EFFECT OF WELDING HEAT INPUT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES AT COARSE GRAIN HEAT AFFECTED ZONE OF ABS GRADE A STEEL

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ABSTRACT

The fabrication and construction of structures used in the offshore and marine industries are made according to the international code and standard requirements to ensure the quality and to extend the life span. Proper material selection needs to be carried out to achieve proper function and to reduce the cost. The American Bureau of Shipping (ABS) Grade A steel is one of the huge materials used in the marine industries. The study has been carried out to scrutinize the effect of welding heat input to the distribution of microstructure formation and its mechanical properties at coarse grain heat affected zone (CGHAZ) of the ABS Grade A steel. Three heat input combinations which designated as low heat (0.99 kJ/mm), medium heat (1.22 kJ/mm) and high heat (2.25 kJ/mm) have been used to the weld specimen by using flux cored arc welding (FCAW) process. The microstructure formation at CGHAZ was consisting of grain boundary ferrite (GBF), Widmanstatten ferrite (WF) and pearlite (P). Significant grain coarsening was observed at the CGHAZ of all the joints, and it was found that the extent of grain coarsening at CGHAZ has also increased along with the heat input. The results of the mechanical investigation indicated that the joints made by using low heat input exhibit higher hardness and impact toughness value than those welded with medium and high heat input. It can be concluded that higher heat input can cause the expansion towards the microstructure's grain size, but will lead to lower hardness and affect the toughness value.

Keywords: Heat Input, Microstructure, Hardness, Toughness, CGHAZ

INTRODUCTION

In practice, the most essential properties of the steels used in marine and offshore structures are good toughness characterized by Charpy V-notch impact test, and tensile strength of the weld joints which made by welding procedures. Due to its high heat inputs during the joining process, the coarse grain heat affected zone (CGHAZ) adjacent to the fusion line of this steel grade represents a region of pronounced low toughness. This is often revealed by fracture toughness tests, which are being increasingly used in marine structural applications.

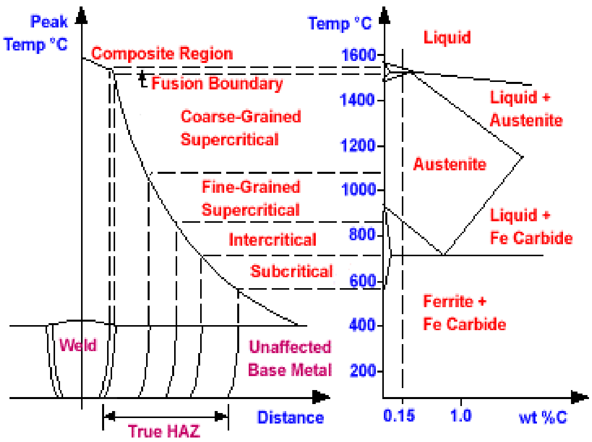
Heat input is known to be one of the factors that influence the formation of microstructure at HAZ. The formation of microstructure especially martensite, bainite and martensite-austenite (MA) constituent potent to affect the toughness of the HAZ, thus lead to the cracking of HAZ just after the welding work. In order to control this problem, it is crucial to understand how the heat input affects a microstructure and relate it to mechanical properties of the material. To date, there are many researches have been done to study the effects of heat input and relate it to the formation of microstructure and its mechanical properties. However, there are still less studies done regarding to the weldments since the previous studies are merely based on simulated HAZ.

Thus, this study aims to characterize and appraise the behavior of microstructure transformation at CGHAZ and its correlation to the heat input. The use of flux core arc welding (FCAW) process during sample preparation reflects the current practice by industry to weld the steel structure. In addition, the elucidation of the transformation behavior can be obtained through the optical microstructure technique and its properties through the mechanical testing. The outcome of this study may provide good information in determining the welding parameter during welding procedure specification (WPS) preparation. The gained knowledge could embark a further research in investigating the optimum heat input range to be set during welding work, thus improve the quality of the weldments.

LITERATURE REVIEW

The microstructure in the HAZ is largely dependent upon the heat input and its location or distance from the fusion boundary. As the distance from the fusion boundary increases, the peak temperature that the base metal microstructure is exposed to decreases. A high heat input increases the time that the base metal microstructure is exposed to the peak temperature. The peak temperature in the HAZ does not reach the melting point of the carbon steel [1]. Generally, the HAZ is the base metal underlying the weld which has been heated to the temperatures above the iron-iron carbide ($Fe\text{-}FeC_3$) metastable phase diagram A1 line (723 ºC) temperature and below the solidus temperature, typically 1495 ºC as shown in Figure-1.

