

DIFFERENT WELDING CURRENT ON MECHANICAL AND ELECTROCHEMICAL BEHAVIOR OF FCAW ASTM A36 CARBON STEEL JOINTS

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Abstract

The effect of different welding current on microstructure, mechanical properties, and corrosion behavior of Flux-Cored Arc Welded (FCAW) ASTM A36 carbon steel joints is studied in the aim of work that used in the welding current like; 180A, 200A, 220A, 240A and 260A corresponding to heat inputs of 1.242, 1.380, 1.518, 1.656 and 1.749 kJ/mm, respectively. The welding process was performed according to the Welding Procedure Specification (WPS) and the Procedure Qualification Record (PQR). Corrosion behaviour of the heat affected zones, weldment and base metal were determined by Tafel polarization curves. It was found that all welding currents, the heat affected zones had the highest corrosion rates which followed by the weldments then the base metal. The welding current at 220A caused the highest corrosion rate in comparison with other welding currents. However, the effect of different welding currents had been studied and measured on microstructures and hardnesses for all specimens after FCAW processes.

Keywords: ASTM A36 Carbon Steel, Corrosion Rates, Flux-Cored Arc Welding, Mechanical Properties

Introduction

Corrosion is widely regarded as one of the most common forms of deterioration experienced by steel structures, seriously affecting their service life. This corrosion induced damage poses a significant threat to the safety and integrity of both building structures and offshore infrastructures as found with major problematic issues in the United States and other parts of the world (Liou *et al.*, 2002; Kannan and Murugan, 2006; Ghazvinlo and Honarbakhsh,

2010). In the past, corrosion has resulted in severe damage and even collapse of both inland and offshore structures causing huge loss of life and property (Badji *et al.*, 2008; Zhang *et al.*, 2012; Dong *et al.*, 2014; Koch *et al.*, 2016). The failure of structures as a consequence of the corrosion can also adversely affect the environment such as, in the 2003 offshore hydrocarbon release of approximately 45% of hydrocarbon (Melchers,

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2003; Ahn *et al.*, 2013). Several researchers have reported the effects of local corrosion on the behavior and performance of structural steels using different corrosion models (Jayaweera *et al.*, 1996; Xu and Qiu, 2013; Qin *et al.*, 2016; Trinet *et al.*, 2016). The early detection of corrosion can reduce associated maintenance costs and improve the service life of steel structures. To improve the corrosion resistance and service life of structural steels, various welding technologies have been developed (Townsend, 2001; Priyantha *et al.*, 2003; Gunasekaran and Chauhan, 2004; Daghash and Ozbulut, 2017). Welding technology with high deposition rates such as flux cored arc welding (FCAW) are increasingly being used in repair welding and to increase the long-term service life of steel structures. The Flux-Cored Arc Welding FCAW process is extensively used in different industries such as pipelines, marine vessels, railways and constructions due to its excellent mechanical properties. Compared to other welding processes such as manual metal arc welding (MMAW), a small amount of heat is introduced into workpieces with the use of hollow electrodes resulting in a smaller heat affected zone (HAZ). Gas tungsten arc welding (GTAW) is the most popular technology for welding, producing. High-quality welds but has low productivity restricting its use in wide applications (Murti *et al.*, 1993; Murugan, and Parmar, 1994; Sireesha *et al.*, 2001; Muthupandi *et al.*, 2003). The benefits of welding are high deposition rates, more tolerance of rust and mill scale and requiring less operator skills compared to gas metal arc welding (GMAW), simpler and more adaptable providing higher productivity than the shield metal arc welding (SMAW), and good surface appearance. The FCAW process were appreciated by industry for many years (Harris and Smith, 1983; Welding and Soldering, 1993; AWS Standard, 1995; Li *et al.*, 2016). Most of the engineering applications require both high strength and corrosion-resistant materials for the long-term reliability and performance. The strength could frequently be achieved by the use of steels that did not possess the required corrosion resistance. A possible way to combine materials solution in order to provide structural components combining carbon, manganese, phosphorus, sulphur, silicon and corrosion resistance, steels was found as being the common and mostly used material in this process (Karadeniz *et al.*, 2007; Coronado *et al.*, 2009; Kumar and Shahi, 2011) investigated SMAW and FCAW. It was found that FCAW gave higher abrasion wear resistance rates than the SMAW. (Patrick *et al.*, 2012) used the high steels (SHS9290) and tungsten carbide-Ni-based matrix which was compounded with SMAW

welding. Hence, it was found that SHS9290 had lower wear rates compared to WC-Ni-based MMC in the dry sand rubber wheel tests and pin-on-flat tests that used garnet abrasive. The results were also similar to the report by (Sitthipong *et al.*, 2017) that also employed MAG, FCAW and SMAW welding on the propeller shaft AISI with X111T5- K4, ER110S-G, and E11018-GH4R electrode.

