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Effect of Heat Input on Microstructure and Mechanical Properties of Submerged Arc Welded SM570-TMC Steel

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Abstract. SM570TMC is high-strength steel (HSS), which is commonly used in structures that require higher-strength components. In this research, submerged arc welding (SAW)-welded SM570 TMC steels' microstructure and mechanical characteristics were examined. SM570 plates with 12mm thickness were multi-pass welded by using a 3.0 mm diameter of ESAB OK Autrod 13.40 (AWS A5.23: EG) filler metal. The joint design is a single V multi-pass butt weld with a backing strip. Two welded joints were prepared by using heat inputs of 2.2 and 2.9 kJ/mm. The microstructures of two welded joints were observed by using optical microscopy and scanning electron microscope (SEM). Hardness tests were performed in the weld metal, heat-affected zone, and base metal. The mechanical properties of welded joints were assessed using the tensile test and Charpy V notch impact test in HAZ and weld metal areas. The result showed that the strength of joints is satisfactory with no fracture in weld metal while the impact energy of weld metal and HAZ is acceptable for lower temperature application.

Keywords: Mechanical properties; Microstructure; SAW; SM570-TMC; TMCP

1. Introduction

High-strength low-alloy steel (HSLA), also known as micro-alloyed steel, is increasingly used in many technical sectors due to its advantageous mechanical properties and comparably inexpensive cost to mild steel. It also provides many favorable properties, such as better ductility and weldability and higher impact toughness than conventional carbon steel (Nugraha & Mochtar 2023; Igi & Miyake 2021). The application of HSLA in the construction field makes it possible to design lightweight structures, which means less material consumption and lower fabrication and erection costs (Igi & Miyake 2021; Kah, Layus & Ndiwe 2022).

SM570-TMC is a Japanese standard HSLA steel that is frequently employed in welded structural applications (JIS, 1999). The thermo-mechanical control process (TMCP) is what makes this steel product. TMCP is an advanced manufacturing technology to strengthen steel through microstructural refinement, which consists of two stages: controlled rolling and accelerated cooling (Hu et al. 2014). These stages can produce a fine microstructure of steel that results in excellent combinations of strength, toughness, and weldability (El-Shenawy & Reda 2019; Roccisano et al. 2021). Besides regular alloying elements (Cr, Ni, Mo, Cu, etc.), some micro-alloying elements (Nb, V, Ti, and B) are added to enhance the strength and toughness by hindering grain growth during the reheating process of TMCP (Zhu et al. 2022; Igi & Miyake 2021; Yang et al. 2022; Fatriansyah et al. 2023). TMCP uses fewer alloying elements than conventional steel, which

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reduces the carbon equivalent of steel to improve weldability in a high-input welding process (Donizete Borba et al. 2017).

Fusion welding is a joining method that is frequently used to fabricate metal products. Heat input during the welding process may lead to the transformation of microstructure, residual stress, and weakening of strength and toughness (Donizete Borba et al. 2017; Tong et al. 2018). However, welding with a high input is preferable to meet the production requirements, especially for welding heavy and thick plates (Donizete Borba et al. 2017). Therefore, it is important to qualify the mechanical properties of welded joints to prevent any failure, which costs money and lives. The Charpy v-notch impact test and the tensile test are frequently used to evaluate the mechanical characteristics of welded joints. AWS D1.1 authorizes impact testing in the weld metal and at numerous locations in the heat affected zone (HAZ) (AWS 2020).

Changes in the microstructure and mechanical characteristics of weld metal are influenced by heat input and chemical content. Selection of proper welding parameters should be made to meet the quality requirements. For low-temperature operation, it is essential to maintain the higher toughness of welded steel to prevent brittle fracture (Lee, Shin & Park 2012; Kah, Layus & Ndiwe 2022). The addition of nickel element can enhance the low temperatures toughness of steel weld metal (Bhole et al. 2006; Wang et al 2018). Nickel contributed as a nucleation site for acicular ferrite which improves the impact toughness of steel. Pamnani et al. 2016 studied the impact toughness of HSLA steels welded by different arc welding methods. They proposed that grain size, chemical composition, inclusion content, and acicular ferrite all affect the weld metal's toughness at low temperatures.

