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Effects of welding on the change of microstructure and mechanical properties of low carbon steel

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Abstract. Steel construction is mostly connected by using a welding technique. The result of the welding process can cause the change of mechanical properties of the welding zone. Therefore, it needs to be reviewed to guarantee the quality of the welding zone. This research aims to assess the effect of welding on the change of microstructure and the mechanic characteristic of welded connection. Low carbon steel was welded by using Shield Metal Arc Welding method (SMAW) with electrode E7016, diameter 2,6 mm. Type of notch used was single V with angle 70° and welding position was 1G. Then, the Charpy impact test, Rockwell hardness and micro-macro structure monitoring on the welding zone including base metal, Heat Affected Zone (HAZ) and weld metal, are conducted. The results show that the highest impact toughness value at metal welding area is 251 joule/mm^2, and lowest impact toughness is at the heat affected area (HAZ) is 119 joule/mm^2. Hardness values of welding zones are found of about 87,6 HR_B for weld metal, 73,9 HR_B for HAZ zone and 67,1 HR_B for the base metal. The microstructure of weld metal zone, HAZ and base metal are included on ferrite and pearlite formed by welding on low carbon steel AISI 1010 observer by using an optic microscope.

1. Introduction

Technological advances and the need to produce robust steel construction have made welding a top choice in the steel connection process. Today, the steel construction involves many elements of welding. This is due to the welding is one of metal connecting techniques that is easy to implement. The welding has been widely used in the construction of ship, bridges, steel frame, pressure vessel, rail, pipeline and so forth [1].

Welding is a process of connecting metal rods using heat energy either with or without filler metal. The type of welding that is often used is electric arc welding or shielded metal arc welding (SMAW) [2]. The electric arc welding (SMAW method) uses the electric arc to melt both the base and filler metal. This welding technique uses a metal electrode covered by a flux. An electric arc is evoked between the base metal and the tip of the electrode. Due to the heat from this electric arc, the base metal and the tip of the welding electrode melt and subsequently solidify simultaneously [3].

The characteristics and conditions around the welding area of the welded metal change during the welding process. These changes affect the mechanical properties and microstructure of the newly welded metal (steel). In addition, these changes induce the internal stress that can decrease the

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toughness of the welded metal. Therefore, a comprehensive study is needed in order to understand the changes occurred in microstructure and mechanical properties of the welded area.

This study aims to understand the effect of welding on the changes in microstructure and mechanical properties (i.e: toughness and hardness) of low carbon steel. Thus, the impact and hardness tests, as well as the micro and macro structure observations of the welded low carbon steel, are necessarily conducted.

2. Literature review

2.1 Shielded metal arc welding (SMAW)

The covered electrode welding is the welding process by liquefying the base material using heat from electricity flowing through the tip of the flux-covered electrode which melts away during the welding process. In the covered electrode welding, an electric arc-induced between the tip of the electrode and the base metal will generate heat. The heat dilutes both the tip of the electrode and the base metal simultaneously. The electric arc is generated by a welding machine and used the flux covered electrodes. The type of electrode used will greatly determine the welding results [4].

2.2 Covered electrode

An electric arc weld requires an electrode comprising a core metal covered by a chemical mixture (flux). The electrode serves as a trigger as well as a filler material. The electrode coating protects the molten metal from the air environment, producing the protective gas, and stabilizing the arc [1].

The flux material used for the electrode E7016 is low hydrogen potassium, which is also known as the lime type. This flux yields a joint with low hydrogen levels so that the susceptibility of the joint to the crack is very low and its toughness is very satisfactory.

The electrode is classified according to the standard system of American Welding Society (AWS) and American Society Testing Material (ASTM). E7016 electrode allows being applied in all welding positions (vertical, horizontal and overhead) either with the AC and DC current. The electrode helps to yield fine jagged surface, Thus, the existing slag will be easy to clean and the arc can be controlled easily [5].

2.3 Electric current

The amount of electric current required for welding depends on the diameter of the electrode, the thickness of the welded material, the type of electrode used, the connection geometry, the core diameter of the electrode, and the welding positions. The welding zone has a high heat capacity, thus, substantial electric current is required [6].

