Effect of post-weld heat treatment and cooling techniques on mechanical performance of AH36 steel for marine structures

Ahmad Firdhaus[1], Blinka Hernawan Prasetya[2], Muhammad Adnan Rivaldi[1], Parlindungan Manik[1], Tuswan[1]
[1]Department of Naval Architecture, Faculty of Engineering, Diponegoro University, Semarang, Indonesia
[2]Department of Civil Engineering, Faculty of Engineering, Diponegoro University, Semarang, Indonesia

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ABSTRACT

The mechanical properties of structural steels used in marine environments are significantly affected by welding procedures. This research examines the impact of various cooling techniques, coupled with post-weld heat treatment (PWHT), on the strength and ductility of AH36 steel welded via shielded metal arc welding (SMAW). Heat treatments were conducted at temperatures of 450 °C, 600 °C, and 750 °C. Oil quenching and normalizing were employed as the two cooling processes. Tensile strength, elastic modulus, elongation, and impact toughness were measured through mechanical testing. The findings demonstrate that oil quenching after treatment at 450 °C yields the most favorable tensile strength and elongation properties, surpassing established safety standards. Conversely, increasing the treatment temperature to 600 °C and 750 °C reduces strength and ductility, presumably due to grain coarsening and microstructural weakening. Impact toughness is substantially improved by normalizing, especially at 600 °C, which offers the best balance of strength and toughness. These findings show that PWHT at 600 °C followed by normalizing markedly improves the mechanical properties of AH36 steel, ensuring dependable performance in harsh marine environments. This research helps improve weld quality and the safety of marine structures by carefully selecting heat treatment and cooling procedures.

Corresponding Author:

Ahmad Firdhaus
Department of Naval Architecture, Faculty of Engineering, Diponegoro University
Teknik Perkapalan Building, Tembalang, Semarang, 50275, Indonesia
Email: afirdhaus@lecturer.undip.ac.id

1. INTRODUCTION

Marine structures are among the most challenging engineering projects, requiring materials that can endure harsh environmental conditions. These include the corrosive effects of seawater, significant temperature changes, and the dynamic forces created by waves and currents. Among the structural steels employed in marine applications, AH36 steel has become a crucial material for ship hulls, offshore platforms, and underwater infrastructure, primarily due to its favorable combination of strength, toughness, and weldability [1], [2].

The designation “AH36” signifies a high-strength structural steel with a minimum yield strength of 355 MPa (36 Ksi), specifically designed to meet the stringent requirements of marine construction standards. The widespread use of AH36 steel in marine applications is attributable to its advantageous mechanical properties and adherence to the requirements of international maritime classification societies. This particular steel grade is frequently employed for joining ship plates and underwater repair work, thereby attracting significant research attention in the domain of marine welding [3], [4]. The material's design is intended to achieve a balance of strength and toughness. This is particularly important for safe operation in marine settings, where a brittle failure could have serious consequences.

Welding AH36 steel in marine settings poses distinct challenges compared to conditions encountered in standard atmospheric welding. Shielded metal arc welding (SMAW), the predominant industrial technique, employs an electric arc to generate the elevated temperatures required to fuse the base metal with the consumable electrode. In challenging conditions, SMAW's flexibility reflects its leading status, as seen in its use across the construction, transportation, and heavy machinery sectors [5], [6]. Welding process parameters in marine environments are sensitive to environmental conditions. Statistical and experimental studies have demonstrated that welding current significantly influences the yield strength and chemical interactions during underwater SMAW of AH36 steel [7], [8]. This environmental sensitivity suggests that seasonal and temperature changes can significantly affect the quality and performance of marine welds. As a result, this requires flexible welding methods and post-weld treatments.

Post-weld heat treatment (PWHT) has been widely acknowledged as a beneficial technique for enhancing the characteristics of welded connections by mitigating residual stress, improving mechanical properties, and reducing hydrogen levels [9], [10]. Nevertheless, the implementation of PWHT on AH36 steel within marine settings introduces specific complexities and prospects that remain under-investigated in existing research. Underwater electromagnetic induction heating, applied post-weld, has shown the capacity to lower the maximum heat-affected zone (HAZ) hardness beneath the AWS Class A threshold in ship steel experiments, thereby demonstrating the practicality of underwater HAZ-softening methods [9]. This development is particularly significant for marine applications where conventional furnace-based PWHT is not feasible. Laboratory studies on other high-strength steels have shown that PWHT can improve the mechanical properties of the HAZ and weld metal [11]. For example, PWHT applied to linepipe/API X70 steels improved properties after extended tempering in reported trials [12]. On the other hand, the effectiveness of PWHT depends significantly on the specific parameters used, including temperature, heat application duration, and cooling method.

