SINERGI Vol. 30, No. 1, February 2026: 91-102
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2026.1.009

Experimental investigation of PWHT and normalizing effects on SMAW low-carbon steel joint properties

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Abstract
The influence of post-weld heat treatment (PWHT) followed by normalizing on the mechanical properties of AH36 low-carbon steel is significant, particularly in the context of marine applications, such as shipbuilding welded joints. According to the extant literature, PWHT has been demonstrated to reduce residual stresses and enhance microstructural uniformity. However, the suitable PWHT temperatures for AH36 steel welds to balance strength, ductility, and toughness prior to normalizing remain underexplored. The objective of this study is to ascertain the suitable PWHT temperatures prior to normalizing, with the aim of improving weld performance in marine environments. A parametric study was conducted on AH36 steel specimens welded using shielded metal arc welding. The specimens were subjected to PWHT at 0°C (as-welded), 450°C, 600°C, and 750°C, followed by normalizing. Tensile, bending, and Charpy impact tests were utilized to assess the mechanical properties against established maritime safety standards. The results show that 600°C is the optimal PWHT temperature, effectively reducing residual stresses and promoting microstructural homogeneity. This, in turn, ensures that welds meet safety standards while preserving mechanical integrity. Higher temperatures increased the risk of brittleness, while lower temperatures provided insufficient stress relief. This study demonstrates that precise selection of PWHT temperature prior to normalizing is critical for ensuring reliable welds in marine structures. It identifies the optimal condition that maximizes strength, ductility, and impact toughness of AH36 steel while satisfying the Indonesian Classification Bureau (BKI) maritime safety standards.

Keywords:
Low-carbon steel;
Mechanical properties;
Normalizing;
Post-weld heat treatment;
Shielded metal arc welding;

Article History:
Received: April 2, 2025
Revised: July 14, 2025
Accepted: August 12, 2025
Published: January 7, 2026

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INTRODUCTION

Welding is a fundamental technique in metal manufacturing, with Shielded-Metal Arc Welding (SMAW) being a commonly used approach. This procedure utilizes the thermal energy produced by an electric arc to liquefy the base material and electrode. Arc welding is a technique widely used in a variety of sectors, including construction, automotive, and manufacturing, owing to its effectiveness and versatility in welding different types of metal [1], [2]. Moreover, it facilitates welding in various situations and environments. Welding is a dependable method of uniting steels, including low-carbon steel. Low-carbon steel is a steel variant that is often utilized in construction engineering due to its superior mechanical qualities, rendering it appropriate for diverse building applications, including maritime constructions such as ship hulls, marine plates, and oil tanks. A notable instance of such a steel is AH 36.

Post-welding, residual stresses may persist in the heat-affected zone of the metal, potentially resulting in deformation and alterations in the material's mechanical characteristics and microstructure. These alterations may compromise the integrity of the welded connections, requiring post-weld treatments to either restore or augment their strength [3]. Among the numerous approaches to mitigate these issues, thermal therapies, specifically Post Weld Heat Treatment (PWHT), are the most often used. The PWHT process is contingent upon three essential elements: holding duration, heating temperature, and cooling pace. Normalizing is a heat treatment procedure in which the material is heated to the austenite phase and then air-cooled to ambient temperature. This procedure aids in reinstating the material's microstructure, which may have been altered by extreme temperatures encountered during the welding process, consequently restoring the material to a more stable state [4].

According to the extant literature, post-weld heat treatment (PWHT) has been shown to effect substantial alterations in the characteristics of welded joints by inducing microstructural changes, including a decrease in residual stress and an augmentation in toughness [5]. The impacts demonstrate a significant temperature dependency [6], with particular temperatures augmenting the toughness of high-strength steels and elevated temperatures boosting the characteristics of other alloys [7, 8, 9]. Investigations into the heating time have revealed that temperature normalization significantly influences steel microstructures [10], while post-weld heat treatment duration dictates hardness progression in dissimilar welds [11]. The time of solution annealing has been demonstrated to affect the strength of aluminum alloys [12]. Conversely, normalizing treatments may diminish microstructural heterogeneity in carbon steels [13][14]. The synergistic effects of post-weld heat treatment (PWHT) temperature selection before normalizing in AH36 shipbuilding steel, which directly influences marine safety, have not been thoroughly investigated, especially in its relation to adherence to maritime standards.

