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Investigations on Impact Toughness and Microstructure Characteristics of Gas Metal Arc Welded HY-80 Steel Plate

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Abstract. HY-80 is the high yield steel that commonly used for naval ship and submarine. Arc welding operations are a critical stage in the fabrication of this steel. During welding, the problem may occur in the heat affected zone due to the high temperature makes the microstructure suddenly changes. Coarse grain heat affected zone (CGHAZ) develops close to the fusion line, steel become brittle and the impact toughness decrease. This research investigated the microstructure of HY-80 weldment, impact toughness at sub-zero temperatures, and hardness distribution along the cross-section of the welded joint. ER100S welding wire, Ar+10%CO_2 shielding gas mixture and single V-groove butt joint with an angle of 60° were selected before welding. 12 mm thick of HY-80 steel plate that used in this experiment was multipass welded by gas metal arc welding (GMAW). Impact toughness at sub-zero temperature, hardness and microstructure evolutions of base metal (BM), heat affected zone (HAZ) and weld metal (WM) were observed. The result shows at a temperature of -80 °C; the lowest impact toughness was measured at WM (61 J) as compared to fusion line (101 J) and BM (217 J). The hardness measurement shows the maximum hardness was measured in CGHAZ followed WM and BM. Vickers hardness test result of the weld joint at the bottom area is higher than top area. It may cause of the low heat input of back weld compared to other passes. The lower heat input, the cooling rate increased and initiated the formation of a hard phase. The microstructure of WM shows acicular ferrites and non-metallic inclusions, these inclusions may deteriorate the impact toughness.

Introduction

HY-80 is high yield steel of 80 ksi containing 0.12 to 0.20% carbon. This steel shows a right combination of strength, ductility, toughness, and weldability [1,3,4,5]. HY-80 has been developed since 1960 by the U.S. Steel Corporation in cooperation with U.S. Navy for construction of naval ships and submarines [1,2]. This steel is used in quenched and tempered condition which leads to a tempered bainite martensite microstructure [1,3].

Fusion welding operation is commonly used in the fabrication of high strength steel for ship and submarine construction [6,7,8] so that the weldability is considered to be a critical issue in developing this steel for commercial purpose. However, the problem may occur in the CGHAZ where coarse grains develop and reduce the mechanical properties of the weldment [5,9,10]. The CGHAZ has low impact toughness which may be attributed to grain growth and formation of martensite-austenite (M–A) constituent [5,10,11].

The mechanical properties of HAZ are influenced by microstructure evolution that determined by phase transformation during welding operation [12]. During solidification in the weld pool, the dissolved oxygen and deoxidizing elements in the molten metal react to form complex oxide inclusions. Further cooling from 800 °C to 300 °C the austenite decomposes to different ferrite morphologies, the acicular ferrite formation would nucleate at inclusion particles [13]. In a previous study by Y.M Kim et al. [14], acicular ferrite tends to increase with increasing of hot-deformation in the austenite region. The acicular ferrite is formed around a temperature of 600 °C; its formation temperature tends to be decreased with increasing the amount of austenite stabilizer elements [14].

H.K. Sung et al. [15], reported volume fraction of acicular ferrite in HAZ of API X80 line-pipe steel to tend to increase with increasing the oxides and decreased with increasing welding heat input (cooling rate decreased). Charpy impact test of -20 °C show ductile fracture was dominant when the volume fraction of acicular ferrite more than 20% [15].

The impact toughness value of the WM at sub-zero temperatures was found to be determined by the grain size, chemical composition of WM, acicular ferrite formation and inclusion content [7]. Microstructural constituents in WM are influenced by O_2 and CO_2 content in the shielding gas [16,17]. Microstructural aspects influence fracture micro-mechanism of deteriorated HAZ toughness [18]. Accordingly, to S. Kumar et al. [5], the impact toughness of HY-85 welded joint is more or less constant between ambient temperature to -50 °C for BM and CGHAZ, furthermore when the temperature keeps decrease the impact toughness values drastically drop. R. Pamnani et al. [7] suggested the higher amount of acicular ferrite and refined microstructure in WM of high strength low alloy steel can improve the impact toughness at sub-zero temperatures. The impact toughness of the WM at sub-zero temperatures is directly proportional to nickel amount in the WM [7]. Strength and low-temperature impact toughness in WM significantly improved by increasing nickel content due to nickel contributed to the formation of predominant acicular ferrite [19].

Homogeneous microstructure suddenly changes when the temperature increase during the welding operation. Microstructure evolution at each area differs which correlated with how far from the heat source. Due to microstructure changes significantly during welding, strength and toughness also change drastically. The microstructure of high strength steel is found tempered martensite and bainite. It was found that different phases present such as some ferrite morphologies and also M-A constituents. On the other hand, a major concern on the microstructure is increasing segregation of inclusion/precipitation [9].