Previous work has been done to study the SM570-TMC welded joint behaviour at low temperatures. Lee, Shin & Park 2012 investigated the applicability of SM570-TMC in cold regions. They reported that welding parameters and weld metal composition should be chosen properly. Oktadinata, Winarto, & Siradj 2020 studied the influence of heat input on the microstructure and impact toughness of SM570-TMC plates welded by flux cored arc welding (FCAW) method. They suggested that the impact toughness of weld metal showed a satisfactory result for low-temperature operation. Winarto et al. (2020) studied the effect of different nickel contents of weld metal on the impact toughness of SM570-TMC welded joint. They concluded that additional nickel element increased the low-temperature toughness of the weld metal.

Submerged arc welding (SAW) is another welding method commonly used to fabricate heavy plates, considering its welding speed and ability to weld thicker plates (Donizete Borba et al. 2017; Kah, Layus & Ndiwe 2022). A higher heat input welding process than FCAW will affect the microstructural changes in the weld metal and HAZ. In this study, experimental work was carried out using the SAW method to evaluate the effect of heat input variations on the microstructures and mechanical properties of SM570-TMC. The microstructures were observed by using optical microscopy (OM) and scanning electron microscopy (SEM), while mechanical properties were measured using a tensile testing machine, hardness tester, and impact tester in the weld metal and HAZ area. The mechanical properties of these joints will determine the applicability of SM570-TMC in low-temperature environments.

2. Methods

2.1. Materials and Welding Design

Two plates of SM570-TMC steel with dimensions of 400 x 200 x 12 mm were prepared for this experiment. The chemical composition of base metal was measured by using optical emission spectroscopy (OES) and presented in Table 1. The carbon equivalent calculation for SM570 TMC is 0.34. Based on this result, preheat is not applied. The joint design is a 30^{o}-single V groove with a 5mm root gap. The grooves were machined, and a backing strip was tack welded to avoid the leakage of the molten metal.

The filler metal selected in this experiment is ESAB OK Autrod 13.40 (AWS A5.23: EG) with a 3 mm diameter, which is frequently used to fabricate HSLA steel with minimum tensile strength up to 620 MPa. The chemical composition of filler metal is represented in Table 2. The filler metal contains nickel and molybdenum elements to achieve a good strength and toughness combination (Bhole et al. 2006; Wang et al. 2018). Ni contributes to the nucleation site for acicular ferrite microstructure. The flux used in this work is ESAB OK 10.62 (AWS A5.23 standard).

Table 1 Base metal chemical composition (wt%)

Material	C	Si	Mn	P	S	Ni	Mo	Nb	V	Ti	$C.E_q$
Base metal	0.07	0.36	1.61	0.009	0.002	0.005	0.002	0.05	0.04	0.02	0.34

Table 2 Filler metal Esab OK Autrod 13.40 chemical composition (wt%)

Materials	C	Si	Mn	Ni	Mo
Filler Metal	0.11	0.16	1.63	0.86	0.51

Table 3 exhibits the parameters used in this work. Two weldments were welded using the submerged arc welding (SAW) method with two variable heat inputs, low heat input of 2.2 kJ/mm (designed as LI), and a high heat input of 2.9 kJ/mm (designed as HI). The experimental setup and the welded joints are presented in Figure 1. After the completion of welding, a radiographic test was performed to visualize the welding quality.

