International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

Effect of Quenching Media on Mechanical Properties and Intergranular Corrosion of GMAW-Welded Stainless Steel 201 in Train 612 Underframe

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Abstract— *Quenching is a rapid cooling process applied after welding to improve the mechanical properties and corrosion resistance of materials. In the fabrication of the underframe of Train 612 at PT Industri Kereta Api (INKA), stainless steel 201 was observed to experience intergranular corrosion after undergoing Gas Metal Arc Welding (GMAW). This study aims to analyze the effect of quenching media variations on the tensile strength, hardness, corrosion resistance, and the macro- and microstructures of stainless steel 201. Three quenching conditions were applied to each weld layer: non-quenching, pressurized air quenching, and water quenching. The experimental procedures included tensile testing, Vickers hardness testing, corrosion testing, macro examination, and microstructural examination. The results show that pressurized air quenching provides the highest tensile strength and ductility, while water quenching produces superior hardness and corrosion resistance. In contrast, non-quenching yields the lowest hardness and corrosion resistance. Microstructural analysis further revealed that water quenching minimizes chromium carbide precipitation, thereby reducing intergranular corrosion, whereas non-quenching exhibited the most severe intergranular damage. This study contributes to future research references and the development of Process Instructions (PI) at PT INKA to mitigate undetected intergranular corrosion, which may compromise railway underframe safety.*

Keywords— *Stainless steel 201, quenching media, mechanical properties, corrosion resistance, intergranular corrosion.*

I. INTRODUCTION

PT INKA is a railway manufacturing company that contributes to the production of the 612 train. Based on observations, the middle part of the underframe of the 612 train is constructed from stainless steel 201 using the GMAW method [1].

The problem identified is the occurrence of intergranular corrosion in stainless steel 201 after the GMAW welding process. This condition has the potential to reduce the material's strength and impact the operational safety of the train. One proposed solution to address this issue is the application of various quenching media in each welding layer. Quenching is known to improve material hardness through the formation of martensitic structures, thereby inhibiting carbide precipitation and reducing the potential for intergranular corrosion [1], [2].

Previous studies have shown that stainless steel 201 with a thickness of 4.5 mm experiences intergranular corrosion due to slow cooling at room temperature after GMAW welding with a current of 125 A. This condition causes the material to remain within the sensitization temperature range (500–850 °C), resulting in carbide precipitation in the Heat Affected Zone (HAZ), which decreases the mechanical properties of the material [2]. Sensitization occurs when austenitic stainless steel is heated within this temperature range and cooled slowly, leading to grain boundary precipitation that reduces material hardness and mechanical strength [3]. This problem is particularly critical because intergranular corrosion is difficult to detect directly, which means underframe damage may go unnoticed and could compromise train safety.

Based on this issue, the present research focuses on analyzing the effect of quenching media variations on the mechanical properties and corrosion resistance of stainless steel 201 in the middle part of the 612 train underframe. The State of the Art (SOTA) of this study is that it represents the first research at PT INKA addressing intergranular corrosion in stainless steel 201 after GMAW welding by applying quenching media variations to the underframe of the 612 train. The quenching variations used in this study are water quenching, compressed-air quenching, and non-quenching. The objective of this research is to analyze the tensile strength, hardness level, corrosion resistance, as well as the macro- and microstructures of stainless steel 201 after applying different quenching media in each welding layer. The findings of this research are expected to contribute to improving the quality of welded joints in stainless steel 201 and to preventing intergranular corrosion in the underframe of the train.

II. MATERIAL AND RESEARCH METHODS

This research employed a quantitative experimental approach to analyze the effect of quenching media variations on the mechanical properties and the formation of intergranular corrosion in stainless steel 201 welded using the Gas Metal Arc Welding (GMAW) method. The research stages included coupon preparation, welding, quenching, Non-Destructive Testing (NDT), specimen preparation, and specimen testing, which consisted of tensile testing, Vickers hardness testing,

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corrosion testing, as well as micro and macrostructural examinations.

The material used was stainless steel 201 with a thickness of 4.5 mm. Welding was carried out using the GMAW method at a current of 125 A with ER 308 LSi electrodes and a shielding gas mixture of 97.5% Argon (Ar) and 2.5% Carbon Dioxide (CO_2). After welding, cooling treatments were applied using three variations of quenching media: non-quenching, compressed-air quenching, and water quenching, applied to each welding layer.