The cooling procedure implemented after PWHT is of paramount importance, exerting a considerable influence on the ultimate characteristics of the welded connection. Research comparing various steel grades indicates that the cooling medium and quenching velocity substantially affect the resulting hardness and tensile strength. While water or oil quenching following tempering can enhance both hardness and tensile strength, it may simultaneously diminish toughness, contingent upon the steel's specific composition and the particulars of the PWHT process [13], [14]. The choice of cooling medium is especially important in marine environments, where seawater is often the most readily available. However, systematic comparisons of cooling media after PWHT are most often reported in studies of steels other than AH36 [15]. The existing lack of understanding poses a considerable obstacle to the formulation of refined PWHT protocols for AH36 steel in marine contexts. The cooling rate plays a crucial role in determining the steel's ultimate properties, thereby impacting its mechanical attributes, including hardness, strength, and toughness. Elevated cooling rates often correlate with increased hardness and strength; however, they can also diminish toughness and heighten the potential for cracking. Conversely, more gradual cooling rates usually enhance ductility, although they may potentially undermine the requisite strength.

AH36 steel is frequently used in maritime applications, and PWHT is essential; however, appropriate treatment methods are unknown. Much of the research on AH36 welding has reported mechanical parameters, hardness profiles, hydrogen diffusion, and residual stress distributions, but few have used controlled PWHT experiments with different cooling procedures. PWHT recipes for AH36 in marine applications are not agreed upon. Another research gap is the lack of systematic studies on cooling media. Although cooling media have been studied across several steel grades, data on AH36 are limited, making it difficult to predict the optimal marine cooling technique. Marine settings may make traditional cooling methods impractical or unavailable, making this constraint extremely important. The long-term behavior of PWHT-treated AH36 welds in marine service is poorly understood, leaving the industry short.

This study examines the mechanical properties of maritime building material AH36 steel after PWHT and cooling. The main goal is to understand how PWHT settings and cooling methods affect the mechanical characteristics and performance of AH36 steel weld joints. The investigation will include welding heat-input profiles that simulate field repairs, PWHT temperatures, and cooling media such as air normalization and drum oil quenching. The study will evaluate Charpy toughness and tensile strength to develop PWHT protocols for AH36 steel that meet marine fabrication standards, such as the Indonesian Classification Bureau (BKI) ship classification and material specifications. This is crucial for shipbuilding and offshore platform stability, where welding residual stresses can cause fatigue cracking and reduce service life under wave loads and in hazardous environments. This study goes beyond academic interests; optimizing PWHT procedures for AH36 steel could improve the stability and lifespan of maritime structures.

2. METHOD
2.1. Material preparations
This study focuses on AH36 steel, a high-strength steel with low carbon content, typically less than 0.3%. This steel is often used in construction and structural applications, such as ship hulls, marine plates, and oil tanks. Table 1 and Figure 1 illustrate the properties of AH36 steel.

Figure 1. AH36 steel specimens for mechanical testing

Table 1. Material properties of AH36 steel

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

The welding technique used in this study followed AWS standards. SMAW was used, with a direct current electrode positive (DC+) polarity. The 1G position was used to prepare a single V-groove butt joint with an included angle of 60°, using E7018 electrodes. Table 2 presents the essential welding parameters, including the current range, voltage, and travel speed.

To evaluate the impact of thermal processing on AH36 steel, the PWHT conditions for the experimental specimens were established, as shown in Table 3. Specimen A, which was called the control, received no treatment. After the welding process, specimens B, C, and D were heated to 450 °C, 600 °C, and 750 °C, respectively, and held at those temperatures for 1 hour. After all of the animals were heated, they were cooled in two different ways. As a first step, regulating cools things down slowly with air until they reach room temperature. Quenching is the second way. It uses a water medium mixed with Dromus Oil in a 1:10 ratio.

