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# Effect of Welding Heat Input on the Mechanical Properties of Mild Steel at Coarse Grain Heat Affected Zone (CGHAZ)

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**ABSTRACT**

Welding is a joining method often used in industry, especially involving mild steel. Welded areas have a high probability of failure, especially if there are defects because of the welding process. Therefore, the welding area known as the Coarse Grain Heat Affected Zone (CGHAZ) needs to be given high attention. The heat input value is the main factor that shapes the microstructure changes in the CGHAZ area. This change in microstructure results in a change in the mechanical properties of the material. In this study, the effect of heat input using the Gas Metal Arc Welding (GMAW) method on the microstructure and mechanical properties of mild steel is studied. Nine different heat input values are used by setting a combination of current (50 A, 100 A and 150 A) and voltage (15 V, 20 V and 25 V). Observations in the CGHAZ area were carried out using an optical microscope (OM). The presence of Austenite, Grain Boundary Ferrite (GBF), Widmannstetter Ferrite (WF), Acicular Ferrite, Pearlite (P), Ferrite, Cementite, Upper Bainite, Lower Bainite and Martensite phases are observed in CGHAZ. Vickers hardness test and Charpy impact test were also performed to see the change in the mechanical properties of the material. It was found that the hardness and toughness values decrease with increasing heat input values. It can be concluded that a higher heat input causes a larger grain size of the microstructure in the CGHAZ part, which causes a reduction in the hardness and toughness values of the material. In addition, it also increases the probability of cracking and reduces the integrity of the overall structure.

***Keywords:***
Mild steel; welding; heat input; bumper beam

## 1. Introduction

Welding is the technique of combining two or more pieces using heat [1, 2]. In the welding process, one of the things that is emphasized is the Heat Affected Zone (HAZ), as shown in Figure 1 on the parent metal. Heat input affects the crystallographic structure at CGHAZ [3–12]. The

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production of microstructure, particularly the components martensite, bainite, and martensite-austenite (MA), can affect the CGHAZ's toughness. The M-A constituents are a mixture of untransformed austenite and martensite that form at the intercritical or subcritical temperatures during cooling. They have various shapes and sizes, such as dot-like, slender, or blocky. The lack of toughness due to the microstructure formed in the CGHAZ area will cause stress points to occur in the CGHAZ area and result in cracks [10, 13]. It is essential to be aware of the main process parameters influencing the welding zone and select the appropriate set, avoiding any trial (i.e. tools and machine cost, manpower, time, material, waste production and management), to obtain the component with the best performance [14]. Thus, studies are actively conducted both experimentally and numerically [14–17] to explain the association. Therefore, it is necessary to understand how the heat input changes the formation of the microstructure and mechanical characteristics in the CGHAZ area, which is an area with a high probability of experiencing a defect and connect it to the material's mechanical properties to reduce the occurrence of defects in the CGHAZ area. Numerous studies have been conducted to investigate the effect of heat input on changes in microstructures and mechanical properties of welded materials.