Accordingly, to H. Dong et al. [12], it was found that HAZ and WM have a higher hardness than BM at gas tungsten arc welded HSLA steel, the hardness changed depend on the value of heat input. K. Prasad et al. [6] reported submerged arc welded HSLA steel. According to them, the hardness reduces significantly at a distance away from weld centerline (heat source) toward BM.

This paper investigated weldability of gas metal arc welded HY-80 steel with Ar+10%CO_2 shielding gas mixture and ER100S electrode. This study including observations of microstructure analysis of weldment, the performance of impact toughness at sub-zero temperatures and hardness measurement of the welded joint.

Experimental Design

Material Preparation and Welding Experiments

HY-80 plate is used in this research for the parent metal. The elements analysis of the present HY-80 was performed by optical emission spectroscopy (OES), and the result is displayed in Table 1. Referring to Table 1, the nominal composition of present HY-80 meets to standard specification according to MIL-S-16216K(SH)

The received plate was cut to the dimensions of 300 × 100 × 12 mm, and then single V-groove butt joint configuration with an angle of 60° was welded as shown in Fig. 1. The multi-pass welds were made by using GMAW with the horizontal position (2G). 1.2 mm diameter of solid wire ER100S was used in this welding experiment. The nominal composition of the welding wire is presented in Table 2, and the welding parameters used in this experiment can be seen in Table 3. The welding parameters in this experiment are derived from industrial experiences and the literature.

Table 1 The nominal composition of base metal (in wt. %)

C	Mn	P	S	Si	Ni	Cr	Mo
0.14	0.29	0.004	0.002	0.22	3.03	1.49	0.437

Table 2 The nominal composition of ER100S welding wire (in wt. % – from the manufacturer)

C	Si	Mn	Cr	Mo	Ni
0.08	0.6	1.7	0.2	0.5	1.5

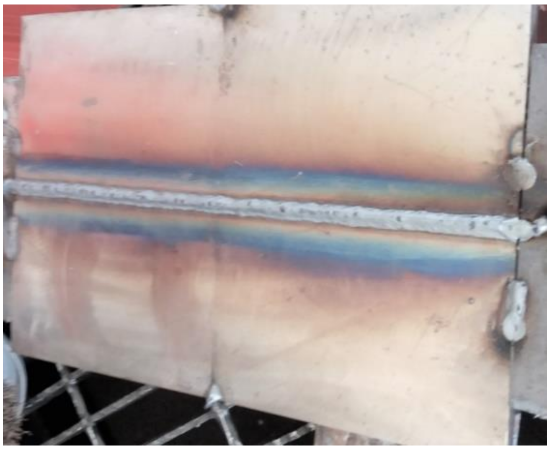


Fig. 1 Gas metal arc welded HY-80 steel plate

The GMAW experiments were performed in seven passes as shown in Table 3. Welding parameters of arc voltage E (Volt), welding current I (Ampere) and arc travel speed S (mm/min) were recorded during the experiment. Heat input H (J/mm) was calculated referring to below formula:

$$H = E \times I \times 60 / S \quad (1)$$

The test plate is preheated at a temperature of 50 °C minimum before welding is performed. Then the welded plate was cut transversally to the weldment. The test specimens for mechanical test and metallurgical observation were machined from welded plate to the required dimensions referring to the DNV Standard.

Microstructural Analysis

The observation of the microstructure of the welded plate, the specimens were extracted transversally to the welding direction. The test specimens were polished to mirror surface finish according to the standard metallographic procedure. The metallography procedure is used by using 2% nital as an etching solution to reveal the microstructure features. Both optical microscope and SEM were used to investigate microstructure evolutions after welding operation. SEM is equipped with energy dispersive x-ray (EDX) for chemical analysis.

Table 3 The main welding parameters and welding heat input used to deposit the welding wire

Seq.	Pass	Current (A)	Voltage (V)	Welding speed (mm/min)	Heat input (kJ/mm)
1	Root	100	15	137	0.66
2	Hot Pass	170	18	286	0.64
3	Filler	170	18	295	0.62
4	Filler	170	18	295	0.62
5	Capping	170	18	305	0.60
6	Capping	170	18	273	0.67
7	Back weld	170	18	353	0.52

Mechanical Tests

The standard test specimens for tensile test, Charpy impact test, and hardness test were prepared for mechanical properties investigation. The tensile test was performed at room temperature (25 °C) by using SHIMADZU UH 100A machine with a capacity of 100T. The specimens were extracted by wire cutting across the welded joints according to ASTM E23 for standard 55 × 10 × 10 mm Charpy V-notch (CVN) specimens. To ensure the notch was located in the correct position, impact test specimens were etched by 2% nital to exhibit the outline of both WM and HAZ. Charpy impact test was performed using an impact testing machine (300 Joule impact tester WOLPERT) at various temperatures.

