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INFLUENCE OF HEAT INPUT ON CARBON STEEL MICROSTRUCTURE

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ABSTRACT

Low heat input is the most common welding parameters selected in industries application due to its ability to produce refined microstructure, less stress and distortion of weldment. However, low heat input has limit penetration and can result in weaken the weldment joint. Recently, high heat input parameter is widely used in shipping industry where it provide deeper penetration. However, high heat input can cause coarse microstructure and decrease weldment toughness which lead to greater amount of distortions. Due to this issue, it is important to know the real effects of applied heat input to the steel microstructure. In this study, two types of carbon steels undergo gas metal arc welding (GMAW) process were investigated to find the effects of low, medium and high heat input on steel microstructures, respectively. From this study, the results revealed that heat input parameters were effect the carbon steel at heat affected zone (HAZ) size, coarse grain heat affected zone (CGHAZ) area and fusion line (FL) length.

Keywords: carbon steel, microstructure, coarse grain heat affected zone, fusion line.

INTRODUCTION

Steel is an Iron-carbon (Fe-C) alloys usually contained less than 2.11 wt. % carbon and widely used in material industries due to its low cost, good mechanical strength, abundance source, high melting temperature, and variety mechanical properties [1-3]. There are several types of steel such as carbon steel, stainless steel, alloyed steel and tool steel. Carbon steel is commonly used for shipping and automotive industries. Usually, this steel undergoes welding process with different heat input to form necessaries part.

Heat Input is a relative measure of the energy transferred per unit length of weld. Heat input is one of the crucial parameter that has to be concerned during welding procedure specification (WPS) preparations. Heat input values will be the determinants for decision of post weld heat treatment (PWHT). The values also influence cooling rate which is the primary factors to determine the final metallurgical structure of the weld and Heat Affected Zone (HAZ). Heat input also one of the factors in determining HAZ grain size and width [4]. Moreover, these welding parameters also act as the main factors in affecting the embrittlement of weld joints [17].

Microstructures play significant effects on steel strength and toughness[5-6]. From literatures, few studies of microstructures have been done on HAZ, but the specific study on Coarse Grain Heat Affected Zone (CGHAZ) and fusion line (FL) are not well documented. Hence, the main focus of this research is to identify the effects of welding heat input parameters (low, medium and high) on the certain numbers of low and high carbon steels microstructures especially in CGHAZ and FL of carbon steel regions.

MATERIALS AND METHODS

Samples preparation

In this study, six (three low carbon and three high carbon steel) samples with dimensions of with 6 mm x 200 mm x 125 mm were provided. Table-1 shows the steel chemical compositions for both low and high carbon steel. The sample undergoes Gas Metal Arc Welding (GMAW) process with three different welding parameters as shown in Table-3. Filler material was used to join the welds and chemical composition for the electrodes presented in Table-2. The samples were then cut into 6 mm x 5 mm x 15 mm as shown in Figure-1.

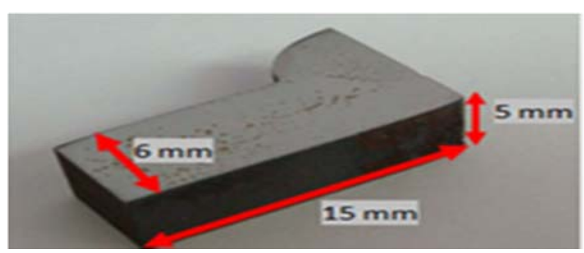

Figure-1. Carbon steel sample.

Table-1. Chemical composition.

Mill certificate	Chemical composition, %								
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo
ABS Grade A	0.17	0.14	0.49	0.018	0.005	0.02	0.02	0.03	0.01
S50C	0.48	0.19	0.69	0.013	0.003	0.01	0.01	0.03	-

Table-2. Chemical composition of filler material.

Wire designation	Wire dimension (mm)	Chemical composition (%)					Tensile strength (N/mm^2)
		C	Si	Mn	P	S	
K-71T	1.2	0.04	0.55	1.25	0.015	0.011	580

Table-3. Welding parameters.

Sample designation	Welding current (A)	Voltage (V)	Welding speed (mm/sec)	Heat input (kJ/mm)
A	135	22	180	0.99
B	166	22	180	1.22
C	196	23	120	2.25

Microscopic study

Microscopic study for both low and high carbon steels were carried out in analyzing their microstructures characteristics. Steel surfaces were grounded and polished with silicon carbide (SiC) and diamond abrasive papers into mirror surface using Metkon Forcipol 2V Grinder Polisher machine. The steels were then etching using 2% Nital solution containing 2ml Nitric Acid (HNO_3) and 98ml ethanol (C_2H_5OH). Nital solution was used to highlighted weld, base, and Heat Affected Zone (HAZ) for more visibility. In this analysis, Metallurgical Microscope (MT8100) with an inbuilt camera (Digital Microscope Camera ProgRes® CT3) as shown in Figure-2(a) was used to observe steel microstructures. The steel microstructures were captured and measured using ProgRes® CapturePro Camera Control Software version 2.8.8 as shown in Figure-2(b). The biggest grain at CGHAZ were then chosen and captured for region of interest (ROI) area measurements. Fusion line (FL) was determine by choosing and captured the widest line before determine its width.