Besides, it could be explained that the grain structure of the welding metal by FCAW was finer and harder compared to the other welding. At the welding zone structure which was finer, the HAZ Vickers test of FCAW was also produced higher hardness values than other welding resistance of the abrasive wear. This evidence research demonstrated that many industries commonly use FCAW to join the metals and alloys. Incidentally, several research papers have suggested that there was a new and well-known FCAW process which was already used in hardfacing and underwater welding. According to our understanding, the investigation on the effect of welding currents on the vicinity of mechanical properties and corrosion behaviors regarding ASTM A36 carbon steel was not extensively conducted. This paper highlights an experimental study which was carried out in order to analyze the effects of welding varying currents in the FCAW processes. This paper also investigated on various types of carbon steels which were 180A to 260A ASTM A36, respectively. However, there are not many studies and pieces of information regarding microstructures, mechanical properties and corrosion behavior in the region of the Heat-Affected Zone (HAZ), Weld Metal (WM), and Base Metal (BM). The above processes were observed and discussed as follows.

Materials and Experimental Procedures

The six millimeters thick ASTM A36 carbon steel plate used in this study has the chemical composition given in Table 1. Coupons, as shown in Figure 2, were machined from the steel plate in preparation for welding the test specimens. The single V-groove design, with total angle of 60°, was prepared using a semi-automatic gas cutting machine. A flux-cored wire electrode, AWS A5.20 E71T-1C, of 1.2 mm diameter with the chemical composition

shown in Table 2, was used in the flux core arc welding (FCAW) process. In Table 3 shows the parameters for the welding procedure specification (WPS) and procedure qualification record (PQR) used in the FCAW process in this study.

Table 1. Chemical compositions of carbon steel ASTM A36 (% by weight)

Elements	C	P	S	Si
Amounts (%)	0.25	0.04	0.05	0.40

Elements (Continued)	Cu	Mn	Fe
Amounts (%)	0.20	0.80	remaining

Table 2. Chemical compositions of flux-cored wire electrode (AWS A5.20 E71T-1C)

Elements	Amounts (%)
C	0.12
Mn	1.75
P	0.03
S	0.03
Si	0.90
Cu	0.35
Ni	0.50
Mo	0.30
Cr	0.2
V	0.08

Table 3. The welding procedure specification (WPS) and procedure qualification record (PQR) is used in FCAW Process

Name	Parameters
Polarity	DCRP
Shielded gas	CO ₂
Shielding gas flow	20 L/min
Travel speed	200 mm/min

Prior to mechanical testing, the welded specimens were abraded by abrasive wheel then washed with distilled water and air drying as specified by AWS D1.1. Having based on Figure 1, the preparation of the corrosion resistance for the welded specimens is used as a working electrode by connecting with copper wire and mounted in epoxy resin.

Microstructural analysis was carried out. Specimens were successively ground by 180, 400, 600, 800 and 1000 grit silicon carbide (SiC) papers. The ground specimens were then rinsed with ethanol and ultrasonicated in distilled water. The specimens were then etched in 3% nitric acid.

For the corrosion investigation, specimens of 100 mm² were cut from the base metal (BM), the heat affected zone (HAZ) and the weld (WM) for each of the weld conditions. Moreover, the cutting of specimens was used as a working electrode as to connect with the copper wire and to mount in epoxy resin.

The electrolyte used to investigate the corrosion behavior was a 3.5 wt% NaCl solution.

