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Analysis of Mechanical Properties and Microstructural Characteristics of Aluminum 6061 under Reforming Temperature Variations in the KCMP Sidewall Prototype

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Abstract**—***Aluminum 6061 is widely applied in railway manufacturing due to its lightweight, corrosion resistance, and high formability. Nevertheless, welding processes often induce distortion, which reduces its mechanical performance. This study investigates the influence of reforming temperature variations on the mechanical properties and microstructure of Aluminum 6061 used in the sidewall prototype of the Merah Putih High-Speed Train (KCMP). Experimental methods were employed, including tensile testing, bending testing, Vickers hardness testing, and microstructural examination on 8 mm-thick Aluminum 6061 subjected to reforming at 125–150 °C, 175–200 °C, and 225–250 °C. The results show that increasing reforming temperature decreases yield strength, ultimate tensile strength, bending stress, and hardness, while elongation increases, indicating improved ductility. Microstructural analysis confirms the reduction of Mg_2Si precipitates at higher temperatures, leading to decreased hardness. The most optimal performance was obtained at 175–200 °C. These findings demonstrate that reforming temperature significantly affects the mechanical behavior and microstructural characteristics of Aluminum 6061 in KCMP sidewall applications.*

Keywords**—** *Aluminum 6061, Reforming, Mechanical Properties, Metallography.*

I. INTRODUCTION

PT INKA, an Indonesian railway manufacturing industry, which is currently developing the Merah Putih High-Speed Train (KCMP). One of the main components produced is the sidewall structure. The fabrication of the KCMP sidewall employs Aluminum 6061 due to its formability, high conductivity, and corrosion resistance [1]. In the manufacturing process, sidewall assembly is carried out using welding techniques [2]. Observations conducted at PT INKA (Persero) revealed the occurrence of distortion or deformation in welded specimens. Distortion was identified as a critical issue due to its impact on fabrication delays and increased production costs of the KCMP sidewall [3]. To mitigate distortion, reforming processes are required to restore the dimensions of the sidewall [4]. However, improper thermal treatment temperatures during reforming may degrade the mechanical properties, thereby necessitating the selection of suitable temperature parameters [5].

In previous research concerning the effect of reforming temperature variations after GMAW welding on the tensile strength and metallography of 4 mm Aluminum 6061, with temperature variations 100–150 °C, 150–200 °C, and 200–250 °C. The results of this research show that higher reforming temperatures produce larger precipitation phases, resulting in a decrease in the tensile strength of the material[6]. Another previous research was conducted of aluminum 6061 using the precipitation hardening method at a temperature of 450°C for 30 minutes, and followed with artificial aging at varying temperatures of 150°C, 190°C, and 230°C with holding time for 5 hours. The results of this research show that higher temperatures lead to a greater amount of precipitation and tighter grain boundaries [7].

The aim of this study is to evaluate the mechanical properties and microstructure of Aluminum 6061 after the reforming process, with the goal of determining the most effective reforming temperature. This research is expected to provide solutions to industrial challenges at PT INKA (Persero), particularly in optimizing reforming temperature parameters for the production of KCMP sidewalls, which serve as safety components in transportation equipment to ensure passenger protection. In addition, the findings can be used as a reference for reforming process on aluminum 6061, as well as to broaden knowledge and technical expertise in engineering applications within the railway industry.

II. LITERATURE REVIEW

A. Sidewall KCMP

The sidewall of the KCMP train functions to form the structure and strength of the train body and to support the train roof [8]. The KCMP sidewall made of aluminum 6061 has lightweight characteristics and is corrosion resistant, making it suitable for high-speed trains [9]. The structure of the sidewall of the KCMP prototype is in the manufacturing process at PT INKA

B. Aluminum 6061

The 6xxx aluminum alloy is a lightweight metal that has corrosion-resistant properties and is a heat treatable metal [10]. Aluminum 6061 has a main chemical composition of Silicon

(Si), Magnesium (Mg), and Aluminum (Al) with a tensile strength of 206 MPa, yield strength of 110 MPa, and elongation of 10% [11].

C. Distortion

The change in the shape of material caused by heat treatment during welding or manufacturing processes that leaves stress on the material during cooling, resulting in warping [12].