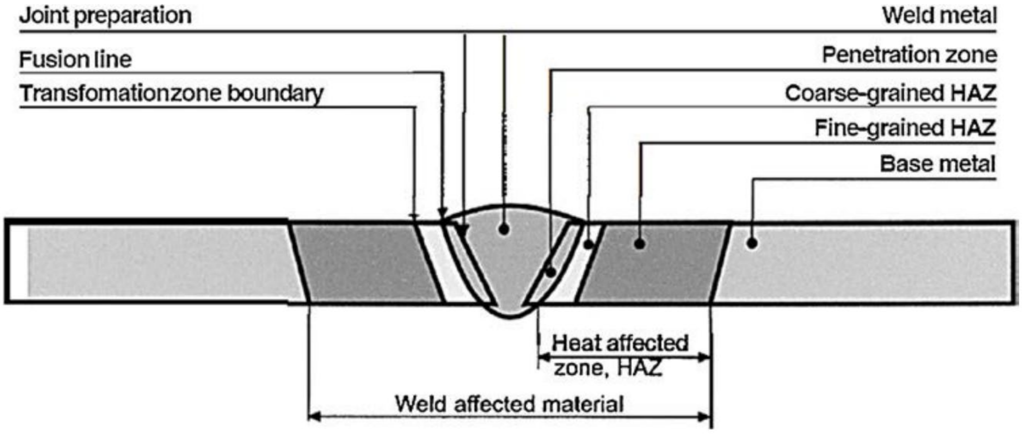

**Fig. 1.** Different zones formation due to welding process [18]

Different heat inputs during the welding process affect the metal's microstructure. The varying microstructure of the metal influences its various properties and thus can affect how it performs. In a previous related study, all the analysis is to investigate the relationship between the value of heat welding input and the phase transformation in microstructure at CGHAZ, but by using a different steel type, for example, the effect on root welding heat input on X80 pipeline steel [7] or Nitrogen-induced microstructure refinement and toughness improvement of a low carbon Mo–V–Ti–B [5].

It is claimed by Deng *et al.,* [4] that carbide precipitation causes a significantly decreased in toughness, while fine grain strengthening plays a key role in increasing strength. In addition, by extending the cooling period, which was assessed using a potentiodynamic polarisation test, the corrosion resistance is also can be improved [8].

Besides that, according to the experimental findings by Zhang *et al.,* [8] increasing the cooling time and heat input causes a drop in the percentage of random high-angle boundaries and an increase in low coincidence site lattice (CSL) grain boundaries. In other words, when the heat input is increased, the percentage of CSL boundaries and high-angle boundaries in the weld beam decreases. This matter is also supported by Hu *et al.,* [6] that the change of some brittle microstructures, from coarse-grained austenite at a very slow cooling rate under high heat-input welding, is commonly reduce the CGHAZ toughness. With that, Fan *et al.,* [5] suggested inducing nitrogen as the addition of more nitrogen improved the CGHAZ's impact toughness.

The HAZ area will be more likely to experience damage if there is an excessive increase in heat input because it will lead to too many rapid and fragile changes in the microstructure. Heat input values that are excessively low compared to the ideal range, however, are also bad since they will result in inadequate joint penetration. With that, it is suggested to choose the ideal welding heat input, use the proper welding method suitable to the application, and do some heat treatment to the material before welding and throughout the welding while maintaining a certain heat, to strengthen the microstructure in HAZ, to produce and secure the quality of the design and production as well as the product. However, even though mild steel is the most widely used steels in the industry as according to the Mark & Rex [19], this issue received little research on Coarse Grain Heat Affected Zone (CGHAZ) in mild steel. Therefore, a study was made. There are some guidelines that will be used as a research scope which are mild steel plates as the material specimen and use the Gas Metal Arc Welding (GMAW) method as the welding technique in this study. Considering that heat input affects the microstructure of metal, the suitable value of heat input needs to be implemented to get high-quality welding that may benefit society. Through this study, we can find out the ideal value of heat input welding for specific welding techniques by examine the effect of welding heat input on the distribution of microstructure development and mechanical characteristics at CGHAZ and study their correlation.

## 2. Methodology

### *2.1 Welding Parameters*

To investigate the effect of welding heat input on the microstructure and mechanical properties of mild steel, the GMAW welding method is used for welding samples using variable parameters of welding current and voltage. Nine different combinations of heat inputs are used as variable parameters in this experiment using 50 A, 100 A and 150 A for current and 15 V, 20 V and 25 V for the voltage is applied to the welding specimen. This combination will produce nine heat inputs that have a range from the lowest temperature to the highest temperature. Microstructure Identification was made using an optical microscope (OM) while mechanical identification was made using the Charpy V-Notch Test and Vickers Hardness Test. The analysis of microstructure in mild steel is significantly needed to eliminate and reduce the potential of defects in the Coarse Grain Heat Affected Zone (CGHAZ) after welding. In this investigation, other welding parameters such as welding speed, arc length, torch angle, electrode diameter are held constant. The heat input for all samples needs to be known to study the effect of welding heat input on microstructure and mechanical properties. Eq. (1) is used to calculate the heat input [20, 21] .

$$\text{Heat Input, HI} = \frac{\text{I} \times \text{V} \times 0.06}{\text{T}} \tag{1}$$

where HI is Heat Input (kJ/mm), I is Current (Ampere), V is Voltage (Volts) and T is Travel Speed (mm/min). The calculation results using the heat input equation, have been shown in Table 1 which is a list of heat input values for each sample.