Table 3 Welding parameter

Weldments	Current (A)	Voltage (V)	Speed (mm/min)	Heat Input (kJ/mm)	Number of Passes	Preheat Temperature (°C)
HI	442	29.1	266	2.9	4	NA
LI	355	27.5	266	2.2	4	NA

Figure 1 The experimental setup (left) and the welded joints (right)

2.2 Metallography and Mechanical Testing

The metallographic specimens were cut from the weldments of LI and HI for microstructure examination. To examine the fusion line and microstructure of weld metal and HAZ, the specimens were ground and polished using standard metallographic procedures before being etched using 3% Nital. Metallography analysis was then observed using optical microscopy (OM) on the Leica DM1750M and scanning electron microscopy (SEM).

To measure the mechanical properties of welded joints, tensile tests, Charpy V-notch tests (CVN), and hardness tests were carried out. The tensile test is done to measure the strength of the welded joint by following the ASTM E8 standard. Two specimens were prepared from each weldment. By using the Tinius impact tester, the CVN test measured the impact energy. The specimen size is 55 x 10 x 10 mm with a notch depth of 2 mm following the ASTM E23 standard. For low-temperature testing, the specimens were cooled using a cooling box containing methanol. The tests were performed at 25, 0, and -20 °C, with two specimens at each temperature. The distribution of Hardness in the weld metal, HAZ, and base metal was measured by using a Vickers microhardness tester with a 30 kgf load.

3. Results and Discussion

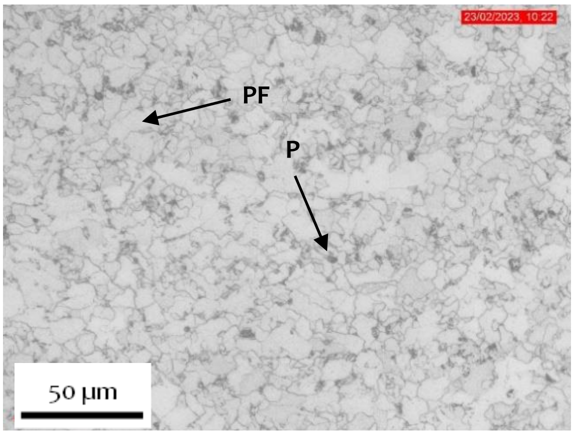
3.1. Chemical and Microstructural analysis

The chemical composition was determined by using optical emission spectroscopy (OES). The result of the measurement is presented in Table 4, which is the average value of 3-point measurements. The Ni and Mo content in the weld metal is 0.66 and 0.35, slightly lower than listed in the filler metal composition 0.86 and 0.51 respectively.

Tabel 4 Chemical composition of weld metal (wt%)

Materials	C	Si	Mn	P	S	Ni	Mo	Nb	V	Ti
Weld metal	0.06	0.24	1.47	0.015	0.001	0.66	0.35	0.02	0.02	-

The microstructure of base metal consists of polygonal ferrite (PF) and pearlite where the fraction of ferrite is greater than pearlite as presented in Figure 2. Base metal grain size is fine because of the TMCP process during steel production. The material is processed by heating the steel slab at a temperature range of 1000-1200 °C to dissolve the micro-alloying element and continued by controlled rolling in recrystallization temperature and accelerated cooling to room temperature (Hu et al. 2014; Fatriansyah et al. 2019; Roccisano et al. 2021). This results in the fine microstructure of TMCP steel.