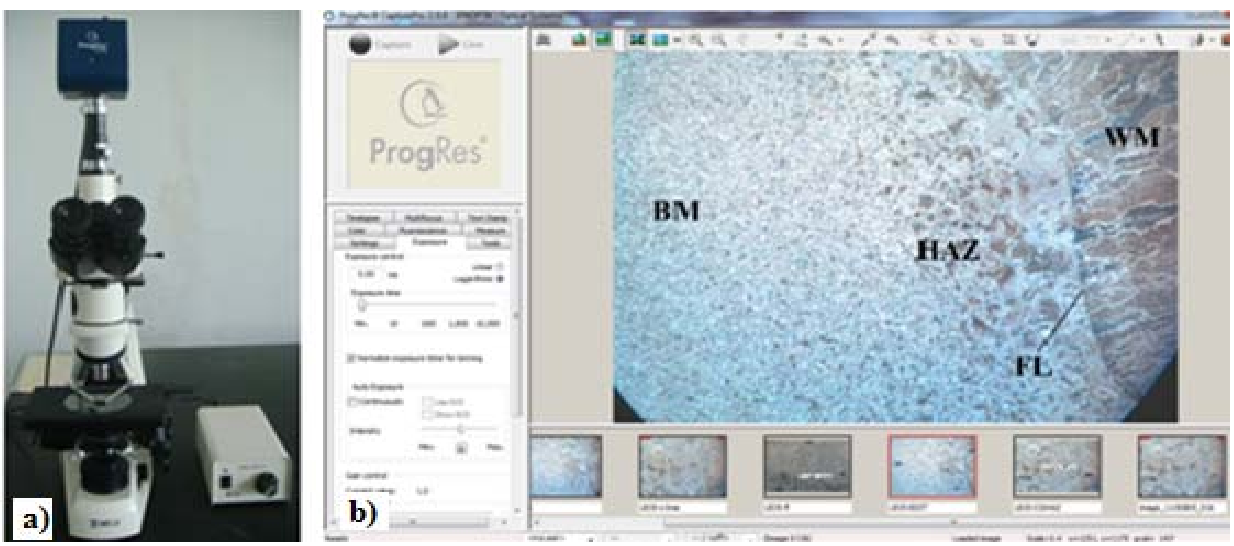

Figure-2(a). Metallurgical microscope (MT8100) and (b). ProgRes® CapturePro 2.8.8 software.

RESULTS AND DISCUSSIONS

Welding steel microstructure

Welding involves heating process that jointwo base metal (BM) together to form into a single component. During the welding process, weld area will be heated up rapidly until melting point and followed by rapid cooling which effect the weld metal microstructures and properties. Meanwhile, BM area was unaffected due to its ROIis relatively far from the heat source. As results, its microstructure and properties are same before and after the welding process. Hence, there will be two main areas after the welding process which are the unaffected area of BM and affected area of weld metal (WM) as shown in Figure-3. Weld area can be defined as an area that comprises of weld metal (WM), fusion line (FL) and heat affected zone (HAZ).

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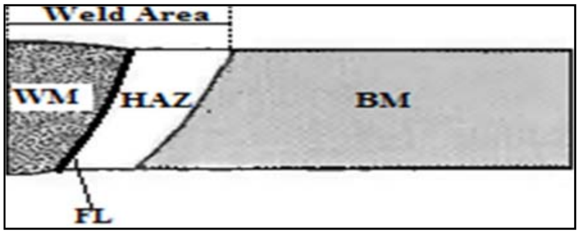

Figure-3. Welding steel component.

During welding process, weld area was heated up rapidly until melting point and followed by rapid cooling. Rapid heating and cooling process will cause microstructural and property alterations, where recrystallization and grain growth of HAZ leads weaken sections and favorable cracking parts at the weldment. HAZ is a part of BM adjacent to the weld which has not been melted, but the mechanical properties or microstructure was altered by heat. The change in HAZ microstructure was depends on the welding parameters and the rate of cooling process. In this case, heat input is one of the parameter in determining the cooling rate as define using the following function [7]:

$$R \propto \frac{1}{To \times Q} \quad (1)$$

where R = cooling rate, To= preheat temperature and Q = heat input.

From the equation, as heat input increase, the cooling rate will decrease. This situation directly expresses the major role of heat input parameters in determining HAZ microstructure. Heat input can be calculated by using following equation:

$$Q = \frac{I \times V}{s} \quad (2)$$

where Q = Heat Input (kJ/mm), I = Current (A), V = Voltage (V) and S = Welding speed (mm/s).

Normally, as heat input increased, HAZ of the joints was increased proportionally. This is because the heat input was moving further in HAZ from the fusion line [8]. Figures-4-6 shows the microstructures of Base Metal (BM), Heat Affected Zone (HAZ), Fusion Line (FL) and Weld Metal (WM) of low carbon steel. Based on the figures, steel with low heat input obtained less coarse HAZ microstructures while the steel with high heat input obtained coarser microstructures than others.

