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Toughness and Structural Analysis of Welds and HAZ of Sumerged Arc Welding on SM 490 Steel

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ABSTRACT

The welding process is a metal joining method that utilizes high heat energy, which can trigger changes in the microstructure, deformation, and the emergence of residual stress in the area around the joint. This study aims to examine the impact of variations in heat input in the Submerged Arc Welding (SAW) process on the microstructure and toughness of SM 490 steel, especially in the weld area and heat-affected zone (HAZ). The SAW method was chosen because it has high efficiency, is easy to automate, and is able to produce good quality joints. This study used three levels of heat input, namely 2.1 kJ/mm, 3.16 kJ/mm, and 4.3 kJ/mm. Based on the test results, increasing heat input causes slower cooling, which affects the formation of microstructures such as ferrite at the grain boundary, acicular ferrite, Widmanstätten ferrite, bainite, and martensite. Acicular ferrite with fine size and interlocking pattern is known to contribute to increasing the toughness of welded joints. The maximum toughness in the weld zone, amounting to 117 Joules, was achieved at a heat input of 3.16 kJ/mm with a test temperature of 0°C. Meanwhile, the best toughness value in the HAZ of 17.5 Joules was recorded at a heat input of 2.1 kJ/mm at a temperature of -20°C. The results of this study confirm that appropriate heat input settings are very important to obtain optimal microstructure and toughness in welding SM 490 steel using the SAW method.

KEY WORDS:. *Submerged Arc Welding (SAW), Heat Input, Microstructure, Toughness, SM 490 Steel*

1.0 INTRODUCTION

Welding is a technique for joining two or more metal parts using heat energy. This process causes changes in the metallurgical structure, deformation, and the emergence of thermal stress in the area around the weld joint. To minimize these negative impacts, it is very important to apply appropriate welding methods and procedures, including the selection of the right filler material. According to Cary [1], welding is widely used because of its relatively low cost, fast and simple implementation process, and allows for more flexible construction designs. Despite its various advantages, welding also has disadvantages, such as the emergence of high stress due to changes in the microstructure around the weld area, which can reduce the strength of the material. In addition, welding can also cause residual stress and the potential for cracks in the joint.

The welding process using the Submerged Arc Welding (SAW) method, also known as submerged arc welding, is carried out on the principle where the molten metal is covered by a layer of flux that flows through a certain cross-section. In this process, the flux and solid filler wire are supplied continuously, allowing the welding process to take place automatically, efficiently, and easily operated with a high level of reliability [2].

Due to its process characteristics, this welding method allows for automation, ease of operation, and produces reliable joints. In steel construction applications, such as bridges and pressure vessels, welded joints must meet stringent quality standards. Among these, the material's tensile strength and toughness must be at a high level, reaching at least 27 Joules at –50°C or 100 Joules at 0°C [3].

This toughness standard can be achieved if the weld metal microstructure is dominated by acicular ferrite. Based on the opinion of Harisson and Farrar [4], this type of ferrite is able to increase the tensile strength of the weld joint because it has fine-sized grains, while high toughness is obtained from the interlocking structure pattern between the grains.

1.1 Background

In the construction and manufacturing sectors, metal joining is a crucial step that plays a significant role in determining the strength and durability of a structure. Submerged Arc Welding (SAW) is a widely used method for joining metals, particularly in heavy structures such as bridges, high-rise buildings, and piping systems. This method is widely used because it is efficient, easily automated, and capable of producing high-quality joints.[1].

However, the welding process not only joins metals but also causes changes in their microstructure due to the high temperatures generated during welding. These changes are particularly visible in the weld zone and the heat-affected zone (HAZ), and can impact the overall toughness and mechanical properties of the metal. Therefore, it is important to understand how the microstructure and toughness of the material around the weld zone change to maintain the quality of the joint. [2].

One of the materials commonly used in heavy construction is SM 490 steel. This low-carbon steel boasts good mechanical properties, but it still faces the risk of performance degradation due to the heat of the welding process, particularly in the HAZ. This study aims to examine how variations in heat input during the SAW process can affect the microstructure and toughness of SM 490 steel, particularly in the weld zone and HAZ. By understanding this, the research results are expected to contribute to the development of more effective and safe welding procedures for this material [3].

