Microstructure and Impact Toughness Relationship for Different Nickel Level of Electrode in Multi-pass FCA Welded SM570-TMC Steel Joint*

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A study was carried out to evaluate the relationship of microstructure and impact toughness for different nickel level of electrodes in multi-pass flux-cored arc welded SM570-TMC steel joint. The base metal used in this study was SM570-TMC plate with 16 mm thickness. The multi-pass welds were run by using flux-cored arc welding (FCAW) with a flat position (1G). Three SM570-TMC welded plates were fabricated with varying amounts of the nickel content of electrodes, 0.4, 1.0 and 1.5% Ni. The effects of nickel were studied on the weld metals. The investigations consist of observation on the microstructure and mechanical tests. The results indicated that at a temperature of 25 °C and 0 °C there was no obvious different impact energy value of weld metal by using electrodes 0.4 and 1.0% Ni. Besides, at a temperature of -20 °C the impact energy of weld metal containing 1.0% Ni was superior to the other. It seems the acicular ferrite (AF) formation on the weld metal containing 1.0% Ni effectively improves low-temperature impact toughness. On the other hand, the impact energy of weld metal, 1.5% Ni was the lowest. It is found that the higher nickel content caused the microsegregation as observed by the electron probe micro analyzer (EPMA).

Key Words: Microstructure, Impact toughness, Nickel, SM570-TMC, Acicular ferrite, Weld metal

1. Introduction

SM570-TMC is the high strength steel grade with a minimum tensile strength level of 570 MPa, which is commonly used in many applications, e.g., bridge construction and steel buildings. In Indonesia, the elevated toll road of Jakarta-Cikampek was constructed with SM570-TMC steel. Furthermore, developing of impact toughness of this steel welded joint at low temperatures has been a great challenge. Because it had known that the impact toughness of weld metal is deteriorated when the temperature decreased. In the earlier report, it has also known that the impact toughness of weld metal is much lower than base metal [1-2].

Some factors that influence the toughness performance of weld metal at low temperatures include grain size, material chemistry and inclusion size in the weld metal. The grain size is controlled by heat input; higher heat inputs enlarge the austenite grains and reduce the toughness. The effect of chemical composition is determined by Mn and Ni, which act as austenite stabilizers. Higher Mn and Ni decrease austenite-ferrite transformation temperature so that it completes the transformation from austenite to some ferrite morphology. The inclusions size is related to the presence of potent inclusion, which can stimulate AF formation. Increasing Ni effect to stabilize austenite grains significantly and decreases ferrite transformation temperature, thus promoting AF, at the expense of grain boundary ferrite, ferrite side plate and martensite-austenite (M-A) constituents in the weld metal [3-5]. In the low Ni content, the volume of M-A fraction is high because of incomplete transformation, with higher Ni completing the transformation of austenite. At sub-zero temperatures, weld metals with higher Ni having better toughness than low Ni [4,6]. Ni and Mn may improve toughness of the weld metal. On the other hand, they might be degrade toughness when their concentration becomes too high, promote intergranular fractures and microsegregation [4, 7-9].

Z.Q. Wang et al. [4] reported the high strength steel welded using electrodes with different Ni content and 1.6% Mn, and toughness increased with increasing Ni from 0.9% Ni to 1.45% Ni. Z. Zhang et al. [3], who investigated BS970-070M201 steel welds, suggested the optimum toughness was achieved with 0.6-1.4% Mn and 1-3.7% Ni. If Ni is more than 3.7%, martensite and other microstructures may be formed, it reduces the toughness. B.Y. Kang et al. [7] studied the mild steel weldment; according to them, optimum toughness was achieved with 0.5-1% Mn and 4-5% Ni. E. Keehan et al. [8] observed the high strength steel weldment and found the optimum toughness was achieved by 0.6% Mn and 6.6% Ni. F.S. Jaberi et al. [9] suggested for weld metal of high strength steel API X-80, the optimum AF was achieved with 1.6% Mn and 3.4% Ni. At a temperature of -60 °C the impact toughness in weld metal was higher with increasing Ni from 0.74% to 2.27% for high strength low alloy (HSLA) steel weld [6].