Although prior studies have established the benefits of PWHT in inducing microstructural changes, reducing residual stresses, and enhancing toughness in various materials, such as stainless steel, aluminum alloys, and other high-strength steels, these studies typically examine isolated parameters. These parameters include temperature dependency, heating duration, or microstructural homogeneity in carbon steels. The combined influence of specific PWHT temperatures followed by normalizing in the case of AH36 low-carbon steel, particularly in the context of maritime applications where welding-induced alterations can compromise joint integrity and structural safety, however, remains an area of research that has not yet been thoroughly explored. This gap is especially critical given the material's pervasive utilization in ship hulls, marine plates, and oil tanks, where adherence to safety standards for marine applications, such as those stipulated by the Indonesian Classification Bureau (BKI), is essential. Consequently, there is a pressing need for parametric studies evaluating the mechanical properties under these integrated heat treatment conditions. Such studies are necessary to optimize weld quality and ensure compliance with maritime safety requirements, rather than relying on generalized findings from other alloys or treatments.

The present study assessed the impact of various post-weld heat treatment (PWHT) temperatures (0°C, 450°C, 600°C, and 750°C) on the strength, toughness, and ductility of AH36 steel in conjunction with normalizing. A parametric study was conducted on welded specimens that underwent post-weld heat treatment (PWHT) followed by normalizing, and their mechanical characteristics were evaluated through tensile, bending, and Charpy impact tests. The results were confirmed per the marine safety requirements of the Indonesian Classification Bureau (BKI) to ensure structural reliability in maritime applications.

METHOD

Research Methodology

Welding reduces mechanical strength by forming coarse grains and residual tensions during the process. By reducing stress, facilitating transitions, and homogenizing the microstructure, post-weld heat treatment (PWHT) and normalization increase the strength and durability of materials. However, elevated temperatures induce grain coarsening and reduced ductility. Consequently, an optimal “window” emerges, particularly around 600 °C, where finely refined grain structures balance high tensile properties with suitable fracture resistance. This aligns with the broader metallurgical principles of stress relief, phase equilibrium, and microstructure-property relationships essential for marine engineering applications.

The methodology of this study, as illustrated in Figure 1, commenced with the selection of AH36 steel as the base material and the application of a controlled SMAW procedure to ensure consistency. After welding, the samples were exposed to PWHT at different temperatures,

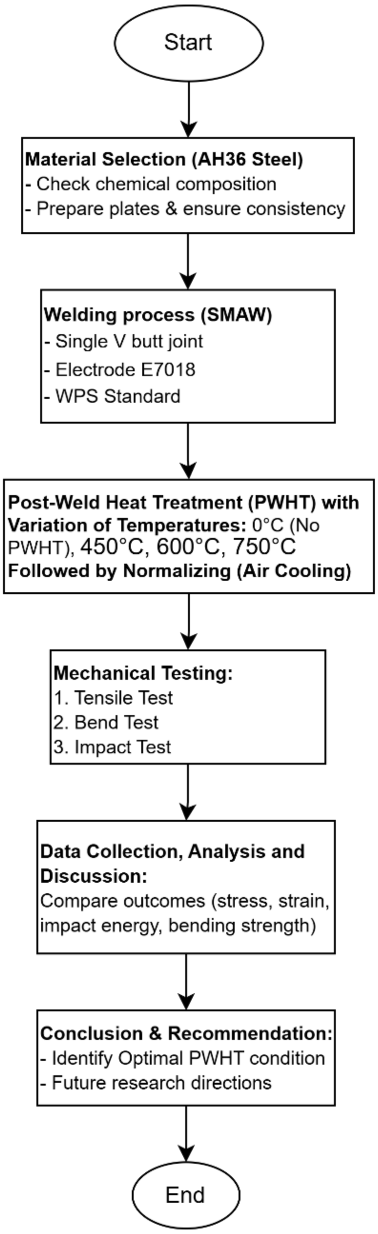


Figure 1. Flowchart of the methodological framework

followed by normalizing. A series of mechanical tests, encompassing tensile, bending, and Charpy impact tests, were conducted to evaluate alterations in structural integrity and to establish a correlation with industry requirement standards. A comparative analysis of the data was conducted to ascertain the optimal compromise between strength and toughness for each heat-treated condition. The process was concluded with the recommendation of a specific PWHT temperature (600 °C) that met classification standards while preserving weld performance.

Material Preparation

The object of study was AH 36 steel, a type of high-strength steel with a low carbon content, typically below 0.3%, or alternatively referred to as low-carbon steel. This steel is commonly utilized for general structural and construction applications, including ship hull construction, marine plates, and oil tanks, among others. The chemical composition of AH36 steel is detailed in Table 1, while Figure 2 depicts the AH36 steel plates utilized in this study.

The welding process in this study employed a method of welding that utilizes an electric arc as a heat source to melt the metal, namely shielded metal arc welding (SMAW), referring to AWS NUMBER 3 standards. The welding position was a 1G Butt Joint single V-Groove with a welding angle of 60°. The filler material used was filler metal E 7018. The detailed specifications of the welding procedure are presented in Table 2.