D. Reforming

The reforming process is a heat treatment to correct the distorted shape of the material. The reforming process can improve the quality of the material [13].

E. Tensile Test

The tensile test is conducted by pulling the material with a gradually increasing static load until fracture occurs, resulting in a stress-strain relationship that generates yield strength (MPa), ultimate tensile strength (MPa), and elongation (%) data [14].

F. Bending Test

The bending test is performed to assess the material's resistance to plastic deformation when subjected to bending loads, thus obtaining bending strength data (MPa) [15].

G. Vickers Hardness Test

The Vickers hardness test is conducted to analyze the mechanical properties of materials by applying a constant load using a diamond pyramid indenter on the surface of a flat specimen, and then measuring the area of the indentation to obtain hardness values (HV)[16].

H. Micro Examination

Micro examination is performed to identify phases, grain types, and microstructural defects in materials using a microscope with magnifications ranging from 50 to 3000 times [17].

The method used for this research is a quantitative experimental method with variations in reforming temperature of 125–150 °C, 175–200 °C, and 225–250 °C and material Aluminum 6061 thickness of 8 mm. This research uses three types of variables: an independent variable (reforming temperatures), dependent variables (results from tensile test, bending test, vickers hardness test, and microstructure examination), and a control variable (Aluminum 6061). The study's results were analyzed using Analysis of Variance (ANOVA) to ensure accuracy. The research process is outlined in the flow chart shown in Figure 1.

III. METHODOLOGY

The reforming and specimen preparation were conducted at PT INKA (Persero), while the testing procedures, including tensile, bending, vickers hardness, and micro examination, were carried out at the Material Testing Laboratory of Madiun State Polytechnic. The equipment and materials used in this research are mentioned in Table 1.

TABLE 1. Equipment and Materials

Equipment	**Materials**
Band Saw Machine	Aluminum 6061
Brander	Grinding and Cutting Stone Blade
Thermogun (-32°C - 550°C)	Gas LPG
Laser Cutting	Belt Sander (Grid 240- 600)
Polisher Machine	Polishing Paper (Grid 800 -5000)
Tensile Tester (300 kN)	Polishing Cloth
Bending Tester (300 kN)	Metal Polish
Digital Microscope	Etching solution
Marking Tool	Aquades
-	Alcohol

