Variant analysis in coarse grain heat affected zone of low carbon steel

Mohammad Khairul Azhar Abdul Razab*, Sarizam Mamat, Muhammad Iqbal Ahmad and Nurul Syahida Mohd Nasir

Advanced Materials Research Cluster, Faculty of Bioengineering and Technology, Universiti Malaysia Kelantan Jeli Campus, Locked Bag No. 108, 17600 Jeli, Kelantan, Malaysia

E-mail: azhar@umk.edu.my

Abstract. Coarse Grain Heat Affected Zone (CGHAZ) is a part of Heat Affected Zone (HAZ) that affected by heat during welding process. Application of different heat input dramatically varies CGHAZ microstructures without a noticeable changing in prior austenite grain size. The unique coarse microstructure and crack initiated at CGHAZ show there were possibility changes in crystallographic structure which may relate to the variant selection phenomenon. The aims of this study are to find the effects of heat input to the variant selection especially to the biggest grain at CGHAZ, hence correlate to the toughness and properties of the welded steel. The results show that heat input affected the variant selection at the biggest CGHAZ grain of low carbon steel. As heat input increase, grain area was increased and becomes coarser. Variant selection phenomenon present at low carbon steel due to the increase in grain diameter and high angle value. It was found that variant selections had occurred during the transformation.

1. Introduction

Carbon steel is most popular material used in large scale industries due to abundance source, low cost and variety mechanical properties. In order to meet those large scale industries such as shipping and automotive demand, the steel usually joined by welding technique. Usually in welding carbon steel, low carbon steel is the most preferred material based on weldability and machinable properties because most of their steel phase are ferrite and pearlite. There are many factors in produce secure weld joined, by manipulate welding heat input, defect and discontinuity can be reduce. According to Nasir (2016) [1], heat input is one of the dominant welding parameter should be considered in controlling the production of residual stress on welded material that lead to material defects. Moreover, the different applications in heat input results changes in microstructure, mechanical and physical steel properties especially at coarse grain heat affected zone (CGHAZ). Most crack initiate at CGHAZ due to the microstructural and property alteration that are influenced by the heat input [2].

The variant selection and formation may improve or cause defect to the steel quality. There are a lot of studies on the variant selection occurring at specific martensite or bainite grain/phase, but studies on variant formation/selection for other phases are still not well documented. Due to this issue, a study was conducted to unveil and correlate the effect of heat input to the variant and its formation at coarse grain heat affected zone (CGHAZ) of low carbon steel during phase transformation, which is known to have some effect on the toughness of the steel. In this study, low carbon steel undergoes Flux Cored Arc Welding (FCAW) process by using three designated heat input parameters which are
low (0.99 kJ/mm), medium (1.22 kJ/mm) and high (2.25 kJ/mm) heat input. Electron backscatter
diffraction (EBSD) was used to investigate variant analysis of low alloy carbon steels.

2. Experimental Procedure
Through this research, ABS Grade A steel plates were welded using filler wire. The chemical
compositions for both materials were presented in Table 1 and 2, respectively. For this experiment,
each steel plate was welded by three different heats inputs based on Muda (2015) [3] and welding
procedure specification (WPS) of Sime Darby Engineering Sdn. Bhd. Table 3 shows the three
parameters of heat inputs has been applied which are low (0.99 kJ/mm), medium (1.22 kJ/mm) and
high (2.25 kJ/mm).

| Table 1. ABS Grade A chemical composition |
|------------------------------------------|
| Chemical Composition (%)                |
| Mill Certificate | C | Si | Mn | P | S | Cu | Ni | Cr | Mo |
|------------------|---|----|----|---|---|----|----|----|----|
|                  | 0.17 | 0.14 | 0.49 | 0.018 | 0.005 | 0.02 | 0.02 | 0.03 | 0.01 |

| Table 2. Filler wire chemical composition |
|------------------------------------------|
| Wire Designation | Wire Dimension (mm) | Chemical Composition (%) |
| K-71T            | 1.2                | C | Si | Mn | P | S |
|                 |                    | 0.04 | 0.55 | 1.25 | 0.015 | 0.011 |
|                 |                    | Tensile Strength (N/mm²) |
|                 |                    | 580 |

| Table 3. Welding parameters |
|-----------------------------|
| Sample | Current (A) | Voltage (V) | Speed (mm/s) | Heat Input (kJ/mm) | Indicator |
|-------|-------------|-------------|--------------|-------------------|-----------|
| A     | 135         | 22          | 180          | 0.99              | Low       |
| B     | 166         | 22          | 180          | 1.22              | Medium    |
| C     | 196         | 23          | 120          | 2.25              | High      |

2.1. Sample preparation
The samples were prepared using Flux Cored Arc Welding (FCAW) under the single pass welding
method. The welding processes were carried out at the Faculty of Mechanical, Universiti Malaysia
Pahang (UMP) using MIG machine model DM-500EF made by Ripson Machinery Sdn.Bhd.,
Malaysia and semi-automatic welding table as shown in Figure 1.