Testing was performed at the room temperature. The counter electrode and the reference electrode were Pt and Ag/AgCl respectively. The corrosion rates were obtained by polarization techniques using an electrochemical station (Autolab, series PGSTAT 30 model, Metrohm). Prior to starting the corrosion measurements, the working electrode was equilibrated for 10 minutes in the electrolyte solution. The specimens were then potentiodynamically polarized and scanned from the cathodic potential to the anodic potential at a scan rate of 0.5mV/ s. The potentiodynamic polarization curves were analyzed using EC-Lab Software version 9.4x (Metrohm), (Gao *et al.*, 2016; Varshney *et al.*, 2016; Feng *et al.*, 2017; Guo *et al.*, 2017).

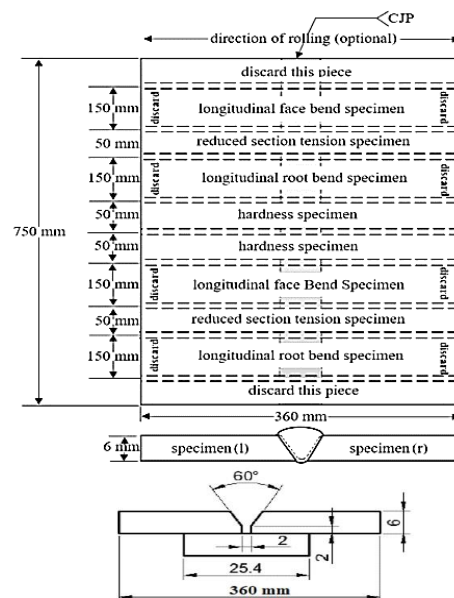


Figure 1. Shows the details and the dimensions of mechanical properties: schematic of the tension specimens, schematic of the hardness specimens and schematic of the bending testing specimens

Results and Discussions

Microstructures of the welded specimens by the optical microscope

The cross-sectional images of the welded specimens at welding currents of 180, 200, 220, 240, and 260 Amp are shown in Figure 2(a), 2(b), 2(c), 2(d) and 2(e) respectively. As shown in Figure 2, as the welding current increased, the width of the weld increased and the reinforcement convex height (R) decreased. All of the welding currents showed

complete penetration. The higher welding currents produced more heat input resulting in and therefore wider HAZ's and slower cooling rates (Gao *et al.*, 2016; Trinet *et al.*, 2016; Guo *et al.*, 2017).

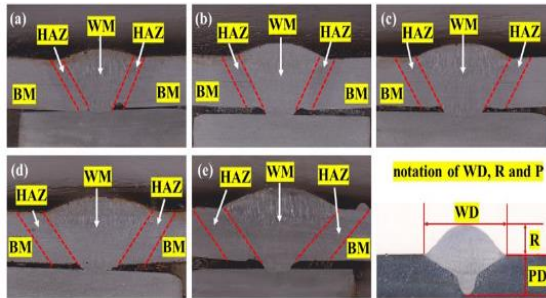


Figure 2. The cross-sections of welded test specimens by FCAW process at (a) welding current of 180 A, (b) welding current of 200 A, (c) welding current of 220 A, (d) welding current of 240 A, and (e) welding current of 260 A. after etching with 3% nitric acid

Note: R is reinforcement of the weld profile. In the visual inspection acceptance criteria AWS D1.1/D1.1M:2015 assigned from 0 to 3 mm or (1/8 inch.) as its maximum. It had affected the strength of the welding. Having used more welding currents, the height of reinforcement would be shorter, whilst the width of the welding bead was wider. Having used the lower welding currents, the height of the reinforcement would be converging increased. However, the width of the welding bead would be narrowed down. The reinforcement of weld derived from this experiment and it accepted various criteria of AWS D1.1/D1.1M:2015.

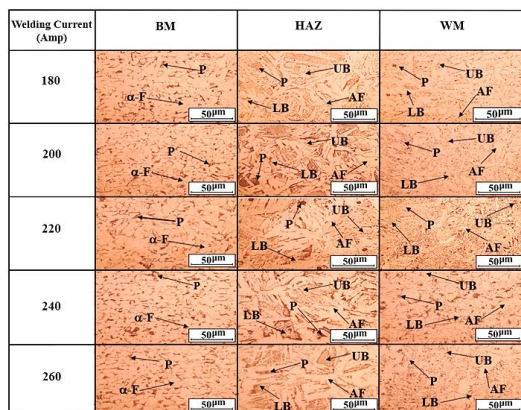


Figure 3. The microstructure of welded test specimens at BM, HAZ, and WM welded by the FCAW process at different welding currents after etching with 3% nitric acid

The micrographs of the BM, HAZ and WM for each of the welding conditions are shown in Figure 3. For the microstructure of the base metal, consists of ferrite and pearlite, the major phase being ferrite. As to be expected there was no difference observed in microstructure for any of the BM specimens because, by definition, they are outside the heat affected zone and thus, phase transformations did not occur.