2.4 Thermal cycle of the welding zone

The welding area can be classified into three zones namely, the weld metal zone, HAZ and the unaffected heat metal zone.

a. The weld metal zone is the part of the metal that melts and solidifies during the welding process. The weld metal comprises of the base metal and the filler material of the electrode.

b. The Heat affected zone (HAZ) is the area of the base metal adjacent to the weld metal zone that undergoes rapid heating and cooling during the welding process, thus, yielding the most critical of the welding joint.

c. The base metal zone is the area of the metal that does not experience both microstructure and properties changes due to the welding temperature. Besides these three main divisions, there is still one area of heat influence, called the fusion line [7].

2.5 The toughness of the welding zone

The toughness of the welded metal depends on its microstructure, similarly for the base metal and the fusion line. During the welding process, the welded metal melts and solidifies, Thus, it contains oxygen and other gases.

The composition of the welded metal depends on the welding process applied. It should be noted that the effects of other elements absorbed during the welding process, especially oxygen [1].

3. The tested material and research method

The material utilized in this study was low carbon steel. The mechanical properties and chemical compositions of the material are shown in Tables 1 and 2, respectively.

Firstly, the notch was made before the welding process. The notch that suits for a 10 mm plate is a single v with an angle of 70° as shown in Figure 1.

Table 1. Chemical compositions of AISI 1010 steel [8].

Matters	C	Mn	P	S	Si
Composition (% weight)	0,08-0,13 max	0,30-0,60 max	0,040 max	0,050 max	-

Table 2. Mechanical properties [9].

Properties	Metric	Unit
Density (ρ)	8,030	kg/m^3
Hardness	60	HR_B
Modulus Young (E)	210	Gpa
Shear Strength (τ)	260	MPa
Poisons Ratio (v)	0,30	-
Yield Strength (σ_y)	305	Mpa

The welding was conducted by SMAW method with the E7010 electrode and 1G welding position for a plat with dimensions of 10 mm x 10 mm. Table 3, summarises the chemical compositions of AWS A5.1 E7016 electrode by weight percentage.

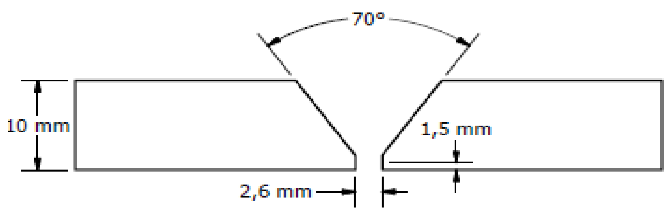

Figure 1. a single v-notch.

Table 3. Chemical compositions of AWS A5.1 E7016 electrode (% weight) [10].

C	Mn	Si	S	P	Ni	Mo	Cr	V
0.12	1.6	0.75	0.035	0.040	0.30	0.30	0.20	0.08

The welded material was cut into a specimen with dimensions as specified by ASTM E-23. Then, the impact strength (toughness) of the specimen was tested. Figure 2 shows the schematic of the tested specimen.

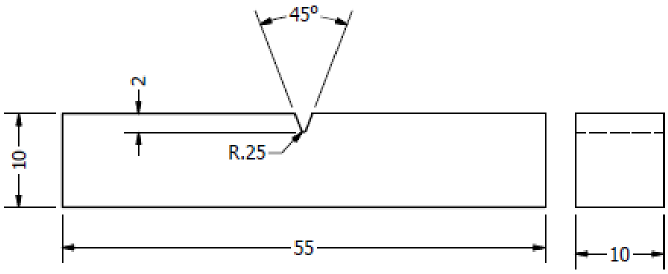

Figure 2. The schematic and dimensions of the specimen

4. Result and discussion

4.1 Chemical compositions

Data obtained from the test of the chemical composition of the specimens was compared with that provided by the AISI 1010 standard for steel. The experimental results reveal that the chemical compositions of the specimen close to that provided by AISI 1010 standard (see Table 4). It is observed that the carbon content of the tested specimen is 0.10%. This value is within the range provided by the AISI 1010 standard namely, 0.08% - 0.013%. While the high-level content of sulfur in the steel can reduce the ductility (steel ductility) and increase the chances of cracking. The sulfur content obtained from the specimen is 0,007% which is a good agreement with that provided by the AISI 1010 standard. It is found that the phosphor content of the specimen is less than the maximum value provided by the AISI 1010 (0,040%). This indicates that the experimental value is in accordance with that suggested by AISI 1010. The Mangan (Mn) content in the low carbon steel can increase the ductility. It is found from the experiment the Mn content of the specimen is 0.27 which is also meet the AISI 1010.

Table 4. Compositions comparison between the specimen and AISI 1010 low carbon steel.

