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Research Article

Analysis of Tube Expansion Percentage on Microstructure and Hardness of 316L Stainless Steel Tube-to-Tubesheet Connections with GTAW Process

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Abstract

This study analyzes the effect of varying tube expansion percentages on the mechanical properties, microstructure, and hardness of SA-213 TP316L tubes joined to SA-240 TP316L tubesheets in a shell-and-tube type heat exchanger. The tube expansion process was carried out using a roller expander with three expansion levels: 4%, 8%, and 12%, followed by Gas Tungsten Arc Welding (GTAW) at 150 A. Microstructural observations revealed that all joint zones were dominated by austenite with small amounts of delta ferrite, where increasing expansion percentages induced significant changes in the expand area: slight deformation at 4%, grain elongation at 8%, and pronounced grain distortion at 12%. Macrostructural observations showed perfect fusion between the tube and tubesheet for all variations, with no macro defects such as lack of fusion or porosity. Vickers hardness testing indicated the highest values in the expand area for all variations, with a maximum of 377 Kgf/mm^2, exceeding the standard limit of 250 Kgf/mm^2 for stainless steel. The hardness of the base metal was around 180 Kgf/mm^2, while the weld metal ranged from 220–230 Kgf/mm^2 due to delta ferrite formation. The increase in hardness in the expand area was attributed to cold working effects, indicating that post-tube expansion heat treatment is necessary to reduce residual stress and restore the optimal mechanical properties of the material.

Keywords: Stainless Steel 316l, GTAW Process, Tube Expansion, Hardness, Microstructural

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INTRODUCTION

A heat exchanger is equipment used to transfer heat between two fluids with different temperatures without direct mixing. One of the important components in the construction of shell-and-tube-type heat exchangers is the connection between the tube and tubesheet. This connection must have high structural integrity to prevent leakage and ensure heat transfer efficiency [1]. As an illustration, the connection configuration can be seen in Figure 1.

There are several types of tube-to-tubesheeet connections, and the quality of these connections affects the performance, efficiency, and safe operation of the device. The strength of the tube-to-tubesheeet connection is critical to providing structural integrity to the shell and tube heat exchanger. Welding processes and tube expansion are commercialized techniques for producing tube-to-tubesheeet connections. The welding parameters and the percentage of expansion affect the tube tensile strength of tube-to-tubesheeet connections [3]. The expanding process is cold working by expanding the inner diameter of the tube using a roller expanding tool. A comparative visualization of the conditions before and after the expansion process is shown in Figure 2.

In fabrication practice, the tube expansion percentage is set to produce an optimal mechanical bond without causing damage to the material. The Tema 11th Edition[5] standard recommends a maximum expansion limit of 8% for stainless steel materials. Based on PT X's internal data, the safe limit of tube expansion applied in the company is 4-6%, which is stricter than the TEMA 11th Edition recommendation for austenitic stainless steel materials. However, in one of the heat exchanger production cases at PT X, an overexpansion phenomenon was found with a percentage reaching 12%. This is caused by excessive tubesheet hole diameter tolerance and expansion pressure settings that are not in accordance with the company's standard operating procedures. This condition has the potential to reduce the mechanical integrity of the connection, increase the risk of

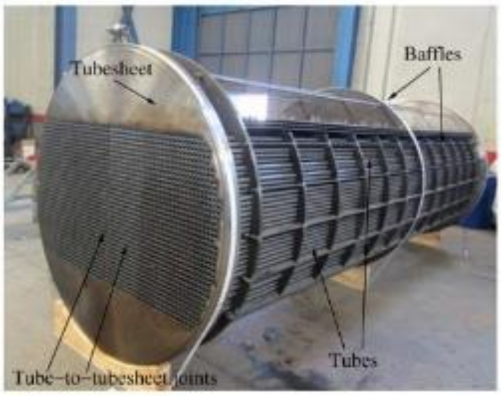


Figure 1. Tube to Tubesheet on Heat Exchanger [2]