Note: α -F= Alpha Ferrite, P= Pearlite, UB=Upper Bainite, LB=Lower Bainite

The next area is the heat affected zone (HAZ). It is subjected to temperatures above the critical temperature ($>723^{\circ}\text{C}$) and, as such, undergoes phase changes on heating to austenite then back again on cooling to phases dependent on the cooling conditions.

With an increase in welding current the heat input also increases with a subsequent decrease in cooling rates. The welding of the molten metal would be solidification, whilst having the high temperatures that went down to the room temperatures. Therefore, the size of grains at HAZ area was an expansion that could not contract and inverse to the original phase microstructures of BM. As a result, it produced the coarse grain microstructures. Due to the Carbon Equivalent (CE) of ASTM A36, which was equal to 0.394 in the HAZ microstructures. The composition of carbon (C) was not enough to combine with Fe in order to the transformation of the Fe_3C martensite structure. After the welding, the γ -austenite microstructure in the solidification state was at the high temperature of ($>723^{\circ}\text{C}$). Suddenly, it had been dropped rapidly from 550 to 400°C which became the condition of γ -austenite phase that began the transformation to the upper bainite. This upper bainite is also called feathery bainite because of its feather appearance. The small plates of carbides were parallel to the direction of the bainite growth after having remained the γ -austenite phase. After that, they would be transformed to the ferrite, pearlite phase, which was originally derived from the BM microstructures (Gao *et al.*, 2016; Varshney *et al.*, 2016; Guo *et al.*, 2017; Feng *et al.*, 2017).

The HAZ microstructures at the lower welding currents would contain faster cooling rates at the room temperatures. The upper critical temperatures dropped rapidly from 400 to 250°C , which was the starting point of γ -austenite phase transformation trend to the lower bainite. The lower bainite was also called the bainite plate which has a needle-shaped acicular. In other words, the acicular processes dark-colored needle appearance. For the lower bainite, the ferrite formed its individual and broader plates which were not the same as lathe. The

lower bainite adopted a lenticular shape which was closer to morphology and martensite plate. After the γ -austenite phase had remained, it would be transformed to the ferrite, pearlite phase that was the origin of the BM microstructure (Boumerzoug *et al.*, 2010; Dong, 2014; Kumar *et al.*, 2014; Merchant, 2015; Muda *et al.*, 2015).

Having had observed on the coarse grain microstructures, we could see α -ferrite phase in the white color. At the same time, the lower bainite was seen as the Needle-Shaped (Nb) of the acicular in dark color. On the other hand, some feathery or upper bainite appears in the dark color areas. Feathery or upper bainite is the feather-shaped bainite structures showing in dark colors like the pearlite microstructures. The microstructure were calculated for the area ratio between white and dark color region via ImageJ software, 3 averaged areas per each condition, which is showed in Table 4.

Table 4. The area ratio between white and dark color region of all conditions of specimen (white:dark)

Welding current (A)	BM	HAZ	WM
180	84.92:15.08	81.25:18.75	86.37:13.63
200	82.84:17.16	75.89:24.11	80.18:19.82
220	82.77:17.23	78.40:21.60	72.53:27.47
240	84.33:15.67	79.58:20.42	81.91:18.10
260	82.92:17.10	71.92:28.10	79.64:20.40

In the weld region (WM) the microstructure would depend on the dilution of A36 BM with the lower carbon, high Mn (AWS A5.20 E71T-1C) tubular wire electrode. The dilution of the first part weld especially for FCAW process is approximately 25 to 40 %. Normally, the low carbon steel welding, occurred when we could control the cooling rates after welding becomes very slow. As a result, the WM microstructure would be receiving the α -ferrite and pearlite (α +Fe₃C) phases for the suitable grain growth.