Material	C	Mn	P	S	Si
Low carbon steel Testing result (% weight)	0.10	0.27	0.019	0.007	014
AISI 1010 (% weight)	0.08-0.13 max	0.30-0.60 max	0.040 max	0.050 max	.

4.2 Changes in microstructure

Observation of microstructure using an optical microscope was conducted to find out the changes in the microstructure of the specimen that occurs due to heating during the welding process (SMAW). The result of observation of microstructure in this study has been etched with 2% nital for 1 minute. Figure 3 illustrates the schematic of the welding zone of the observed microstructure. Figure 4 shows the microstructure of the weld metal and HAZ. Figure 5 demonstrates the microstructure of HAZ and Figure 7 shows the microstructure of the base metal.

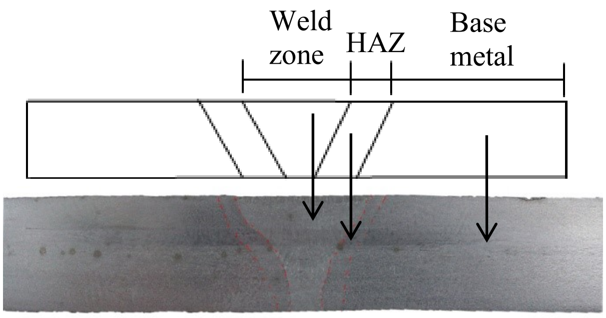

Figure 3. Schematic of welding zone of the observed microstructure.

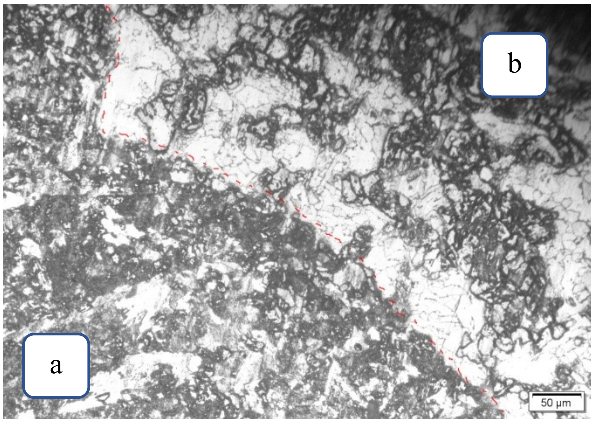

Figure 4. The microstructure of weld metal and HAZ with 20 times magnification a) shows the weld metal zone and b) shows the HAZ.

Figure 4.a illustrates the microstructure of the weld metal zone (formed by the solidified molten metal). As can be seen from the figure, the grain size of the microstructure is finer. Figure 4.b shows the HAZ, while the red line represents the border between the weld metal zone and the HAZ.
Figure 5 shows that the microstructure of the HAZ is coarse ferrite and pearlite. The reason is due to during the welding process, the HAZ adjacent to the fusion line undergoes rapid heating and cooling so that this area is most critical and the peak temperature exceeds the melting point of the steel. Visually, the microstructure of the area close to the melting line is getting coarse. The figure shows that the white ferrite grains (light) are dominant, while the pearlite grains are less (showed by dark colour).

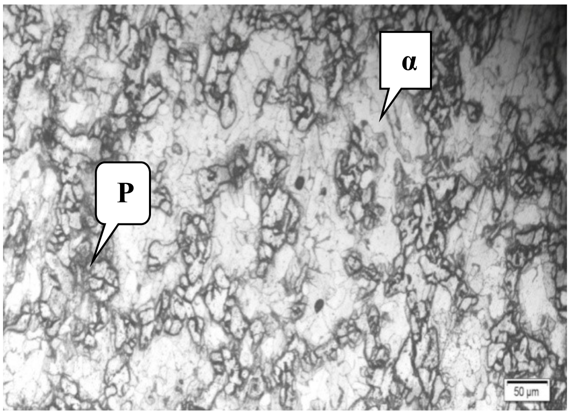

Figure 5. shows the microstructure of the HAZ with 20x magnification, α = ferrite, P = pearlite.