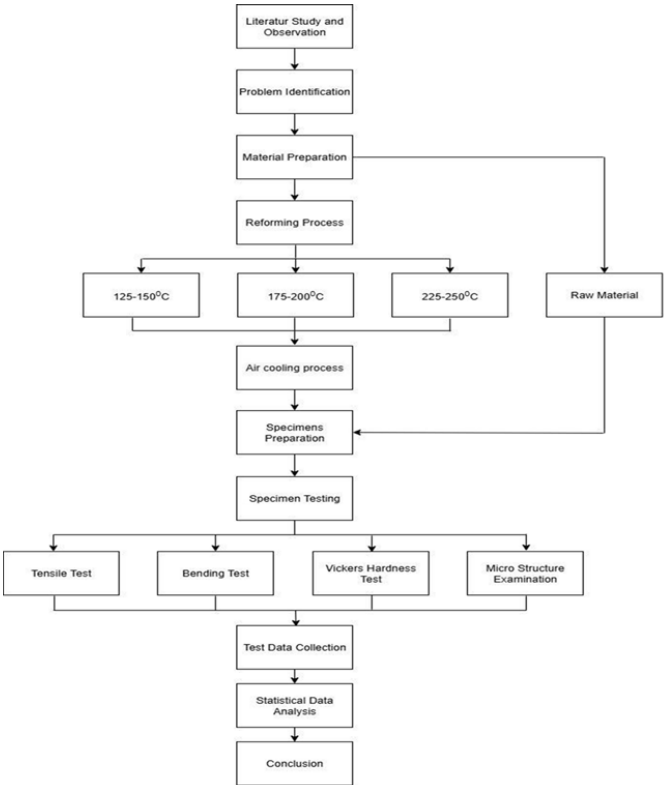


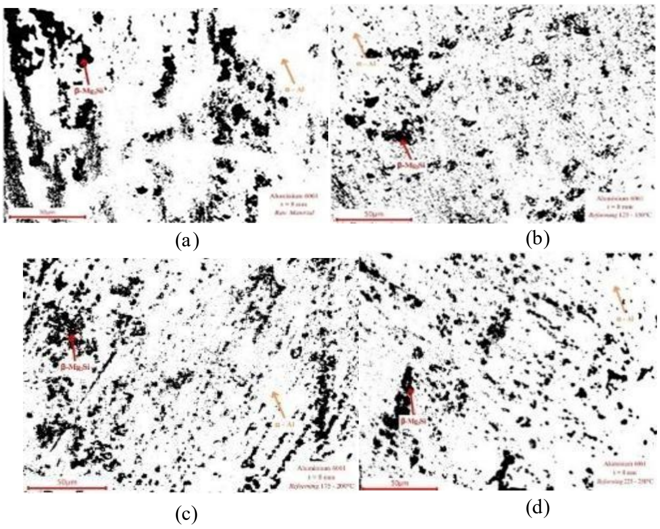
Figure 1. Research Flowchart

IV. RESULT AND DISCUSSION

A. Micro Examination

Micro examination is carried based on ASTM E3 standards [18]. The microstructural examination at 50× magnification was performed on the raw material specimen and the reformed specimens at temperature variations of 125– 150 °C, 175–200 °C, and 225–250 °C are shown in Figure 2.

Figure 2 presents the microstructural examination data of the raw material specimen and the reformed specimens at 125–150 °C, 175–200 °C, and 225–250 °C. The microstructure consists of an aluminum solid solution (α), while the dark regions represent Mg_2Si precipitates (β). In the raw material specimen, the precipitation percentage was 24.64% with aluminum at 75.36%. For the specimen reformed at 125–150 °C, the precipitation percentage decreased to 15.39% with aluminum at 84.61%. At 175–200 °C, the precipitation percentage was 18.24% and aluminum 81.76%. Meanwhile, at 225–250 °C, the precipitation percentage further decreased to 13.88%, with aluminum reaching 86.12%.


(a) (b)

(c) (d)

Figure 2. Microstructural Examination Result
(a) Raw material, (b) Reformed at 125–150 °C, (c) Reformed at 175–200 °C, (d) Reformed at 225–250 °C.

These results indicate that increasing the reforming temperature reduces the precipitation percentage of Mg_2Si [19], leading to a decrease in material hardness. The grain size of the aluminum 6061 microstructure is also affected by reforming temperature, where higher temperatures generate fewer precipitates, resulting in lower hardness [20]. During the reforming process, phase transformations occur that reduce hardness, phase composition, and the proportion of precipitates within the microstructure [21]. Lower reforming temperatures produce harder and more brittle mechanical properties, whereas higher reforming temperatures yield softer and more ductile behavior. Overall, the microstructural examination confirms that higher reforming temperatures reduce the precipitation percentage compared to the raw material, thereby softening the aluminum 6061 and enhancing its ductility.

B. *Tensile Test*

This tensile tests were conducted based on ASTM E8 standard [22]. After completing the tensile tests, data on yield strength, ultimate tensile strength, and elongation were obtained.

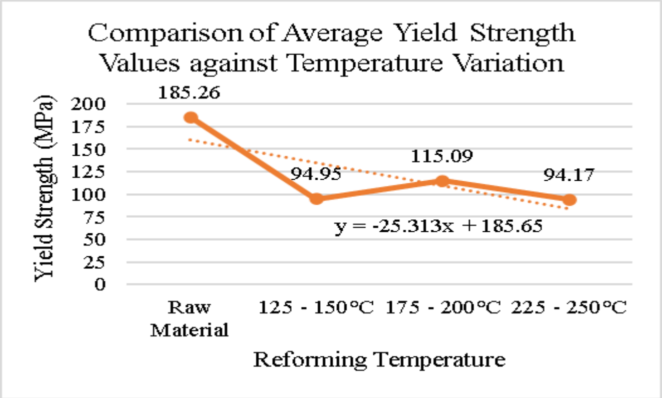


Figure 3. Comparison of Average Yield Strength Values at Different Reforming Temperatures

The graph in Figure 3 shows that the highest yield strength was obtained from the untreated raw material, with a value of 185.26 MPa. As the reforming temperature increased, the yield strength consistently decreased. At the highest temperature range (225–250 °C), yield strength dropped to 94.17 MPa. This trend indicates that higher reforming temperatures reduce the ability of Aluminum 6061 to resist loading prior to plastic deformation [6].