Figure-1. Relationship between heat affected zone and corresponding temperature [1].



Weld area can be defined as the area that includes weld metal and HAZ. The HAZ in metal can be divided into four main areas such as CGHAZ, fine grained supercritical HAZ (FGHAZ), intercritical HAZ (ICHAZ) and subcritical HAZ (SCHAZ). Among these, CGHAZ is the most affected area during welding process due to rapid cooling which caused hardening which in turn can be the main factor of cleavage cracking [1].

In [2] has investigated the effects of coarse initial grain size on the microstructure, hardness and toughness of the weld metal and HAZ of low carbon steel. From the results of the toughness tests, it can be seen that the weld metal of coarse initial grain sized specimens and original specimens exhibited nearly the same toughness values with the same heat input, whereas different HAZ toughness values were obtained with the same heat input. Maximum toughness of HAZ of the coarse initial grain sized specimen was achieved with a high input, while maximum toughness of original specimen was obtained with a medium heat input. As a result, considering the heat input, it was observed that the coarse initial grain size had a great influence on the microstructure, hardness and toughness of HAZ of low carbon steel. The microstructure in weld metal changed from martensite and bainite to grain boundary ferrite, Widmanstaten ferrite, acicular ferrite and pearlite, and the microstructure in GCHAZ changed from martensite, bainite, pearlite and polygonal ferrite to pearlite and polygonal ferrite. The amount of pearlite in GCHAZ increased at the expense of martensite and bainite.

Meanwhile, in [3] investigated the effect of microstructure on hardness and toughness of low carbon welded steel by using inert gas welding. Results showed that by raising the voltage from 20 V to 30 V, the grain size number decreased from 12.4 to 9.8. It was also observed that high heat input and rapid cooling rates in the weld metals produced fine grained polygonal ferrites at ambient temperature. High heat input led to grain coarsening which was more pronounced in the HAZ, as well as reducing the impact energy and toughness. Elevation of heat input reduced the hardness in the HAZ, for instance raising the heat input from 5 to 8 kJ/cm which decreased the hardness from 160 to 148 HBN. This is considered to attribute a reduction in the density of dislocations and microstructural coarsening.

METHODOLOGY

American Bureau of Shipping (ABS) Grade A steel in the form of a 6 mm thick plate was chosen for the study. The welding specimens were prepared in the dimensions of 200 mm x 125 mm. This steel plate is almost exclusively used in the marine industry for the hull structure. This grade is certified by ABS. The steel plate is manufactured by Nippon Steel & Sumitomo Metal Corporation. The chemical composition and mechanical properties of the steel is presented in Table 1.

The technique of FCAW was employed to produce all experimental weld metals analyzed in this work. Welding process was carried out with three different heat inputs (0.99 kJ/mm, 1.22 kJ/mm and 2.25 kJ/mm). The heat input values were adopted from the WPS of Sime Darby Engineering Sdn. Bhd. All welding processes were carried out in a single pass. Subsequent to the welding process, samples were obtained from welded specimens for microstructural examination in the HAZ and in weld metal. The samples were ground, polished and etched with nital 2%.

Microstructure investigations were done by using Meiji MT 8100 optical microscope (OM). Meanwhile, JEOL JSM-6380LA scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM / EDX) was used to analyze quantitative elemental information at the microstructure. The image of microstructures was analyzed by using ImageJ software in order to obtain the grain size and grain area.

Micro hardness indentations in the welding zone and HAZ were made with a 1 kg load. The test was carried out in accordance to ASTM E384. The toughness values of the CGHAZ were determined by Charpy V-notch testing (5 x 10 x 55 mm) at room temperature which according to ASTM E23.

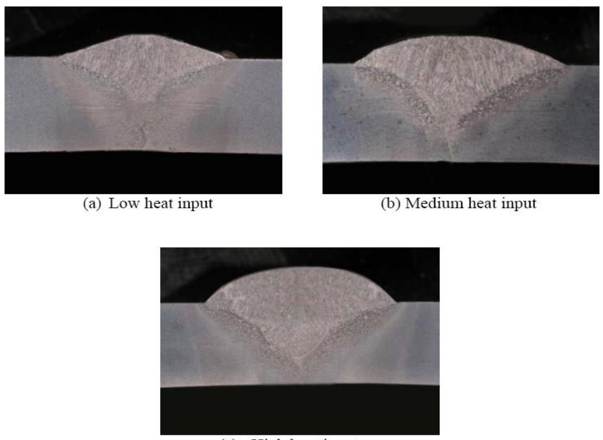
Table-1. Chemical composition and mechanical properties of ABS Grade A steel plate.