Table 1. Material Properties of AH 36 Steel

Elements	Content (%)
Ferrum (Fe)	98
Carbon (C)	0.18
Silicon (Si)	0.50
Mangan (Mn)	0.9
Sulfur (S)	0.035
Phosphorus (P)	0.035
Chromium (Cr)	0.20
Nickel (Ni)	0.40

Figure 2. AH36 steel

Table 2. Welding Procedure Specification

Items	Description
Electrode	E 7018
Currents	150-200 A, DC+ Polarity
Voltage	26-29 V
Travel Speed	8-12 cm/min
Welding Position	1G
Connection type	60 ° Single V butt joint

This study sought to quantify the effect of post weld heat treatment (PWHT) temperatures (450-750°C) on the mechanical performance of AH36 steel. The objective was to identify optimal parameters that balance microstructural homogenization with improved mechanical performance. This study is expected to provide insights for enhancing weld integrity and longevity in marine and construction environments. The following key parameters were measured: ultimate tensile strength, strain at fracture, and modulus of elasticity from tensile testing; impact energy from Charpy V-notch testing; and maximum bending stress from three-point bend tests. The values obtained were benchmarked against the Indonesian Classification Bureau (BKI) Rules for Welding requirements for hull structural integrity [15]. Subsequent to this, all specimens underwent an identical normalizing treatment, which involved controlled air cooling to room temperature. The complete experimental matrix is detailed in Table 3.

The material listed here is only the main ingredient, and it must be accompanied by the brand and its purity level (for example, H_2SO_4 (Merck, 99%)). The equipment enumerated in this section includes exclusively the leading equipment equipped with the brand (e.g., Electric Furnace (Carbonite)).

It is not necessary for ancillary equipment components to be listed. The main toolsets presented in this section are accompanied by image captions. Image captions are incorporated as part of the figure caption rather than within the image itself.

Tensile Test

After all the specimens were welded using SMAW and subjected to heat treatment, tensile testing was conducted using a universal testing machine (UTM). The purpose of the tensile test is to determine the stress and strain of the specimens. The tensile test was conducted in accordance with the testing standard outlined in the Bureau Veritas (BV) NR 216, Rules on Materials and Welding for the Classification of Marine Units, Chapter 2, Section 2, which details tensile test procedures for materials [16].

Table 3. Specimen Variation

Specimen	PWHT	Temp. (°C)	Condition
A	No	0	As-welded state
B	Yes	450	Subcritical annealing range
C	Yes	600	Inter-critical region
D	Yes	750	Full austenitizing temperature

The dimensions of the tensile test specimens were meticulously designed to ensure precise and representative outcomes. The configuration of each specimen is detailed as follows. The gauge length (G) was determined by adding 60 mm to the width of the weld bead, and the length of the reduced section (A) was measured based on the actual dimensions of the specimen. The specimen had a width (W) of 25 mm and a thickness (T) of 6 mm. The fillet section at the ends of the specimen featured a radius of 25 mm, and the overall length (L) of the specimen was 200 mm. The grip section had a width (C) of 40 mm and a length (B) of 50 mm. Figure 3 illustrates the shape and dimensions of the tensile test specimen utilized in this study.

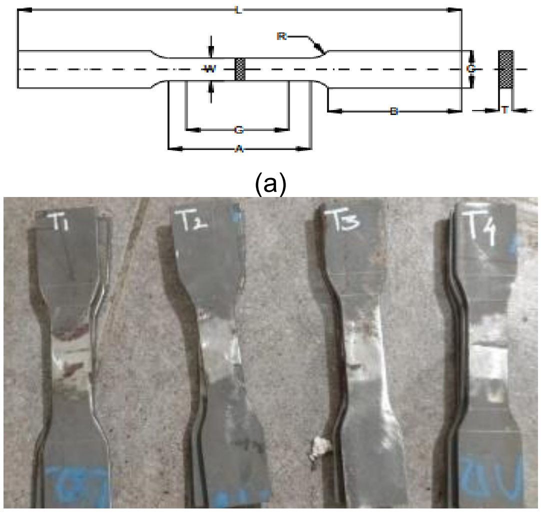
The data acquisition system from UTM continuously recorded the applied force and elongation. The tensile stress (σ) was calculated as (1)

$$\sigma = \frac{F}{A_0} \quad (1)$$

Where F represents the applied tensile force (measured in Newtons, N), and A_0 denotes the initial cross-sectional area of the specimen (expressed in mm^2). The engineering strain (ε) was determined using (2)

$$\varepsilon = \frac{\Delta L}{L_0} \quad (2)$$

where ΔL is the elongation of the specimen (measured in mm) and L_0 denotes the initial gauge length (also measured in mm).