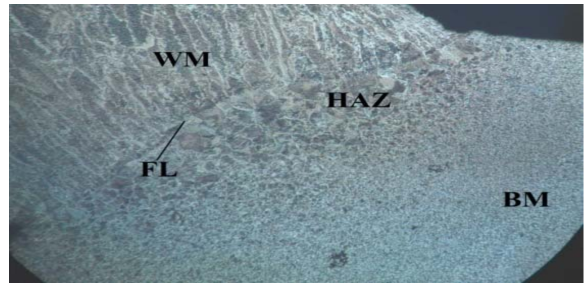

Figure-4. Optical micrograph for low heat input of low carbon steel.

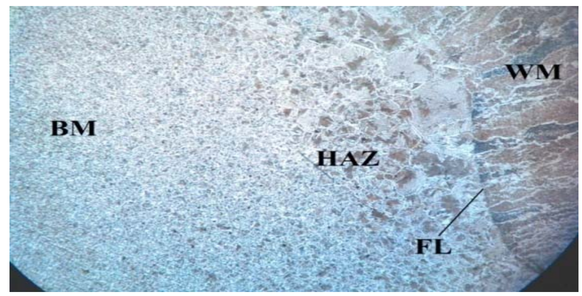

Figure-5. Optical micrograph for medium heat input of low carbon steel.

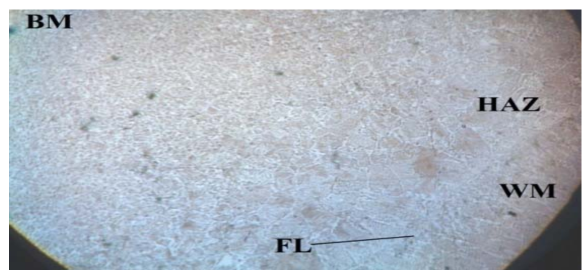

Figure-6. Optical micrograph for high heat input of low carbon steel.

Meanwhile, Figures-7-9 has shown the microstructures of BM, HAZ, FL, and WM of high carbon steel. Based on the figures, steel with low heat input obtained less coarse HAZ microstructures while the steel with high heat input obtained more coarse microstructures than others. Basically high heat inputs cause coarsening of microstructures in HAZ [9], because of that both steel (low and high carbon steel) that undergo high heat input had coarsed microstructure than others heat input. Between low and high carbon steel it looks like low carbon steel had more coarse HAZ microstructures than high carbon steel. This is because the microstructures and mechanical properties of low carbon were changes more rapidly than high carbon steel.

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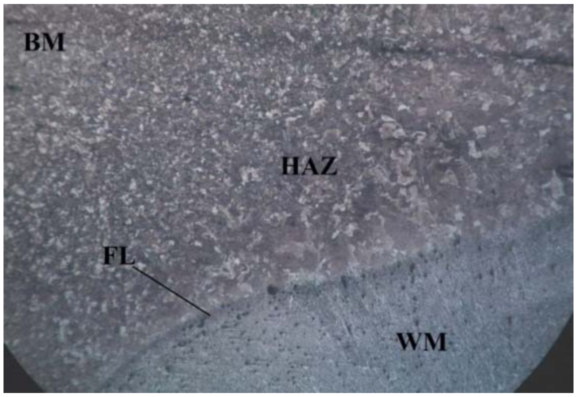

Figure-7. Optical micrograph for high heat input of high carbon steel.

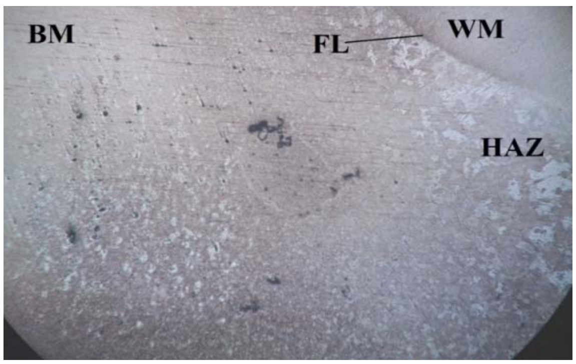

Figure-8. Optical micrograph for high heat input of high carbon steel.

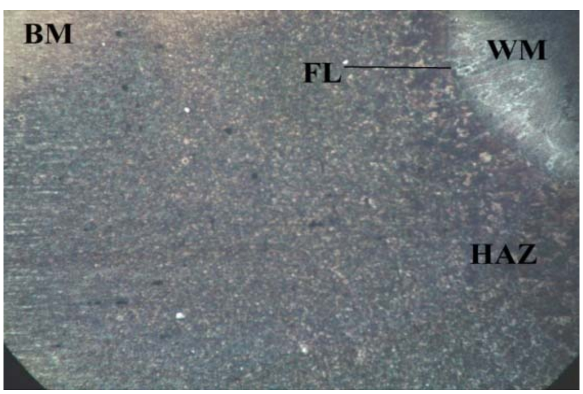

Figure-9. Optical micrograph for high heat input of high carbon steel.