Chemical Composition [%]	C	0.17
	Si	0.14
	Mn	0.49
	P	0.018
	S	0.005
	Cu	0.02
	Ni	0.02
	Cr	0.03
	Mo	0.01
Tensile Strength,Rm [N/mm^2]		448
ElongationA_c [%]		28

RESULTS AND DISCUSSION

Weld Specimen and Profile

The location of the different zones in the weld profile is clearly shown in Figure-2. The weld cap, weld penetration and HAZ area which can be seen in the macro figures below. The influence of heat input is noticeable from the diagrams, as the weld cap and HAZ zone are wider with higher heat inputs. It is important to note that the complete joint penetration cannot be obtained where the experiment was carried out in single pass welding. The suitable weld pass for 6 mm thick plates are two in order to obtain the complete joint penetration (CJP) of the weld. However, due to multiple heat treatments that would occur in the area, single pass welding was used during sample preparation.



(a) Low heat input (b) Medium heat input (c) High heat input

Figure-2. Macrograph of weld specimen at the different heat input.

Dimension of weldment and HAZ are shown in Figure-3. At low heat input, the average weld width is 8 mm. Meanwhile, the average depth of penetration and

HAZ width is 4 mm. When the heat input increased to 1.22 kJ/mm and 2.25 kJ/mm, the average welds width, depth of penetration and HAZ indicated the increment. As indicated by these values, it was found that as heat input increases, the fusion areas of the joints also increased proportionately. The same trend was followed in the HAZ area associated with each of these joints. In [4] has reported similar trends while studying TIG welded 304 stainless steel and SMAW welded duplex stainless steel, in which fusion zone and HAZ area increased with increasing of heat input value.

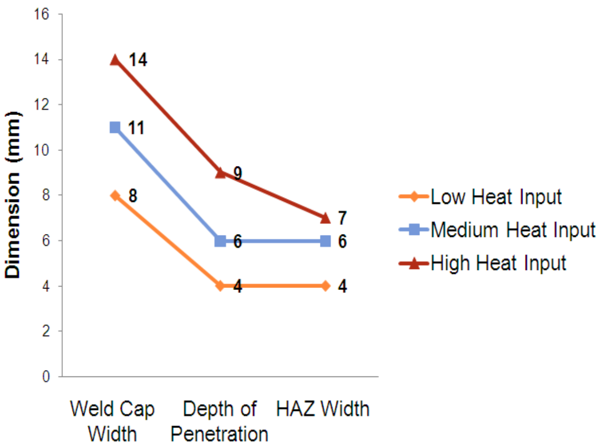


Figure-3. Dimension of weldment and HAZ at different heat input.

Weld Microstructure of ABS Grade A Using FCAW

Micrograph of all the weld specimens was taken. The micrograph in Figure-4 shows the different zones which include the weld metal, fusion line and HAZ (CGHAZ and FGHAZ) for different heat input. As the heat input increased, the HAZ areas of the joints also increased proportionally. The heat input moved the place of HAZ further from the fusion line. The average grain size also increased with the increasing heat input value. The highest concentration of pearlite was observed in the CGHAZ. The FGHAZ is the zone after CGHAZ, in which the microstructure is smaller than the latter.

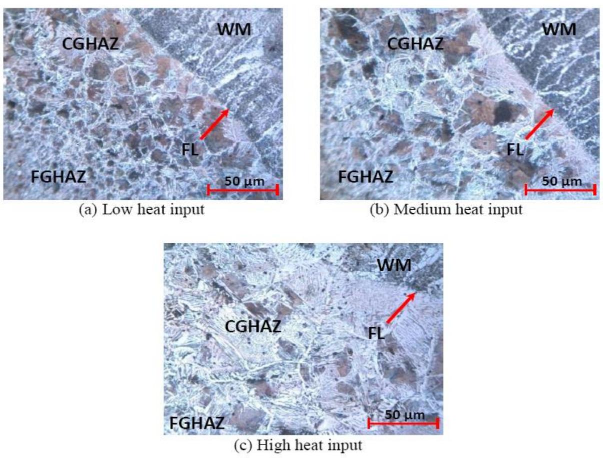


Figure-4. Microstructure of ABS grade A at different heat input.