**Table 1**
List of Sample

| Samples | Current, I (A) | Voltage, V (V) | Travel Speed, T (mm/min) | Heat Input, HI (kJ/mm) |
|---|---|---|---|---|
| 1 | 50 | 15 | 100 | 0.45 |
| 2 | 100 | 15 | 100 | 0.90 |
| 3 | 150 | 15 | 100 | 1.35 |
| 4 | 50 | 20 | 100 | 0.60 |
| 5 | 100 | 20 | 100 | 1.20 |
| 6 | 150 | 20 | 100 | 1.80 |
| 7 | 50 | 25 | 100 | 0.75 |
| 8 | 100 | 25 | 100 | 1.50 |
| 9 | 150 | 25 | 100 | 2.25 |

The plate was mild steel. Table 2 lists the chemical composition of the mild steel. Two layers of weld beads were applied to fill the V-grove in this study. The wire filler type used is AWS A5. 18 ER70S.6 which corresponds to the use of carbon dioxide as a protective gas.

**Table 2**
Chemical composition (weight percentage) of mild steel

| Fe | C | Mn | Si | P | S | Cu |
|---|---|---|---|---|---|---|
| 98 | 0.29 | 1.03 | 0.28 | 0.04 | 0.05 | 0.2 |

### *2.2 Sample Preparation*

After the welding process, the size of the sample V-shaped butt plate that joined using welding of 5 mm thick, 50 mm long and 60 mm wide were than was cut to be smaller by cutting the sides of the sample and getting only the middle part of the sample for solid weld, which is 10 mm x 60 mm in size as shown in Figure 2.

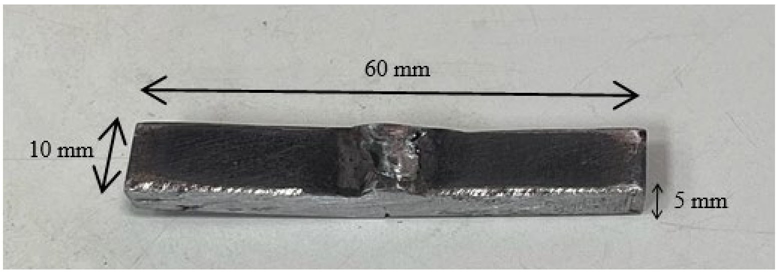

**Fig. 2.** Sample size dimension

Preparation of metallographic specimens must be made before carrying out the microstructure testing to determine the microstructure of the specimen in the CGHAZ area. There are several processes that need to be done in order, namely sectioning, mounting, grinding, polishing and etching before performing microscopic tests. In metallurgy specimen preparation, the first step is to carefully select the appropriate area of interest for sectioning. This involves identifying the CGHAZ region that best represents the material's microstructure under investigation. Next, the specimen is hot-mounted onto a sample holder using an appropriate mounting material, resin (PolyFast), ensuring proper alignment and orientation. After mounting, the sample's surface is ground using coarse abrasives (sandpaper) to remove any surface imperfections, scratches, or previous deformation using grit 240, 320, 400, 600, 800 and 1200.

The grinding process is followed by polishing, which involves using finer abrasive materials which is polishing cloth with the help of alumina slurries, progressively to obtain a smooth, scratch-free surface. Polishing enhances the specimen's reflectivity, allowing for better examination under a microscope. Once polished, the specimen is etched to reveal the microstructure. Etching involves immersing the sample in Nital solution before being rinsed with running water. A chemical Nital solution of 2% selectively attacks the material, highlighting different phases, grain boundaries, and other structural features. The etching process may vary depending on the specific material and the desired contrast. Finally, the prepared specimen is thoroughly cleaned to remove any residues from grinding, polishing, or etching before it can be examined and analyzed using various metallurgical techniques.

### *2.3 Microstructural Observation*

The Optical Microscopy method is using Meiji MT 8100 optical microscope (OM). The OM method uses visible light and a system of lenses to magnify an image, allowing observation and evaluation of small structures in detail to be made easily. With image magnification of 10x, 20x, 50x and 100x magnification focal lenses, we can compare the microstructure of all specimens. The microstructure analysis from OM testing shows the heat input will impact weld cap width, depth of penetration and HAZ. The higher the value of heat input, the more the fusion areas of joints also grow. Therefore, the effect plotted on the diagram will show the dimension (mm) versus the different heat input values (kJ/mm).