Table 2. Welding process parameters

Parameter	Specification
Electrode type	E7018
Current	150–200 A (DC+)
Voltage	26–29 V
Travel speed	8–12 cm/min
Joint geometry	60° Single V-groove
Electrode type	E7018

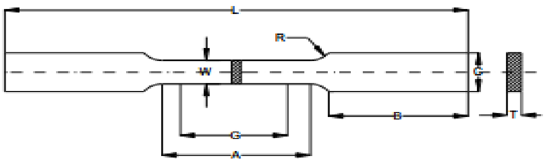
Table 3. Specimens' variation

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

2.2. Mechanical test

Following SMAW and subsequent heat treatment of the specimens, tensile tests were performed in the Department of Naval Architecture Laboratory at Diponegoro University. The primary objective of these tensile experiments was to determine the tensile stress-strain curve for each sample. The tensile test was used to evaluate the elastic modulus. The test programs were conducted in accordance with ASTM E8/E8M-13a [16], which was followed in this investigation.

The tensile test specimens were carefully designed to ensure the accuracy and representativeness of the results. Figure 2 shows the schematic and physical views of tensile test specimens for SMAW-welded AH36 steel after heat treatment. Figure 2(a) shows a drawing of the tensile test specimen, highlighting its important dimensions. The gauge length (G) extended 60 mm beyond the weld width, and the reduced section length (A) was based on actual specimen dimensions. The specimens had a width (W) of 25 mm and a thickness (T) of 6 mm. Additionally, the ends of the specimens had a fillet radius (R) of 25 mm. Overall length (L) was 200 mm, and grip sections had a width (C) of 40 mm and length (B) of 50 mm. Photographs of the fabricated tensile test specimens, designated as 1, 2, 3, and 4 corresponding to each PWHT condition, are presented in Figure 2(b). These images serve as visual documentation of the physical samples after welding and heat treatment, illustrating their consistent form and surface properties before testing commenced.



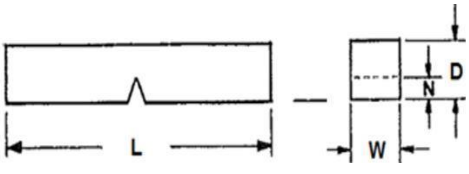
(a)

(b)

Figure 2. Schematic and physical views of tensile test specimens for SMAW-welded AH36 steel after heat treatment for (a) illustration of specimen dimensions for tensile test based on ASTM E8/E8M-13a standard and (b) photographs of specimens labelled 1–4 for various PWHT conditions

Next, the impact test was run to determine the materials' notched toughness. In general, impact testing methods are classified according to the specimen's groove shape and the loading technique, such as pendulum striking or loading with a falling weight. The Charpy impact test, as part of this investigation, was conducted at the Material and Ship Strength Laboratory of Diponegoro University, utilizing a JB-300B Charpy impact testing machine.

The impact test specimens were fabricated in accordance with the dimensions specified in ASTM E23-16b, which governs Charpy impact testing methodologies for materials [17]. Figure 3 shows the schematic and physical views of impact test specimens for SMAW-welded AH36 steel after heat treatment. A schematic representation of the impact test specimen is provided in Figure 3(a), which delineates the critical dimensions and the V-notch configuration integral to Charpy impact testing. This diagram identifies the overall length (L), width (W), notch depth (D), and notch configuration (N), all of which are essential for the standardized assessment of a material's impact resistance, as stipulated by the ASTM standard. Photographs of the manufactured impact test specimens, designated as 1, 2, 3, and 4 corresponding to each PWHT condition, are presented in Figure 3(b). These images illustrate the physical samples post-preparation, showcasing their rectangular form, notched structure, and surface finish before the commencement of the impact tests.