Figure-5 shows the weld microstructure of ABS Grade A steel with low heat input, medium heat input and high heat input. The weld structure of ABS Grade A steel plate was a ferrite-pearlite microstructure. Initial columnar grains formed by epitaxial growth were detected by the presence of grains of polygonal ferrite (PF) and Widmanstatten ferrite (WF) along the former grain boundaries. However, the main constituent is an acicular ferrite (AF) which forming a "wicker basket" structure [5]. The first phase forming on grain boundary ferrite (GBF) during cooling below the A3 temperature is referred to as polygonal ferrite (PF). In [2] also found similar weld metal microstructures on his study about the effect of coarse initial grain size on microstructure and mechanical properties of low carbon steel.

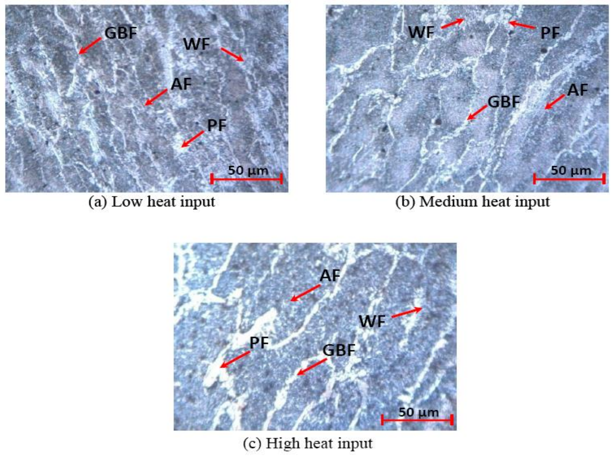


Figure-5. Weld microstructure at different heat input.

At relatively low undercooling temperatures, Widmanstatten ferrite formation occurs. The ferrite plates grow rapidly with a high aspect ratio, resulting in parallel arrays. Widmanstatten ferrite plates grow directly from a GBF or from polygonal ferrite at the grain boundaries. Acicular ferrite is recognized as an intragranular nucleated morphology of ferrite in which there are multiple impingements between grains. The acicular ferrite nucleates on inclusions inside the GBF during the $\gamma \rightarrow \alpha$ transformation. As there is a high density of inclusions, a fine interlocking structure is produced [5].

Effect of Heat Input on CGHAZ Microstructure

The microstructures at CGHAZ were illustrated clearly in the Figure-6. It can be seen that the CGHAZ microstructures contain some colonies of pearlite which was represented by brown region. Meanwhile, the ferrite was represented by white region.

The microstructures at CGHAZ of all specimens consist of GBF, WF and pearlite (P). The results of these microstructures are in good agreement with the study conducted by [2]. The presence of martensite was not identified in all of the specimens. The phenomenon occurred due to the selection of heat inputs used (0.99 kJ/mm, 1.22 kJ/mm and 2.25 kJ/mm) which is still considered as high heat input. It was already known that the higher heat input resulting in slower heating and cooling. Relatively, higher heat input resulting in longer cooling time causes the diffusion of carbon between the carbon-rich austenite and the carbon-poor austenite [2].

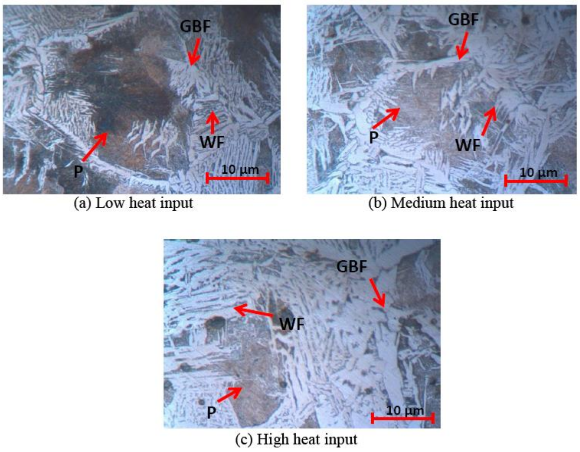


Figure-6. CGHAZ microstructure at different heat input.