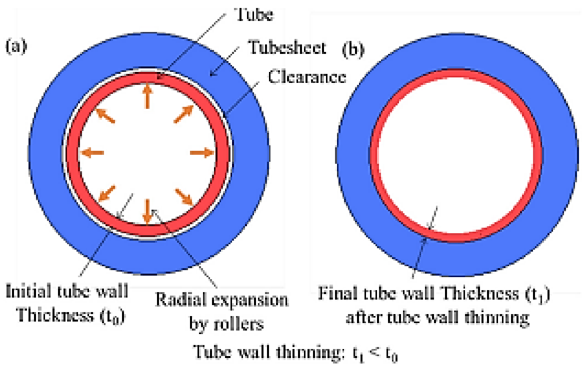


Figure 2. Tube Expansion Process: (a) Before Expansion, (b) After Expansion [4]

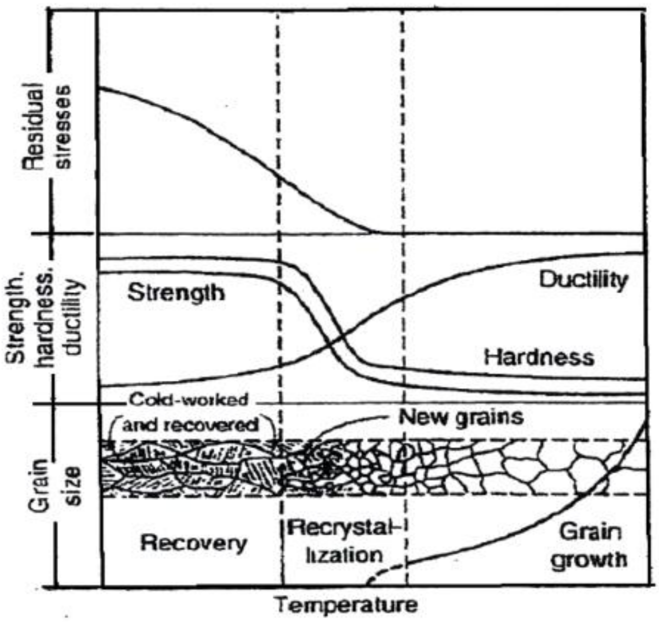


Figure 3. Recrystallization Process [7]

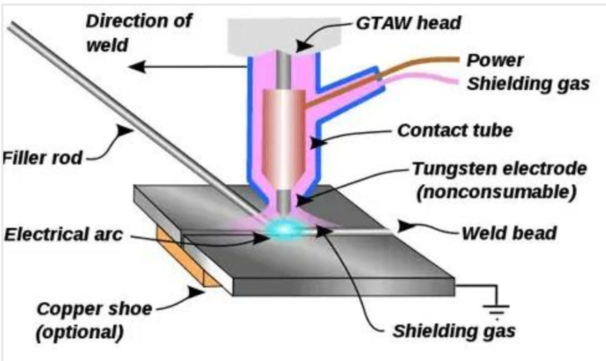


Figure 4. Welding GTAW [9]

leakage, and accelerate the decrease in service life. This condition also has the potential to cause high residual stress, excessive plastic deformation, and changes in the mechanical properties of the material [3].

In the tube expansion process, the mechanism that occurs falls into the category of cold working, which is plastic deformation performed at temperatures below the recrystallization temperature of the material. In 316L austenitic stainless steel, cold working causes an increase in dislocation density and residual stress in the tube wall, which contributes to an increase in the strength and hardness of the material. However, excessive deformation can trigger a decrease in toughness, micro-cracking, and changes in microstructure that affect joint performance [6]. The recrystallization process due to continued heating after cold working can be depicted in the diagram in Figure 3.

Tube-to-tubesheet welding in 316L stainless steel generally uses GTAW because it is able to precisely control heat input, produce high-quality tight joints, minimize distortion in thin tubes, and maintain corrosion resistance. These advantages make GTAW recommended by industry standards such as ASME IX and TEMA 11th Edition [8]. The schematic of the welding process used in this study can be seen in Figure 4.