(a)

(b)

Figure 3. Schematic and physical views of impact test specimens for SMAW-welded AH36 steel after heat treatment for (a) illustration of specimen dimensions for impact test and (b) photographs of specimens labelled 1–4 for various PWHT conditions

3. RESULTS AND DISCUSSION
3.1. Tensile strength

Tensile testing was performed at the Ship Structure and Strength Laboratory of Diponegoro University in Semarang. The outcomes of the tensile test include tensile stress, tensile strain, and elastic modulus, which facilitate the assessment of the tensile strength of AH36 steel post-welding via SMAW with varying quenching and normalizing heat treatment temperatures. The maximum load results obtained from the machine can be calculated using the maximum stress formula, where $\sigma = \frac{P}{A_0}$ So that the tensile strength of each specimen is obtained, where σ is the ultimate tensile strength (UTS) (MPa), P is the maximum load before failure (N), and A_0 is the average cross-sectional area. All measured values were subsequently compared to the safety requirement of tensile strength established by the BKI, as indicated by the red horizontal line in Figure 4. The safety threshold is based on 490 MPa [18].

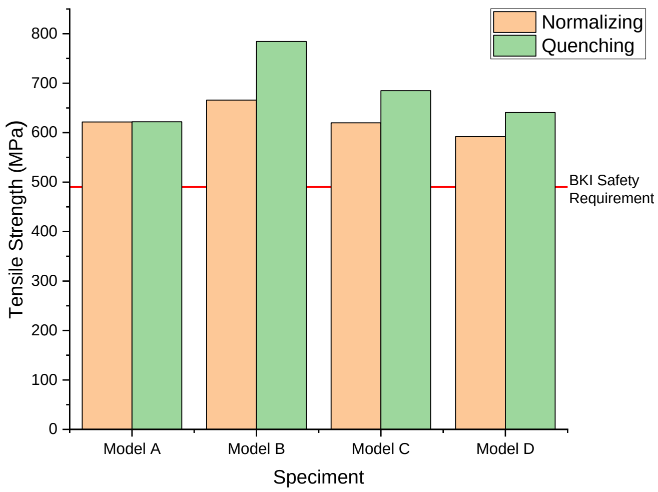


Figure 4. Tensile stress response throughout different test scenarios

The base model, Model A, with PWHT at 0 °C, represents the as-welded condition without thermal stress relief, delivering UTS values of approximately 620 MPa after normalizing and 610 MPa after quenching, both of which comfortably exceed the BKI safety requirement. This baseline performance establishes a reference for untreated weldments, where normalizing provides a marginal strength advantage through gradual cooling that minimizes distortion. At the same time, quenching introduces slight hardening, but this effect is limited by the residual stresses inherent to the welding process.

Among the variants, the most advantageous configuration is Model B with PWHT at 450 °C, where normalizing yields a UTS of approximately 660 MPa, and quenching raises it to over 780 MPa, indicating an optimal balance of stress relief and microstructural enhancement. The substantial gain in quenched specimens stems from partial austenitization followed by rapid oil cooling, which promotes a refined martensitic phase that distributes cyclic loads more uniformly, thereby delaying crack initiation and propagation under repeated marine loading conditions, such as wave-induced stresses [19]. The tensile strengths across specimens exceed the ASTM A131 requirements for AH36 steel by 19%–31%, favorably benchmarking against similar SMAW-welded low-carbon steels in prior studies [20]. The consistent yield strengths, surpassing ASTM A131 minimum yield, correlate with PWHT-induced ferrite-pearlite refinement at 450–600 °C, reducing residual stresses and enhancing homogeneity as per ABS rules for materials and welding; quenching promotes martensite formation for higher UTS, while normalizing favors ductility through slower diffusion, consistent with reported correlations in AWS standards for weld integrity in marine environments [21].

Conversely, the least favorable outcome is observed in Model D with PWHT at 750 °C, yielding UTS values of approximately 595 MPa under normalizing and 650 MPa under quenching, reflecting over-tempering and grain coarsening that compromise mechanical integrity, despite still meeting the minimum BKI requirement. Elevated temperatures at this level lead to excessive carbide coalescence and softening in the HAZ, diminishing the benefits of both cooling methods and resulting in the lowest strength retention across the series. Such degradation underscores the risks of excessive PWHT, highlighting the necessity for precise temperature control to prevent detrimental effects on the performance of welded low-carbon steel in structural applications.