It can be observed that ferrite and pearlite tend to refine in comparison with the microstructure of CGHAZ at low, medium and high heat input. It also can be noted that the amount of pearlite region had decreased with increasing the value of heat input. The rate of pearlite formation can be varied under certain circumstances. An important factor is the amount of carbon diffusing in the metal and its effect of pearlite layer formation. Diffusion is directly proportional to the temperature according to Eqn. (1).

$$D = D_o exp\left(-\frac{Q}{RT}\right) \quad (1)$$

where D is the diffusion coefficient, D_o is the self-diffusion, Q is the activation energy, R is the Boltzmann's constant and T is the absolute temperature. During cooling, austenite to pearlite transformation proceeds at a fast rate due to its nucleation and growth [3].

If a specimen undergoes a low heat input, there would be a suitable condition for nucleation in the edges and grain boundaries. Consequently, carbon can dissipate extensively which resulting in the formation of pearlites.

However, super cooling from a high temperature may contribute to reduce nucleation and hence the formation of ferrites. At high super cooling conditions, there would be a greater tendency for the formation of ferrites from the grain boundaries, possibly in the form of Widmanstatten [3].

The average grain size of CGHAZ increased with an increase of the heat input. It can be seen clearly in Figure-7. At low heat input, the average grain size is 28.31 µm. This indicated that when the heat input was relatively low. Although recrystallization occurred in the HAZ, the coarsening of grains in the HAZ was not obvious. Meanwhile, when the heat input increased to the medium (1.22 kJ/mm) and maximum value (2.25 kJ/mm), the grains in the HAZ grew up to an average grain size of 43.31 µm and 68.90 µm respectively. The grain area also showed the similar trend. Low heat input has the smallest area (1016.83 µm^2) compared to the medium heat input (2091.21 µm^2) and high heat input (4947.56 µm^2).

According to [3], grain coarsening in the HAZ can be explained by the operating thermal cycle and diffusion. The grains close to the fusion line are exposed to higher temperature, therefore grain growth occurs. Clearly, large ferrite grains resulted in large austenite grains.

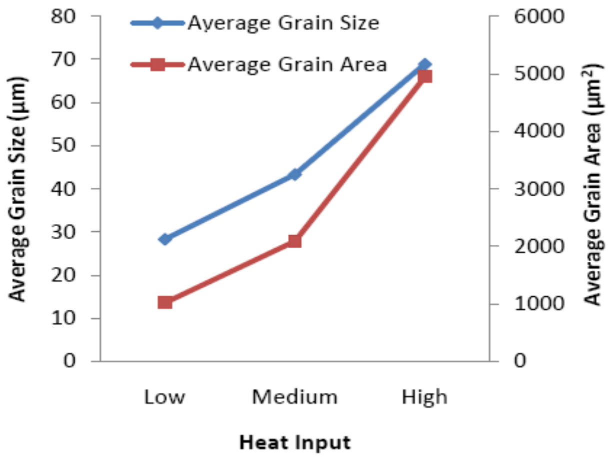


Figure-7. Average grain size and average grain area of CGHAZ at different heat input.

Another important factor that contributes to grain coarsening is grain boundary mobility and fusion. Grain boundary movement depends on diffusion and atomic migration on both sides of the grain boundary. Diffusion itself is a function of retention time at high temperature and leads to the migration of atoms and displacement of grain boundaries. The relation between atomic displacement and time is given by the Eqn. (2):

$$r = 2.4\sqrt{Dt} \quad (2)$$

where r is the radial distance from the origin, D is the diffusion coefficient, which is related to the temperature and t is the elapsed time. It can be seen that the atomic displacement is directly proportional to the square root of time. Low welding speed and high heat input led to larger grain size.

Effect of Heat Input on CGHAZ Hardness

In this study, micro hardness test was conducted on the base metal, weld metal and HAZ areas at 1 mm intervals. It can be observed that the lower the heat input, the higher the micro hardness of the HAZ and weld metal. As an example, elevation of heat input from 0.99 kJ/mm to 1.22 kJ/mm reduced the range of hardness from 152-197 HVN to 157-169 HVN.

Meanwhile, range of hardness of 204-226 HVN, 207-216 HVN and 197-199 HVN were measured in the corresponding welded material. The micro hardness profile at different zones in the weld metal at low heat input, medium heat input and high heat input which can be seen clearly in the Figures-8-10 respectively.

As the indentor moves from the left of base metal towards the fusion boundary and weld metal, micro hardness increases from 134 to 226 HVN for low heat input, 135 to 216 HVN for medium heat input and 139 to 199 HVN for high heat input. It was found that micro hardness of the weld metal is the highest compared with HAZ and base metal.