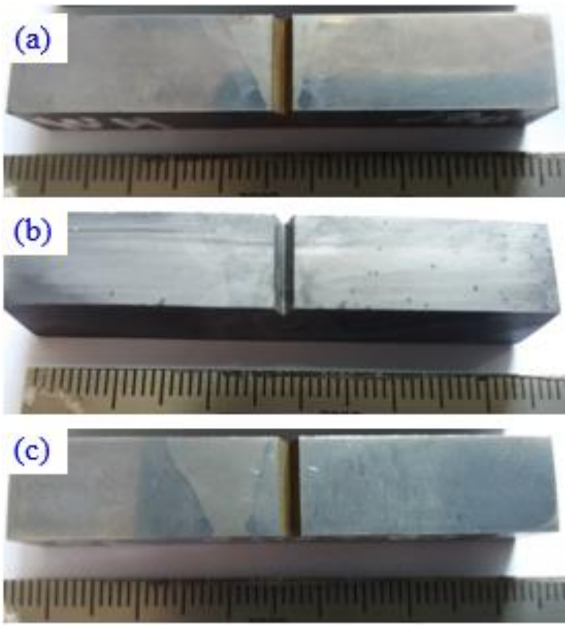


Fig. 2 Specimens of Charpy impact test with V-notch at (a) WM, (b) FL, (c) FL+3mm

Charpy V-notches was located at the WM, FL, and BM. The tests were performed to evaluate the impact toughness at each location; (i) the specimens with the notches of Charpy V at BM were prepared for the test temperatures of 20, -20, -60 and -80 °C; (ii) the specimens with the notches of Charpy V at WM, FL, and FL+3 were prepared for the test temperatures of -80 °C (see Fig. 2). The specimens were immersed in the freeze box which contains methanol as a cooling media before the Charpy impact test is performed. Two specimens of each test temperature were tested, and average values of energy absorbed during fracture were measured.

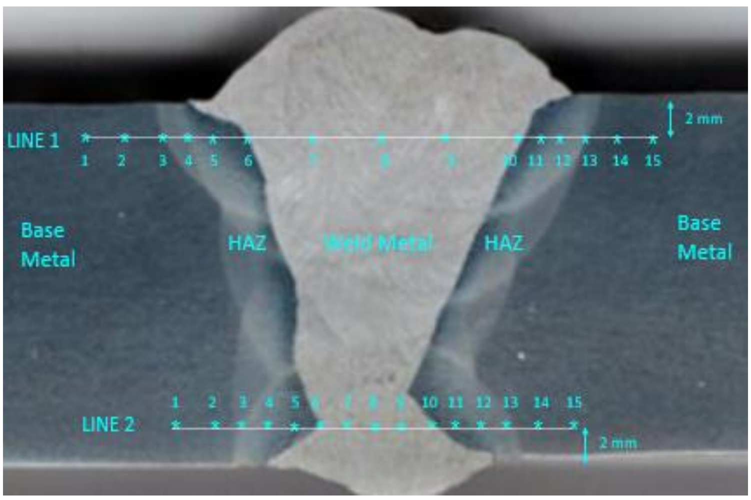


Fig. 3 Indentation points of hardness Vickers across the GMAW weldment of HY-80

The hardness measurement was conducted according to ASTM E92-82 standard specification. Vickers hardness tester for a ten kgf transverse load is employed to this specimen. The hardness tests were performed across the weldment as shown in Figure 3 where the indentation was applied at 2 mm from the surface of the plate, at top and bottom surface respectively. The indentation of hardness represents three different zones in order to obtain its hardness characteristic.

Results and Discussion

Microstructure Characterization

Microstructures were observed by using the optical microscope (OM). The observation was performed in the BM, HAZ, and WM, as shown in Fig. 4. Microstructural observation in BM and HAZ show a mixture of granular bainite (GB), tempered martensite (M) and some amount of ferrites (F). It seems that the microstructure observation result agrees with the previous investigation by S. Kumar et al. [5]. The microstructure of WM shows acicular ferrite (AF) and inclusions. AF surrounding by some inclusions appears in the area of WM.