SA-213 TP316L and SA-240 TP316L materials belong to the austenitic stainless-steel category, which has a microstructure dominated by the austenite (γ) phase with a very small amount of ferrite. These microstructure characteristics can be explained through the Fe-Cr-Ni phase diagram at a fixed iron content of about 70% [10]. This diag-

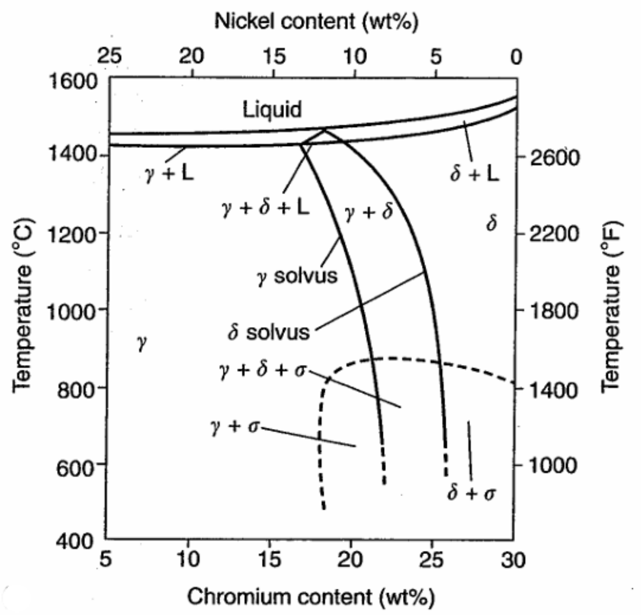


Figure 5. Fe-Cr-Ni Diagram at 70% Iron Content [10]

ram shows that the composition of chromium and nickel determines the solidification path, where high nickel content will form primary austenite, while high chromium tends to form primary delta ferrite. The relationship between alloy element content and phase formation can be seen in Figure 5.

This research is focused on analyzing the effect of varying the percentage of tube expansion on the microstructure, macrostructure, and hardness of SA-213 TP316L tube to SA-240 TP316L tubesheet connections, especially in the expansion range relevant to industry standards. The results of the research are expected to provide technical recommendations regarding the safe limits of tube expansion and optimal welding parameters to maintain joint quality and component life.

METHODS AND ANALYSYS

This research begins with a literature study, which includes the study and collection of relevant reference sources as a reference in carrying out research. Field studies are conducted to obtain information or real data in the field, such as the process of controlling the percentage of tube expansion and the tube-to-tubesheet welding process on the heat exchanger. The result of direct observation is to get a direct picture of the tube expansion process and whether the tube experiencing overexpansion will affect the hardness value, macro- and microstructure. So that it can provide more accurate analysis results and avoid research errors, and facts can be expressed as a realization of existing theory. The next step is to prepare the tools and materials and prepare the test specimens before carrying out the experimental process.

Si content can strengthen the material. Increase hardness and improve oxidation resistance up to high temperatures (up to 1000°C). It is often used in heat exchangers, boilers, and high-temperature applications [12]. For welding, Si acts as a deoxidizer, binding oxygen during welding, thereby reducing porosity and improving weld metal quality [13].

The tube expansion process is performed using a pressure-regulated tube expander that produces three variations of expansion percentage, namely 4%, 8%, and 12%. The percentage expansion is calculated based on the relationship between the tubesheet hole diameter, tube thickness, and the desired percentage expansion using equation 1 [5]. Where IDAE is the inside diameter after expansion (mm), HL is the hole diameter tubesheet (mm), T is the thickness of tube (mm), and JE is the joint expansion (%).