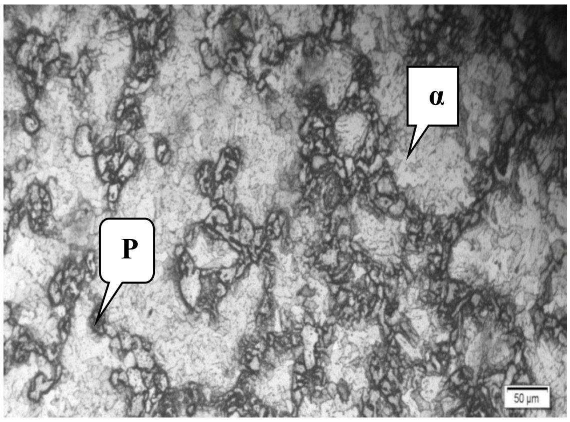

Figure 6. The microstructure of the base metal with 20x magnification, α = ferrite, P = pearlite.

Figure 6 shows that the microstructure of the base metal zone is finer than others. The heat generated during the welding process does not induce the changes in the metal microstructure and properties. As illustrated in the figure, the microstructure is predominantly ferrite which is white in colour. While the pearlite (dark colour) is less. From the microstructure observation, it can be concluded that there is no change in microstructure and grain sizes of the base metal.

4.3 The hardness of the welding zone

The mechanical properties of the specimen not only depend on its chemical compositions but also its microstructure. The microstructure depends on the process of work, especially in the heat treatment process [11]. The hardness of the specimen (i.e. base metal zone, HAZ, and weld metal zone) from point 1 to 11 (see Figure 7) is summarized in Table 5. It is found the average value maximum of the hardness of the welding zone is 87,0.

Table 5. The hardness of the welding zone.

	Hardness HR_B			
No	Point 1	Point 2	Point 3	Average
1	67,1	66,6	66,7	66,8
2	67,8	67,5	68,7	68
3	70,7	69,1	70	70
4	71,1	71,8	73	72,0
5	79	74,1	81,4	78,2
6	86,2	87,6	87,1	87,0
7	81,8	80,1	80	80,6
8	73,9	73,4	71,6	73,0
9	70,9	70	70,2	70,4
10	67,8	68,4	69,4	68,5
11	66,8	65,8	66	66,2

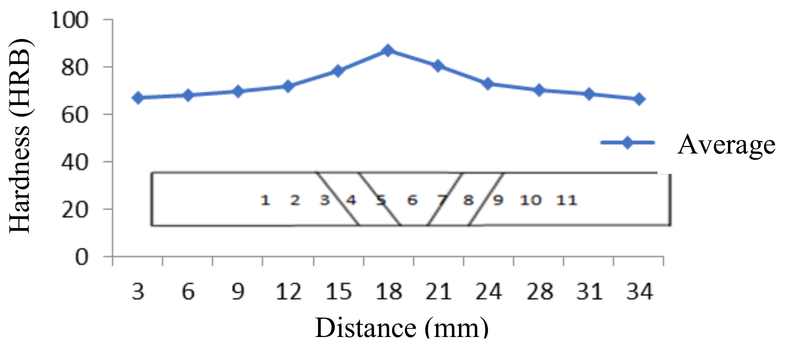

Figure 7. Hardness values of the specimen.

Figure 7 shows the hardness values of the specimen. It is observed that the hardest part of the specimen is at the weld metal zone. This tendency is affected by a higher Mn content in the weld zone than other areas namely 1.6% (see Table 3). As a result, the hardness and toughness of the weld metal zone increase [13]. While the HAZ is slightly harder than the base metal. The reason is due to there is no changes in the microstructure and mechanical properties of the base metal induced by the heat generated during the welding process.

4.4 Toughness of the welding zone

The toughness values of both the weld metal and the base metal are investigated by the impact test. In the test, the energy absorbed (W) by the specimen is measured in Joule and notch impact (K) is in

Joule/mm^2. Table 6 summarises the notch impact values of the weld metal zone, HAZ, and the base metal.

Table 6. The toughness of the specimen of the welded metal.

No	Impact value of welding zone (joule/mm^2)		
	Weld metal	HAZ	Base metal
1	215	119	125
2	251	122	133
3	209	119	140
average	225	120	133

Table 6 demonstrates the result of the impact on each region of the specimen that undergoes the welding process. The result shows that the highest toughness value of the specimen is obtained from the weld metal zone. It is 225 joule/mm^2. While the base metal is 133 joule/mm^2. The lowest value of toughness is gained from HAZ namely, 120 joule/mm^2.