In this experiment, some WM characteristics appeared when welding currents increased much higher, whilst having effected heat inputs. However, the cooling rates would be much slower or decreased. Hence, enough time was provided at the time of welding solidification, particularly, for the grain growth in its full-grown process. When the decreased welding currents had affected the heat inputs, the cooling rate was faster. The grain growth of WM microstructure would be dropped before the full-grown during the welding solidification, if it was not good enough.

Furthermore, the weld dilution of WM was derieved from the BM at the time of solidification of welding at the room temperatures. As a consequence, some γ -austenites would be transformed to the bainite phase. At the higher welding currents and higher heat inputs, some γ -austenites would also be transformed to the upper bainite compared to the lower bainite phase and vice versa. (Bakhtiari and Ekrami, 2009; Eghlimi *et al.*, 2015; Srikarun and Prapas, 2018).

Mechanical properties: tensile test, bending test and its hardness

According to the results from the bending test, all of the welded specimens from different types of welding currents had shown no cracks of the WM. This was examined by the Visual Test (VT), which would be followed by AWS D1.1/D1.1M:2015.

As the welding current levels increased, the tensile strength decreased. The trend depended on the fact that the welding currents had increased or not. If the welding current increased, the heat inputs would increase too. While the γ -austenite phase in HAZ area was cooling down, the welding could have reversed to the original phase of the BM. Additionally, this had given enough time for the recrystallization to refine grains or to lessen the coarse grains as seen in Figure. 3, (Dong *et al.*, 2014; Kumar *et al.*, 2014). When these lessen coarse grains were attracted to their own molecules comparing to the coarser grains, the microstructure received higher strength. All of the welded test specimens were observed to be fractured at the HAZ area. The fracture tensile strength of this experiment, especially of each welding current condition is illustrated in Figure 4.

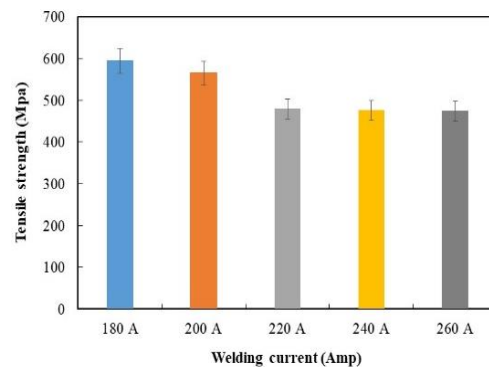


Figure 4. The tensile strength values of the welded test specimens to be fractured at the HAZ area at different welding currents

The stress-strain curve had been fractured at the HAZ area, is illustrated in Figure 4. With in this Figure 5, the researcher observed the invisibility of the clear upper-lower yield stress. That is, the HAZ area was affected from the heat during the welding. After that, ductility, elongation and toughness of the test specimens would be lower down to be lessen than the BM, which was the un-affected heat from the WM areas. These are reasons why all of these specimens tests had been fractured at the HAZ area (Hu *et al.*, 2013; Koch *et al.*, 2016).

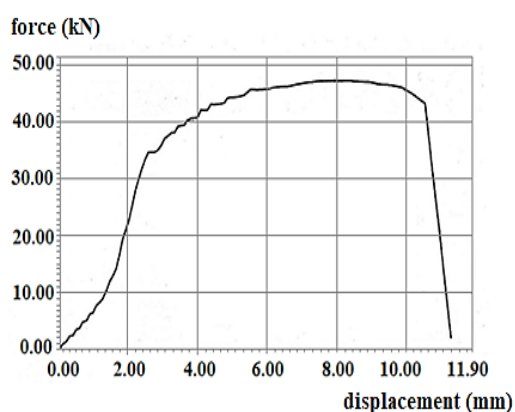


Figure 5. Characteristic of stress - strain curve form experimental

The hardness of the BM, HAZ and WM at different welding current levels was tested by Vickers' s. The result of the hardness values was shown in Figure 6. The hardness values conducted by Vickers' s test the specimens had given the summary to the hardness of the WM which was higher than that of the HAZ and BM. The hardness of HAZ was more than the BM (Boumerzoug *et al.*, 2010; Kumar and Shahi, 2011; Hasrizam *et al.*, 2015; Merchant, 2015). However, as the welding current increased, the cooling rates slowed. These conditions encouraged the microstructure to approach that of the original BM. Furthermore, the amount of bainite phase decreased. After that, it was affected to the hardness which could be decreased at the same time. WM was in the fusion zone or at the higher welding currents. The higher inputs of the welding could slow down the cooling rates, and had more time for the grain growth to the full-grown in suitable grain sizes. In this studies, the FCAW experimental processes of the welding single pass over the single V was resulted into joints. At the higher welding currents, it would have higher heat inputs as well as higher dilution of welding. In these conditions, a lot of welding dilutions taken from the BM, which was about 24 to 40% could be diluted