Coarse grain heat affected zone (CGHAZ) microstructure

Heat affected zone (HAZ) can be divided into four areas which are Coarse Grain Heat Affected Zone (CGHAZ), Fine Grained Heat Affected Zone (FGHAZ), Inter-Critical Heat Affected Zone (ICHAZ) and Sub-Critical Heat Affected Zone (SCHAZ) as shown in Figure-10. In HAZ regions, CGHAZ was the most affected and critical area due to the heat treatment during the welding process [17].There was reported that there are stress relief cracking occurs primarily in CGHAZ [10] due to stress and changes in its microstructure. CGHAZ is the nearest area to the fusion line that exposed to high temperature, which cause the grain growth to occur. Based on Figure-10, CGHAZ was formed during temperature heating between 1100^{O}C to 1500^{O}C [11]. Heat input is the main factor in determining the grain size in HAZ [4]. This is because by increasing the heat input, HAZ size will be increase as well as the CGHAZ area. Both low and high carbon steel were shows the same results, where increasing the heat input will increase the sizes of grain areas obtained as shown in Figure-11. In addition, it also revealed the grain areas for high carbon steel are always smaller than low carbon steel. This phenomenon is due to amount of carbon inside the high carbon steel is higher than low carbon steel [12].

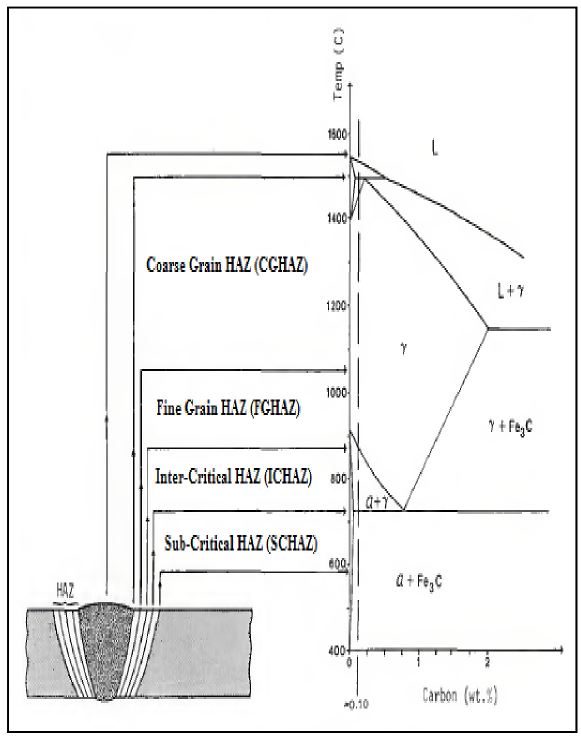

Figure-10. Heat affected zone (HAZ) region superimposed on the iron-carbon phase diagram.

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Table-4. Average CGHAZ grain area forlow and high carbon steel with low, medium and high heat input.

Heat Input (kJ/mm)	**Low Q** (0.99)	**Medium Q** (1.22)	**High Q** (2.25)
Low Carbon Steel (μm²)	72040.83	154974.17	298275.00
High Carbon Steel (μm²)	33993.08	69870.83	204762.50

