Effect of Preheating and Current Variation on the Mechanical Properties of S355J2+N Steel in the GMAW Welding Process

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**Abstract.** The Gas Metal Arc Welding (GMAW) process applied to S355J2+N steel requires precise parameter optimization to ensure high joint quality. This study investigates the effect of 100°C preheating and varying welding currents (170 A, 220 A, and 270 A) on the mechanical properties of S355J2+N steel using ER70S-6 filler metal. The specimens were examined using non-destructive testing methods (magnetic particle inspection and ultrasonic testing) as well as destructive testing (tensile testing and macroetch examination). Results of the magnetic particle inspection indicated that the specimens welded with 170 A and 220 A currents were free from surface defects, while the specimen welded at 270 A exhibited a linear discontinuity measuring 6 mm, which did not meet the AWS D1.1, M:2020 acceptance criteria. Ultrasonic testing revealed sub-surface weld defects due to incomplete fusion at 220 A (60 mm) and 270 A (170 mm). Tensile testing showed that the 170 A current yielded the highest average tensile strength of 540 MPa, while 220 A and 270 A resulted in 529.9 MPa and 527.6 MPa, respectively. Macroetch examination showed that the heat-affected zone (HAZ) width increased with higher current levels: 3.17 mm at 170 A, 4.5 mm at 220 A, and 5.7 mm at 270 A. It can be concluded that the combination of 100°C preheat and 170 A current produced the most favorable mechanical properties.

# INTRODUCTION

Along with the rapid advancement of science and technology, the manufacturing industry has experienced significant growth. This is reflected in the continuous increase in production output over time. In the modern industrial era, construction technology has also undergone extraordinary development, particularly in the design and engineering aspects, which are becoming increasingly complex and high in precision [1]. Innovations in design development not only enhance manufacturing efficiency but also contribute to the creation of superior products that can compete in the global market. The ability of industries to adapt to market demand dynamics heavily relies on the application of the latest technologies, including in the field of metal welding.

Welding is a process of joining two metals by melting part of the base metal and filler metal, either with or without the addition of other metals, to produce a continuous metallic joint [2]. Several fusion welding methods commonly used in industry include Submerged Arc Welding (SAW), Shielded Metal Arc Welding (SMAW), Gas Tungsten Arc Welding (GTAW/TIG), and Gas Metal Arc Welding (GMAW/MIG) [3]. GMAW is one of the most widely applied welding methods in industry due to its ability to produce strong and efficient joints. This process uses a continuously fed filler wire and an electric arc shielded by inert gas, such as argon or helium, to prevent contamination from the surrounding air [4].

Improved weld quality can be achieved through the use of assistive devices designed to substitute the physical functions of the operator, thereby controlling bending deformation, crack propagation, and residual stress. These devices also contribute to the efficiency of post-weld heat treatment by saving labor and energy [5].

Various welding methods such as GTAW, SMAW, and FCAW can be selected based on specific needs. For instance, GTAW utilizes an electric arc between a non-consumable tungsten electrode and the base metal as a heat source, producing high-quality welds free from contamination [6]. Among modern welding techniques, GMAW is considered one of the most innovative. However, despite its efficiency, GMAW still poses risks of defects such as incomplete penetration. To accurately detect such defects, Automated Ultrasonic Testing (AUT) has proven highly effective, particularly for narrow groove welds produced by mechanized welding [7]. Furthermore, GMAW offers cleaner welds with minimal spatter due to the flux-coated filler wire, which maintains arc stability during the process [8].

Preheating is a method used to reduce stress differences between the specimen and the electrode [9]. Preheating before welding aims to reduce the temperature difference in the specimen to prevent weld defects caused by thermal stress during the welding process [10].

One commonly used non-destructive testing (NDT) technique is Magnetic Particle Testing (MPT), which is effective for detecting surface and near-surface defects in ferromagnetic materials [11]. Magnetic Testing (MT) utilizes a magnetic field and fine magnetic particles, such as iron powder, to identify defects in welds or on the surface of metallic components. The effectiveness of this method depends on the ferromagnetic properties of the material, such as iron, nickel, and their alloys, which can be optimally magnetized [12]. Ultrasonic Testing (UT) is another NDT method used to detect defects or imperfections in weld joints or internal structures. This technique works by transmitting ultrasonic waves into the material and analyzing the reflected signals to identify potential discontinuities [13].