1.2 Submerged Arc Welding (SAW)

Submerged Arc Welding (SAW) is an automated welding method in which the electric arc and molten metal are protected by a layer of powdered flux, while filler wire is continuously supplied. The heat transfer efficiency in this process is very high, reaching around 90%, because only a small amount of heat is lost through radiation [2].

1.3 Flux

Flux is a powder-like material that forms a slag layer to protect molten metal from exposure to the surrounding air. Furthermore, flux also plays a role in maintaining the stability of the electric arc, acting as a deoxidizing agent, producing shielding gas, reducing sparks and vapors during the welding process, and contributing alloying elements to the weld metal. The acidity or basicity of a flux can be determined through the Basicity Index (BI), which indicates the character of the flux. The BI value is categorized as follows: the flux is acidic if the BI is <1, neutral if it is between 1 and 1.5, semi-basic for the range of 1.5 to 2.5, and basic if the BI is more than 2.5.

1.4 Heat Input

Heat input is the amount of heat energy per unit length of the weld when the heat source is moving. Heat input (H) is expressed by the following equation [1]:

$$H = P/v = EI/v \tag{1}$$

where:
P: Input power (watts)
E: Electric potential (volts)
I: Electric current (amperes)
v: Welding speed (m/s)

Heat input also affects the weld cross-sectional shape (bead-on-plate), which includes the size of the molten parent metal surface, the filler material surface, and the HAZ.
The primary function of the heat source in fusion welding is to melt the metal, which has two effects: the formation of the weld microstructure and the thermal cycle of the weld zone, each of which is explained below.

1.5 Thermal Cycle of Weld Area

During welding, the weld metal and heat-affected zone (HAZ) undergo a series of thermal cycles, namely heating to a maximum temperature followed by cooling. This thermal cycle affects the microstructure of the weld metal and HAZ, where the weld metal undergoes a series of phase transformations during the cooling process, changing from liquid weld metal to δ-ferrite, then γ (austenite), and finally to α (ferrite). Generally, the cooling time between 8000°C and 5000°C is used as a reference for welding carbon steel, because during this temperature range, the phase transformation from austenite (γ) to ferrite or bainite occurs, depending on the cooling rate. The cooling time can be calculated using the following equation [1]:

$$\Delta t_{8/5} = \frac{q/v}{2\pi k}\left[\frac{1}{500 - T_0} - \frac{1}{800 - T_0}\right] \tag{2}$$

Where:
ΔT8/5: Cooling time between 800 0C and 500 0C
T0: Final weld temperature (0C)
q: Heat input (kJ/mm)
v: Welding speed (mm/s)
k: Thermal conductivity (J/mm s-1 K-1)

1.6 Weld Micro

During the cooling process from a liquid state to room temperature, the welded metal undergoes various phase changes. In low-carbon steel (with a carbon content below 0.1%), these changes begin from the liquid phase to Ferrite δ upon solidification, then transform into Austenite γ, and finally to Ferrite α and Pearlite. The type of microstructure formed is determined by the cooling characteristics that occur. Factors such as the final composition of the weld metal, the type of filler metal, and the environmental conditions during welding also influence the formation of the microstructure.

Cooling during the welding process occurs gradually (continuously), without a drastic decrease in temperature. Based on research by Abson and Pargeter (1986), several types of microstructures can emerge as a result of the welding process, namely:

1. Proeutectoid Ferrite, including grain boundary ferrite and polygonal ferrite within grains, forms at temperatures between 1000–650°C.
2. Widmanstatten Ferrite, or ferrite with an ordered second phase, forms in the temperature range of 750–650°C.
3. Acicular Ferrite grows within austenite grains at temperatures around 650°C.

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4. Bainite forms at temperatures of 400–500°C.
5. Martensite forms when the cooling rate is very high.

Generally, the cooling process after welding is rapid, so the use of phase diagrams cannot accurately depict the microstructural transformations that occur. This is because phase diagrams are only relevant for slow-cooling conditions where atomic diffusion still occurs. Therefore, to more accurately understand and analyze the microstructure of the weld, a Continuous Cooling Transformation (CCT) diagram is used.