(a)

(b)

Figure 3. (a) Sample size as determined using the BV standard and (b) Material for the tensile test

The modulus of elasticity (E), indicative of the material's stiffness, was derived from the linear elastic region of the stress-strain curve, expressed as

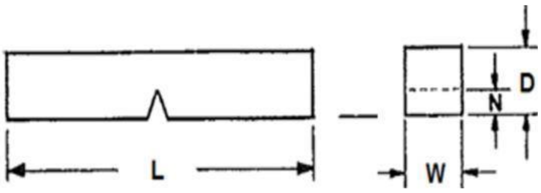
$$E = \frac{\sigma}{\varepsilon} \tag{3}$$

This parameter was calculated by fitting a linear regression to the elastic portion of the stress-strain data.

Impact Test

The impact test is a methodical procedure performed to ascertain the notched toughness value of materials, such as steel, plastic, and ceramics. The categories of impact testing can be classified in general based on the loading method (e.g., pendulum striking or loading with a falling weight) and the type of specimen based on the notch shape. In this study, the impact test was conducted using the Charpy Impact Testing Machine JB-300B, which is available at the Material and Ship Strength.

The specimens for the impact test were in accordance with the standards outlined in Bureau Veritas (BV) NR 216, Rules on Materials and Welding for the Classification of Marine Units, Chapter 2, Section 4, which describes the procedures for conducting Charpy impact tests on materials [16], as shown in Figure 4. The dimensions of the impact test specimen consist of an overall length (L) of 55 mm, a width (W) of 10 mm, and a thickness (T) of 5 mm. The Charpy notch on the specimen exhibited an angle of 45°, which is the standard notch shape used in Charpy impact testing.



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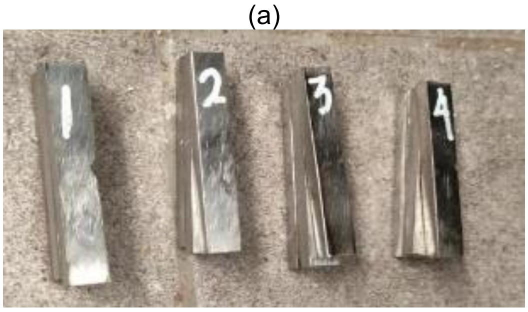


(b)

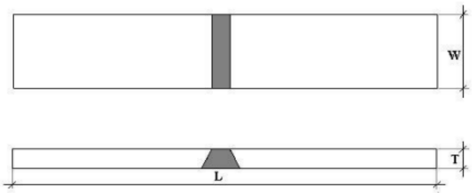
Figure 4. (a) Sample size as determined using the BV standard and (b) Material for the impact test

The impact energy (E_i), representing the energy absorbed by the specimen during fracture, was directly measured in Joules (J) using a calibrated pendulum impact tester. As this parameter is an intrinsic output of the testing apparatus, no additional equations were required for its determination.

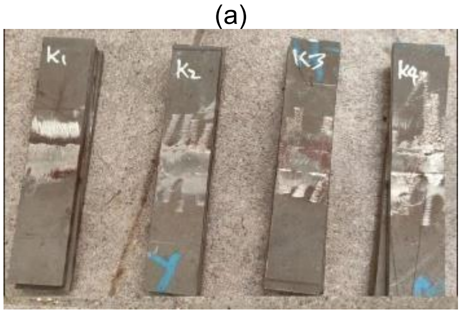
Bending Test

Three-point bending tests were conducted in accordance with the standards outlined in Bureau Veritas (BV) NR 216, Rules on Materials and Welding for the Classification of Marine Units [16], to assess the resistance of the welded joints to flexural deformation. This test is essential for evaluating the strength and ductility of the material after it has been subjected to loading, particularly for assessing the behavior of the welded joint, both in the weld metal and the heat-affected zone (HAZ). The HAZ in welded metallic materials is a critical region adjacent to the fusion zone, experiencing significant microstructural changes due to welding heat [17]. This area is susceptible to property deterioration, which may result in reduced resistance to brittle fracture.

The specimens utilized for the bending test were carefully prepared in accordance with the specifications outlined in the standard. The specimens had an overall length (L) of 150 mm, a width (W) of 30 mm, and a thickness (T) of 6 mm, as shown in Figure 5. These dimensions ensure that the specimens can be tested under controlled conditions in order to accurately assess their ability to withstand bending forces and to analyze the material's response to deformation.