Oxygen or carbon dioxide in the shielding gas plays a role in the formation of oxides as potent inclusions where inclusion acted as nucleation site for the AF [10-11]. The potent inclusions are the
oxides sized between 0.5 to 1 micron, which formed between (Mg, Ti, Al) and O [10]. The small size of oxide is not useful in establishing AF, while the large size may initiate cracks. AF is formed in the cooling process from a temperature of 800 °C to 300 °C when the austenite phase decomposes into several different ferrite morphologies. AF nucleates on the potent inclusions, if there are no potent inclusions present then bainitic ferrite might form instead of AF [11-12].

At temperature of 27 °C and -30 °C, impact toughness rises when O2 increased from 2% to 4% then decreases when O2 goes to 5% [13]. As explained by X.L. Wan et al. [14], oxide promotes the formation of AF during welding because it acts as a suitable place for nucleation of AF, and prevents the formation of bainite and martensite. Alloying elements (Ti, Al, and Mg) effectively form oxides as nucleation sites for AFs during the transformation of austenite into ferrite. Accordingly to H.K. Sung et al. [10], the addition of Mg and O2 in API X80 steel produce 1-2 micron oxide, and the number of oxide increases with increasing Mg and O2. AF may be well nucleated if the non-metallic inclusions are more than 0.5 micron. Z. Cui et al. [15] suggested that inclusion is surrounded by ferrite lath, which can be radial, symmetrical and acicular. The number of ferrite laths that are nucleated at one inclusion = 2, 4, 6. AF provides high strength and excellent low-temperature impact toughness because this structure is characterized by interlocking morphology [12-16].

Although previous studies have revealed that Ni and Mn act as an austenite stabilizer, it may contribute to improve the toughness of the weld metal through AF formation. However, there has been no agreement from the researchers about the amount of Ni or Mn needed for optimum AF formation. The objective of this present study was to examine the effect of nickel level of electrodes to microstructure and impact toughness of FCA welded SM570-TMC steel joint.

### 2. Experimental design

#### 2.1 Material preparation and welding experiments

The steel used in this study was SM570-TMC plate of 16 mm in thickness. Six test plates were machined to the dimensions of 370 × 150 × 16 mm. Single V-groove butt joint with an angle of 60° was designed. These test plates were joined, producing three welded plates measuring 370 × 300 × 16 mm.

Three typical electrodes were selected, E71 LT H4, E81-Ni1 and E81-K2 with the nickel content of 0.4, 1.0 and 1.5%, respectively. Based on the data manufacturer provided, the nominal composition of three selected electrodes is presented in Table 1. Chemical composition analysis of base metal SM570-TMC is also displayed in Table 1.

### Table 1 The composition of base metal SM570-TMC and electrodes (wt%)

| Material          | C    | Mn    | P    | Si   | Ni   | Cr   | Mo   | V    | Nb   | Ti   |
|-------------------|------|-------|------|------|------|------|------|------|------|------|
| SM570-TMC         | 0.156| 1.469 | 0.010| 0.002| 0.517| 0.010| 0.020| -    | 0.005| 0.048| 0.013|
| E71 LT H4         | 0.02-0.06| 1.0-1.5| 0.025 max| 0.025 max| 0.30-0.5 | 0.35-0.5 | 0.2 max| -    | 0.08 max| -    |
| E81-Ni1           | 0.04 | 1.3   | 0.012| 0.01  | 0.25 | 0.92 | 0.03 | 0.003| -    | -    | -    |
| E81-K2            | 0.025| 1.18  | 0.013| 0.009| 0.49 | 1.44 | -    | -    | -    | -    | -    |

### Table 2 Chemical composition of weld metals (wt%) used in this experiment

| Weld Code | C    | Mn    | P    | Si   | Ni   | Cr   | Mo   | V    | Nb   | Ti   |
|-----------|------|-------|------|------|------|------|------|------|------|------|
| WM-Ni04   | 0.039| 1.21  | 0.010| 0.005| 0.326| 0.390| 0.030| 0.002| 0.013| 0.008| 0.041|
| WM-Ni10   | 0.057| 1.637 | 0.012| 0.004| 0.358| 0.821| 0.031| 0.003| 0.019| 0.014| 0.041|
| WM-Ni15   | 0.047| 1.350 | 0.010| 0.005| 0.431| 1.368| 0.035| 0.003| 0.018| 0.012| 0.028|