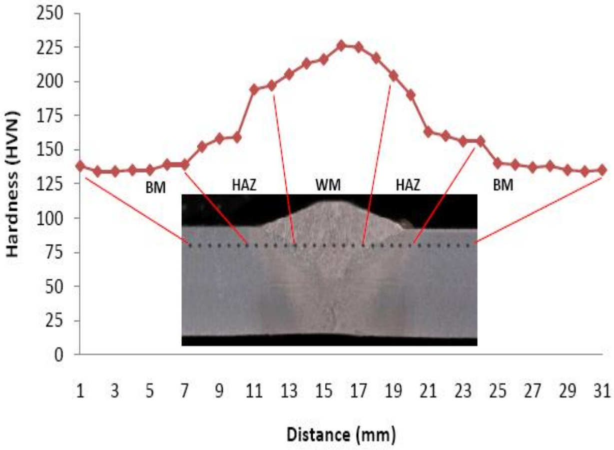


Figure-8. Micro hardness profiles at low heat input.

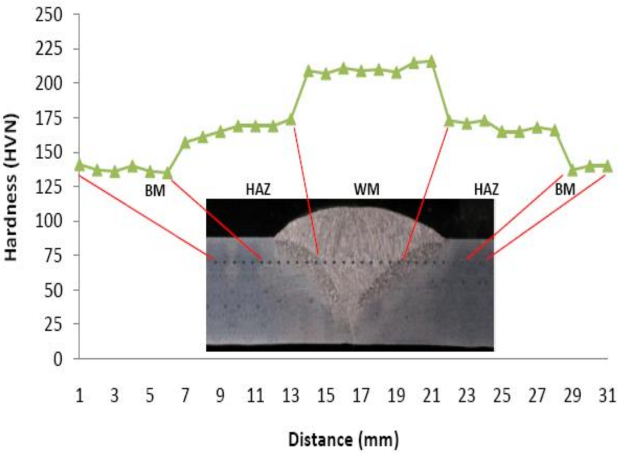


Figure-9. Micro hardness profile at medium heat input.

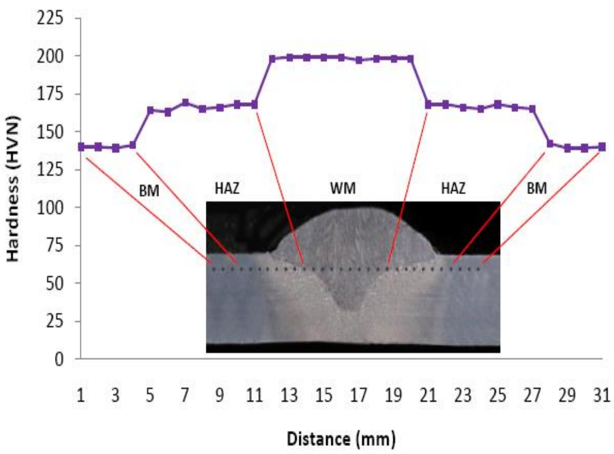


Figure-10. Miro hardness profiles at high heat input.

One of the factors contributing to lower hardness in the HAZ zone is that of the high heat input, and hence retention of heat in this region. In [3] explained the above-mentioned phenomenon in his study on low carbon welded steel using inert gas welding. Generally, grain nucleation and growth of austenite can lead to reduced dislocations and work hardening compared to its elementary condition. Annealing of the HAZ can have pronounced effect on phase and morphology. The net effect reduces dislocations and hardness.

In spite of the presence of high temperature in the welded metal, the cooling rate is also high which presents the nucleation of very fine grains. Besides, fine grain structures exhibit low intergranular spacing. The stress for dislocations to cross grains can be calculated by using the Eqn. (3):

$$\tau_o = Gb/L \tag{3}$$

where G is the shear Young modulus, b is the dislocation Burger's vector and L is length of separated distance. High hardness in the welded zone may be attributed to the fine grain size, needle shaped ferrite or the existence of Widmanstatten inside ferrite grains. Hardness and grain size are inversely proportional [6] as given by Eqn. (4):

$$H = Ho + K/\sqrt{d} \tag{4}$$

where H is hardness, K is proportionality constant and d is grain size. Thus, the lower hardness in the HAZ may be related to grain growth and the existence of the ferrite phase in this region, which has been reported by [7,8].