3.2. Modulus of elasticity and strain

Figure 5 illustrates the stress-strain curve for AH36 steel in Model A, which serves as the baseline without PWHT. It demonstrates a linear elastic region, wherein stress is proportional to strain up to a stress of roughly 355 MPa and a modulus of elasticity of around 200 GPa. This is succeeded by plastic deformation accompanied by strain hardening, achieving an UTS of 490–620 MPa, followed by necking and fracture at an elongation of 25%–28%, demonstrating considerable ductility. These behaviors align with prior studies on untreated AH36 steel. Comparable structural steels, such as ASTM A36, exhibit similar profiles, including distinct elastic and plastic phases, and meet shipbuilding elongation standards. Literature on AH36 confirms high ductility and a modulus near 200 GPa at room temperature in the absence of PWHT, supporting its application in marine structures requiring toughness, consistent with ASTM A131 specifications, though influenced by welding and compositional variations [22].

The ratio of the increase in an object's length to its initial length is the definition of strain. Tensile strain arises when the rod is subjected to pulling forces. The measurement can be utilized to determine the tensile strain using the formula: $\varepsilon = \frac{\Delta L}{L_0} 100\%$, where ΔL is the increase in length, while L_0 is the length of the original specimen.

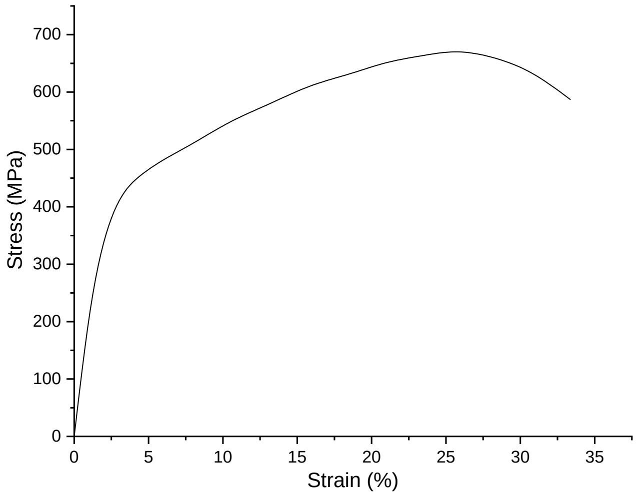


Figure 5. Stress-strain curves of AH36 steel Model A as baseline model

In terms of strain, the graphs in Figure 6 illustrate a more pronounced decline as PWHT temperature rises, starting from higher values of about 25%–28% in Model A and decreasing to around 20%–22% in Model D. Notably, quenching consistently yields lower strain values compared to normalizing at each temperature level, indicating reduced ductility under rapid cooling conditions. This pattern highlights a trade-off where faster cooling may enhance specific properties, but at the expense of elongation. In marine applications, this translates into superior resistance to environmental degradation, with PWHT-optimized welds exhibiting reduced porosity and improved intergranular cohesion [23].

Regarding modulus of elasticity, the values exhibit relative stability across the models, ranging from approximately 200–210 GPa. There is a subtle downward trend with increasing PWHT temperature, manifesting as minor reductions (less than 10%) from Model A to Model D, irrespective of the cooling method. This suggests that higher PWHT temperatures exert only a limited influence on the material's elastic stiffness post-treatment. All strain findings meet the minimum safety standard of 22 mm established by the BKI [16], as indicated by the red line.

The reduction with elevated PWHT temperatures and the inferior performance under quenching are consistent with established findings. Quenching promotes martensite formation, which is associated with increased fatigue life due to microstructural uniformity that diminishes stress concentrations at weld regions. Normalizing, through slower air cooling, refines grain structure and enhances elongation, aligning with its application in maintaining balanced mechanical properties for shipbuilding [24]. However, at temperatures exceeding the optimal range (e.g., 750 °C), the literature reports potential ductility loss due to microstructural coarsening, which is consistent with the downward trend in the graph. Nevertheless, some studies report improvements in elongation with moderate PWHT for stress relief [25], [26]. Overall, these trends adhere to the metallurgical principles outlined in standards such as ASTM A131, with recommendations for tailored testing in specific applications to verify outcomes.

