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Analysis of Post-GMAW Cooling Media Variations on the Mechanical Properties and Intergranular Corrosion Formation of SUS201 Material in the Underframe of the 612 Train

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Abstract *— During the fabrication process of train underframes at PT INKA (Persero), several problems occurred, one of which was distortion or abnormal changes in the shape of the material. To solve this problem, a reforming process (shape restoration) was carried out using heat treatment and cooling engineering with appropriate parameters, as this affects the mechanical properties of the material. This study aims to determine the appropriate temperature and cooling medium parameters for the reforming process at PT INKA (Persero). The research method used reforming with a burner at temperatures of 500oC, 600oC, and 700oC and cooling media of water and air on underframes made of S355J2 and SS400 steel. This study produced data from tensile test values, Rockwell hardness tests, and micro examinations, which were compared with the results of test specimens before and after the reforming process. The hypothesis of this study is that an increase in temperature during the reforming process results in a decrease in the mechanical properties of the material, and that materials using air as a cooling medium produce higher mechanical properties compared to those using water as a cooling medium.*

Keywords *— S355J2 Steel, SS400 Steel, Cooling Media, Reforming, Temperature.*

I. INTRODUCTION

Based on observations at PT INKA (Persero) during the construction of the New Generation 612 Stainless Steel (SS) Train project. This project complies with the regulations of Minister of Transportation Regulation No. 24 of 2015, which emphasizes the importance of safety in train operations, both for passengers and goods [1]. Every production and maintenance process for train components, especially those directly related to safety such as the underframe, is carried out strictly and accurately. The underframe functions as the main structural support for the carbody. The underframe material must be able to withstand both static and dynamic loads [2].

One of the constituent materials is AISI 201 stainless steel, which must be processed carefully, including during the welding stage, to avoid potential structural failure [3]. In addition to AISI 201 stainless steel, carbon steel is also used in railway construction for certain components that require high strength at a lower cost. Carbon steel has a relatively low risk of sensitization, but is susceptible to general corrosion if not properly coated or protected. These differences in properties make it an interesting comparison to AISI 201, especially in terms of mechanical properties [3]

Welding on the middle part of the underframe was performed using the Gas Metal Arc Welding (GMAW) method with a current of 75 A and a butt joint connection. Welding on stainless steel can cause sensitization due to slow cooling (between 850ºC and 450ºC), which causes the formation of chromium carbide ($Cr_{23}C_6$) deposits at the grain boundaries [4], [5]. As a result of sensitization, the chromium protective layer thins and causes intergranular corrosion [5], [6].

In some materials, the corrosion process occurs laterally along parallel planes toward the surface, a process known as exfoliation, and occurs along the austenite grain boundaries due to slow cooling [7] To minimize this, it is recommended to add a rapid cooling process using water or pressurized air after welding. This rapid cooling can prevent the material from remaining at a sensitization temperature for too long, thereby reducing corrosion formation and maintaining the strength of the welded joint [8], [9].

Based on observation and literature study, this research is related to the effect of cooling media variation on mechanical properties (tensile test, hardness test, and fatigue test), corrosion test, and micro examination on AISI 201 stainless steel and carbon steel. Therefore, the cooling media variations applied in this research are rapid cooling with water, pressurized air, and without rapid cooling.

II. METHOD

This study This study used AISI 201 stainless steel (4.5 mm thick) and SM570 carbon steel (12 mm thick) materials. The welding process was carried out using the Gas Metal Arc Welding (GMAW) method with a current of 125 A, position 1G, and butt joint connections by a certified welder from PT INKA (Persero). After welding, rapid cooling variations were applied using water, compressed air, and no rapid cooling. The rapid cooling process is shown in Figure 1.

Figure 1. Rapid Cooling Process

The test specimens were cut according to the cutting plan using a Gap Shear Machine with an additional 5 mm gap from the cutting area. A series of tests were then conducted, namely tensile test, fatigue test, hardness test, corrosion test, and micro examination. The tensile test referred to ASTM E8, the fatigue test to ASTM E606, the hardness test used the Microindentation Vickers method (ASTM E384), the corrosion test followed ASTM A262 Practice F, while the micro examination was conducted in accordance with ASTM A262 and ASTM E3.

The test results included tensile strength (UTS, YS, and elongation), fatigue strength (fatigue limit and fatigue life), hardness (HV), corrosion rate (mm/year), and microstructure characterization in the form of grain morphology, phase distribution, and grain boundary corrosion indications.

III. RESULTS AND DISCUSSION

Based on the tensile test data visualized in the form of a graph shown in Figure 2 and 3.