Further observation with SEM show microstructure evolution in HAZ compared to BM (see Fig. 5a and 5b). Fusion welding affected to grain growth in HAZ (Fig. 5b). Grain growth occurred in HAZ near the fusion line (which known as CGHAZ) which may cause higher hardness and lower impact toughness.

SEM which equipped with EDX analysis continues profound observation in WM. The observation in WM indicated acicular ferrite (AF) with some amount of inclusions (see Fig. 5c). Non-metallic inclusions were observed in WM (see Fig. 5c). The EDX analysis revealed the chemical composition of the inclusions possible combination of (Fe, C, Si) O as shown in Fig. 6. The oxides present in WM may result from the oxygen of shielding gas Ar+10%CO_2 which react to silicon of welding wire that used during welding. Under high temperature, the CO_2 decomposed into CO and O and increased the oxygen content in WM [20].

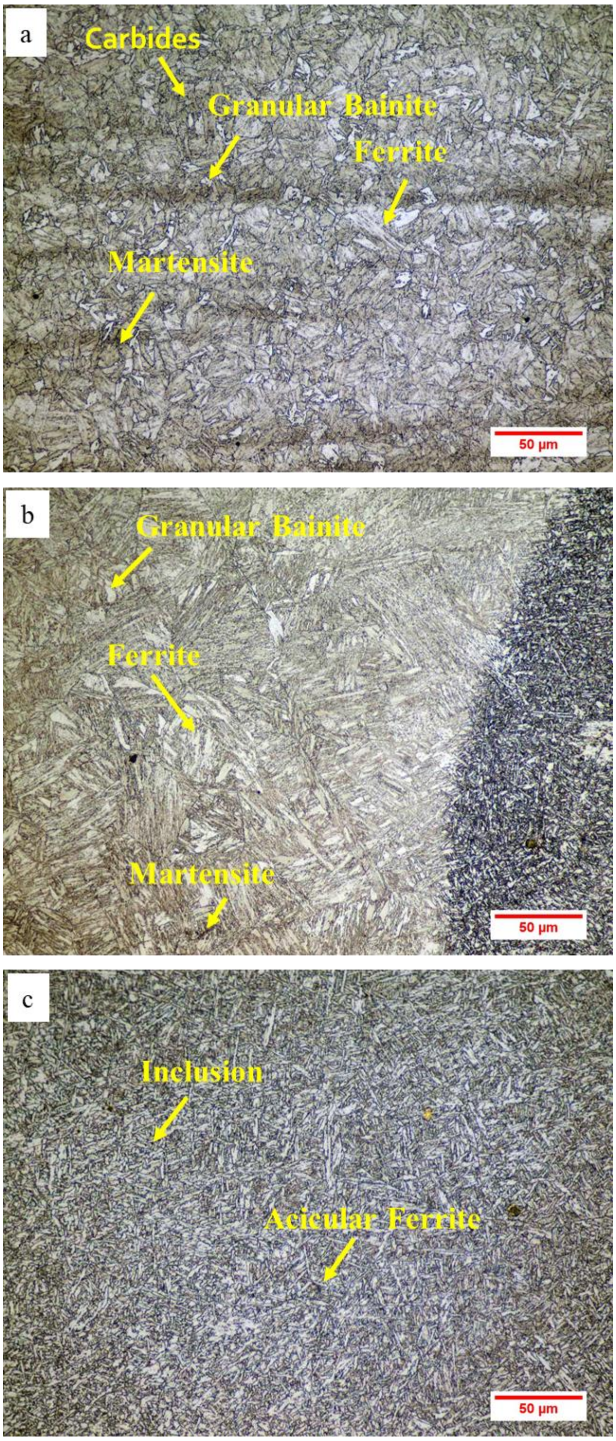


Fig. 4 Optical microstructure of gas metal arc welded HY-80 steel plate at a) BM, b) HAZ, c) WM