2.0 RESEARCH METHODOLOGY

The material used in this study was SM 490 with a thickness of 20 mm, which has a tensile strength of 490–610 N/mm2 and a yield strength of 325 N/mm2. The welding process used the SAW method with an EH 14 φ 4 mm electrode and CHF 101 flux (by Atlantis), with heat inputs of 2.1 kJ/mm, 3.16 kJ/mm, and 4.3 kJ/mm. To determine the toughness of the material, impact testing was conducted. The specimen shape and size conformed to ASTM standards [5], as shown in Figure 1. The chemical compositions of the base metal, filler, and flux are shown in Tables 1, 2, and 3.

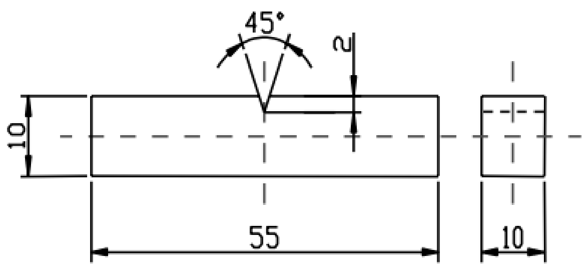

Figure 1; Impact Test Specimens as per ASTM E23-96 [5]

Table 1: Base Metal Chemical Composition (wt%)

C	Mn	S	P	Ni	Cr
0.146	0.321	0.022	0.012	0.021	0.031

Table 2. Welding Electrode Chemical Composition (wt%)

C	Mn	Si
0.1	1.9	0.2

Table 3. Flux Chemical Composition (wt%)

C	Mn	S	P	Ni	Cr
0.12	1.5–1.9	0.035	0.035	0.31	0.2

3.0 RESULT

During slow cooling, ferrite begins to form at the tips and along the austenite grain boundaries, then grows inward toward the austenite grains. Ferrite formed at these grain boundaries is known as grain boundary ferrite, and its formation occurs through a carbon diffusion mechanism. This ferrite grows from the austenite grain boundaries inward in the form of elongated plates. Meanwhile, acicular ferrite growth is supported by a high density of nucleation points. Inclusions play a role in facilitating the growth of acicular ferrite, which has a needle-like shape with random orientation. As the cooling rate increases, carbon becomes difficult to diffuse into the austenite, resulting in the formation of a bainite microstructure, a combination of ferrite and cementite (Fe3C).

Bainite is divided into two types: upper bainite and lower bainite. Upper bainite consists of ferrite growing from the austenite grain boundaries in the form of plates, with Fe3C located between the ferrite plates. Meanwhile, in lower bainite, Fe3C is found within the ferrite in the form of plates. if the cooling rate is very fast, the transformation occurs without carbon diffusion, resulting in martensite. To obtain an optimal weld microstructure, the alloy composition, cooling time, and austenite grain size must be precisely controlled [6]. The microstructure of the weld area is showed as Figure 2.

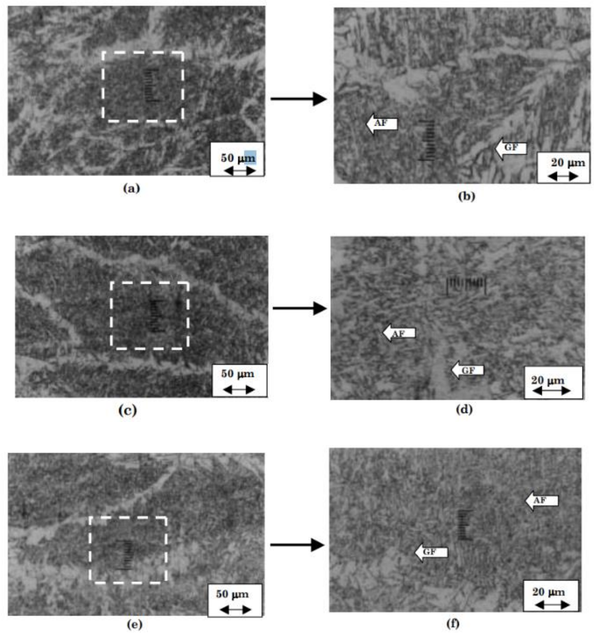

Figure 2; Microstructure of the Weld Area [6]