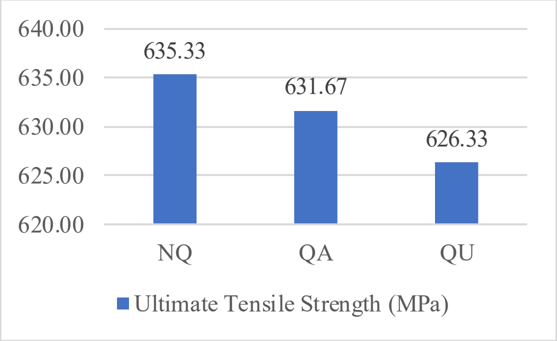


Figure 2. Variation Graph against Ultimate Tensile Strength

The phenomenon shown in Figures 2 and 3 indicates that the Ultimate Tensile Strength (UTS) and Yield Strength (YS) values in the non-quenched variation reached the highest values of 635.33 MPa for UTS and 412.57 MPa for YS compared to the quenched variation. This is explained by the fact that materials that do not undergo rapid cooling retain a more stable microstructure to support tensile strength and resistance to plastic deformation [8]. Meanwhile, in the rapid cooling variation using water as the cooling medium, the rapid cooling rate causes a transformation to a harder microstructure, but this has the potential to reduce tensile strength and resistance to elastic deformation [10].

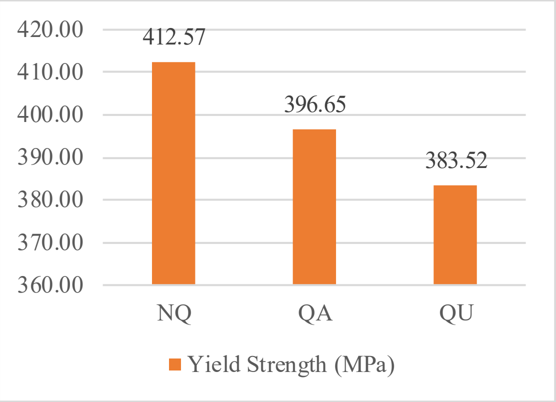


Figure 3. Variation Graph against Yield Strength

Based on the fatigue test data results visualized in the form of a graph shown in Figure 4.

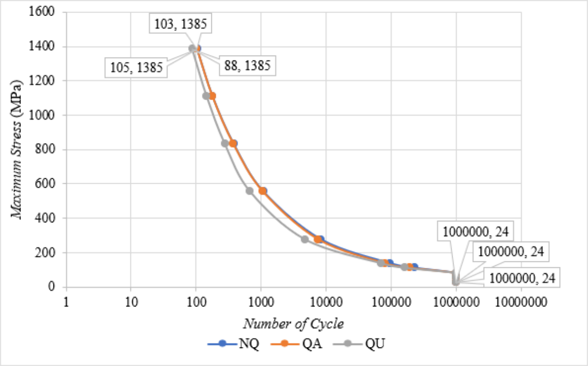


Figure 4. Graph of Number of Cycles versus Maximum Stress

Fatigue testing simulations based on Figure 4, at various load levels, show different material responses to cyclic loads. At a low load of 1 kN, with a maximum stress of 24 MPa, the NQ, QA, and QU specimens showed high fatigue resistance, characterized by the ability to withstand up to 1,000,000 cycles without failure. This condition indicates that at low stress levels, the material is within its elastic limit and does not experience significant damage. This resistance is directly proportional to the material characteristics that maintain the fatigue limit against cyclic loads with low stress [11].

A high load of 50 kN, indicating a maximum stress of 1,385 MPa, caused a drastic decrease in the fatigue life of the specimens. The NQ specimen failed after 105 cycles, the QA specimen after 103 cycles, and the QU specimen only reached 88 cycles. The better performance of the NQ specimen compared to QU and QA indicates that the slow cooling process produces a more stable microstructure with a lower residual stress distribution.

Meanwhile, rapid cooling through water or air media produces a harder microstructure transformation, but tends to increase residual stress and the risk of early crack initiation. This indicates that a high cooling rate affects the material's resistance to cracking due to high cyclic loading. The phenomenon shows that thermal processes with high cooling rates reduce fatigue life due to phase changes in the microstructure [12].

Based on the results of the Vickers microindentation hardness test data visualized in the form of a graph shown in Figure 5.