Tensile testing is a mechanical testing method that aims to determine the extent to which a material can withstand tensile forces before failure. In this test, a specimen is subjected to axial loading until it fractures, allowing for the evaluation of tensile strength and material behavior under stress [14]. Macroetch examination is a visual inspection method of a material’s surface using direct observation or low-magnification lenses. It aims to identify defects such as cracks, pores, or fractures in brittle metallic structures and evaluate fracture patterns that can be compared with other metallurgical characteristics as needed [15].

This study is designed to explore the effect of preheating and current variation on the results of the Gas Metal Arc Welding (GMAW) process on S355J2+N steel, focusing on changes in the resulting mechanical properties. Through comprehensive analysis, it is expected to gain a deeper understanding of the relationship between welding parameters.

The discussion on preheating and current variation serves as a reference for determining optimal welding parameters to achieve high-quality welds on S355J2+N steel. This study is limited to specific mechanical property tests and a defined range of welding currents, with the ultimate goal of contributing useful findings for the development of more efficient and reliable GMAW welding technologies for manufacturing and construction industries.

# Methodology

This research was conducted in collaboration with a national-scale manufacturing facility located in East Java, Indonesia. All experimental activities, including specimen preparation, welding, testing, and data collection, took place over a period from September 11 to December 22, 2023.

The study employed an experimental design with a quantitative approach to investigate the mechanical properties of S355J2+N structural steel subjected to the Gas Metal Arc Welding (GMAW) process. The welding was performed using a constant preheat temperature of 100°C, while the welding current was varied at three levels: 170 A, 220 A, and 270 A. Evaluation of the welded joints included both non-destructive and destructive testing methods. The non-destructive tests involved magnetic particle testing and ultrasonic testing, while the destructive tests included tensile testing and macroetch examination.

To perform magnetic particle testing, a standard yoke was used along with supporting tools such as a gauss field meter, light meter, pie-shape block, and cleaning materials. The inspection was facilitated by magnetic particle ink and white contrast paint to enhance the visibility of indications on the material surface. Ultrasonic testing was conducted using a flaw detector equipped with straight and angled probes, calibrated through standard blocks, with the aid of couplant material to ensure optimal signal transmission. These methods aimed to detect surface and sub-surface discontinuities in the welded joints.

Tensile testing was conducted using a universal testing machine. The welded plates were cut and machined into standard tensile test specimens. Each specimen was marked and dimensionally verified before testing. The test results provided data on yield strength, ultimate tensile strength, and fracture characteristics. In addition, macroetch examination was conducted by polishing cross-sections of the welds and etching them using a solution of nitric acid and ethanol. This procedure revealed the macrostructure of the weld bead, fusion zone, and heat-affected zone, allowing visual inspection of welding penetration and potential defects.

The research procedure began with a comprehensive literature review related to the GMAW process, mechanical properties of welded joints, and evaluation techniques for welded metals. Based on this review, experimental parameters were determined and adjusted, including the selection of welding current levels and the use of preheating. Welding was then carried out according to the specified procedure, and data were collected systematically for all specimens.

Following welding, the specimens were prepared for testing. Tensile specimens were milled according to standard geometry, while macro specimens were ground and etched for structural observation. Non-destructive tests were applied to all weld samples to ensure integrity and identify potential defects. After completing all tests, the data were analyzed quantitatively to evaluate the influence of welding current variation on the resulting mechanical properties. The findings were compiled in the form of a research report that included a detailed discussion, conclusions, and recommendations for future studies.

# Results and Discussion

## Magnetic Particle Inspection Results

Magnetic Particle Inspection (MPI) was carried out to detect surface discontinuities on the material. Table 1 presents the results of the MPI for S355J2+N steel welded using the GMAW method at currents of 170 A, 220 A, and 270 A.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **TABLE 1.** Magnetic Particle Inspection Report. | | | | | |
| **No** | **Material** | **Current (A)** | **Thickness (mm)** | **Evaluation** | **Remarks** |
| 1 | S355J2+N | 170 | 12 | √ Accepted | - |
| 2 | S355J2+N | 220 | 12 | √ Accepted | - |
| 3 | S355J2+N | 270 | 12 | √ Repaired | Linear Indication (LI) |

Based on the MPI results, no welding defects were detected on the surface of specimens welded at 170 A and 220 A using ER70S-6 electrodes. These specimens meet the acceptance criteria specified in AWS D1.1 M:2020. However, at 270 A, a linear discontinuity measuring 6 mm was found on the surface, which failed to meet the standard acceptance criteria.

