol. 2. no. 3. pp. 167–174. Jul. 2014. [Online]. Retrieved from : https://ejournal3.undip.ac.id/index.php/jtm/article/view/9608B
21. E. N. Laksono. A. W. B. Santosa. and S. Jokosisworo. "Analisa Perbandingan Kekuatan Tarik. Impak. dan Mikrografi Pada Sambungan Las Baja ST 40 Akibat Pengelasan Flux-Cored Arc Welding (FCAW) Dengan Variasi Suhu Normalizing." Jurnal Teknik Perkapalan. vol. 8. no. 4. pp. 520-531. Aug. 2020. [Online]. Retrieved from : https://ejournal3.undip.ac.id/index.php/naval/article/view/28307/0
22. Y. M. Pratama, U. Budiarto, and S. Jokosisworo, "Analisa perbandingan kekuatan tarik, tekuk, dan mikrografi pada sambungan las baja SS 400 akibat pengelasan FCAW (Flux Cored Arc Welding) dengan variasi jenis kampuh dan posisi pengelasan," *Jurnal Teknik Perkapalan*, vol. 7, no. 4, pp.

203–208, 2019. [Online]. Retrieved from: https://ejournal3.undip.ac.id/index.php/naval/article/view/24216

23. M. H. Fakhryyah Santoso. W. Amiruddin. and K. Kiryanto. "Analisis Pengaruh Durasi Post Weld Heat Treatment Annealing Pada Pengelasan GMAW Baja ST60 Terhadap Kekuatan Uji Tarik. Uji Impak. Uji Bending dan Struktur Mikro." Jurnal Teknik Perkapalan. vol. 12. no. 3. Aug. 2024. [Online]. Retrieved from : https://ejournal3.undip.ac.id/index.php/naval/article/view/44832
24. Nurudin. A. T. A. Salim. I. Yuwono. A. Rahmatika. dan Suparman. "Analisis Sambungan Las GMAW Baja ASTM A36 yang Terpapar Panas Tinggi dna Pendinginan Cepat". JTT (Jurnal Teknologi Terapan). Vol. 8. No.2. pp. 166–173. 2022. [Online]. Retrieved from : https://jurnal.polindra.ac.id/index.php/jtt/article/view/436
25. Tri. Mulya. Prayogo. Tri. Hartutuk. Ningsih. "Pengaruh Holding Time PWHT terhadap Kekuatan Tarik pada Proses Pengelasan SMAW Baja S45C". Jurnal Inovasi Teknologi Manufaktur (JITM). Energi. dan Otomotif. Vol. 2 . No.1 pp. 77–83. 2023. [Online]. Retrieved from: https://jurnal.poliwangi.ac.id/index.php/jinggo/article/view/113
26. W. Widayat and D. D. Saputro, "Pengaruh variasi suhu post weld heat treatment annealing terhadap sifat mekanis material baja EMS-45 dengan metode pengelasan Shielded Metal Arc Welding (SMAW)," *Jurnal Teknik Mesin*, vol. 10, no. 1, pp. 147–152, 2022. [Online]. Retrieved from: https://journal.unnes.ac.id/nju/index.php/sainteknol/article/download/5547/4415
27. M. K. Al Amin. A. M. Zakaria. Bachtiar. E. R. Widodo. Arif Rachman. Muhammad Fauzi "Preheat and PWHT analysis of FCAW A573 grade 70 welds results of HT and NHT materials on hardness and microstructure". Journal of Welding Technology. Vol. 6. No.1. pp. 27–37. 2024. [Online]. Retrieved from : https://e-jurnal.pnl.ac.id/Welding_Technology/article/view/5239
28. B. Prabawanto dan A. H. A. Rasyid. "Pengaruh Annealing Terhadap Sifat Mekanis Daerah HAZ Pengelasan GMAW Baja SM490 Normalizing Dan Tanpa Normalizing Pada Bogie Kereta Api Di PT.INKA Madiun." JTM. vol. 6. pp. 75–82. 2018. [Online]. Retrieved from : https://ejournal.unesa.ac.id/index.php/jtm-unesa/article/view/24210/22136
29. M. Arif. A. T. Agus Salim. I. Yuwono. A. Dharmawan. D. L. Zuirah "Experimental Study The Mechanical Properties of GMAW Welding Results on S355j2+N Material with Post Weld Heat Treatment (PWHT)". Jurnal Media Mesin. Vol. 25 No. 1. pp. 1–9. 2024. [Online]. Retrieved from: https://journals2.ums.ac.id/index.php/mesin/article/view/2848
30. D. Qin, X. Gao, T. Liu, H. Wu, M. Zhang, and L. Du, "Effect of Annealing Process on Microstructure and Mechanical Properties in Microalloyed Medium Manganese Steel," *Steel Res. Int.*, vol. 92, no. 1, pp. 1–13, 2020. [Online]. Retrieved from: https://www.researchgate.net/publication/347823039_Effect_of_Annealing_Process_on_Microstructure_and_Mechanical_Properties_in_Microalloyed_Medium_Manganese_Steel