Before performing the Destructive Tests (DT), the specimens underwent Non-Destructive Testing (NDT), including visual inspection and liquid penetrant testing in accordance with the AWS D1.1 standard, to ensure weld quality and detect surface defects such as cracks, porosity, and inclusions not visible to the naked eye [4], [5].

Subsequently, specimens were cut using a gap shear machine according to the ASME BPVC Section IX standard, adjusted to the required testing dimensions. The Destructive Tests (DT) conducted were as follows:

1. Tensile Test in accordance with ASTM E8/E8M, to determine the values of Ultimate Tensile Strength (UTS), Yield Strength (YS), and Elongation (%EL) [6].
2. Vickers Hardness Test following ASTM E92, using a controlled load to measure hardness values (HV) across the Base Metal (BM), Weld Metal (WM), and Heat Affected Zone (HAZ) [7].
3. Corrosion Test based on ASTM A262 Practice F (Strauss Test), to evaluate the susceptibility of stainless steel 201 to intergranular corrosion [8].
4. Macro Examination according to ISO 17639:2013, using a digital microscope with magnifications up to 1600x to analyze weld fusion width and joint quality [9].
5. Micro Examination based on ASTM E3 and ASTM E407, involving mounting, grinding, polishing, and electrolytic etching processes to identify grain morphology, carbide precipitation, and indications of intergranular corrosion [9].

The experimental results were analyzed quantitatively to evaluate the effect of quenching media variations on the mechanical properties and corrosion resistance of stainless steel 201 in the middle part of the 612 train underframe.

A. Materials and Tools

Materials	Tools
Stainless steel 201	GMAW welding machine
ER 308 LSi electrode	Computer Numerical Control (CNC) milling machine
Micro cutting disc blade	Hand grinder
Grinding wheel	Metallurgical cutting machine
Shielding gas (97.5% Ar + 2.5% CO_2)	Polishing machine
Polishing cloth	Universal Testing Machine (UTM)
Polishing papers (Grid 80, 240, 500, 600, 800, 1200, 2000)	Vickers hardness test machine
Metal polishing paste	Apparatus corrosion test
Copper sulfate-sulfuric acid	Microscope optic micro and macro examination
Aquades	Polisher (P220) Machine grit SiC paper
Etching Liquid	Measurement Tool (Ruler, Caliper)
Spray and Anti-Rust Liquid	Marking Tools
Alcohol 96%	

III. RESULTS AND DISCUSSION

The research entitled "Analysis of Quenching Media Variations on the Mechanical Properties and Intergranular Corrosion Formation of Stainless Steel 201 in the Middle Part Underframe of Train 612" achieved the following results:

A. Tensile Test Result

The tensile test is a method of testing specimens by applying a tensile force until the specimen reaches its maximum stress and strain limit, leading to deformation [10]. The results of the tensile test are presented in the graph below.