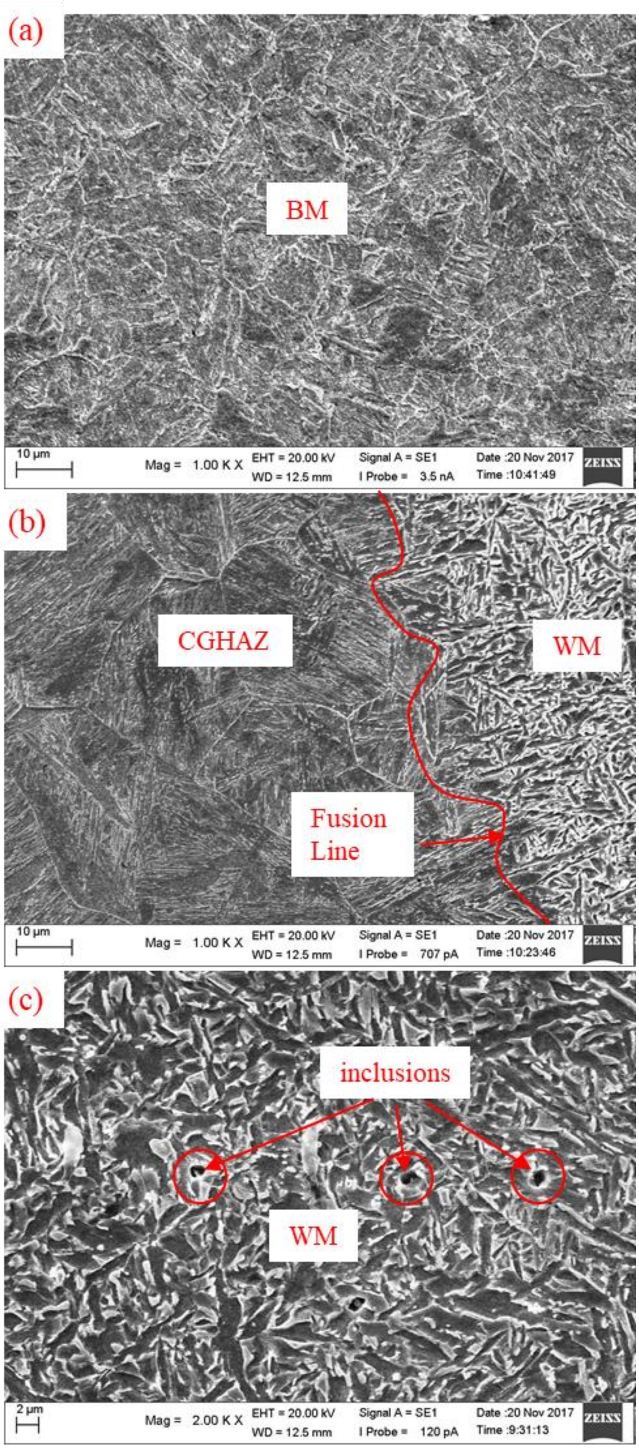
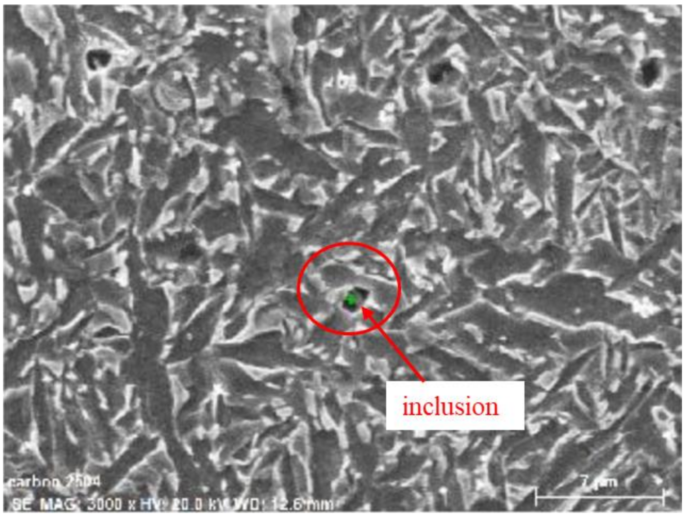
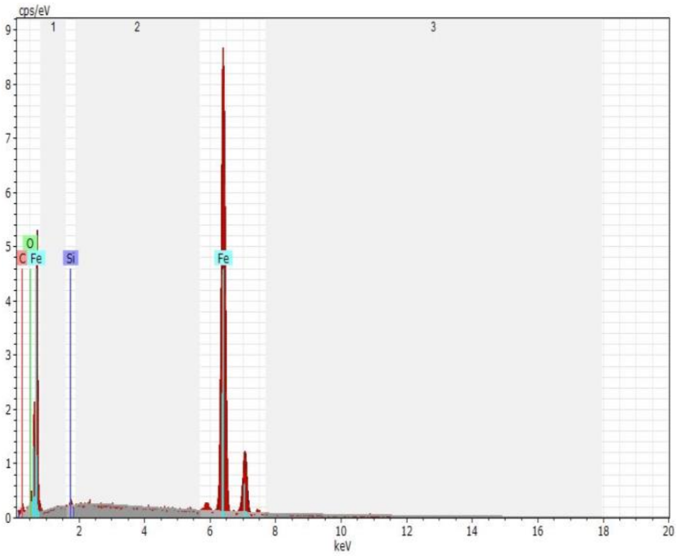


Fig. 5 SEM images showing microstructure at : (a) BM, (b) CGHAZ, (c) WM

The microstructure evolution in HAZ and WM during welding may contribute to impact toughness and hardness. The hardness values of the weldment strongly depend on the microstructural characteristic, higher hardness values of HAZ and WM were related to lath martensite/bainite formation during welding [12].