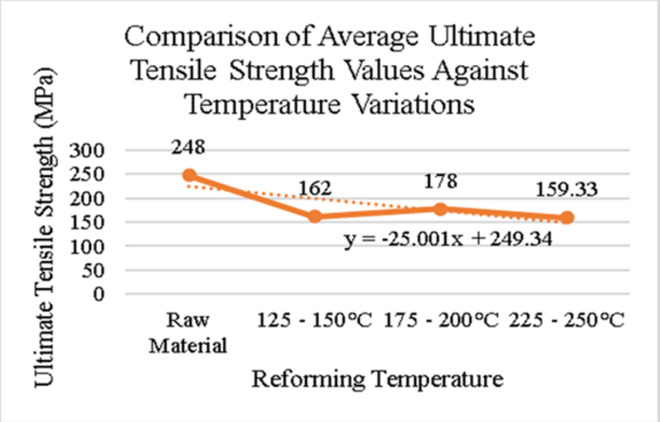


Figure 4. Comparison of Average Ultimate Tensile Strength (UTS) Values at Different Reforming Temperatures

As shown in Figure 4, the highest ultimate tensile strength (UTS) observed in the raw material, reaching 248 MPa. A sharp decrease occurred at the 125–150 °C range, with UTS dropping to 162 MPa. At 175–200 °C, the value slightly increased to 178 MPa before declining again to 159.33 MPa at 225–250 °C. Overall, UTS decreased with increasing reforming temperature, although minor fluctuations were observed. This trend indicates that the maximum resistance of the material before fracture was reduced due to thermal treatment [23].

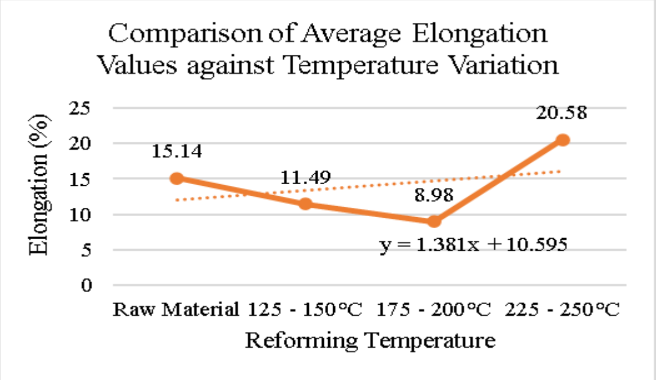


Figure. 5. Comparison of Average Elongation Values at Different Reforming Temperatures

As illustrated in Figure 5, the highest elongation was obtained at the 225–250 °C range, reaching 20.58%. The lowest elongation occurred at 175–200 °C, with a value of 8.98%. For the raw material, elongation was measured at 15.14%, which was higher than most reforming conditions below 225 °C. With increasing reforming temperature, the ductility of Aluminum 6061 tended to improve, particularly at higher temperatures [23]. This indicates that the material became softer and more capable of undergoing larger deformation before fracture.

The findings confirm that reforming temperature reduces the mechanical strength of Aluminum 6061, as reflected in lower yield strength and UTS values. However, higher temperatures promote ductility, especially in the 225–250 °C range. In other words, as the reforming temperature increases, the material becomes more ductile but less strong.

TABLE 2. Analysis of Varians (ANOVA)

		Sum of Squares	df	Mean Square	F	Sig.
Yield Strength	Between Groups	16664.064	3	5554.688	95.406	.000
	Within Groups	465.775	8	58.222		
	Total	17129.839	11			
Tensile Strength	Between Groups	20177.103	3	6725.701	218.000	.000
	Within Groups	277.667	9	30.852		
	Total	20454.769	12			
Elongation	Between Groups	228.314	3	76.105	10.941	.003
	Within Groups	55.649	8	6.956		
	Total	283.963	11			

ANOVA analysis in Table 2 shown that the reforming temperature has influence on the values of elongation, ultimate tensile strength, and yield strength.