### *2.4 Vickers Hardness Test*

Hardness, which measures the resistance to indentation, is determined using the Vickers Hardness Test by measuring the permanent depth of the indentation. In this test, a square-based diamond pyramid with an angle of 136 degrees between the opposing faces is pressed into the surface of the test piece. The length of the diagonals of the resulting indent left on the surface after removing the test force is measured. The chosen test force should be appropriate for the hardness, thickness, and width of the region being tested. A 1 kg load is used in this experiment for microhardness indentations in the welding zone and HAZ, following the guidelines of ASTM E384. The test is performed on a polished surface, and measurements are taken at 1 mm intervals in the base metal, weld metal, and HAZ areas. The top and bottom surfaces of the test piece should be flat, smooth, and free from oxide scale, dirt, and grease. Using a universal clamp and levelling device ensures parallelism between the surfaces. The test piece should be securely supported during the test to prevent displacement. The test area is selected under the microscope, and the test force is applied perpendicularly to the surface without shock or vibration. Hardness indicates the resistance to indentation, with higher values indicating greater hardness. Heat input affects the hardness value of a metal differently. Therefore, a diagram can illustrate the relationship between hardness value (HVN) and the distance of various heat input values, suggesting that lower heat input results in higher microhardness in the HAZ and weld metal. The lower hardness in the HAZ zone is attributed to the higher heat input.

### *2.5 Charpy V-Notch Test*

Brittleness and impact loading resistance are measured using Charpy V-notch tests, where the energy absorbed during the test indicates the material's impact strength. To determine the toughness values of the Coarse-Grained Heat-Affected Zone (CGHAZ), Charpy V-notch testing is conducted on specimens measuring 5 x 10 x 55 mm at room temperature, following ASTM E23 standards. The fixed parameter in this experiment is the Charpy-V notch specimen, which has specific dimensions. The details of the notch specimen are 55 mm long, 10 mm high and 2 mm deep, with a 45° angle and a tip radius of 0.25 mm radius along the base. The notch serves as a stress concentration zone. The procedure involves raising the pendulum to the locked position and setting the pointer to the maximum scale reading or resetting the digital display. The test piece is carefully placed on the supports beside the anvils, ensuring that the notch's plane of symmetry is within 0.5 mm of the striker's swing plane. The pendulum is released smoothly without causing shock or vibration, and the brake is pressed after one complete swing of the hammer. Some metals can transition from ductile to brittle behavior, and the impact toughness is affected by temperature. Therefore, a diagram can illustrate the relationship between impact toughness value (J) and different heat input values, suggesting that the impact toughness value decreases with increasing heat input temperature.

## 3. Results

### *3.1* M*icrostructure Examination*

Figure 3 show below are the microstructure of the Coarse Grain Heat Affected Zone (CGHAZ) on sample metal that has been taken using an Optical Microscope (OM) with a magnification of 100X.