The multi-pass welds were run by using FCAW in flat position (1G). The welding experiments were performed manually in 10 passes with welding voltage of 30V, welding current 160-199A and welding speed was vary. Based on the applied welding parameters, the welding heat input was calculated to be 0.9 kJ/mm on average.

Three welded plates were designed to as WM-Ni04, WM-Ni10 and WM-Ni15 according to nickel level of electrodes used, wherein 04, 10, and 15 correspond to 0.4, 1.0, and 1.5% Ni. Table 2 shows the chemical composition of the weld metals of three samples based on the test results by optical emission spectroscopy.

#### 2.2 Microstructural analysis

After welding, metallographic specimens were cut from the weld joints. These specimens were ground, polished, and etched with a solution of 3% nital (3 ml HNO3 + 97 ml ethanol) for
metallographic observation. The microstructure of steel welds was observed by using an optical microscope Leica DM 1750M and a high resolution scanning electron microscope (SEM). The EPMA instrument, Shimadzu EPMA 1720H was performed to measure distribution of Ni element (wt%) in the weld metals.

2.3 Mechanical Tests

The mechanical tests consist of tensile test and CVN impact test. Tensile test specimens were prepared according to AWS D1.1, and the testing was performed at 25 °C (ambient temperature) by using UTM Zwick Roell 1200kN. The CVN specimens were extracted from the weldment as presented in Fig. 1 in the dimensions of (55×10×10) mm³ according to ASTM E23.

![Fig. 1 Position of V-notch in the CVN specimen](image)

The impact testing was performed with Tinius Olsen Impact Tester 542J machine under three different conditions: (a) at -20 °C; (b) at 0 °C; and (c) at 25 °C (ambient temperature). For the low temperatures test, the CVN test specimens were immersed in the cooling box, which contains methanol as a cooling media until it reach the specified temperature before the CVN impact test was performed. The impact test was performed on two specimens for each test temperature, and average values were calculated.

3. Result and discussion

3.1 Microstructure Characterization

Microstructures were observed by using the optical microscope in the weld metal as shown in Fig. 2. Widmanstätten ferrite was detected in the WM-Ni04, while WM-Ni10 has predominantly AF and WM-Ni15 indicated polygonal ferrite (PF). Proportion of AF was significantly increased in the weld metal of WM-Ni10 compared to WM-Ni04 and WM-Ni15. Fig. 2b showed that AF clearly identified in the weld metal of WM-Ni10. A similar observation has been reported in previous studies [2,17-18].

Further observation in the weld metal of WM-Ni10 showed the inclusions surrounded by AF laths (Fig. 3b), while inclusions in the WM-Ni04 and WM-Ni15 did not trigger the formation of AF (Fig. 3a and 3c). However the other phases also found, such as PF and M-A constituents. The small inclusions found in the weld metal of WM-Ni15 seem to be not effective acts as nucleation site for AF.

![Fig. 2 Optical micrograph showing the weld metals of: a) WM-Ni04, b) WM-Ni10 and c) WM-Ni15](image)

SEM-EDS results demonstrated the existence of the non-metallic inclusions in the weld metal. It could be the inclusions in the weld metal containing 1.0% Ni are more effective in forming AF than weld metal containing 0.4 and 1.5% Ni. As a consequence of this, the weld metal of WM-Ni10 has more AF compared to WM-Ni04 and WM-Ni15. It seems that the WM-Ni10 having the potent inclusions which may acts as nucleation site for AF. As shown in Fig. 4, the inclusions in the weld metal of WM-Ni10 were oxides with a possible combination of (Ti, Mn, Si, Al) O. Similar observations were made by other researchers where oxide inclusions serve as suitable places for nucleation of AF [5,9-10].