(a)



(b)

Figure 5. (a) Sample size as determined using the BV standard, and (b) Material for the bending test

The maximum bending stress (σ_b) at the outer fiber of the specimen was calculated using (4):

$$\sigma_b = \frac{M.c}{I} \quad (4)$$

where denotes the applied bending moment, is the distance from the neutral axis to the outermost surface of the specimen, and represents the moment of inertia of the cross-sectional area. The tests were performed until the specimen achieved a predetermined bend angle or exhibited visible cracking, with load and deflection data recorded continuously.

After all the specimens were welded using SMAW and subjected to heat treatment, tensile testing was conducted using a universal testing machine (UTM). The purpose of the tensile test was to determine the stress and strain of the specimens. The tensile test was conducted in accordance with the testing standard outlined in the Bureau Veritas (BV) NR 216, Rules on Materials and Welding for the Classification of Marine Units, Chapter 2, Section 2, which details tensile test procedures for materials [16].

RESULTS

This chapter presents the results of the mechanical testing experiment conducted on AH36 steel. The experiment was conducted under two different conditions: without heat treatment and with post-weld heat treatment (PWHT) at varying temperatures. The first assessment entailed a tensile test to determine the tensile properties of AH36 steel. The material was subjected to PWHT at four different temperatures (Model A: 0°C, Model B: 450°C, Model C: 600°C, Model D: 750°C). Subsequent to the PWHT, the material underwent a process of normalizing. Using a Universal Testing Machine (UTM), the material's tensile properties were assessed. The ultimate load (P_{max}), tensile strength ($\sigma_{tensile}$), strain (ε), and modulus of elasticity (*MOE*) were quantified for each specimen.

Figure 6 depicts the ultimate tensile strength (UTS) of AH36 steel welded joints following PWHT at varying temperatures, ranging from the as-welded state to 750°C. In general, the UTS exhibited a progressive increase with escalating PWHT temperature, transitioning from substandard values in untreated specimens to superior compliance with Indonesian Classification Bureau (BKI) criteria at higher temperatures [18]. This trend underscores the broader efficacy of PWHT in enhancing mechanical performance through residual stress mitigation, microstructural homogenization, and phase transformations such as recrystallization and carbide redistribution. Collectively, these processes strengthen the weld metal and heat-affected zone (HAZ) without inducing excessive softening [19, 20, 21]. These mechanisms highlight the temperature-dependent optimization of PWHT for low-carbon structural steels like AH36, balancing weld integrity against potential embrittlement risks in demanding applications such as shipbuilding [22].

Figure 7 depicts the modulus of elasticity (E) and the elongation at fracture for shielded metal arc welded (SMAW) low-carbon steel joints, with these joints having been subjected to various PWHT and normalizing settings. The modulus of elasticity exhibited slight fluctuation, constantly between 190 and 205 GPa. This is due to the fact that heat treatments mainly influence secondary microstructural characteristics without modifying the essential interatomic bonding and crystal lattice that dictate stiffness in ferritic steels [23].

Conversely, elongation demonstrated a significant temperature-dependent decline, illustrating a broader pattern in which PWHT facilitates microstructural alterations, including tempering, carbide precipitation, and possible grain coarsening. These alterations improve stress relief and strength but diminish ductility by limiting dislocation movement and encouraging brittle failure mechanisms [24][25].

This highlights the critical trade-off in PWHT optimization for welded low-carbon steels. The trade-off is achieved by mitigating residual stress mitigation and achieving microstructural homogenization to improve overall mechanical integrity while avoiding excessive thermal exposure that could lead to embrittlement, thereby informing parameter selection for enhanced performance in structural applications.

The results of the bend testing of AH36 steel using the WEW-1000B Universal Testing Machine are demonstrated in Figure 8. The results indicated uniform bending stress values (800 MPa) throughout all PWHT conditions: as-welded (0°C, Model A), 450°C (Model B), 600°C (Model C), and 750°C (Model D), succeeded by normalizing. Despite the variation in heat treatment temperatures, no statistically significant variations in bending strength were detected. This finding suggests that post-weld heat treatment and normalization within this temperature range had minimal impact on the material's resistance to bending force. The consistency in the findings indicates that microstructural alterations did not affect bending performance under these circumstances. The normalizing procedure ensured uniformity across all specimens.