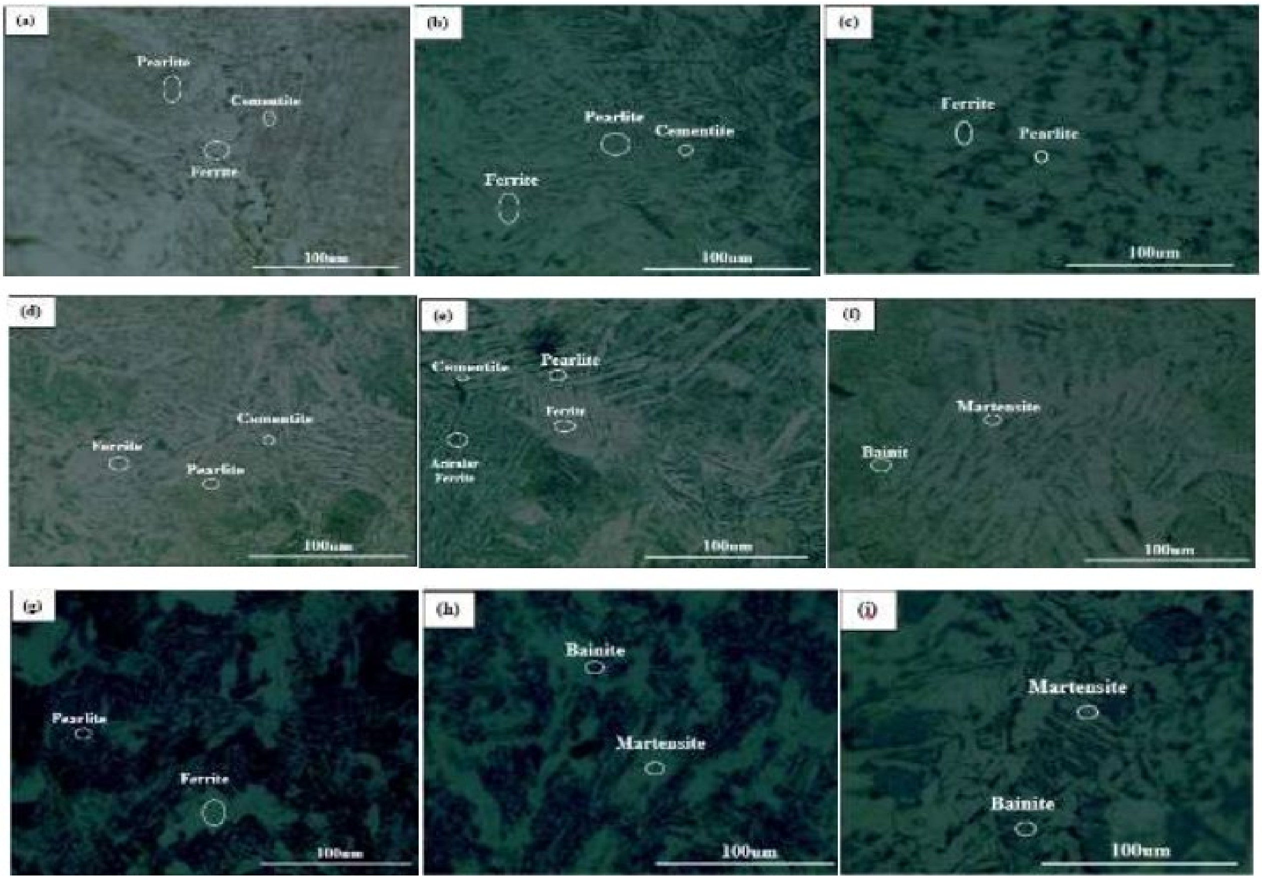

**Fig. 3.** Optical Microscope (OM) of CGHAZ with a 100x of magnification (a) Sample 1 (b) Sample 2 (c) Sample 3 (d) Sample 4 (e) Sample 5 (f) Sample 6 (g) Sample 7 (h) Sample 8 and (i) Sample 9

Grain Boundary Ferrite (GBF) was formed at prior austenite grain boundaries. The higher the heat input, the volume fraction of GBF is also seen increasing and more visible. When this GBF increases, the microstructure size also gets bigger, and the grain also appears to become coarser as seen in Sample 6, 8 and 9. These three samples have highest heat input compared to the other six samples; therefore, the grain microstructure is clearer and larger.

For samples with low heat input which are Sample 1, 2, 4 and 7 and all these samples have a common characteristic, which is the presence of only cementite, ferrite, and pearlite phases in the microstructure of the HAZ area. However, starting in the case of Sample 5 with a heat input of 1.2 kJ/mm, other microstructure phases such as bainite and martensite start to appear in the HAZ area. Based on the heat input, it is observed that as the heat input energy increases, the volume fraction of the Acicular Ferrite microstructure decreases. The formation of bainite and martensite is also observed to appear in the CGHAZ region in Figures of Sample 6, Sample 8, and Sample 9. Next, in the microstructure of the HAZ region that is far from the fusion boundary, it is observed to have smaller austenite grains and a slower cooling rate. As a result, the formation of martensite is reduced. On the other hand, the presence of the pearlite phase in this region is clear and seen to grow along the austenite grain boundaries.