Spectrum: Acquisition

Element	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Carbon	K-series	2.32	2.71	11.10	1.12
Oxygen	K-series	1.15	1.35	4.14	0.47
Silicon	K-series	0.35	0.41	0.72	0.06
Iron	K-series	81.72	95.53	84.03	2.29
	Total:	85.55	100.00	100.00	

Fig. 6 SEM image and EDX analysis showing non-metallic inclusions in WM

Tensile and Impact Toughness Properties

The tensile tests were carried out at a temperature of 25°C according to the DNV standard. The test results show the fracture occurred at BM which means the strength of both HAZ and WM are higher than BM (Fig. 7). Fracture appearance shows ductile fracture where necking and cup-cone shape occur.

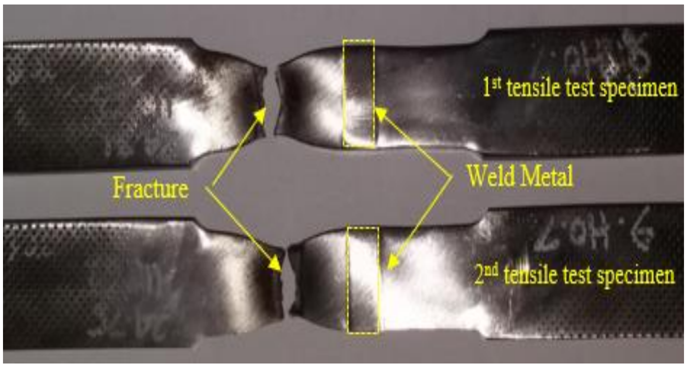


Fig. 7 The broken specimens of tensile test

The impact toughness of BM at different testing temperatures (20, -20, -60 and -80 °C) has been studied. The impact toughness values of BM decreased when the test temperature decreased as shown in Fig. 8. Decreasing of impact toughness from the temperature of -60 to -80 °C is more significant than from temperature of 20 to -60 °C. However, at all test temperatures, the impact toughness still meet to HY-80 standard specification. According to MIL-S-16216-K(SH) impact toughness of HY-80 steel is 47 J minimum at -84 °C and 81 J minimum at -18 °C.

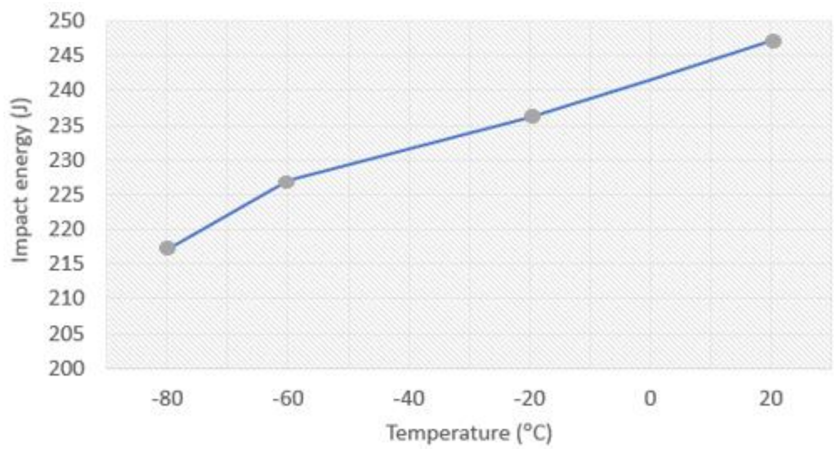


Fig. 8 Impact energy (J) of the HY80 base metal steel plate in various temperatures (20, -20, -60, -80 °C)

The impact toughness was also tested in various locations of HY-80 steel weldment: WM, FL, and FL+3mm. The result presented in Fig. 9. At WM the impact toughness descents a great deal and shows the lowest value. At the test temperature of -80 °C, the impact toughness at WM is 28% (61 J), and FL is 49% (101 J) in comparing with FL+3mm (217 J). It is comparable with S.K. Dhua et al. [21] who reported the impact toughness of HSLA-100 steel plate at -50 °C resulted in the lowest impact toughness in WM (105 J) followed HAZ (130 J) and BM (179 J).