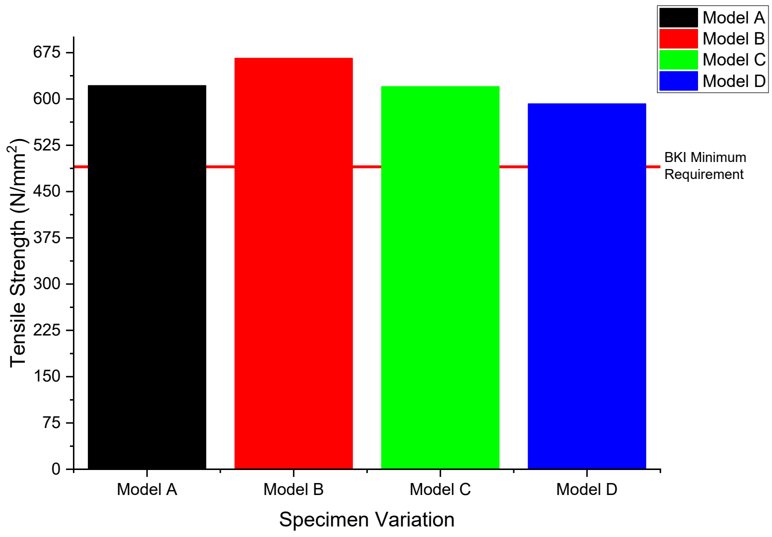


Figure 6. Average tensile stress response across four testing scenarios

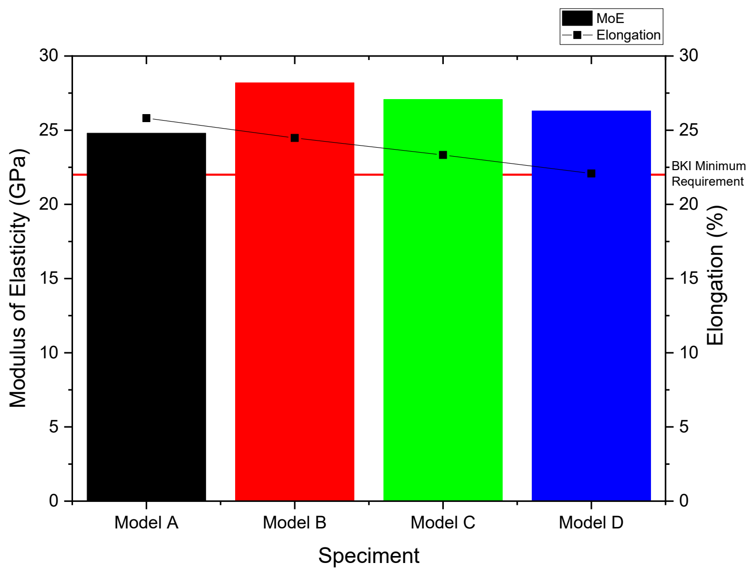


Figure 7. Modulus of elasticity and strain behavior under various testing conditions

The Charpy impact testing results for AH36 steel, as seen in Figure 9, demonstrated a temperature-dependent correlation between PWHT and impact energy. The as-welded specimen (0°C) exhibited negligible toughness (≤25 J), attributable to residual stresses and a brittle microstructure characterized by coarse grains and untampered martensite.

At a temperature of 450°C, a partial stress alleviation was observed, which resulted in an enhancement of the impact energy to 40 J. However, the material exhibited brittleness, owing to an inadequate phase change that occurred under the lower critical temperature (727°C). The maximum toughness (75 J) was observed at 600°C, a temperature at which partial austenitization and subsequent normalizing resulted in a refined ferrite-pearlite microstructure, improving ductility and stress redistribution. Treatment at 750°C, however, led to a decrease in impact energy (50 J), attributable to the coarsening of austenite grains and the instability of carbides during extended tempering. This finding highlights the pivotal influence of temperature in reconciling microstructural refinement and degradation.