At low heat input, the maximum hardness value of HAZ area was 197 HVN on the left and 190 HVN on the right welds metal. The location was close to the fusion boundary and it was determined as CGHAZ. The similar location was found in the medium heat input and high heat input. The maximum hardness values at HAZ were 174 HVN on the left and 173 HVN on the right for medium heat input. Meanwhile, for high heat input the maximum hardness values were 168 HVN for both sides. The results show that any increase in the heat input has an inverse effect on the hardness of at CGHAZ. The micro hardness comparison of different heat input can be clearly shown in the Figure-11.

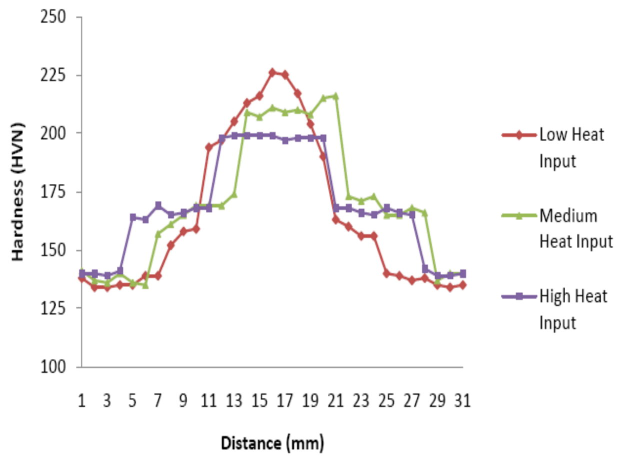


Figure-11. Micro hardness profiles at different heat input.

Effect of Heat Input on CGHAZ Toughness

According to [9], lower toughness values occur because of a wide HAZ. The lowest toughness values were in CGHAZ. As the HAZ is wide, all zones will be wider and then the Charpy V-notch test place is more in CGHAZ and fusion line. In this study, the same results have been observed. The impact toughness values of the CGHAZ tested at room temperature are presented in Figure-12.

It can be observed that the impact toughness values are proportionally decreasing when heat input increase. The maximum of impact toughness value of 66 J was achieved after welding with low heat input (0.99 kJ/mm). At medium heat input and high heat input, the average impact toughness values are 35 J and 30 J respectively. The average impact toughness value of base metal is 103 J.

Absorption of impact energy can be controlled by chemical composition, microstructure and the heating cycle. Excess grain growth can lead to reduced strength and increase crack initiation and growth. Furthermore, it can adversely affect the fracture toughness which may arise due to heating and cooling cycles [3].

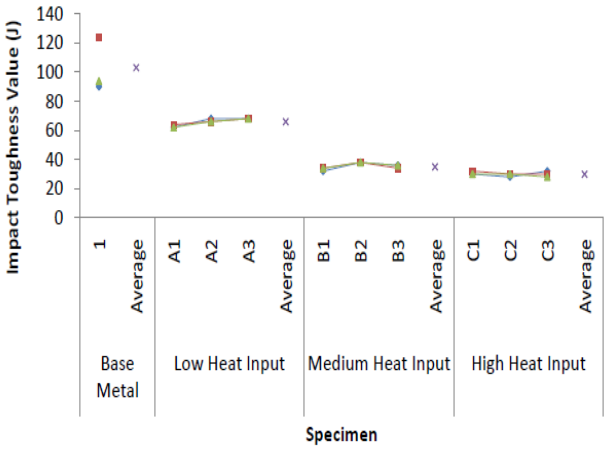


Figure-12. Charpy V-notch test result of all samples at different heat input.

The fracture surfaces were also evaluated by SEM, and the results are shown in Figure-13. As seen in the figure, dimples of varying size and shape were observed in all the fractured surfaces which indicate that a major fracturing mechanism was ductile.

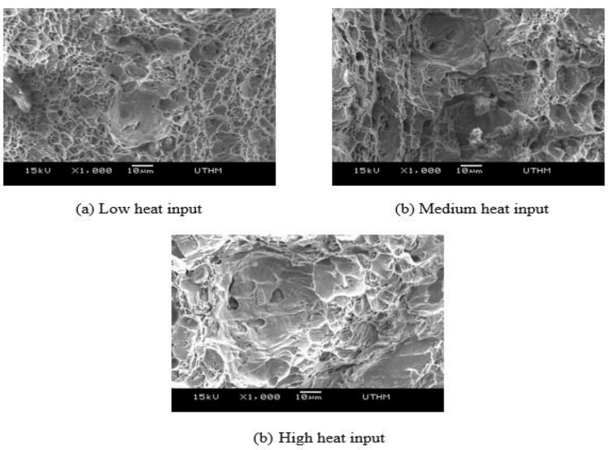


Figure-13. Fracture surface of specimens at different heat input.