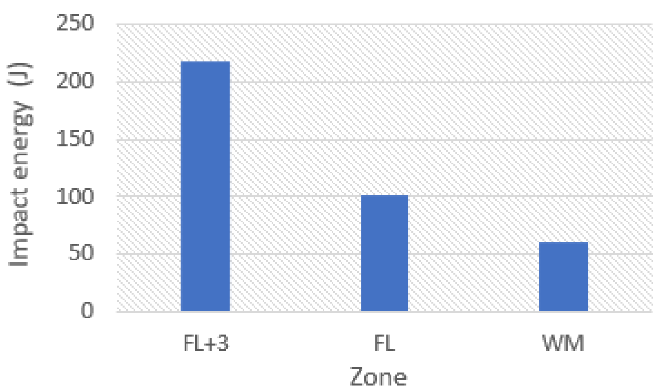


Fig. 9 Impact energy (J) of HY80 steel welds at -80 °C in various location (WM, FL, and FL+3)

The low impact toughness at WM may occur due to oxidation effects which reduces some elements at high temperature during the welding operation. Oxygen in WM may come from the use of CO_2 addition to argon in the shielding gas of Ar+10% CO_2. During welding, the CO_2 decomposed into CO and O and increased the oxygen content in WM which may affect to degraded the toughness [20].

S. Kumar et al. [5] indicated that in the weld HAZ region, impact energy of high strength steel should not be less than 50 J at minus 50 °C. In this experiment, the lowest impact toughness was measured at WM (61 J), and the highest impact toughness was at FL+3 (217 J). The impact toughness at FL+3 has similar value with BM which may consider the HAZ width is more and less 2 mm. However, the impact test result for HY-80 in both WM and FL at test temperature -80 °C show the value above 50 J as S. Kumar recommended for high strength steel. These impact toughness values can be compared with an investigation by P. Yayla et al. [3] who investigated the impact energy of HY-80 GMAW butt welded at -20 °C which shows the lowest value at WM (65J) and higher value at HAZ (125J) while BM shows the highest (260J). The toughness of WM lower than HAZ in temperatures range of 20 to -140 °C also reported by V. Grabulov [11] for the weld deposit of a SMAW weldment of NN 70 steel (class of HY-100).

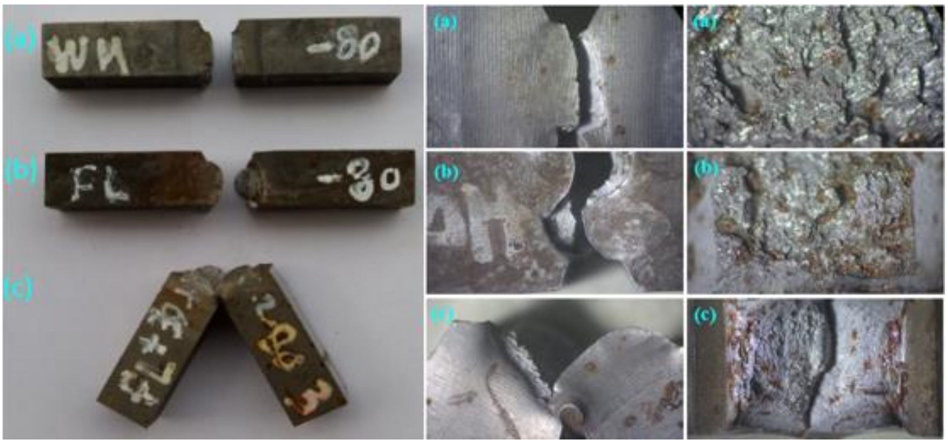


Fig. 10 The broken specimens after impact test at -80 °C with various notch locations at a) WM, b) FL, c) FL+3mm

The broken specimens as seen in Fig. 10 shows fracture appearance are a brittle fracture after impact test -80 °C on WM and HAZ specimens where the specimens broke on a flat plane. The ductile fracture was observed at FL+3mm specimens which still indicated a plastic deformation.

Hardness Distribution Test

The hardness distribution across the weldment had been observed. Indentation location of hardness Vickers test is shown in Fig. 3. There are 15 indentation location on both Line A (2 mm away from the upper surface) and Line B (2 mm away from the lower surface). The test results show the hardness of weldment at Line B is higher than Line A as shown in Fig. 11. It may cause the welding heat input of back weld is 0.52 kJ/mm which is lower than other passes with a heat input of 0.60 to 0.67 kJ/mm. Lower heat input contributed to faster cooling which is associated with the formation of hard phases. It is comparable to H. Dong et al. [12] who suggested martensitic microstructure was produced at a high cooling rate and increased the hardness at HAZ and WM of gas tungsten arc welded HSLA steel.