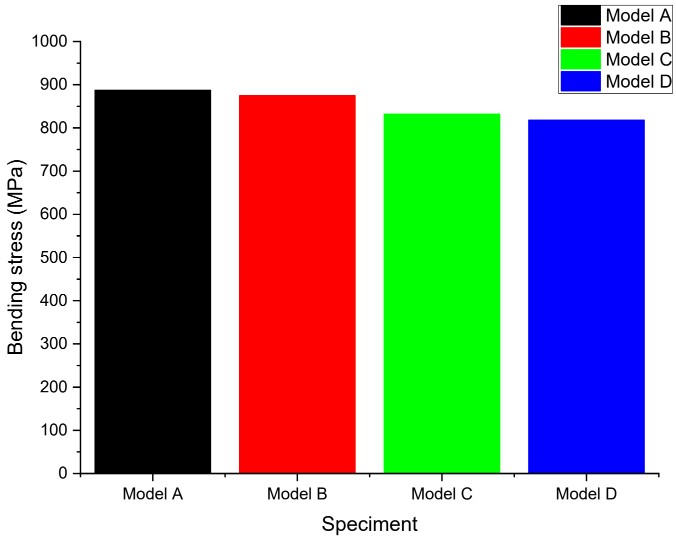


Figure 8. Distribution of bending stress under four distinct testing scenarios

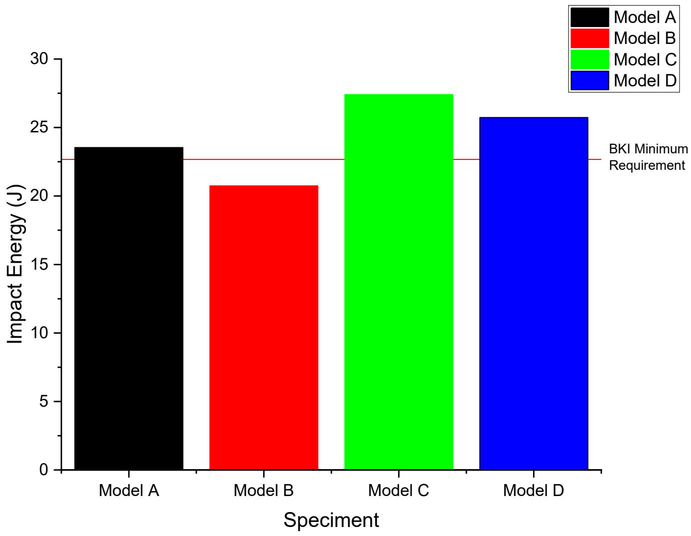


Figure 9. Average impact energy across various conditions

DISCUSSION

This chapter discusses the findings of the mechanical testing experiment conducted on AH36 steel. The experiment involved testing the steel both without heat treatment and with post-weld heat treatment (PWHT) at varying temperatures. The observed variations in tensile strength across the PWHT temperature range underscore the substantial influence of heat treatment on the mechanical properties of AH36 steel. At 0°C (as-welded), the absence of stress-relief processes led to significant residual stresses, which compromised the structural performance and resulted in subpar tensile strength [26]. While grain refinement and stress relief were observed at 450°C, these processes proved insufficient for primary phase transformation, yielding only marginal improvements. Conversely, the marked rise in tensile strength at 600°C was attributed to more pronounced stress relief and enhanced grain refinement, which helped homogenize the microstructure [27]. At a temperature of 750°C, the maximum tensile strength was attained due to complete phase transformation and refined microstructural uniformity. Nonetheless, it is advisable to exercise caution in higher temperatures to avert excessive grain growth, as this may compromise other mechanical attributes such as ductility and toughness, which are critical for structural applications in marine environments.

The stability of the modulus of elasticity underscores that the stiffness of low-carbon steel is governed by atomic bonding and compositional factors rather than thermal microstructural modifications, aligning with ferritic-pearlitic steel behavior [28]. Concurrently, the ductility reduction at higher temperatures highlights a strength-ductility trade-off: martensite formation and grain refinement at 750°C enhance tensile strength but restrict plastic deformation, increasing brittleness [29]. While moderate PWHT (650°C) has been demonstrated to optimize residual stress relief without severe ductility loss, normalizing at 750°C has been shown to risk embrittlement in applications requiring toughness. These findings emphasize the necessity for temperature-specific heat treatment strategies that strike a balance between microstructural homogenization and strength gains, on the one hand, and service requirements for ductility, on the other hand, particularly in dynamic loading environments. Future research is recommended to explore hybrid thermal approaches to mitigate this trade-off.

The constancy of bending stress values in the preceding chapter highlights that the bending resistance of AH36 steel is determined by its inherent material strength and ductility, rather than by thermally induced microstructural changes throughout the 450–750°C range. According to the extant literature, post-weld heat treatment (PWHT) has been demonstrated to be associated with modified tensile or elongation characteristics (e.g., martensite formation at 750°C); however, the bending strength stays unchanged, owing to the predominance of bulk mechanical properties over localized structural modifications [30][31]. The normalization method reduced temperature-dependent changes by standardizing grain structure, ensuring consistent dislocation distribution and stress balance. This finding indicates that the bending performance of AH36 steel is less affected by heat treatment parameters than tensile or ductility measures, highlighting its dependence on inherent material properties. In engineering applications, this stability facilitates parameter selection for post-weld heat treatment, allowing bending-critical components to undergo thermal processing without jeopardizing structural integrity under flexural pressures.