Table 1. Chemical Composition of Materials [11]

Materials	C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cr (%)	Ni (%)	Mo (%)
SA-213 TP 316L	0.035	2	0.045	0.03	1	16.0 – 18.0	10.0 – 14.0	2.0 – 3.0
SA-240 TP 316L	0.03	2	0.045	0.03	0.75	16.0 - 18.0	10.0 - 14.0	2.0 - 3.0

Table 2. Expand Variation Calculation

No.	Specimen	HL (mm)	T (mm)	JE (%)	IDEA (mm)
1	Expand 4%	19.3	1.5	4	16.42
2	Expand 8%	19.3	1.5	8	16.54
3	Expand 12%	19.3	1.5	12	16.66

$$\mathrm{IDAE} = \mathrm{HL} - [2 \times \mathrm{T} \times \left(1 - \frac{JE}{100}\right)] \quad (1)$$

After the tube expansion process, the joint was followed by welding using the Gas Tungsten Arc Welding (GTAW) method in the 5F position. The welding parameters used were a current of 150 A, a voltage of 10–14 V, a shielding gas flow rate of 10–15 L/min, and a single-layer, single-pass welding sequence. The filler metal employed was ER316L with a diameter of 1.6 mm, and the tungsten electrode used was EW-Th-2 with a diameter of 2.4 mm. The selection of the GTAW method with these parameters aimed to achieve high-quality fusion, minimize distortion in thin-walled tubes, and maintain the corrosion resistance of 316L stainless steel.

THE TEST SPECIMEN

After the tube expansion and welding processes, the next step is to perform a visual inspection and a liquid penetrant test. If the results are rejected, repair work must be carried out; if the results are accepted, it means the specimen has passed the inspection and can proceed to the specimen preparation stage. Preparing specimens for tube-to-tubesheet joint testing is an important step to ensure the quality and strength of the joint. This process must follow specific standards to ensure that the test results are reliable and accurately reflect the actual condition of the joint in service. The preparation process is carried out by cutting the complete specimen into several test pieces for microstructure, macrostructure, and hardness testing. Based on ASME Section IX [14], mock-up welds for tube-to-tubesheet joints must be cut transversely through the center of the tube. The cutting plan is defined with code A for 4% expansion, code B for 8% expansion, and code C for 12% expansion, as shown in Figure 6.

Macroscopic testing was performed on cross-sections of the joints after surface preparation and etching using aquaregia solution, with the aim of observing the fusion pattern and possible defects such as lack of fusion or porosity. Micro-precipitation was performed using an optical microscope at 200x and 500x magnification, where the samples were polished and etched to reveal grain morphology, phase distribution, and precipitation in the weld metal, heat affective zone, and base metal. Meanwhile, hardness

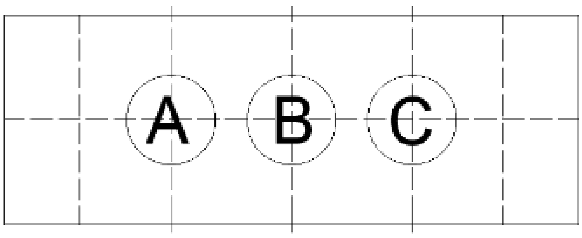


Figure 6. Specimen Cutting Code for Test Specimens

testing was performed using the Vickers method with a load of 1 kgf for 12 seconds, with a minimum of three test points taken in each zone, and the results were averaged.