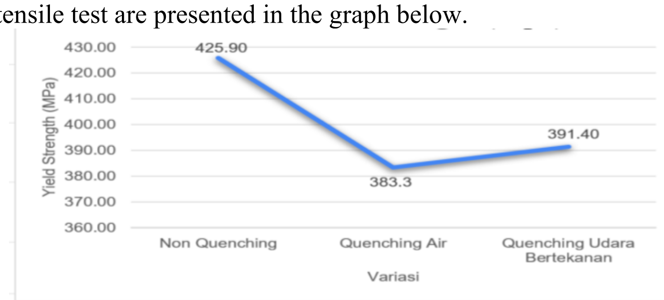

Figure 4.1 Yield Strength Graph

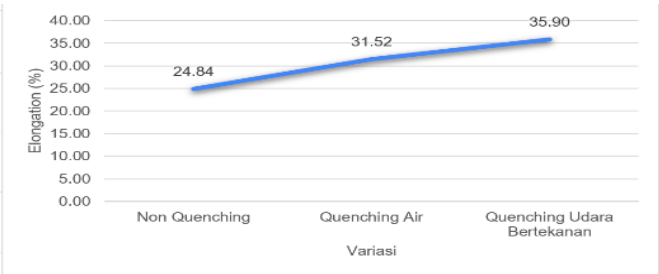

Figure 4.2 Elongation Graph

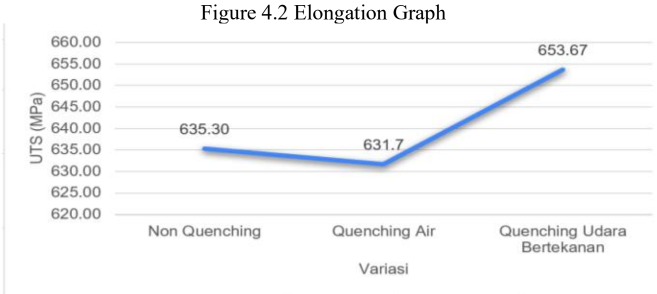

Figure 4.3 Ultimate Tensile Strength Graph

Based on the tensile test results, the variation of quenching media has a significant effect on the mechanical properties of stainless steel 201. Compressed-air quenching produced the best mechanical properties compared to water quenching and non-quenching.

B. Vickers Hardness Test Results

The Vickers hardness test is a hardness measurement method that uses a diamond indenter with a square base [11]. The results of the Vickers hardness test show the hardness values in the welded area for each quenching media variation. The comparison of these hardness values is presented in Figure 4.4.

Based on the Vickers hardness test results, compressed-air quenching produced the highest hardness values in most zones, while non-quenching resulted in the lowest hardness. This

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indicates that compressed-air quenching can significantly increase the material hardness.

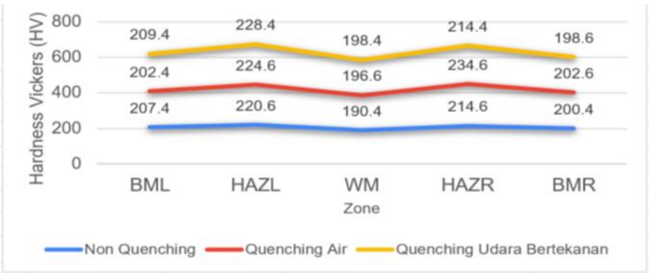


Figure 4.4 Comparison Graph of Vickers Hardness Values

C. *Corrosion Test Results*

The corrosion test was conducted by immersing the specimens in boiling sulfuric acid solution containing copper sulfate for a specified period, following ASTM A262 Practice F [8]. From the corrosion test, the corrosion rate values were obtained in units of millimeters per month and per year, as presented in the graph below.

Figure 4.5 Graph of Corrosion Rate Values (mm/Month)

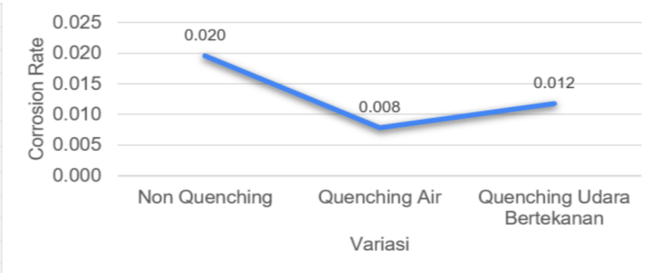


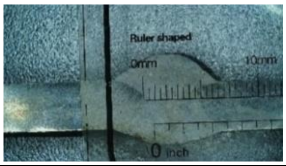
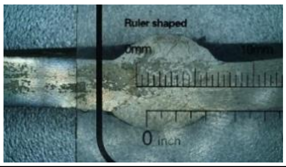
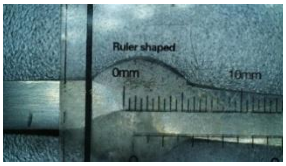
Figure 4.6 Graph of Corrosion Rate Values (mm/Year)

Based on the corrosion test results, the variation of quenching media had a significant effect on the corrosion resistance of stainless steel 201. Water quenching was the most effective in reducing the corrosion rate, followed by compressed-air quenching, while non-quenching resulted in the lowest corrosion resistance. This indicates that the application of quenching, particularly with water as the medium, provides higher corrosion resistance compared to non-quenching, making it more effective in ensuring long-term protection of railway components against environmental degradation.