C. Bending Test

This test was carried out based on ASTM E290[24]. As illustrated in Figure 6, the bending stress of aluminum 6061 was significantly affected by thermal reforming treatment. The untreated sample exhibited the highest bending stress at 2012.1 MPa. After reforming at 125–150 °C, the bending stress decreased sharply to 977.89 MPa. When the temperature was further increased to the range of 175–250 °C, the bending stress values recovered partially, although they did not reach the level of the raw material.

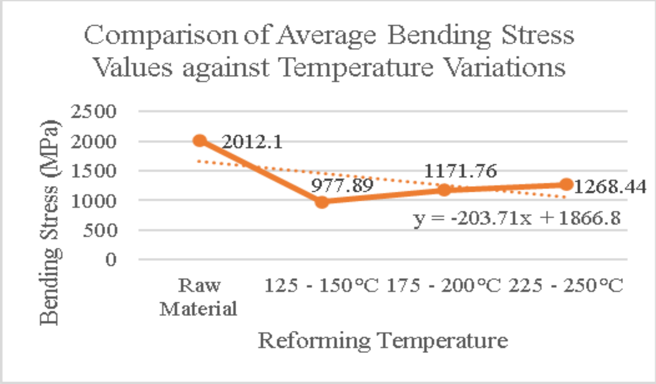


Figure 6. Comparison of Average Bending Stress Values at Different Reforming Temperatures

Overall, higher reforming temperatures tended to reduce the bending strength, particularly at lower temperature ranges, while subsequent heating at higher ranges improved the bending resistance to some extent[6].

TABLE 3. ANOVA results of the bending test data

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	214.776	3	71.592	10.804	.003
Within Groups	53.009	8	6.626		
Total	267.786	11			

Based on the ANOVA results in Table 3, the varying reforming temperature significantly affects the bending stress values.

D. Vickers Hardness Test

The vickers hardness tests were conducted based on ASTM E92[25].

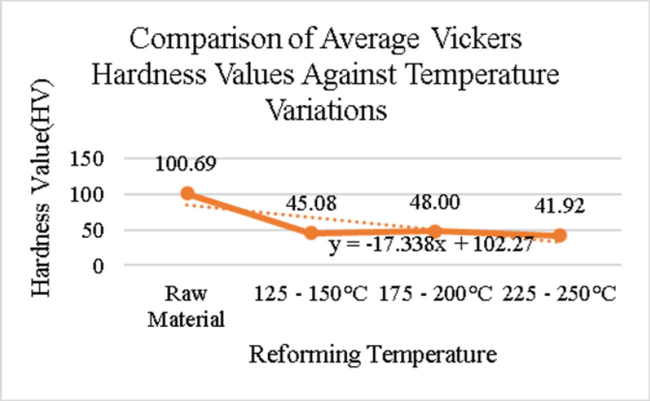


Figure 7. Comparison of Average Vickers Hardness Values at Different Reforming Temperatures

The graph in Figure 7 compares the hardness values of the raw material with those of the reformed specimens. The Vickers hardness test results indicate that increasing reforming temperature leads to a reduction in hardness. The temperature range of 175–200 °C produced the maximum average hardness value of 48 HV. However, a decline in hardness was observed at 225–250 °C, which corresponds to an over-aging condition. This phenomenon occurs because the applied thermal treatment softens the material [26].

Furthermore, the Vickers hardness test results show that reformed specimens exhibited lower hardness values compared to the raw material. As the reforming temperature increased, hardness progressively decreased, reflecting a corresponding reduction in the mechanical strength of Aluminum 6061. This decline in hardness is associated with improved ductility, as the material becomes softer and more pliable.

V. CONCLUSION

Based on the results obtained, it can be concluded that reforming temperature variations significantly affect the mechanical properties and microstructural characteristics of Aluminum 6061 in the KCMP sidewall prototype. Higher reforming temperatures resulted in decreased yield strength, ultimate tensile strength, bending stress, and hardness compared to the raw material, while elongation tended to increase, indicating improved ductility. Microstructural analysis revealed a reduction in the percentage of Mg_2Si precipitates with increasing reforming temperature, which contributed to the decline in material hardness. Among the investigated ranges, the reforming temperature of 175–200 °C provided the most optimal balance of mechanical performance and microstructural stability.

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