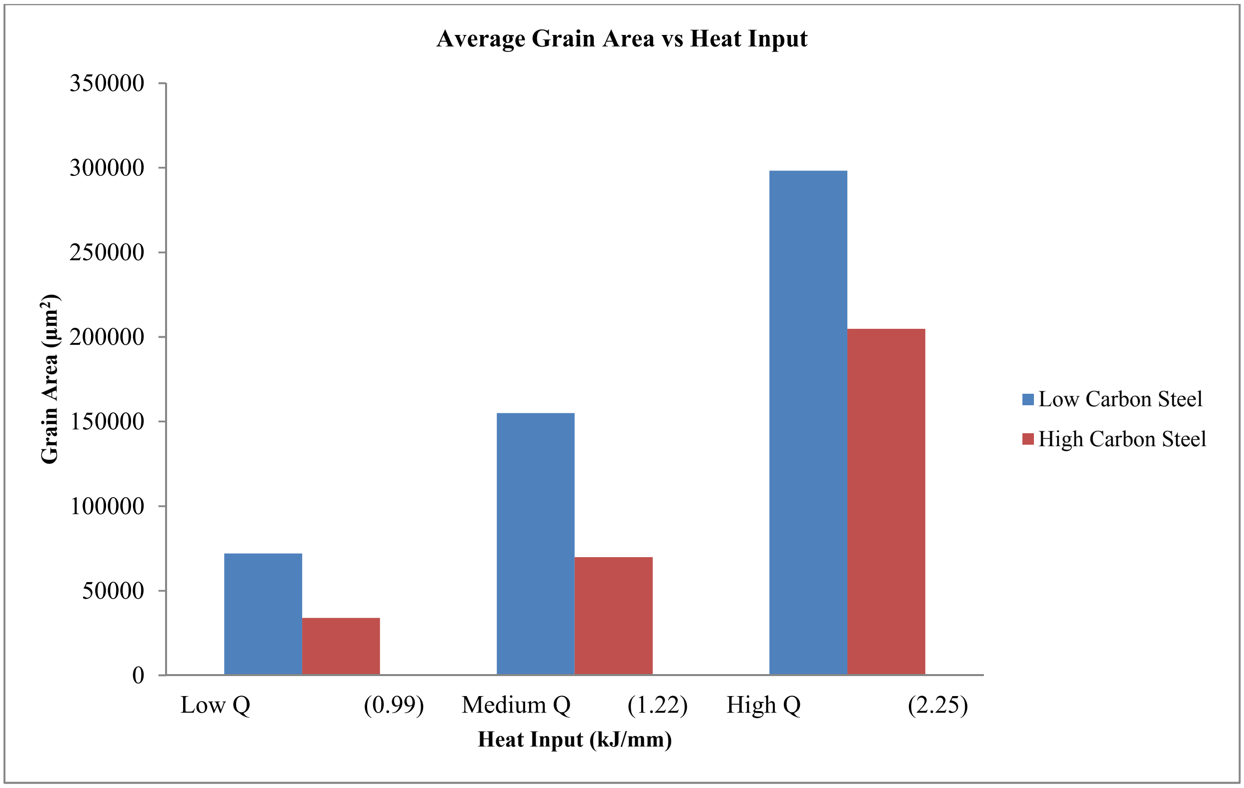

Figure-11. Average grain area for the biggest grain at CGHAZ of low and high carbon steel with low, medium and high heat input.

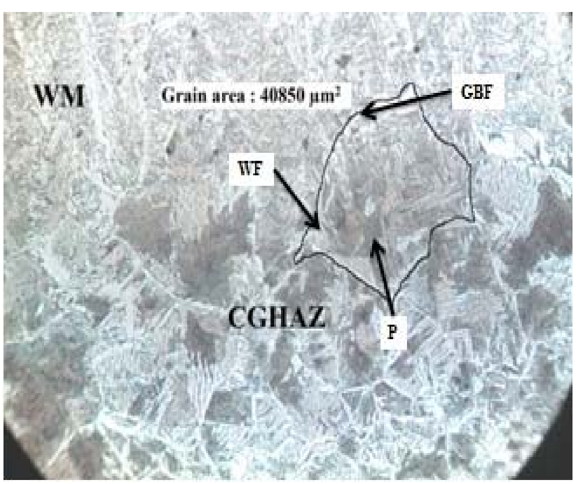

Figure-12. CGHAZ grain area optical micrograph for low carbon steel with low heat input.

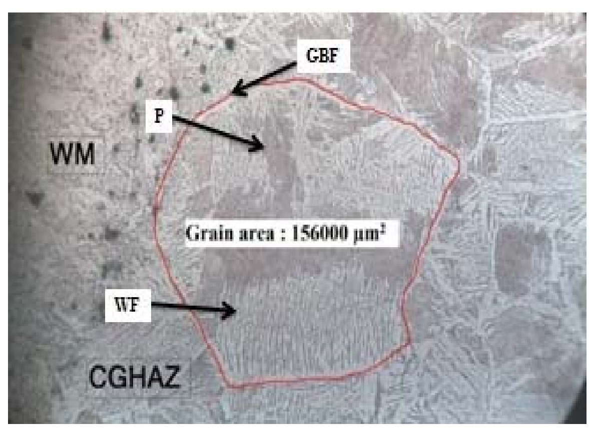

Figure-13. CGHAZ grain area optical micrograph for low carbon steel with medium heat input.

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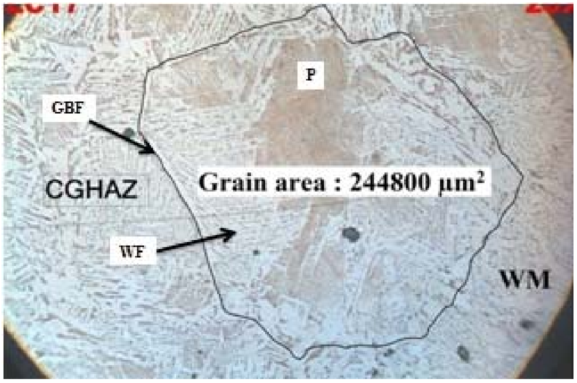

Figure-14. CGHAZ grain area optical micrograph for low carbon steel with high heat input.

Usually, steel that with low heat input will have fine or less coarse HAZ grain microstructures whereas the steel with high heat input will have coarser HAZ grain microstructures [13]. This is because when steel was introduced with low heat input, the steel undergo rapid cooling and lead austenite to transform into martensite and formed fine grain HAZ microstructures. Meanwhile, steel that undergo high heat input will have slow cooling rate and make austenite has enough time to transform into pearlite which formed coarse HAZ microstructures.