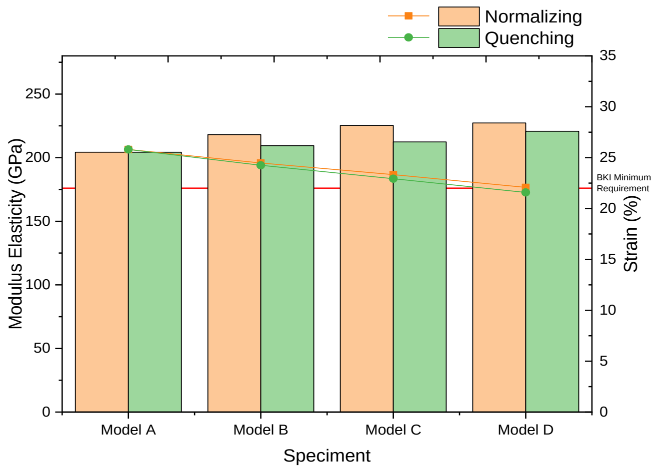


Figure 6. Results of modulus of elasticity and strain under different layer configurations throughout different test scenarios

3.3. Impact energy

The results of the impact energy test for AH36 steel, which was SMAW and then subjected to PWHT at 450 °C, 600 °C, and 750 °C, are shown in Figure 7. Following each thermal treatment, two cooling methods were applied: normalizing, which included moderate air cooling, and quenching, which involved rapid cooling. The horizontal red line in the graph represents the minimum impact energy requirement set by the BKI for maritime applications. This line serves as a benchmark for evaluating the steel's performance.

The findings demonstrate that normalizing consistently yields higher impact energy values than quenching across all PWHT temperature ranges. Specimen A, which did not receive PWHT, sustained impact energy levels above the BKI minimum irrespective of the cooling technique, indicating that as-welded AH36 steel has satisfactory inherent toughness despite residual stresses and heterogeneous microstructures after welding. Treatment at 450 °C (Specimen B) reduced impact energy, especially under quenching, which fell under the BKI standard. This reduction is likely due to inadequate temperature, which does not appropriately alleviate residual stresses or improve the microstructure arising from the welding process.

Conversely, Specimen C, subjected to treatment at 600 °C, exhibited the most favorable performance, particularly during normalization, when the impact energy reached its peak among the specimens. While quenching at 600 °C yielded impact energy measurements that met the BKI standards, the normalizing method demonstrated improved performance. The enhancement at 600 °C may be attributed to efficient recrystallisation and microstructural refinement, along with substantial alleviation of residual stress, thereby improving the material's toughness. Conversely, Specimen D, treated to 750 °C PWHT, exhibited satisfactory impact energy with normalizing but did not meet the BKI standard when quenched. The diminished efficacy of the quenching process at 750 °C is likely attributable to increased grain growth at high temperatures, which reduces toughness, especially when combined with fast cooling that may result in the development of a brittle martensitic structure.

The impact toughness of AH36 steel after welding is revealed by examination of the findings, as the PWHT temperature and cooling technique significantly affect it. The most successful method identified for improving material toughness without excessive grain development was PWHT at 600 °C, coupled with normalizing. By contrast, the quenching technique, whether used at lower or higher PWHT temperatures, tended to generate impact energy levels under the minimal threshold defined by BKI safety criteria. These results show that when high toughness and mechanical dependability are essential criteria for maritime structural applications, quenching is less appropriate.

The enhanced tensile properties resulting from effective PWHT and cooling methods have direct implications for ship repair protocols. Quenching at 450 °C enables rapid on-site stress relief, reducing hydrogen-induced cracking and facilitating safer, more durable hull repairs in dry dock or floating conditions without compromising ductility (24%–28%). In offshore platform fabrication, normalizing after PWHT promotes uniform ferrite-pearlite microstructures, thereby improving resistance to dynamic loads and corrosion-fatigue in saline environments, and extending service life for risers and jackets while meeting BKI standards. For underwater welding scenarios, these regimens minimize residual stresses and embrittlement risks, enhancing weld integrity against hydrostatic pressure and ensuring reliable hyperbaric repairs with minimal distortion, as supported by the consistent yield strengths observed across variants.