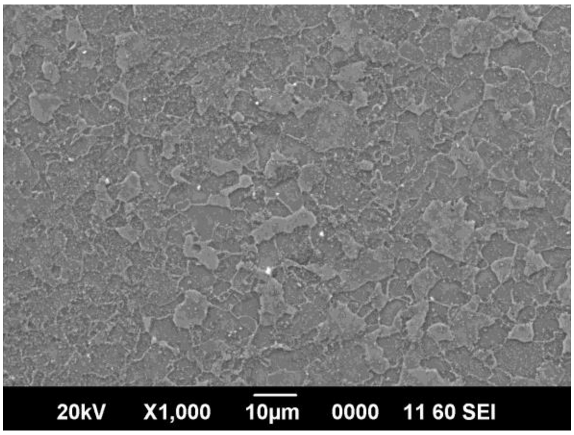
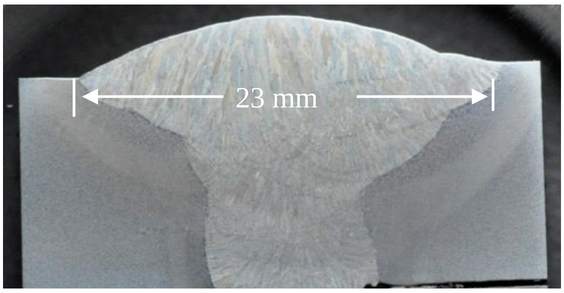


Figure 2 Microstructure of SM570 TMC (Base metal), OM 500X (left) and SEM 1000X (right)

The macro-analysis of weldment is shown in Figure 3 while the microstructure of weld metal and HAZ is shown in Figure 4 and Figure 5 respectively. The microstructure of weld metal is finer than base metal for both LI and HI. It can be seen from Figure 4 that the microstructure of both weld metals consists of acicular ferrite (AF), grain boundary ferrite (GBF), and ferrite side plates (FSP). AF is good for toughness while GBF and FSP are detrimental to strength and toughness (Pamnani et al. 2016; Wang et al. 2018). Weld metal HI has more grain boundary ferrite than weld metal LI. The microstructure of the HAZ areas is coarser than base metal and weld metal. This is attributed to the excessive heating during the welding process that leads to grain growth. The microstructure in both heat inputs consists of acicular ferrite and polygonal ferrite. The microstructure analysis was also performed via scanning electron microscopy, as presented in Figure 6. More voids in the microstructure of HI weld metal may result from the higher heat input. This may result in the deterioration of weld metal toughness.



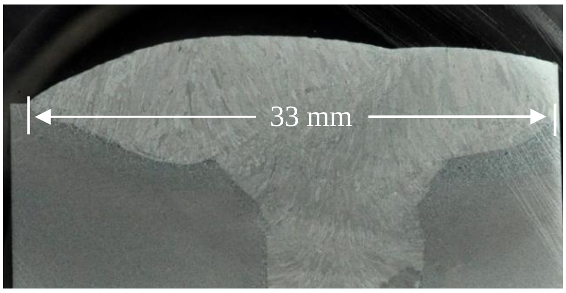


Figure 3 Macrograph of the welded joint, LI (left) and HI (right)

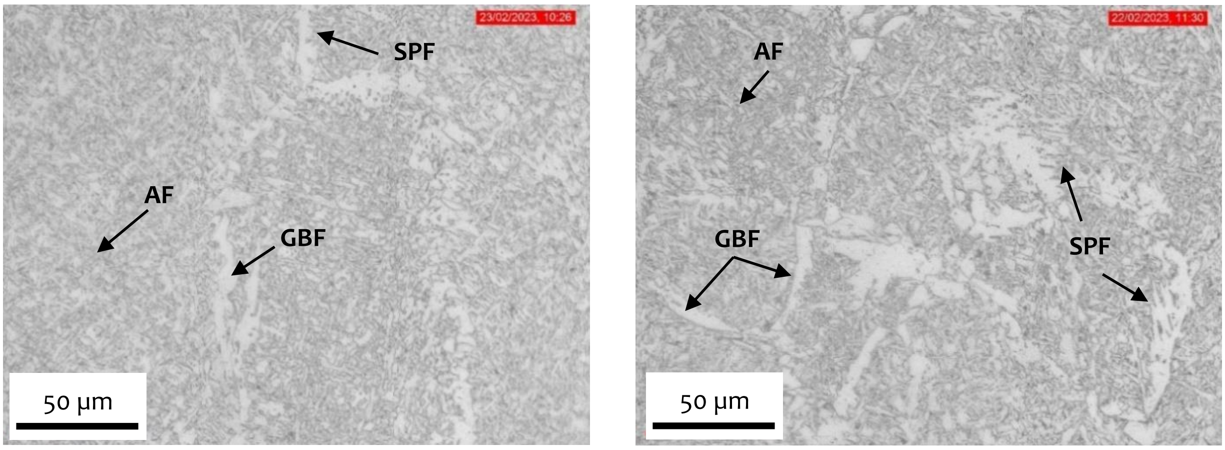


Figure 4 Optical micrograph of the weld metal, LI (left) and HI (right) 500X.