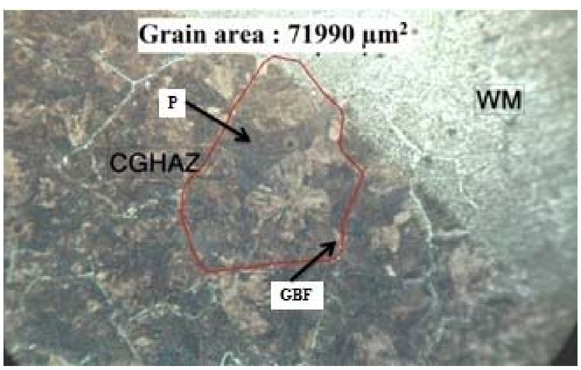

Figure-15. CGHAZ grain area optical micrograph for high carbon steel with low heat input.

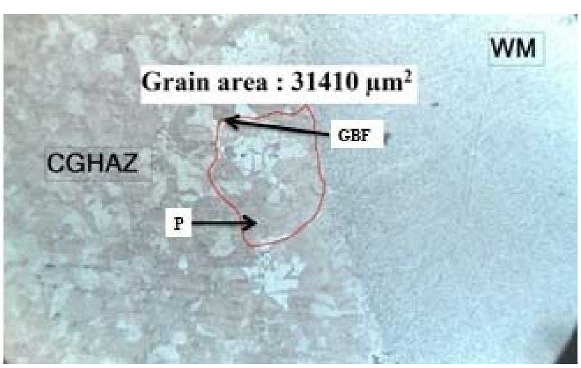

Figure-16. CGHAZ grain area optical micrograph for high carbon steel with medium heat input.

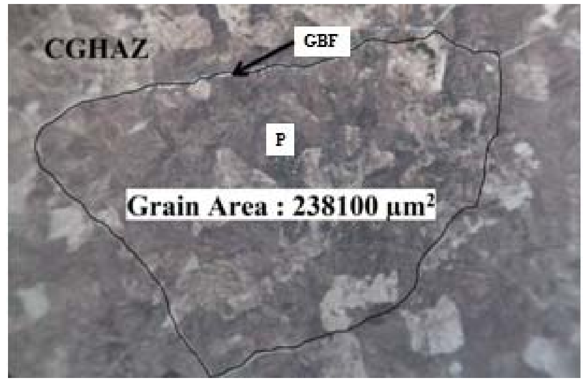

Figure-17. CGHAZ grain area optical micrograph for high carbon steel with high heat input.

Figures-12-14 shows the CGHAZ areas and microstructures for low carbon steel with low, medium and high heat input. Meanwhile, Figures-14-16 shows the CGHAZ areas and microstructures for high carbon steel with low, medium and high heat input. The figures show the biggest grain area at CGHAZ which is consisting of grain boundary ferrite (GBF), widmanstatten ferrite (WF) and pearlite (P). From the figures, only low carbon steel has obtained WF structure, and not available for high carbon steel. Increasing heat input will lead to the increasing amount of WF inside the CGHAZ grain area for low carbon steel. Chadwick was mention that largegrain size will encourage the ferrite to form WF from the grain boundaries[14]. Hence, the amount of WF was keep increasingas increased in CGHAZ grain size. Pearlite is a lamellar mixture of ferrite and cementite. Pearlite formation affected the steel hardness. By increasing the amount of pearlite, the hardness also increase [15]. Based on Figures-12-14, the amount of pearlite (brown region) for low carbon steel were keep decreasing with the increasing of heat input amount, respectively. However for the high carbon steel, the amount of pearlite were keep increasing with the increase of heat input as shown in Figures 15-17 respectively. Low heat input for low carbon steel have more amount of pearlite and lead to coarsen the structures than others, which finally harder the steel. High carbon steel which undergo high heat input will produced highest amount of pearlite and coarser the structure. This phenomenon will leads to harder the steel structure compare to low and medium heat input. For low carbon steel, pearlite was transform scattered inside the grain especially with low heat input. Meanwhile, for medium and high heat input, the pearlite was transforms more in the middle grain. For high carbon steel, it seems like heat input does not effects the pearlite transformation locations. This is because the pearlite are randomly scattered inside the grain for all heat treatment (low, medium and high heat treatment).

Fusion line

In fact, HAZ microstructures contribute to the cracking and fusion line structure. Fusion line (FL) is the border between weld and base metal resulted from

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welding process in CGHAZ. Figure-18 shows the average of fusion FL for both low and high carbon steels. From the figure, increasing in heat input was increased the length of FL. The FL of low carbon steel is longer than FL of high carbon steel. Based on Figures-19-24, we can see that there are different structures or layers at FL, consisted of weld and base metal (CGHAZ) microstructures. Mostly, FL consists of widmanstatten ferrite (WF) and the structure become more refine by the increasing of heat input. High carbon steel have more refine of WF than low carbon steel. WF is a ferrite in form of plate or lath which affects in decreasing the steel toughness [6, 16]. Increasing the amount of WF will decrease the steel toughness. Based on the results, FL and CGHAZ mostly have same microstructures of WF. However, there are a few different where FL has shown to has more refine WF microstructures than CGHAZ.