Description:
(a), (b) welding results with a heat input of 2.16 kJ/mm,
(c), (d) welding results with a heat input of 3.4 kJ/mm,
(e), (f) welding results with a heat input of 4.3 kJ/mm
AF: Acicular Ferrite
GF: Grain boundary Ferrite

Meanwhile, the microstructure of the HAZ region can be seen in Figure 3

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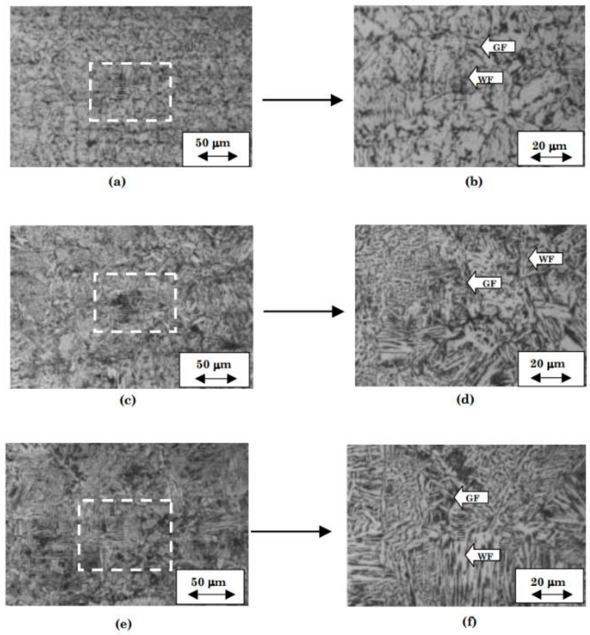

Figure 3: Microstructure of HAZ Region [6]

Description:
(a), (b) welding results with a heat input of 2.16 kJ/mm,
(c), (d) welding results with a heat input of 3.4 kJ/mm,
(e), (f) welding results with a heat input of 4.3 kJ/mm
AF: Acicular Ferrite
GF: Grain boundary Ferrite
WF: Grain boundary Ferrite

Load conditions ensures that efficiency is not sacrificed for performance, or vice versa. Responsive speed adjustments can also reduce mechanical stress on conveyor components, potentially extending the equipment's lifespan and reducing long-term maintenance costs.

4.0 DISCUSSION

4.1 Result Microstructure

The purpose of microstructural observations is to determine the shape, distribution, and size of grains in the weld area and heat-affected zone (HAZ). The microstructure of the weld is influenced by various factors, such as the amount of heat input, electric current, the type of welding wire (filler) and flux used, the welding speed, and the cooling rate.

The impact of heat input on the microstructure of the weld metal can be seen in Figure 2. Figures 2a and 2b show that the microstructure formed is dominated by grain boundary ferrite and acicular ferrite, which form due to the relatively rapid cooling process. Figures 2c and 2d show an increase in the amount of acicular ferrite, although grain boundary ferrite remains quite high, indicating a slower cooling process.

Meanwhile, Figures 2e and 2f show a more dominant amount of acicular ferrite, caused by the increased heat input that supports its formation. In the HAZ area with a heat input of 2.16 kJ/mm, a finer columnar structure and a smaller amount of Widmanstätten ferrite are seen, due to the faster cooling process (Figure 3a). Conversely, at a heat input of 4.3 kJ/mm, the microstructure is dominated by Widmanstätten ferrite and the columnar formed is larger (Figure 3e).

4.2 Toughness

Impact testing aims to determine the toughness of the weld zone. Toughness testing is conducted at temperatures of -60°C, -40°C, -20°C, 0°C, 20°C, and 60°C. Impact testing shows that the amount of heat input affects the weld toughness. The results of the impact toughness test on the weld zone show that variations in testing temperature significantly affect the toughness of the welded joint. Weld Area Impact Test Results can be seen in Figure 4, while HAZ Area Impact Test Results can be seen in Figure 5.