In general, a higher heat input leads to a slower cooling rate, resulting in the formation of coarse grains in the weld metal. Therefore, following the sequence of heat input values, which is a combination of two variable parameters, current and voltage, Sample 9 with the highest heat input has the coarsest grains, while Sample 1 with the lowest heat input has finer grains. Based on the microstructure samples, there is evidence that samples with higher heat input values have coarser grain boundaries compared to those with lower heat input values. However, since the cooling rate is constant at room temperature, external factors like air movement or room humidity can also affect the cooling rate of the sample, which are beyond control. Additionally, it can be observed that the volume fraction of the Acicular Ferrite microstructure decreases as the heat input energy increases. Lastly, the presence of larger grains distinguishes the CGHAZ in the mild steel, as the grain size in the HAZ is much larger compared to the grain microstructure in the filler welding and base metal.

### *3.2 Effect of Heat Input on Hardness Test*

Hardness tests were conducted on nine experimental samples using the Vickers Microhardness Test to determine the hardness level of each sample welded with different heat inputs. The same parameters were used for each sample during the hardness test, applying a force of 980.7 mN (HV0.1) for 10 seconds at three different points of weldment area on each sample. Figure 4 shows graph to compare the effects of different parameters, specifically the hardness values of samples with varying welding voltage and welding current.

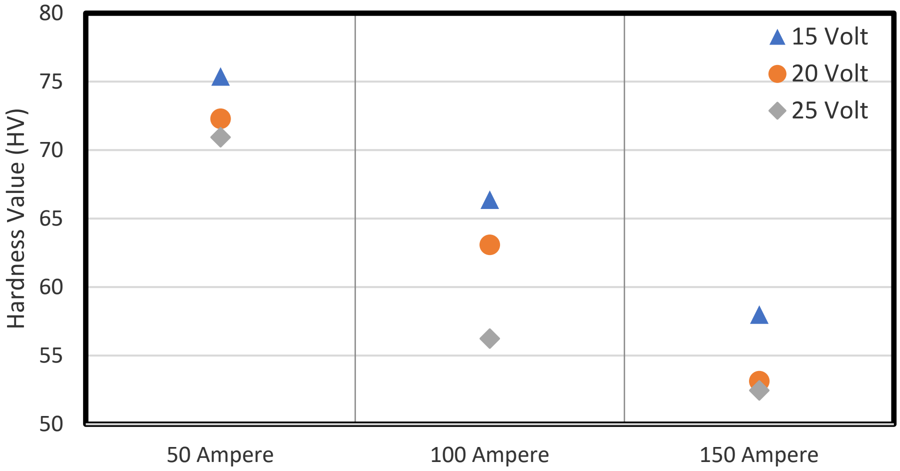

**Fig. 4.** Hardness value of samples

From Figure 3, the graph showed a decreasing trend in the hardness value of different welding voltages for these samples. Based on the trend, it can be concluded that the welding voltage versus hardness value graph opposes the current, where higher welding voltage values result in high heat input and a decrease in the hardness value of the sample. Based on the analysis, it can be concluded that the lower hardness value in Samples 6 and 8 is caused by the occurrence of an acicular ferrite structure in the heat-affected zone (HAZ) area. This is supported by the study from Ismail *et al.,* [22] that stated the annealed specimen with mainly ferrite structure gave the lowest hardness value.

### *3.3 Effect of Heat Input on Toughness Test*

A toughness test has been conducted on nine samples with different heat inputs using the Charpy V-Notch test to determine the level of toughness for each sample. Using the same force, specifically applying 150 Joules of impact energy to the samples, the test results have been obtained and interpreted through the graph shown in Figure 5.