Table-5. Average fusion line length for low and high carbon steel with low, medium and high heat input.

Heat Input (kJ/mm)	**Low Q** (0.99)	**Medium Q** (1.22)	**High Q** (2.25)
Low Carbon Steel (µm)	148.84	222.51	380.18
High Carbon Steel (µm)	81.63	130.83	199.04

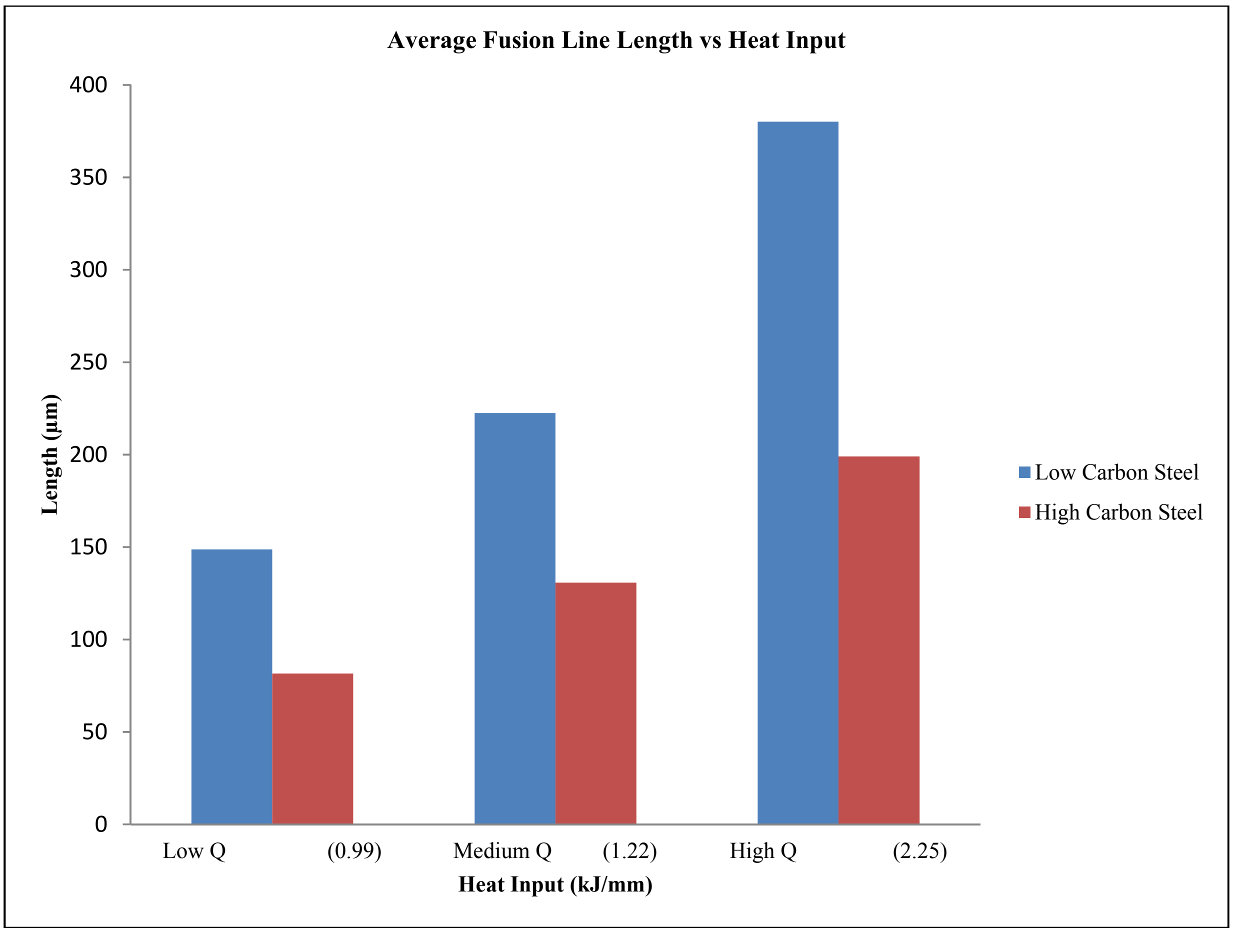

Figure-18. Average of fusion line (FL) length for low and high carbon steel with low, medium and high heat input.

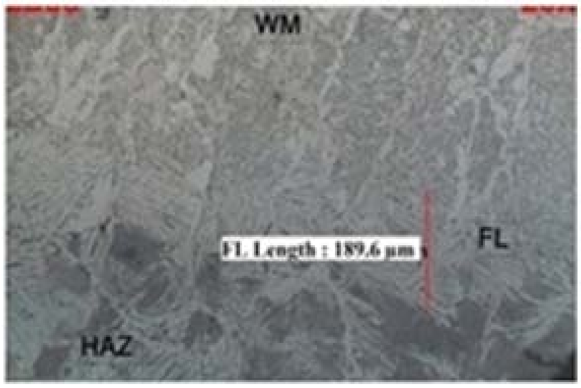

Figure-19. Optical micrograph of fusion line (FL) length for low carbon steel with low heat input.