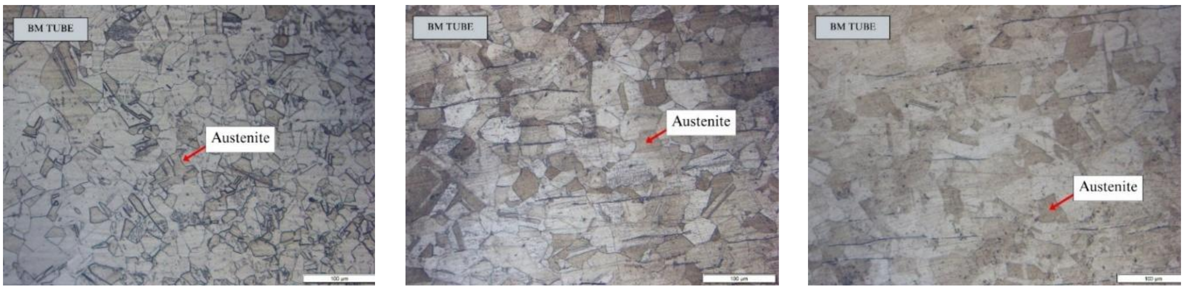
RESULTS AND DISCUSSIONS

The tube expansion process was carried out with three variation percentages, 4%, 8%, and 12%, using the roller expander method. Parameter control was implemented to ensure that the expansion percentage met the target values. Measurement results showed changes in the tube's outside diameter (OD) after the process, as presented in Table 3. This phenomenon of plastic deformation is consistent with the described mechanism, in which roller expansion creates a tight contact between the tube and the tubesheet, thereby increasing the mechanical bonding strength of the joint [15].

Microstructural observations show clear differences between the examined zones: the base metal, HAZ, and weld metal, as shown in Figures 7, 8, 9, 10, 11, and 12. In the tube base metal, the microstructure was dominated by fine and uniformly distributed austenite (γ) grains, accompanied by a small amount of delta ferrite (<3%). Variations in the expansion percentage did not cause significant morphological changes in this zone, as it was located far from the center of deformation and the welding heat-affected zone (HAZ). The tubesheet base metal exhibited similar characteristics, with austenite as the predominant phase and a small fraction of delta ferrite; however, the grain size was larger due to differences in material thickness, which affected the cooling rate [16]. In welds performed with a current of 150 A, the area near the HAZ experienced more noticeable grain growth due to prolonged heat exposure, although no significant phase transformation occurred.

Table 3. Expand Process Result

No.	Specimen	HL (mm)	T (mm)	IDEA (mm)	JE actual (%)
1	Expand 4%	19.31	1.5	16.43	4
2	Expand 8%	19.315	1.5	16.56	8
3	Expand 12%	19.315	1.5	16.68	12



a) b) c)

Figure 7. Base metal Tube a) Expand 4%, b) Expand 8%, dan c) Expand 12%

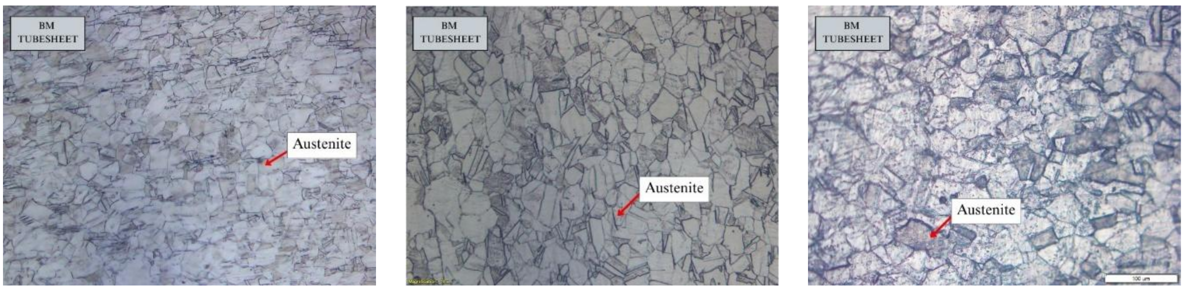


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Figure 8. Base metal Tubesheet a) Expand 4%, b) Expand 8%, dan c) Expand 12%