It was observed that the fractured surface of the specimen at low heat input that contains a large population of small and shallow dimples which is indicative of its relatively ductile fracture. As heat input increases, coarse and elongated dimples were observed. When welding with medium heat input, entirely ductile fracture together with a local cleavage type fracture appeared. The fracture surfaces showed a combination of trans granular fracture and micro void coalescence (MVC). The fracture surface broken with high heat input exhibited brittle fracture behavior. Due to high heat input, trans granular fracture by quasi-cleavage and relatively flat surface that was observed.

At low cooling rates, growth of austenite grains proceeds which ultimately lead to the formation of coarse pearlite and planar ferrite. The existence of acicular ferrite is desired where it improves the toughness of the weld metal. In [10] observed that the toughness of welded metal increases with increasing volume fraction of acicular ferrite. The interlocking nature of acicular ferrite, together with its fine grain size which provide the maximum resistance to crack propagation and cleavage fracture.

Ferrite grains obtain larger than the austenite grains under high heat input conditions. The net effect of such structure is grain boundary growth. Since the yield strength of ferrite grain is lower than that of pearlite, crack initiation and growth is more likely to occur in the ferrite grains. On the other hand, dislocations can move easier in structures which containing large grains that resulting in reduced ductility.

Correlation between Microstructure and Mechanical Properties at CGHAZ

The correlation between microstructure and mechanical properties at CGHAZ can be illustrated in the Figure-14. By raising the heat input, the average grain size was increased from 28.31 µm to 68.90 µm at CGHAZ. Meanwhile, hardness and impact toughness value proportionally decreased when increasing the heat input. The elevation of heat input led to grain coarsening which was more pronounced in the CGHAZ, as well as reducing the hardness and impact toughness value. When the heat input increased, the hardness and impact toughness value was decreased from 197 HVN to 168 HVN and 66 J to 30 J respectively. This is considered to be attributed to a reduction in the density of dislocations and microstructural coarsening.

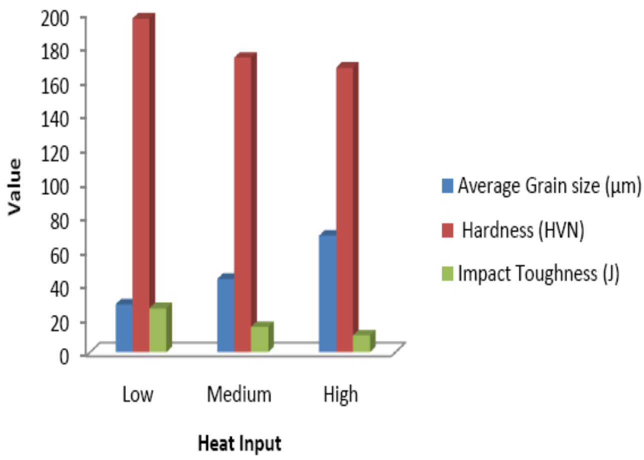


Figure-14. Correlation between microstructures and mechanical properties.

CONCLUSION

In this study, the observation was concentrated to the microstructure and mechanical properties (hardness and toughness) at CGHAZ. The use of the actual FCAW welding process instead of using simulated HAZ produces the actual distributions of microstructure formation and mechanical properties at CGHAZ. In conclusion, the objectives which were to scrutinize the effect of welding heat input to the distribution of microstructure formation and its mechanical properties at CGHAZ of the ABS Grade A steel were achieved. The correlation of heat input and mechanical properties and its relationship with HAZ cracking is also being elucidated.

The main conclusions about the effects of welding heat input on microstructure and mechanical properties at CGHAZ of ABS Grade A steel are as follows:

a) The higher the heat input, the coarser the microstructure. Grain coarsening occurs due to operating thermal cycle and diffusion. The grains close to the fusion line are exposed to higher temperatures, therefore grain growth occurs.
b) The higher the heat input, the lower the hardness value at CGHAZ. Retention of heat in the CGHAZ zone contributes to lower the hardness value.
c) The higher the heat input, the lower the impact toughness value. Excess grain growth led to reduced strength and increased crack initiation and growth. It adversely affected the fracture toughness, which may arise due to heating and cooling cycles.
d) The higher the grain size, the lower the hardness and impact toughness value. High heat input led to grain coarsening which was more pronounced in the CGHAZ. Hardness and impact toughness value decreased when the heat input increased.

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