Ni element stabilizes the austenite grain and decreases the ferrite transformation temperature. Hence it promotes AF through a mechanism to reduce grain boundary ferrite, side plate ferrite, and M-A constituent [3-4]. In low Ni content, M-A could be high because of incomplete transformation.

![Fig. 3 SEM images of: a) WM-Ni04, b) WM-Ni10, c) WM-Ni15](image)

Weld metal of WM-Ni15, although having higher Ni, but does not produce more AF because their small inclusions did not effectively form AF. These results are in agreement with earlier reports where potent inclusions form AF, while bainite might form if there are no potent inclusions present [11]. As suggested by H.K. Sung et al. [10], AF is well nucleated if the inclusion size is more than 0.5 micron.
Distribution of Ni element was investigated at five points on each weld metal of WM-Ni04, WM-Ni10, and WM-Ni15. As shown in Fig. 5, the selected measuring points are 6, 3, 0, -3, -6 which represent the distance (in mm) from the mid-thickness of weld metal. EPMA results showed that the Ni element tends to accumulate in the reheated zone, which is in between measuring point +3 to -3 from the mid-thickness (Fig. 6). Ni might be dissolved into ferrite matrix via solid solution mechanism by substituting Fe with Ni. Effect of tempering which reduce the cooling rate in the reheated zone may caused more Ni dissolved into ferrite matrix than unreheated zone.

Elemental mapping of Fe, O and Ni at mid-thickness of weld metal were presented in Fig. 7. The circle marks showed Fe and O content is lower and higher, respectively. Lower Fe may attributed to the presence of complex oxides (Ti-Mn-Ni-Al-O) as identified by EDS analysis (Fig.4). It can be seen that WM-Ni15 has more elemental segregation than WM-Ni10. It seems that a high level of Ni in the WM-Ni15 leads to the formation of complex oxides without AF nucleation as showed in Fig. 3c.

3.2 Tensile Strength and Impact Toughness

The tensile tests of welded plates were carried out at 25 °C (ambient temperature) with the test specimens were prepared according to AWS D.1.1 standard. The test specimens represent WM-Ni04, WM-Ni10, and WM-Ni15 with two test specimens, respectively. The tensile test results showed the fracture occurred at base metal. It was indicated that the weld joint was stronger than the base metal. Fracture appearance shows ductile fracture where plastic deformation occurs.

The impact toughness of BM SM570-TMC, WM-Ni04, WM-Ni10, and WM Ni15 has been studied. In general, all test specimens showed the impact toughness decreased when the temperature decrease (Fig. 8). AFs which present in the weld metals of WM-Ni04 and WM-Ni10 (Fig. 2a-b) may improve their impact toughness. Their toughness values nearly the same at ambient temperature to zero temperature (Fig. 8). However, at sub-zero temperature, toughness value of WM-Ni04 is lower than WM-Ni10. It may caused WMMni-04 has less AF and also presence of large inclusion (Fig. 3a) and Widmanstätten ferrite (Fig. 2a). Number of AF in the weld metal is significantly contributes to low-temperature impact toughness.

The impact toughness of WM-Ni15 has the lowest at all test
temperatures. It seems even though more Ni present but more microsegregation of elements occurs (see Fig. 7). It may degrade the impact toughness.

![Fig. 8 Impact energy values of WM-Ni04, WM-Ni10, WM-Ni15 and BM SM570-TMC](image)

4. Conclusions

Effect of different nickel levels of the electrode on the material chemistry, microstructural features and CVN impact of weld metals in a multi-pass FCA welded SM570-TMC has been investigated. AF which present at the weld metal of electrode containing 1.0% Ni (WM-Ni10) was much more than both 0.4% Ni (WM-Ni04) and 1.5% Ni (WM-Ni15). It can be attributed to the presence of nickel and potent inclusions which initiated AF formation that contributed to excellent impact toughness at low temperature. The impact toughness of WM-Ni15 has the lowest at all test temperatures. It seems a high level of Ni in the WM-Ni15 leads to the formation of complex oxides without AF nucleation. Microsegregation and less AF nucleation in the WM-Ni15 may degrade the impact toughness.

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