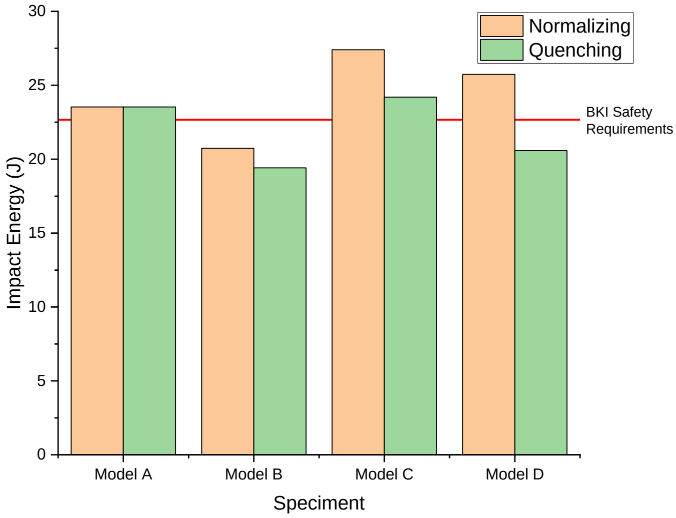


Figure 7. Impact energy results were measured throughout different test scenarios

4. CONCLUSIONS

The experimental investigation into PWHT for SMAW-welded AH36 steel demonstrates that temperatures of 450 °C–600 °C, when combined with normalizing or quenching, yield optimal mechanical properties that exceed BKI safety thresholds. These enhancements result from effective residual-stress relief and microstructural refinement, affirming PWHT's efficacy in improving weld reliability in marine structures. In practical terms, the findings support BKI-compliant protocols for ship hulls and offshore platforms, where quenching maximizes tensile strength under high-load conditions. At the same time, normalizing enhances ductility, thereby improving resistance to fatigue and corrosion. This balance is essential for extending service life in dynamic saline environments. Future studies should investigate microstructural evolution in greater detail to better understand phase transformations and validate mechanical behavior models in welded AH36 structures.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ahmad Firdaus	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓
Blinka Hernawan Prasetya		✓				✓		✓	✓	✓	✓	✓	✓	✓
Muhammad Adnan Rivaldi			✓	✓	✓	✓	✓			✓	✓			
Parlindungan Manik	✓				✓	✓				✓		✓		
Tuswan		✓		✓	✓		✓			✓		✓		

C : **C**onceptualization
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Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [AF], upon reasonable request.

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BIOGRAPHIES OF AUTHORS

Ahmad Firdhaus is an assistant professor. He holds a master of engineering (M.Eng.) in Naval Architecture from Sepuluh Nopember Institute of Technology, Indonesia, in 2020, Bachelor of Engineering (B.Eng.) in Naval Architecture from Diponegoro University, Indonesia, in 2018. He has been a lecturer at the Department of Naval Architecture, Faculty of Engineering, Diponegoro University since 2022. His research interests include ship hydrodynamics and ship structures. He can be contacted at email: afirdhaus@lecturer.undip.ac.id.

Blinka Hernawan Prasetya is a lecturer in civil engineering at the Department of Civil Engineering, Faculty of Engineering, Diponegoro University. He holds a master's degree (M.Eng.) in Civil Engineering and a bachelor of engineering (B.Eng.) in Civil Engineering from Diponegoro University, Indonesia, in 2019. His research focuses on material structure and composites. He can be contacted at email: blinka@live.undip.ac.id.

Muhammad Adnan Rivaldi earned his B.Eng. (2023) from the Department of Naval Architecture, Faculty of Engineering, Diponegoro University. His research interests are welding and ship structures. He can be contacted at email: rivaldi397@gmail.com.

Parlindungan Manik is a professor in Naval Architecture with a demonstrated history of working at Diponegoro University, Indonesia. He holds a Ph.D. in Mechanical Engineering from Diponegoro University, Indonesia in 2022, a master of engineering (M.Eng.) from Sepuluh Nopember Institute of Technology, Indonesia in 2002, and a bachelor of engineering (B.Eng.) from Sepuluh Nopember Institute of Technology, Indonesia in 1997. His research interests are ship materials and composites. He can be contacted at email: parlindungan_manik@live.undip.ac.id.

Tuswan is an associate professor in the Department of Naval Architecture, Faculty of Engineering, Diponegoro University, Indonesia. He holds a Ph.D. in Naval Engineering from Sepuluh Nopember Institute of Technology, Indonesia, in 2021, and a bachelor of engineering (B.Eng.) in Naval Engineering from Diponegoro University, Indonesia, in 2016. His research interests are ship structure and construction. He can be contacted at email: tuswan@lecturer.undip.ac.id.