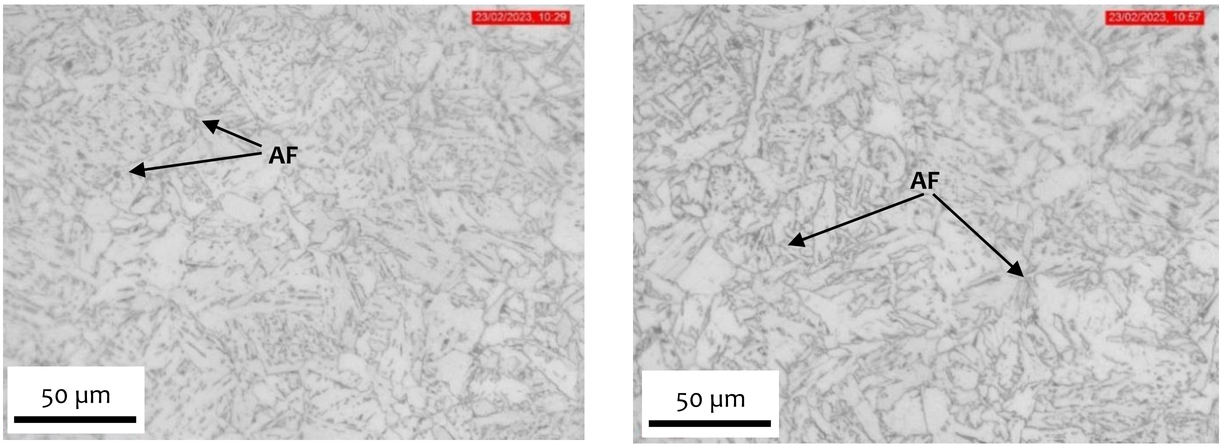


Figure 5 Optical micrograph of HAZ, LI (left), and HI (right) 500X.

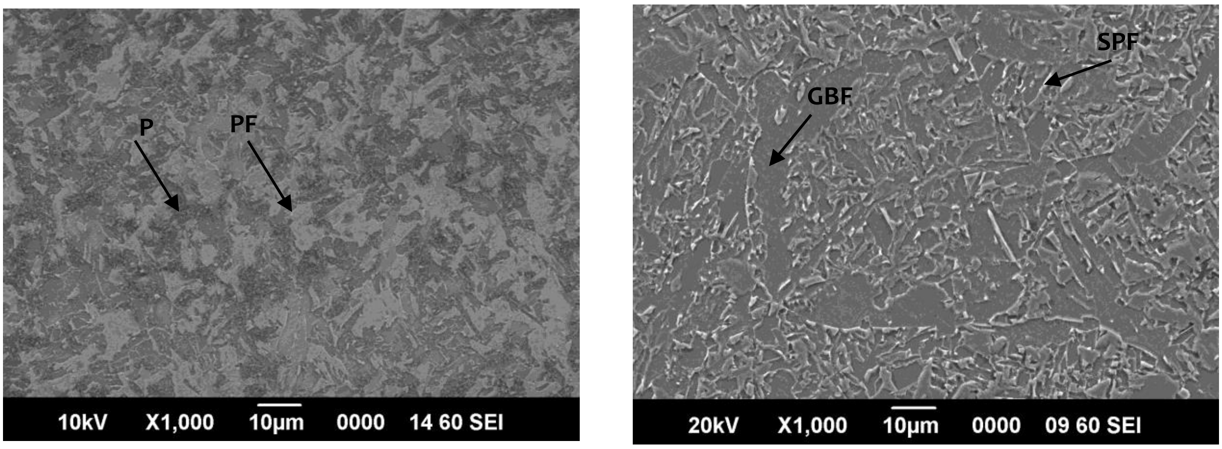


Figure 6 SEM micrograph of the weld metal, LI (Left) and HI (Right) 1000X.