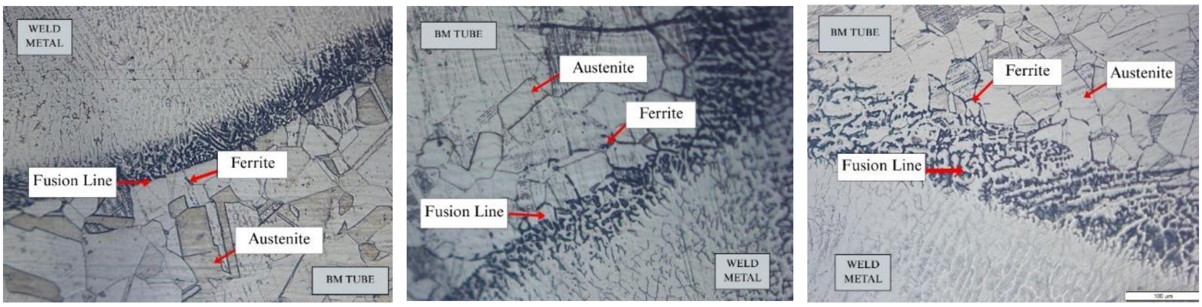

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Figure 9. Fusion line Tube a) Expand 4%, b) Expand 8%, dan c) Expand 12%

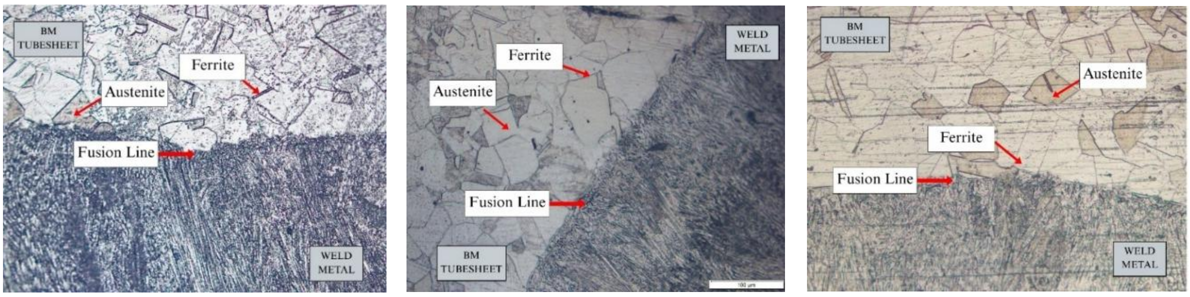

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Figure 10. Fusion line Tubesheet a) Expand 4%, b) Expand 8%, dan c) Expand 12%