D. *Macro Examination Results*

Macro examination was conducted to determine the fusion weld width using a 1600X 12MP Digital Microscope. A total of three specimens were tested (one specimen per quenching variation) in accordance with ISO 17639:2013. The macro examination results are presented in TABLE 3.1.

TABLE 3.1 Macro Examination Results

Macro Examination Results	Description
	The fusion weld width of the non-quenched specimen was 5 mm, and no discontinuities were observed in the fusion weld.
	The fusion weld width of the water-quenched specimen was 4.5 mm, and no discontinuities were observed in the fusion weld.
	The fusion weld width of the pressurized air-quenched specimen was 2.5 mm, and no discontinuities were observed in the fusion weld.

From the table above, it can be analyzed that each variation shows no imperfections, indicating the absence of welding defects.

E. *Micro Examination Results*

Micro examination is a method used to identify microstructural features by employing an optical microscope [12]. The results of the microstructural observations are presented in the following figures.

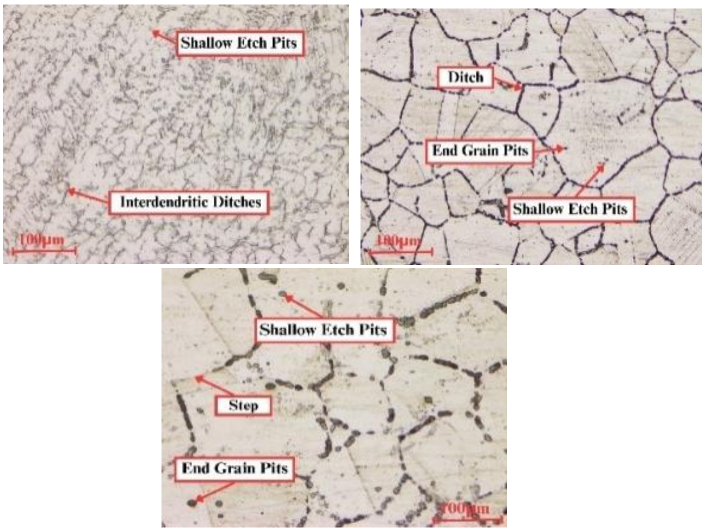


Figure 4.7 Microstructure of Non-Quenched Material

Vivi Aulia Husna Wahidah, Masayu Nazar Surya Kencana, Rohit Efendi Saputra, Fadhel Muhammad Khadafi, Nafisa Ramadhani Putri, Alfi Tranggono Agus Salim, and Dennis Priyangga, "Effect of Quenching Media on Mechanical Properties and Intergranular Corrosion of GMAW-Welded Stainless Steel 201 in Train 612 Underframe," *International Research Journal of Advanced Engineering and Science*, Volume 10, Issue 4, pp. 104-108, 2025.