3.2 Mechanical Tests Result

The average hardness of SM570-TMC weldments is presented in Table 5. The hardness value is the average of the three measurements. The highest hardness value is found in the weld metal area, while the hardness in HAZ and base metal is almost the same.

Table 5 Hardness distribution measurement result

Weldment	Base Metal (HV)	HAZ (HV)	Weld Metal (HV)
LI	201.5	201	235.5
HI	187.5	183	213.5

For the tensile test, two specimens were tested for each HI and LI, following the ASTM E8 standard. Tensile test results are presented in Table 6. The fracture surface showed the cup and cone profile that indicated the ductile fracture. No failure occurred at the welded joint, confirming that the quality of the welded joints is acceptable.

Table 6 Tensile properties of SM570-TMC welded Joints

Tensile Specimen	TS (N/mm^2)	YS (N/mm^2)
LI1	627	523
LI2	627	531
HI2	609	490
HI2	609	557

The impact energy of weld metal and HAZ is shown in Figure 7. Base metal impact energy is also presented as a comparison. The toughness of the material decreased following the decrease in testing temperature. The impact energy of weld metals both HI and LI were lower than the base metal. The toughness of LI weld metal is slightly lower than HI weld metal. The average impact toughness of LI weld metal is 200 J at 25°C, 158 J at 0 °C, and 125 J at -20 °C while the impact energy of HI weld metal is 228 J at 25°C, 161 J at 0 °C, and 139 J at -20 °C. These impact energy results are lower than the previous work done by Winarto et al. 2020. Compared to the base metal, the impact energy of weld metal decreased significantly in all testing temperatures. This is caused by the micro-void that exists in the weld metal.

Table 7 Impact toughness of SM570-TMC SAW welded joints.

Specimens	Testing Temperature (°C)		
	-20	**0**	**25**
BM	244	260	332
WM-LI	125	158	200
WM-HI	139	161	228
HAZ-LI	122	173	195
HAZ-HI	123	165	211

For HAZ impact toughness, the HAZ HI is superior at room temperature to HAZ LI with the impact energy 211 J and 195 J respectively. However, both showed almost the same impact energy at -20 °C, 123 J for HAZ HI and 122 J for HAZ LI. Like weld metal toughness, the impact energy of HAZ also showed deterioration that is because of coarse grain size. The coarsening grain size in HAZ is resulted from excessive heat during the welding process. The coarse microstructure led to deterioration of tensile strength and impact toughness due to less grain boundary. Grain boundary is beneficial for hindering dislocation movements.

4. Conclusions

- The application of SAW welding method was an effective way to join SM570-TMC steel plates with satisfactory result on mechanical properties.
- Weld metal showed fine microstructure for both heat inputs, which consist of AF, GBF, and FSP. While HAZ experienced coarsening microstructure which mainly consist of AF.
- The impact energy of SM570-TMC welded joint at -20°C showed satisfactory performance for application in low temperature environment. For weld metal, the impact toughness is 125 J for WM-LI and 139 J for WM-HI. For HAZ, the impact energy is 122 J for HAZ-LI and 123 J for HAZ-HI.
- There is no significant difference in the weld metal and HAZ impact energy between low and high heat input joints.
- The tensile test showed that the welding quality is excellent with no failure in the weld metal. The tensile strength of low input joint and high input joint is 627 MPa and 609 MPa respectively.

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