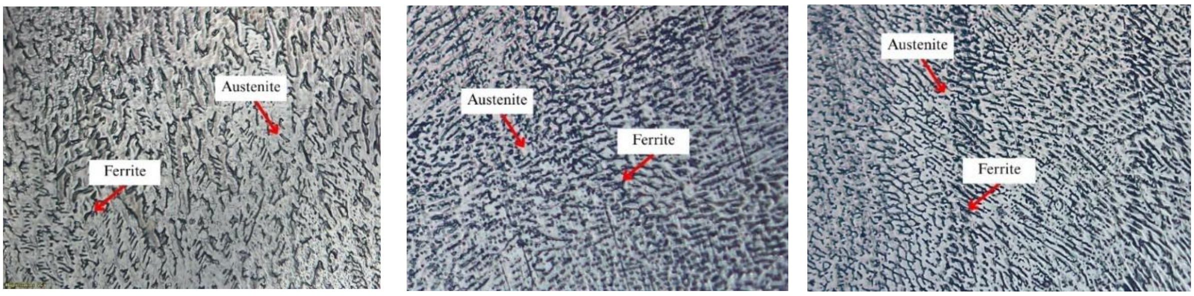

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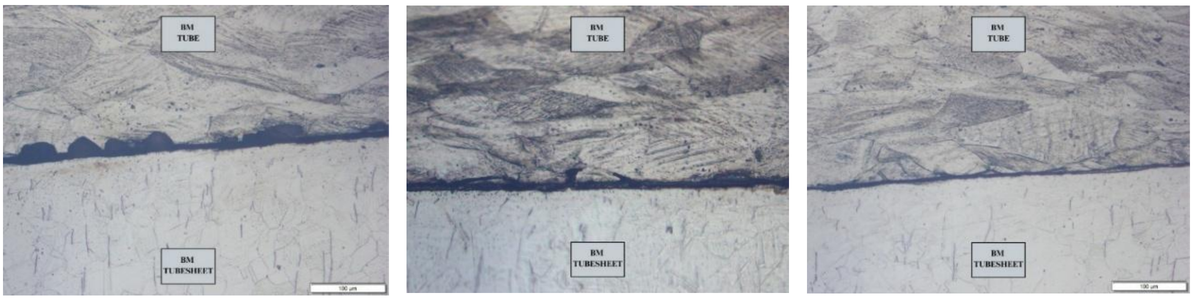
Figure 11. Weld metal a) Expand 4%, b) Expand 8%, dan c) Expand 12%



a) b) c)

Figure 12. Area of Expand a) Expand 4%, b) Expand 8%, dan c) Expand 12%

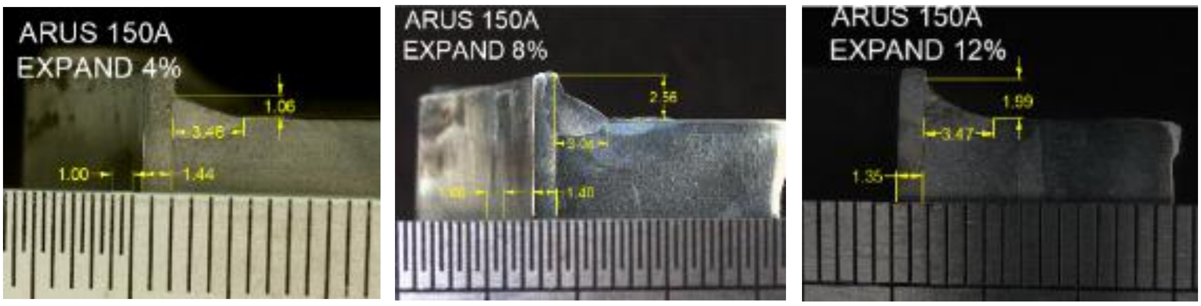
The fusion line zone of the tube and tubesheet showed a transition from the base metal to the weld metal, with a wider HAZ observed at a welding current of 150 A, consistent with findings that higher heat input increases penetration and broadens the transformation zone [3]. In the tubesheet, slower cooling promoted segregation of ferrite-forming elements (Cr, Mo), thereby increasing the delta ferrite content [17].

The weld metal in all variations was dominated by austenite with a fine distribution of delta ferrite. Its microstructure was characterized by dendritic austenite containing delta ferrite (δ). Lathy and acicular delta ferrite phases were found in weld metal produced with low heat input on austenitic stainless steel. The presence of delta ferrite is beneficial in reducing the risk of hot cracking; however, excessive amounts may increase local hardness and reduce ductility [17][18].

The most noticeable changes occurred in the expansion area. A 4% expansion caused only slight deformation, while an 8% expansion induced grain elongation and increased dislocation density. A 12% expansion resulted in a dominant cold-working effect with significant grain distortion [19][20]. Although higher roller expansion improves joint strength [15], excessive deformation can reduce ductility; therefore, post-process heat treatment is recommended to relieve residual stresses [19][21].

Macrostructural observations showed that all expansion variations (4%, 8%, and 12%) at 150 A produced complete fusion between the tube and tubesheet, as seen in Figure 13. No defects, such as lack of fusion or porosity, were found in the joint, indicating that the process parameters used were already optimal. These findings are consistent with recent studies reporting that the right combination of welding parameters with a controlled expansion process can produce a continuous, defect-free metallurgical bond [4].