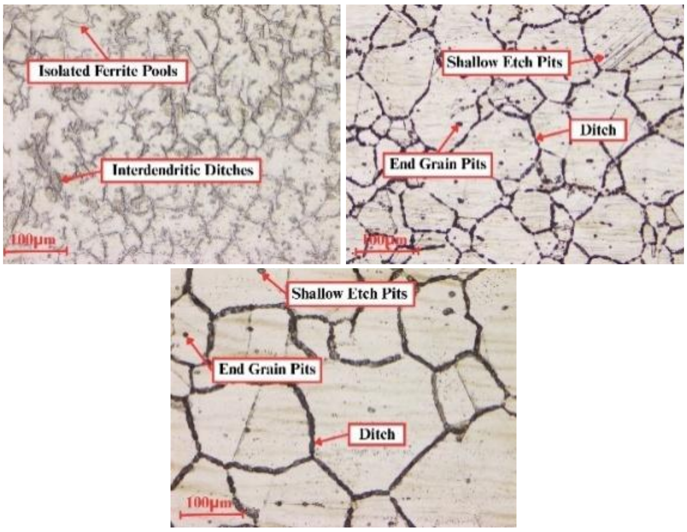


Figure 4.8 Microstructure of Water-Quenched Material

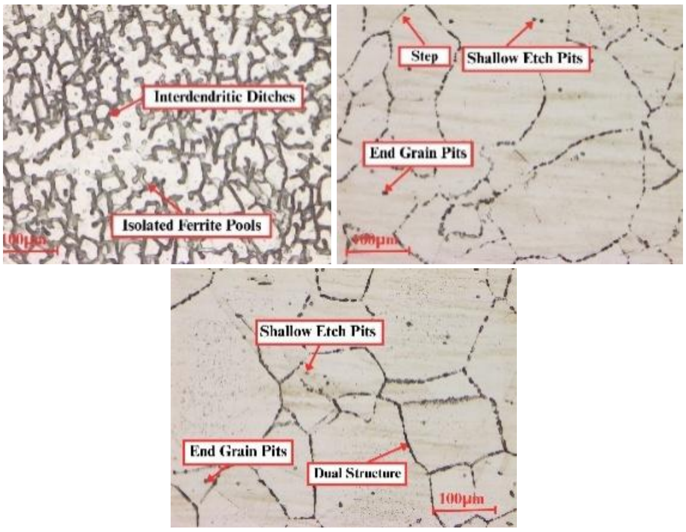


Figure 4.9 Microstructure of Pressurized Air-Quenched Material

The variation of quenching media significantly influenced the formation of intergranular corrosion in the base metal, HAZ, and weld zone. In the non-quenching specimen, severe intergranular corrosion was observed, characterized by the presence of ditch and step structures due to chromium carbide ($Cr_{23}C_6$) precipitation at the grain boundaries [13]. In the air-quenched specimen, intergranular corrosion was still present but less intense compared to the non-quenching condition, showing shallower ditch formation and uneven distribution of damage. Meanwhile, the water-quenched specimen exhibited the best corrosion resistance, with minimal evidence of intergranular corrosion and relatively clean grain boundaries. These differences indicate that water quenching effectively suppresses chromium carbide precipitation, thereby preserving chromium content at the grain boundaries and enhancing resistance to intergranular corrosion.

IV. Conclusion

The variation of quenching media on each welding layer significantly affected the mechanical properties and reduced the risk of intergranular corrosion. The tensile test results showed that pressurized air quenching exhibited the highest Ultimate Tensile Strength (UTS) of 653.67 MPa and the highest elongation of 35.90%, while the non-quenching specimen demonstrated the highest Yield Strength (YS) of 425.90 MPa. Water quenching showed the lowest values in both UTS (631.70 MPa) and YS (383.30 MPa). Overall, pressurized air quenching provided the best combination of tensile strength and ductility.

The Vickers hardness test revealed that pressurized air quenching produced the highest hardness values in most zones, particularly in HAZL (228.4 HV), while the non-quenching specimen exhibited the lowest hardness. This indicates that pressurized air quenching can significantly enhance the material hardness compared to non-quenching.

The corrosion test results showed that water quenching achieved the lowest corrosion rate of 0.001 mm/month (0.008 mm/year), followed by pressurized air quenching at 0.001 mm/month (0.012 mm/year), while non-quenching exhibited the highest corrosion rate at 0.002 mm/month (0.020 mm/year). This demonstrates that quenching, especially with water as the medium, provides superior corrosion resistance compared to non-quenching.

Based on the macro examination results, no defects were found in all welded joints. However, the micro examination revealed that water quenching exhibited the best corrosion resistance with minimal intergranular corrosion, followed by pressurized air quenching. In contrast, non-quenching showed the most severe corrosion attack due to chromium carbide precipitation.

Acknowledgment

The authors would like to express their gratitude to the Directorate of Learning and Student Affairs (Belmawa) for funding support through the Student Creativity Program (PKM) – Exact Research. Special thanks are also extended to the Railway Engineering Program of Politeknik Negeri Madiun, PT INKA (Persero), the Manufacturing Laboratory, the Materials Testing Laboratory, and the Department of Engineering, Politeknik Negeri Madiun, for granting permission and providing facilities that made this research possible.

Sincere appreciation is conveyed to Mr. Alfi Tranggono Agus Salim, S.Si., M.T., as the academic supervisor, and Mr. Dennis Priyangga, S.T., as the industrial mentor, for their guidance, direction, and support throughout the research and the preparation of this scientific article.

Finally, the authors also extend their gratitude to colleagues in the railway engineering field for their collaboration and contributions in completing this research.

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