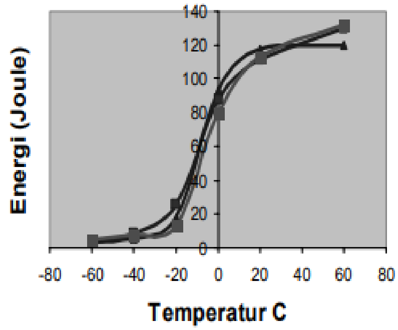

Figure 4: Weld Area Impact Test Results [6]

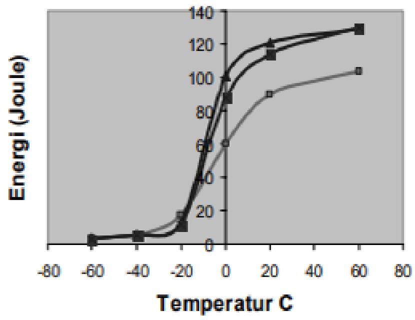

Figure 5: HAZ Area Impact Test Results [6]

Test results show that the lower the test temperature, the lower the toughness value of the welded joint, and the higher the test temperature, the higher the toughness value. At the lowest test temperature, heat input had relatively little effect on weld toughness, as the curve showed very little change. The transition temperature occurred at -10°C, with the highest toughness achieved at a heat input of 2.16 kJ/mm³, or 50 joules. The highest toughness was achieved at a heat input of 3.14 kJ/mm³, or 117 joules. The highest toughness in the HAZ at the transition temperature of -20°C was achieved at a heat input of 2.16 kJ/mm³, or 17.5 joules.

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Improving the mechanical performance of the Heat-Affected Zone (HAZ) requires the optimization of welding parameters, appropriate selection of filler materials, controlled cooling rates, and the application of suitable pre- and post-weld heat treatments to enhance microstructural stability and reduce residual stresses.

A. Before Welding

1. Selecting the Right Material
2. Choose a base metal that is resistant to brittle formation during rapid cooling (for example, steel with a medium to low carbon content).
3. Preheating
4. This is done to reduce the cooling rate after welding, thereby preventing the formation of brittle martensite in the HAZ. The preheat temperature depends on the material type (e.g., medium carbon steel is typically heated to 100–200°C).
5. Selecting the Right Welding Wire and Current
6. Use a filler metal that is compatible with the base metal and provides a good transition between the weld and the HAZ.
7. Use the correct welding current to avoid excessive heat input.
8. Joint Design and Welding Process
9. Use step or multi-pass welding techniques to control heat input and choose a stable and controllable welding method (e.g. GTAW/TIG for precision).

B. During Welding

1. Heat Input Control (Heat Input)
2. Do not make it too high as it can cause coarse grains and reduced toughness in the HAZ.and do not use too low as this can cause rapid cooling and martensite formation.
3. Inter pass Temperature Control (Inter-layer temperature)
4. If multi-pass welding, keep the temperature between layers not too high to avoid excessive expansion of the HAZ.

C. After Welding

1. Post Weld Heat Treatment (PWHT) / Heat Treatment After Welding
2. Performed to eliminate residual stress and improve the HAZ microstructure and can soften the martensite structure or form a tougher bainite structure.
3. Non-Destructive Testing (NDT)
4. Perform inspections (such as ultrasonic, radiography, penetrant test) to ensure there are no cracks in the HAZ.
5. Controlled Cooling
6. Avoid sudden cooling (e.g., with water or in cold air), as this can form a brittle structure.

5.0 CONCLUSION

In general, heat input affects the toughness value and microstructure of the weld area and HAZ of SM 490 steel. At a heat input of 2.1 kJ/mm, the optimal toughness value is 50 joules at a transition temperature of -10 0C. This is due to the higher acicular Ferrite frequency. At a heat input of 4.3 kJ/mm, the smallest is due to the slowest cooling rate, resulting in a microstructure dominated by grain boundary Ferrite. For the HAZ area, an increase in heat input causes an increase in the percentage of Widmanstanten Ferrite.

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