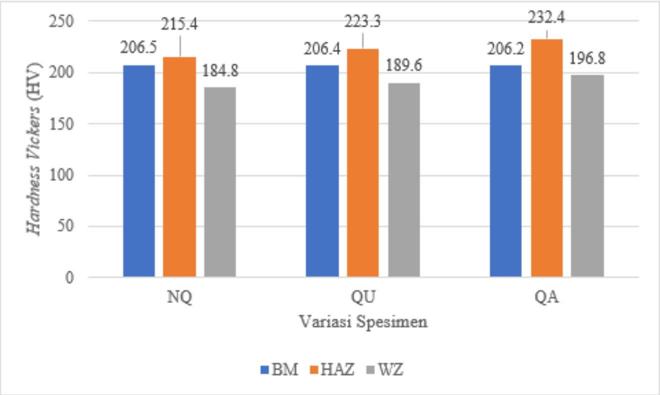


Figure 5. Variation Graph against Hardness Value

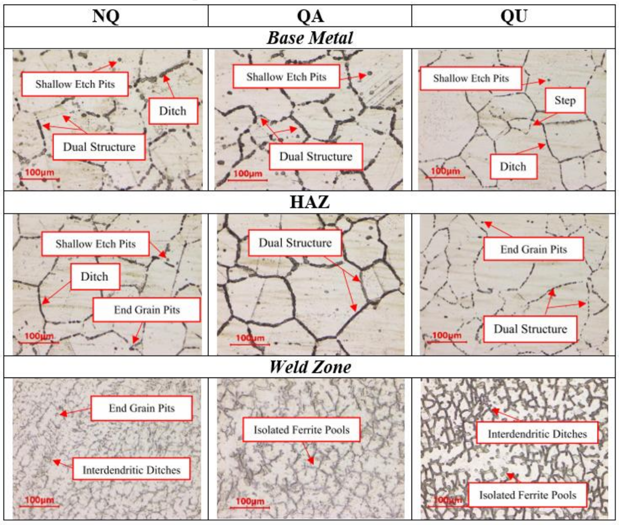
Based on Figure 5. HAZ areas show the highest hardness due to the thermal effects of welding, which modify the microstructure to become harder. Meanwhile, the weld zone shows a decrease in hardness due to the dominance of the relatively soft austenite phase when using ER 308 LSi electrodes. Water quenching produces the highest hardness in the HAZ and weld zone. A high cooling rate increases hardness and limits grain growth, resulting in a finer and harder structure [13].

In corrosion test, the rapid cooling sample with water media (QA) showed the lowest corrosion rate, which was 0.001 mm/month or 0.008 mm/year. Water cooling provides a sufficiently high cooling rate to prevent chromium and carbon diffusion, thereby minimizing the formation of depletion zones. This finding is consistent with research showing that increasing the cooling rate can improve resistance to intergranular corrosion by inhibiting the segregation of critical alloying elements at grain boundaries [14]. Meanwhile, cooling using pressurized air (QU) resulted in a moderate corrosion rate (0.001 mm/month or 0.012 mm/year), because the cooling rate was not as effective as water in optimally preventing carbide precipitation.

The results of this study indicate that the cooling medium plays an important role in determining the structural integrity of AISI 201 material against grain boundary corrosion attack. Thus, the selection of an appropriate cooling method is very important in the heat treatment process for structural components that work in aggressive environments, such as trains. Water cooling has proven to be the most effective option in suppressing the rate of intergranular corrosion, which extends the service life of the material and improves operational safety. This strategy supports efforts to improve the production quality and maintenance of stainless steel components in the modern transportation industry [15].

Examination of AISI 201 material conducted on each rapid cooling variation, as shown in Table 1.

TABLE 1. Comparison of Micro Examination Results Data



The results of micro examination on specimens without rapid cooling showed grain boundary corrosion growth after corrosion testing. Prior to testing, the base metal showed initial indications of grain boundary corrosion in the form of ditch structures. The HAZ zone showed milder attack with the appearance of shallow etch pits, while the weld zone displayed isolated ferrite pools and interdendritic ditches, which are structures resulting from welding solidification. After the corrosion test, the HAZ zone experienced an increase in corrosion intensity with the appearance of ditches and end grain pits. This indicates that slow cooling promotes the precipitation of chromium carbide ($Cr_{23}C_6$) at the grain boundaries, thereby increasing susceptibility to grain boundary corrosion, especially in the HAZ zone, which is sensitive to heat treatment [16].

IV. CONCLUSION

The conclusion of this study shows that AISI 201 was chosen as the main material for the train underframe due to its high tensile strength, even though it is susceptible to changes in properties due to welding. Rapid cooling variations have a significant effect, whereby without rapid cooling the material has higher UTS and fatigue resistance, while cooling with water produces the highest hardness but reduces tensile strength and fatigue resistance due to the formation of a harder microstructure. Rapid cooling, especially with water as the medium, has been proven to reduce sensitization and grain boundary corrosion because it accelerates the critical temperature transition so that the material does not remain in the sensitization range for too long.

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