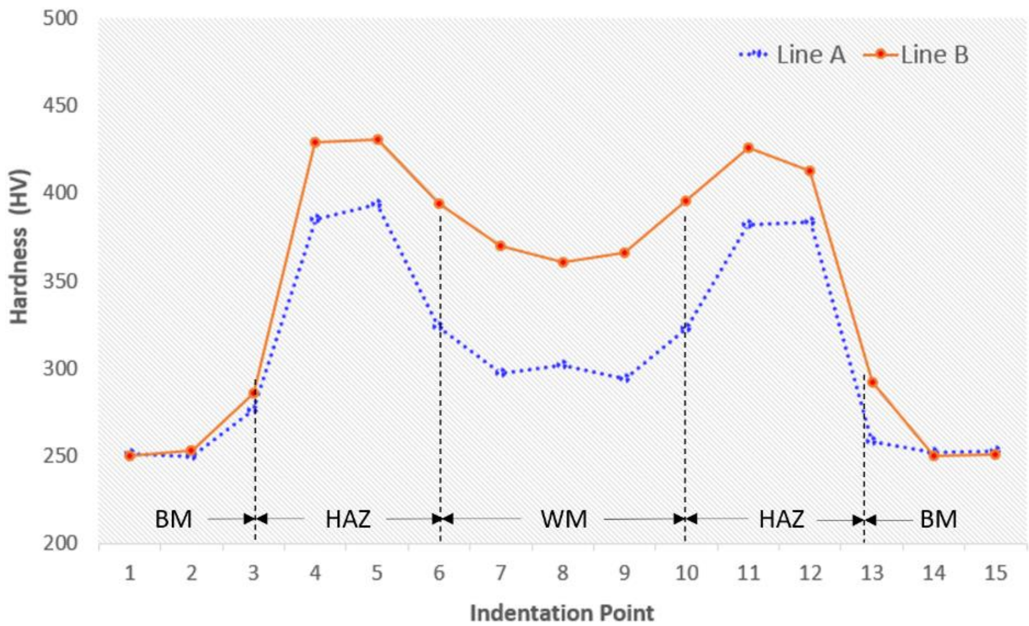


Fig. 11 Hardness distribution along a horizontal line on the cross-section of the weld joint

The hardness of BM at Line A is relatively similar to Line B. But the hardness of WM and HAZ at Line A and Line B show significantly different where the hardness of HAZ was higher than WM. The peak hardness in the HAZ was found 394 HV at Line A and 431 HV at Line B. These results are comparable to another report by P. Yayla et al. [3] who measured the hardness at BM (235 HV) and HAZ (400 HV) for HY-80 steel welded by GMAW. V. Grabulov [11] also reported the maximum hardness was measured in CGHAZ of NN70 steel due to martensite formation.

Vickers hardness distribution test result has shown the measured hardness of CGHAZ is higher than fine grain heat affected zone (FGHAZ). This is related to grain growth in CGHAZ. Similar results were reported by another researcher where the hardness values of CGHAZ were found higher than FGHAZ when the low heat input to be applied [12].

Conclusions

This research investigated microstructure evolution, impact toughness and hardness of gas metal arc welded HY-80 steel. The conclusions can be summarized as follows :

1. GMAW using Ar+10%CO_2 shielding gas mixture and ER100S electrode is suitable for multipass welding process of the HY-80 welded plate.
2. Impact toughness of BM at various temperatures (20, -20, -60 and -80 °C) decreases when the temperature decreases, however, the present HY-80 steel plate show the impact toughness for all test temperatures still meet the minimum standard requirement as specified for HY-80 according to MIL-S-16216-K(SH). Fracture mode of the BM shows ductile fracture at all test temperatures where the specimens indicated a plastic deformation.
3. At sub-zero temperature -80 °C, the impact toughness at WM show the lowest (61 J) followed by FL (101 J) and BM (217 J). The impact test for HY-80 steel welded plates at -80 °C in various locations show brittle fracture at WM and fusion line (FL) where the specimens broke on a flat plane, while BM shows a ductile fracture.
4. The hardness test at BM show 250-253 HV. The maximum hardness was measured in HAZ of Line A (394 HV) and HAZ of Line B (431 HV). The hardness of weldment at Line B is higher than Line A. It may be influenced by the low welding heat input performed for back weld compared to other passes. So it caused higher cooling rate and initiate formation of hard phase.
5. The acicular ferrites were found in WM, and the likely inclusions combination of (Fe, C, Si) O also were observed in WM. The oxides present in WM may come from the shielding gas

Ar+10%CO_2 which under high temperature the CO_2 decomposed into CO and O and increased the oxygen content in WM.

Acknowledgments

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