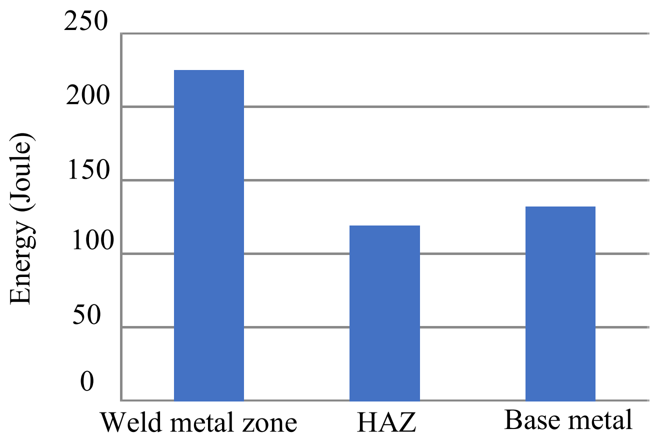

Figure 8. The impact toughness of the welding zone.

4.5 Surface fracture analysis

The observation of macrostructure on fracture surface aims to find out the type of fracture experienced by the welding zone. Therefore, the toughness for the welding zone can be estimated. The higher percentage of fibrous fracture (dimple-shaped) indicates the more ductile the material is. This means the material is tougher. On the contrary, the finer and flatter the fracture surface, the more brittle and fragile the material is. Figures 8-10, show the fracture of the cross-section of the welding zone.

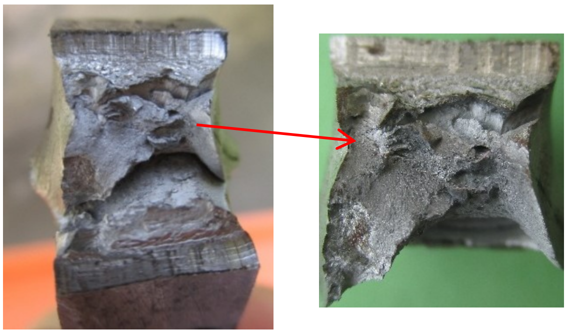

Figure 9. The fracture surface of the weld metal zone.

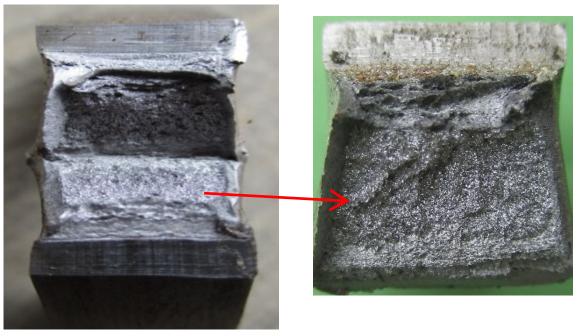

Figure 10. The fracture surface of the HAZ

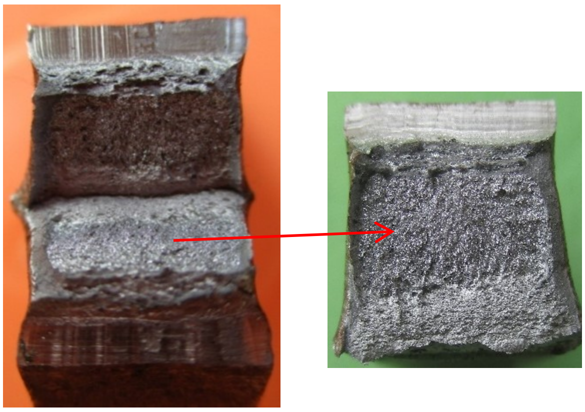

Figure 11. The fracture surface of the base metal.

Figures 9-11 illustrate the fracture surface of the welding metal at three different zones. It is observed that the fracture in the welding metal is a ductile fracture. This is characterized by energy absorption, also accompanied by a considerable plastic deformation around the fracture. As a result, the fracture surface appears rough, fibrous, and grey in colour. In addition, the type of fracture occurred not only influenced by the load itself but also affected by the material compositions. Typically, the ductile fracture occurs on the material which has ferrite, pearlite or bainite microstructures which is low carbon steel.

5. Conclusions

From the results and discussions, several findings from this study are concluded as follows:

1. There are the grain size changes on the weld metal zone, HAZ, and base metal. In addition, the highest hardness value is obtained at the weld metal zone and the lowest is at the base metal.
2. The highest toughness value of the specimen is gained from the weld metal zone with a value of 251 joules/mm^2, followed by the base metal, namely 133 joule/mm^2. While the lowest toughness occurs at the HAZ with a value of 119 joules/mm^2.
3. The highest hardness value is gained from the weld metal zone. This is due to Mn matter contained in the welding electrode wire. As a result, it increases both hardness and toughness.

6. Acknowledgment

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