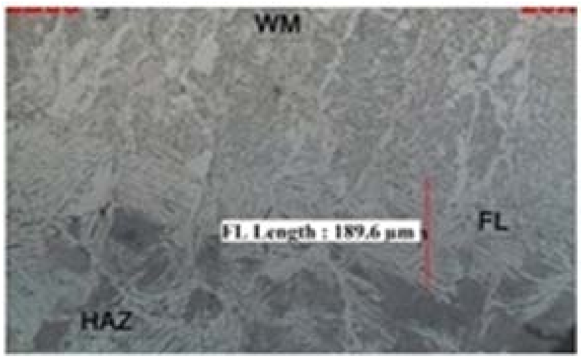

Figure-20. Optical micrograph of fusion line (FL) length for low carbon steel with medium heat input.

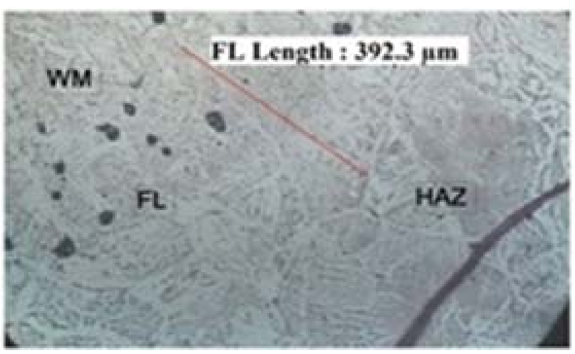

Figure-21. Optical micrograph of fusion line (FL) length for low carbon steel with high heat input.

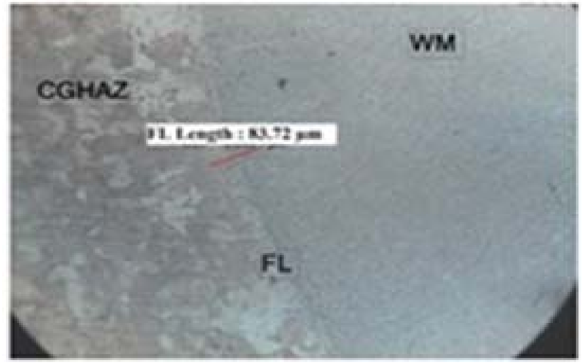

Figure-22. Optical micrograph of fusion line (FL) length for high carbon steel with low heat input.

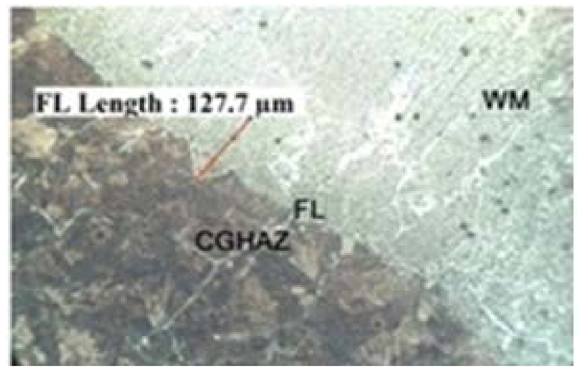

Figure-23. Optical micrograph of fusion line (FL) length for high carbon steel with medium heat input.

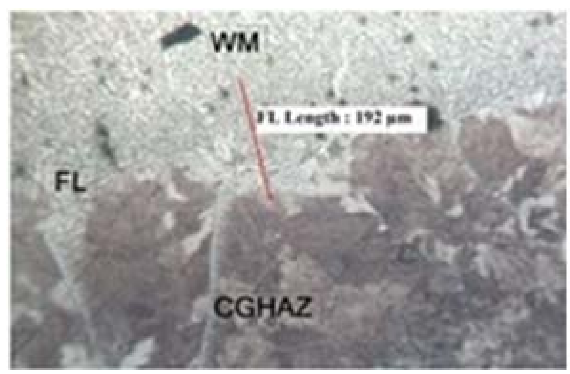

Figure-24. Optical micrograph of fusion line (FL) length for high carbon steel with high heat input.

CONCLUSIONS

Overall of the study, heat input was influenced carbon steel microstructures but the effects are different depending on carbon contents. In this study, it revealed that both of low and high carbon steels will obtain longer fusion line (FL), bigger Coarse Grain at Heat Affected Zone (CGHAZ) size and coarser microstructure with increasing of heat input. The results also show that the biggest grain area at CGHAZ becomes bigger with increasing of heat input. However, there are different in pearlite amount between low and high carbon steels with varies in heat input. For low carbon steel, the amount of pearlite was keep decreasing with increase of heat input. Conversely, the amount of pearlite was keep increasing with increase of heat input for high carbon steel. Fusion line (FL) length was increasing and consist more refine of widmanstatten ferrite (WF) for both low and high carbon steels.

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