The findings of the Charpy impact test indicate that the optimal fracture resistance in AH36 steel is attained at 600°C post-weld heat treatment, where partial austenitization and air cooling enhance the microstructure and alleviate residual stresses [32]. Temperatures below 600°C are ineffective in eradicating brittle phases, while excessive heating above 750°C destabilizes carbides and enlarges grains, undermining the advantages of normalizing [33]. This phenomenon corresponds with the susceptibility of low-carbon steel to thermal processing. Specifically, grain refinement occurring under the top critical temperature improves toughness, but beyond this threshold, the process diminishes hardness and fracture resistance. The results of the study highlight that PWHT settings must reconcile stress relief with microstructural uniformity. The results demonstrated that 600°C provides an industrially feasible compromise for applications requiring strong fracture resistance. This temperature-dependent response highlights the necessity for accuracy in thermal processing to enhance weld integrity under dynamic loading conditions.

The current results demonstrate the optimal efficacy of 600°C PWHT in achieving a balance of mechanical characteristics in AH36 steel, in alignment with analogous prior investigations. Normalizing at 600°C enhances ductility, with ultimate strain increasing from 28.45% to 30.80%, while establishing a defined yield stress of 231 MPa and slightly reducing ultimate tensile strength in AH36 structural steel [34]. This aligns with the microstructural homogenization and stress relief observed in this study. Heat treatment at 600°C, followed by quenching in different media like water or air, markedly enhanced impact energy (up to 73 J) and hardness in the heat-affected zone of ASTM A36 welded joints [35]. This finding corroborates the superior Charpy impact toughness observed at 600°C in comparison to both higher and lower temperatures. Contrasting outcomes were observed in studies on DH36 steel, where higher austenitization temperatures (750–1000°C) followed by quenching resulted in increased hardness up to 364 HV due to martensite formation [36]. This phenomenon may account for the reduced ductility and heightened risk of brittleness at 750°C in the present study. Additionally, post-weld heat treatment at temperatures reaching 610°C on A36 carbon steel led to a reduction in hardness and an enhancement in ductility, without any phase transformations beyond pearlite-ferrite [37]. This observation underscores the strength-ductility trade-off identified in this study at elevated temperatures. These studies illustrate the significance of precisely selecting the PWHT temperature to improve weld performance in marine applications, as well as changes caused by steel grade discrepancies and quenching procedures.

CONCLUSIONS

This study conducted an experimental investigation into the effects of post-weld heat treatment (PWHT) at four distinct temperatures (0°C, 450°C, 600°C, and 750°C) in conjunction with normalizing, on the mechanical properties of AH36 steel, a low-carbon steel that is widely employed in marine structural applications. The methodology entailed the preparation of welded joints using the shielded metal arc welding (SMAW) process, the application of controlled PWHT and normalizing treatments in an electric furnace, and the evaluation of the specimens through standardized tensile, three-point bending, and Charpy V-notch impact tests to quantify parameters such as ultimate tensile strength, ductility, flexural resistance, and impact energy.

The post-weld heat treatment (PWHT) of AH36 steel reveals a crucial equilibrium between mechanical qualities and microstructural development, with 600°C identified as the ideal temperature. It has been demonstrated that, at this temperature, the processes of partial austenitization and normalizing yield a refined ferrite-pearlite microstructure. This results in a reduction of residual stresses and the attainment of an optimal balance of tensile strength, ductility (compliant with BKI safety standards), and maximum Charpy impact energy (109 J) due to improvement in grain refinement and phase stability. Elevated temperatures (750°C) have been shown to enhance tensile strength while diminishing ductility and toughness due to significant grain coarsening and carbide instability. In contrast, untreated specimens (0°C) and those treated at 450°C maintain coarse grains and brittle phases, resulting in inadequate fracture resistance. Bending stress stays constant (~800 MPa) throughout all treatments due to microstructural homogeneity resulting from normalization, which ensures uniform stress distribution. These results highlight the effectiveness of 600°C post-weld heat treatment for maritime applications, demonstrating its capacity to enhance the synergy of strength, ductility, and toughness while preserving structural integrity under dynamic loads.

For shipbuilding applications, it is recommended that post-weld heat treatment at 600°C, followed by normalizing, be employed in order to comply with BKI requirements and ensure structural integrity. Although high temperatures have been shown to enhance tensile qualities, they concomitantly diminish ductility and toughness, which are essential for withstanding severe marine conditions. Subsequent studies are recommended to examine intermediate temperatures ranging from 600°C to 750°C in order to enhance the strength-ductility equilibrium and assess long-term fatigue performance. The results of the present study confirm that optimal post-weld heat treatment techniques may improve weld integrity in AH36 steel, aligning with industry standards and promoting safety in marine engineering applications, including ship hull and marine plate building.

ACKNOWLEDGMENT

The present study was funded by the Junior Lecturer Research (RDM) Fund of the Institute for Research and Community Services (LPPM), Diponegoro University, under the contract number 222-190/UN7.D2/PP/IV/2025.

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