## Ultrasonic Test Results

Ultrasonic testing was used to detect internal weld discontinuities. At 170 A, no defect indications were detected in the weld joint, signifying complete fusion and acceptable weld quality. However, the specimen welded at 220 A revealed an internal defect of incomplete fusion measuring 60 mm in length and located at a depth of 11.1 mm from the surface, with a distance of 6 mm from the Y-axis. A similar type of defect was also detected in the 270 A specimen, with an even larger length of 170 mm and located at a depth of 9.8 mm and 10 mm from the Y-axis. These findings indicate that increasing the welding current leads to more significant internal flaws, possibly due to overheating, turbulence in the weld pool, or inadequate fusion between the filler metal and the base material. Both the 220 A and 270 A welds were categorized as Class A defects and required repair actions. These results confirm that the 170 A current provided the most stable and defect-free welding condition.

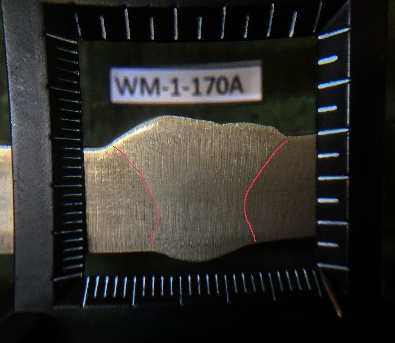
## Tensile Test Result

The tensile test was conducted to evaluate the mechanical performance of the welded joints. As shown in Fig. 2, the highest average ultimate tensile strength (UTS) was achieved by the specimen welded at 170 A, reaching 540 MPa. The specimens welded at 220 A and 270 A produced slightly lower UTS values of 529.9 MPa and 527.6 MPa, respectively. The decrease in tensile strength at higher current levels is attributed to the presence of internal defects and excessive heat input, which could cause grain coarsening or structural inconsistencies within the weld zone. These results support the notion that excessive current, while potentially improving penetration, negatively impacts the mechanical integrity of the weld.

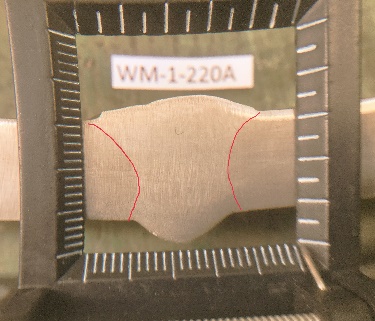
**Figure 2.** Effect of welding current variation on average tensile strength of welded joints.

## Macroetch Examination

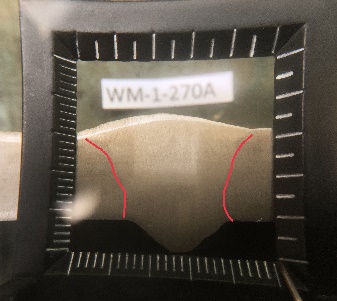
Macroetch examination revealed that the variation in welding current significantly affects the dimensions of the capping and root, while preheating influences the width of the Heat-Affected Zone (HAZ). Observational results are shown in Figs. 3 to 5.

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**Figure 3.** Macroetch Result – 170 A.



**Figure 4.** Macroetch Result – 220 A.



**Figure 5.** Macroetch Result – 270 A.

As shown in the images, no welding defects were observed in all specimens at 170 A, 220 A, and 270 A. Therefore, all macrostructures comply with the acceptance criteria defined in AWS D1.1 Section 6.10.4.1 (2020). The measured HAZ widths on both sides of each specimen are shown in Fig. 6.

**Figure 6.** HAZ Width vs. Welding Current.

Figure 6 clearly indicate that increasing welding current leads to a wider HAZ. At 170 A, the average HAZ width is 3.17 mm; at 220 A, it increases to 4.5 mm; and at 270 A, it reaches 5.7 mm. This trend aligns with the findings of Bagaskoro (2018), who reported a direct relationship between heat input and HAZ width, with current being a major factor influencing heat input in welding processes.

# CONCLUSION

Based on the experimental investigation conducted on S355J2+N steel welded using the Gas Metal Arc Welding (GMAW) process, it can be concluded that welding current significantly influences both the weld quality and the mechanical performance of the joint. Among the three current variations tested (170 A, 220 A, and 270 A), the 170 A current produced the most favorable results. Penetrant and ultrasonic testing confirmed the absence of both surface and internal defects at this current, while tensile testing showed the highest average ultimate tensile strength of 540 MPa. In addition, macroetch examination revealed that the 170 A specimen exhibited the narrowest heat-affected zone, indicating minimal thermal degradation. In contrast, higher welding currents (220 A and 270 A) resulted in the presence of internal defects, reduced tensile strength, and broader heat-affected zones, suggesting excessive heat input and unstable weld pool behavior. Therefore, it is recommended to use a welding current of 170 A for optimal weld quality when joining S355J2+N steel under the specified preheat conditions.

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