into the molten welding pool and solidification. They found in the WM microstructures and at higher welding currents of the WM microstructure trends. These demonstrated some upper bainites and lower bainites at the lower welding currents. Last but not least, the summary of this studies illustrated the hardness of WM, which was harder than BM and HAZ.

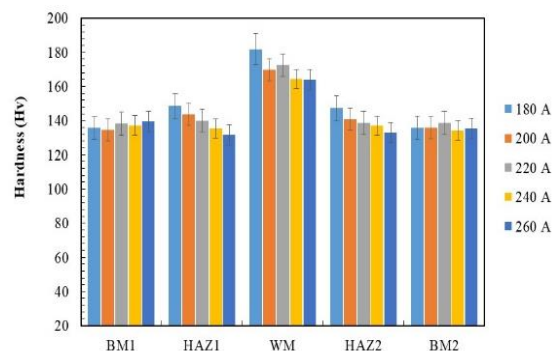


Figure 6. The summary of hardness (HV unit) test value at BM, HAZ, and WM of weld test specimens for welding currents of 180, 200, 220, 240, and 260 Amp.

The Corrosion analysis

Potentiodynamic polarization curves at various welding current levels for BM, HAZ, and WM sepecimens are presented in Figure 7, Figure 8 and Figure 9, respectively. All of the curves show Tafel behavior. Table 5 represents the summary of corrosion potential (E_{corr}), corrosion current density (i_{corr}) and corrosion rates (mm/yr). Inpection of Table 5 shows that the measured corrosion properties of the BM specimens were not affected by welding current as would be expected.

The corrosion behavior of HAZ demonstrated that there was a dramatic difference in the corrosion potential, as depicted in Figure 7 and Figure 8. According to Figure 9, and Table 5, the lowest corrosion resistance potential as well as the highest corrosion rates were observed at a welding current of 220 Amp. At WM, there was a higher corrosion resistance potential than HAZ in every welding current level which was corroded under the same electrochemical reactions seen in Figure 8. As the corrosion resistance potential at HAZ was the lowest one. The above critical temperatures were at ($>723^{\circ}\text{C}$), the α -ferrite microstructures in HAZ were solved to combine with carbon in the γ -austenite phase. Some α -ferrite was previously transformed into the pearlite after the return of the lower critical temperatures. Some losses of α -ferrite

in the HAZ caused corrosion resistance potential effects at HAZ, especially to its decrease. For the WM at the welding current of 220 Amp, its corrosion resistance potential was seen as the lowest one when compared to the others at WM. Moreover, by considering all of the welding currents, the corrosion results demonstrated that the HAZ was severely corroded than WM and BM (Murti *et al.*, 1993; Kumar and Shahi, 2011; Nowacki and Rybicki, 2005; Li *et al.*, 2016; Mirza *et al.*, 2017). Amongst all of the welding currents which were used in this study, it was clearly demonstrated that the carbon steel ASTM A36 could lead to the corrosion rates more than the low alloy steels for the application in the highly aggressive of 3.5 wt% NaCl corrosive solution as shown or referred to on the following sections (Jayaweera, *et al.*, 1996; Townsend, 2001; Priyantha *et al.*, 2003; Xiao *et al.*, 2008; Lee *et al.*, 2009; Geng *et al.*, 2015).