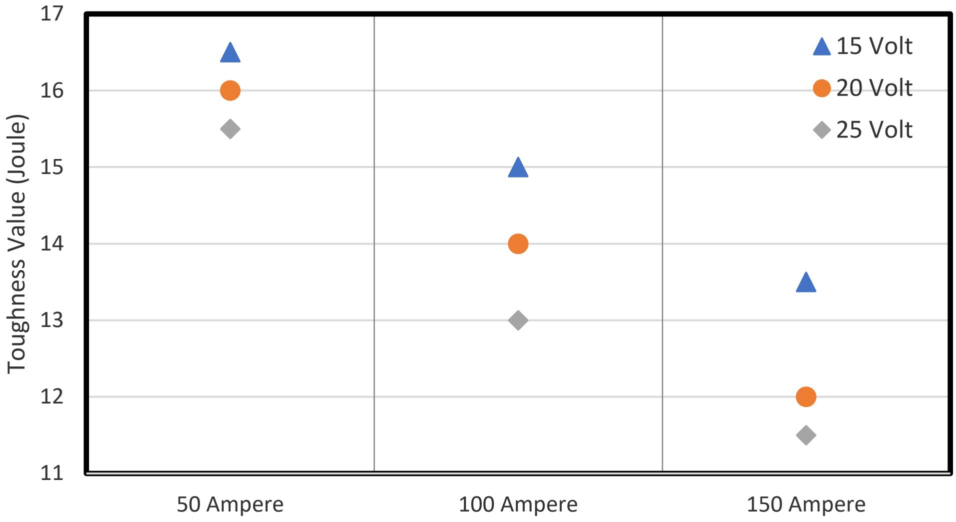

**Fig. 5.** Toughness value of the samples

Based on the Figure 5, a decreasing trend has occurred for different welding voltage. It can be observed that the absorbed energy slightly decreases to about 1 J when the heat input is increased to 0.3 kJ/mm, indicating that the impact toughness has not deteriorated. Then, energy decreases again to 1 J, making the line on the figure have a consistent and equal decreasing trend. A decreasing trend has also occurred for different welding current, where the highest toughness value is in Sample 4, which is 16 J, while the lowest toughness value is in Sample 6, which is only 12 J. The absorbed energy significantly decreases to 2 J with a further increase in heat input to 0.6 kJ/mm. However, when the heat input is increased to another 0.6 kJ/mm, the absorbed energy has a constant decrease level to about 12 J, indicating that the impact toughness has been greatly deteriorated and have the same drop level. It can be formulated that the higher the welding voltage and welding current values, the higher the heat input and consequently the lower the toughness value, where the absorbed energy slightly decreases.

### *3.4 Correlation between Microstructure and Mechanical Properties at CGHAZ*

The HAZ is the region adjacent to the weld in a material that undergoes thermal cycles during welding. These thermal cycles can result in significant changes in the microstructure, which in turn affect the mechanical properties of the material. As the temperature increases, the microstructure of the material undergoes changes which is the phase transformation such as the formation of martensite, bainite, or other intermediate phases. These transformations can have a significant influence on the mechanical properties of the material. This is supported by the study from Mandal [13]. In the phase transformation of this study, there has been a change in grain growth, where higher heat input leads to a slower cooling rate, resulting in the formation of coarse grains in the weld metal. However, from a technical standpoint, excessive roughness is not favourable as it can reduce the material's strength. Generally, finer grains lead to higher strength due to the increased strengthening effect at grain boundaries. In conclusion, the size of grains was affecting the material's strength. Additionally, the formation of coarse grains can have a negative impact on toughness and hardness as the higher heat input also reduces the toughness and hardness value of the material. Having areas with high hardness in the HAZ makes the material less resilient and more prone to cracking. After all, understanding the correlation between microstructure and mechanical properties at the HAZ is essential for optimizing welding procedures, selecting appropriate materials, and predicting the performance of welded structures especially in the construction of functionally graded materials (FGMs) bumper beam system which are which are developed to absorb impact energy during a collision to protect the occupants of the vehicle.

## **4. Conclusions**

The welding heat input has a significant influence on the microstructure and mechanical properties of mild steel at the Coarse Grain Heat-Affected Zone (CGHAZ). The CGHAZ is a critical region in welded structures where coarse grains can form due to the high heat input during welding. These results can change the microstructure and mechanical properties of the material. At the end of this study, three objectives have been achieved for the study. Examine the effect of welding heat input on the distribution of microstructure development at CGHAZ where it can be concluded that increasing the welding heat input leads to larger grain size in the CGHAZ. While for the second objective, which is to examine the effect of welding heat input on the mechanical characteristics at CGHAZ, it has been found that the higher the heat input, the lower the toughness and hardness value of the material. Lastly, for the third objective which is to study the correlation between heat input, microstructure, mechanical characteristics and HAZ cracking, it can be concluded that the increase in welding heat input causes the grain to become coarser which results in reduced strength and toughness of the material. The presence of coarse grains and their associated grain boundaries directly also increase the probability of cracking in the HAZ area and decreases overall structural integrity.

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