The results of the Vickers hardness test are shown in Figure 14 , for the Base Metal Tube (BM T), Fusion Line Tube (FL T), Weld Metal (WM), Base Metal Tubesheet (BM TS), and Fusion Line Tubesheet (FL TS), where the highest hardness value was found in the expansion area with 12% expansion, reaching 377 kgf/mm^2, which significantly exceeded the maximum limit specified by the standard, namely 250 kgf/mm^2 for stainless steel [22]. In the tube base metal, the hardness value was relatively low (around 180 kgf/mm^2), while the weld metal had values ranging from 220 to 230 kgf/mm^2. The increase in hard-



a) b) c)

Figure 13. Macrostructural a) Expand 4%, b) Expand 8%, dan c) Expand 12%

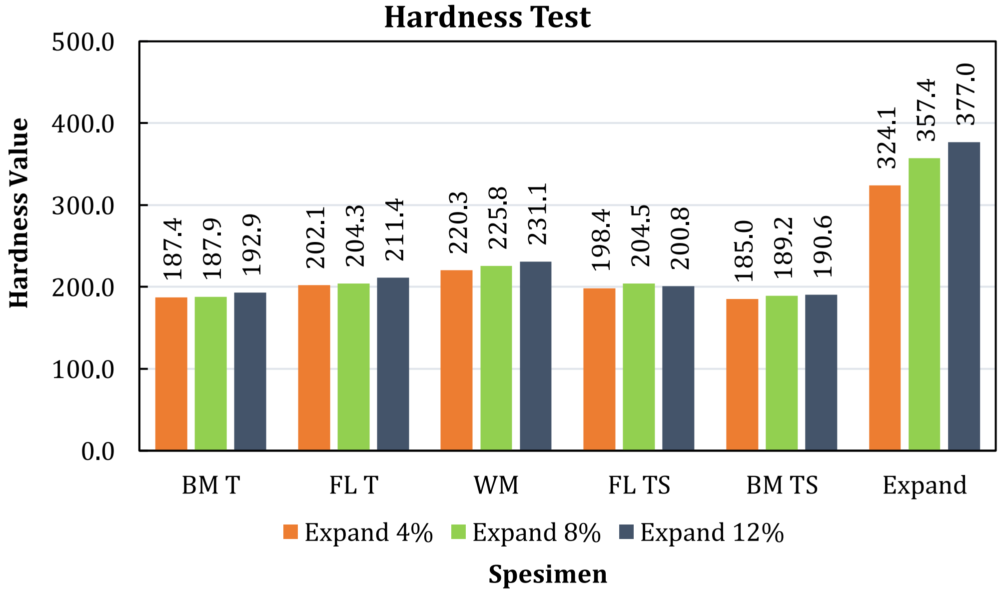


Figure 14. Hardnes Value Graphics

ness in the expansion zone results from the combination of plastic deformation due to cold working and heat input from welding, leading to an increase in dislocation density and the formation of a denser microstructure, indicating the need for heat treatment after the expansion process. Meanwhile, the increase in hardness in the weld metal is due to the formation of a delta ferrite phase, which is beneficial for reducing the risk of hot cracking. However, it can increase local hardness and reduce ductility if the concentration is too high [17]. The hardness values approaching the limit reinforce the recommendation to perform post-process heat treatment to reduce residual stress and restore the material's optimal mechanical properties [19][21].

CONCLUSION

This study demonstrates that variations in tube expansion for SA-213 TP316L to SA-240 TP316L joints have a significant effect on the mechanical properties, microstructure, and hardness of the joint. A 4% expansion produced minimal deformation and safe mechanical properties, while an 8% expansion increased dislocation density and grain elongation. A 12% expansion caused excessive cold working, raising the hardness to 377 kgf/mm², which exceeds the standard limit of 250 kgf/mm², potentially reducing the material's ductility.

GTAW welding at 150 A across all expansion variations resulted in complete fusion without macro defects. The microstructure was dominated by austenite with a small amount of delta ferrite, which is beneficial in preventing hot cracking but must be controlled in quantity. These results recommend using an expansion percentage of 4–6% in accordance with industry standards, along with post-process heat treatment to reduce residual stress and maintain the service life of the joint.

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DECLARATION OF CONFLICTING INTERESTS

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