Table 5. The summary of corrosion potential (E_{corr}), corrosion current density (i_{corr}) and corrosion rates in this experiment

Current (Amp)	Position	i_{corr} ($\mu\text{A cm}^{-2}$)	E_{corr} (mV vs. Ag/AgCl)	Corrosion Rate (mm/yr)
180	BM	4.11	-404.11	0.052
	HAZ	1.03	-391.15	0.075
	WM	4.96	-455.81	0.060
200	BM	3.19	-392.24	0.043
	HAZ	0.82	-435.69	0.081
	WM	4.97	-462.94	0.061
220	BM	4.01	-429.26	0.048
	HAZ	2.22	-523.15	0.118
	WM	4.98	-537.35	0.075
240	BM	3.07	-416.89	0.043
	HAZ	2.36	-437.27	0.100
	WM	4.09	-387.52	0.062
260	BM	4.27	-388.58	0.054
	HAZ	2.75	-451.45	0.093
	WM	4.41	-395.38	0.050

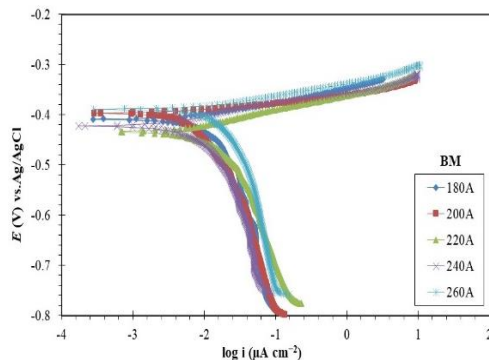


Figure 7. The polarization plot of area un-affected zone of BM, welding ASTM A 36 carbon steel to ASTM A 36 carbon steel by FCAW

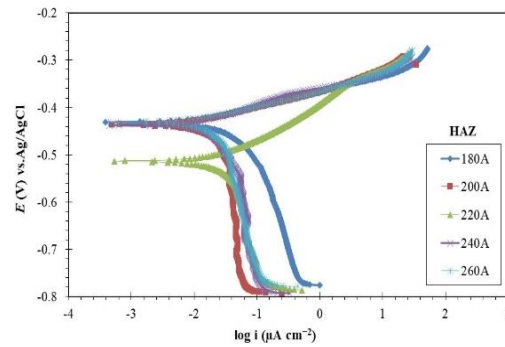


Figure 8. The polarization plot of area heat-affected zone or HAZ of BM when welding ASTM A 36 carbon steel to ASTM A 36 carbon steel by FCAW process at different welding currents of 180, 200, 220, 240, and 260 Amp.

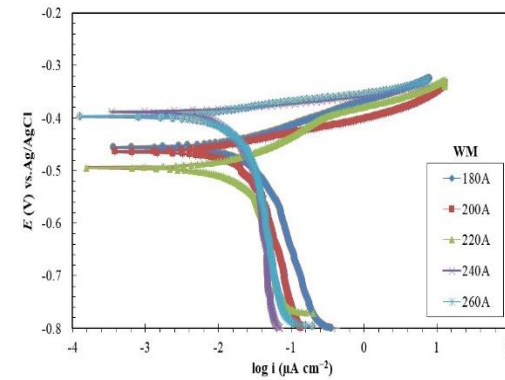


Figure 9. The polarization plot of WM from the welded joint when welding ASTM A 36 carbon steel to ASTM A 36 carbon steel by FCAW process at different welding currents of 180, 200, 220, 240, and 260 Amp.

Conclusion

In this paper, the single V groove welded butt joints of ASTM A36 carbon steels at different levels of welding currents were conducted. The welding current was derived from the heat input which influenced the quality of the welded metal. We have investigated the specimens in these aspects of the microstructure, mechanical properties (tensile strength, bending strength, and hardness) as well as the corrosion behaviors. The following conclusions can be drawn as follows:

1. The microstructures of BM were not transformed due to the effect of heat as they had been welded. Ferrite (α -Fe) and small regions of the

pearlite (α -Fe+Fe₃C) phase appeared in all welding currents.

2. The microstructures of HAZ had received the heat above the critical temperatures at all welding currents especially from 180 to 260 Amp. These were transformed into γ - austenite solid solution.

3. The cooling rates at room temperatures created coarse grain microstructures. The ferrite was shown in white and the bainite appeared in dark colors.

4. The corrosion behaviors of the welded specimens at different welding currents and the corrosion resistance potential at HAZ was considered the lowest ones.

5. The corrosion resistance potentials at BM were similar to different welding current levels.

Author Contribution Statement

Phuri Kalnaowakul: Investigation, Methodology, Software, Trinet Yingsamphancharoen: Supervision, Resources, Writing - review and original draft.

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