![Figure 1. Equipment for semi-automatic welding machine. (a) Power source (down) and Flux Cored Arc Welding Machine (up); and (b) Automatic Welding Table.](image)
2.2. Electron backscatter diffraction (EBSD) analysis

Electron backscatter diffraction (EBSD) is a microstructural-crystallographic characterization technique to study any crystalline or polycrystalline material. The technique involves understanding the structure, crystal orientation and phase of materials in the Field Emission Scanning Electron Microscope (FESEM). FESEM and EBSD were used to analyse grain size, grain misorientation angle, and variant analysis. EBSD became a popular method used to measure grain size because it can observe nano scale grain size [4]. Due to its flexibility, which can differentiate variants, EBSD became a famous method in variant selection studies. In this study, the samples were analysed using EBSD technique to determine its grain size, grain misorientation angle, and variant analysis. All the analysis was focused on the biggest grain at CGHAZ area for each heat input. The sample’s single grain details such as grain size, misorientation angle, and variant analysis were analysed by using OIM analysis software.

2.2.1. Grain size identification

A single austenite grain is consisting of sub-grains or also called variants. Figure 2 shows that within single grain, there are sub-grains or variants with different crystallographic orientation. Variant can be considered as symmetry of crystals which is a distinct number of equivalent combinations of parallel planes and directions [5]. Sub-grains or variant is the 3D crystal within a sample which had different crystallographic orientation between its surrounding. The variants/grains size was identified by defining a critical misorientation angle and grain boundaries. In grain size EBSD analysis, the position of grain boundaries was determined by identifying changes in crystallographic orientation between neighboring grid points of greater than a defined minimum of 10°.

\textbf{Figure 2.} (a) Biggest grain at CGHAZ area; (b) sub grains or variants within single grain and (c) crystal orientation.

2.2.2. Variant analysis

Grain size and misorientation angle were analyzed using tools/application in OIM analysis software. Variant analysis also uses the same OIM analysis, but there were some additional steps that needs to be followed to obtain variant results. Variant formation in a single grain of targeted grain area was determined using inverse pole figure (IPF). The IPF of targeted grain area was then adjusted to the standard IPF as shown in Figure 3. The 24 standard variants of K-S orientation relationship were implemented to investigate the variant selection.
3. Results and Discussion

Variant was analyzed using electron backscatter diffraction (EBSD) to obtain quantitative microstructural crystallographic of steel. EBSD reveals grain size, grain boundary character, grain orientation, texture, and phase identity of steel. There are three criterias which can determine variant selection which were dual orientation, grain boundary plane orientation and growth selection [7]. Any of these criterias can be used to determine variant selection; however, variant selection would be more influenced by grain boundary plane orientation. This study focused on grain size and misorientation which are related to the grain boundary plane orientation.

3.1. Grain size

Figure 4 shows the summarized data for diameter for smallest, biggest and mode sub-grain under low, medium and high heat input of low carbon steel. The diameter for the smallest, biggest and mode grain for low carbon steel increased as the heat input was increased. Even though the grain mode diameter kept increasing, the percentage (quantity) of the mode decreased as heat input was decreased which were 18.23% for low heat input, 17.15% for medium heat input and 16.91% for high heat input. The same situation happened to the biggest grain; the grain percentage decreased as the heat input increased. From figures 4, it can be seen that majority grain diameter (mode) came from the small size diameter. These showed that variant selection had occurred, because certain grain (biggest grain) was preferable than others, the grain had the chance to transform or express more and made the grain bigger than other grains. Due to time and space constraint, some of undesired grains managed to transform and some other grains couldn’t transform. This case caused the undesired grains to transform into different small grain size and some of the grain vanished from the CGHAZ grain.
Misorientation is the transformation required to transform tensor quantities such as vectors, stress, and strain from one set of crystal axes to the other set. Misorientation happen when variants transform; due to time and space constraint, the variants keep pushing each other and cause variant overlaps with each other and make the variants have different orientation. This phenomenon causes the disturbance to its atomic structure of the grain boundary and leads the grain boundary to be in groups of low and high misorientation angle. Researchers have different opinions in low or high angle value. Low angle boundary can be 5° - 15°, ~ 5°, <12° and also can be between 10° - 15°, while, angle larger than 10° - 15° can be classifies as high angle grain boundary [8 - 11]. During EBSD statistical analysis, any angle exceeding 2° is considered as a boundary. Due to that, any grain boundary between 2° to 15° is grouped into low angle grain boundary and other grain boundary exceeding 15° (>15°) is under high angle grain group. Low angle grain boundary is related to two-dimension dislocation network which tilt or twist grain boundary. While high angle grain boundary relates more on coincidence site lattice (CSL) which had influences to the variant selection phenomenon.

Figures 5 - 7 represent fraction of misorientation angle for low carbon steel under low, medium and high heat input. From the figures, all three CGHAZ grain of low carbon steel under low, medium and high heat input were dominated by grains/variants with low misorientation angle (<15°), while high misorientation angle (>15°) was the minority. However, by increasing the heat input, misorientation angle with <15° kept decreasing with increasing misorientation angle >15°.
Figure 5. Misorientation angle fraction of CGHAZ low carbon steel under low heat input.

Figure 6. Misorientation angle fraction of CGHAZ low carbon steel under medium heat input.
Figure 7. Misorientation angle fraction of CGHAZ low carbon steel under high heat input.

During transformation, grain growth occurred and filled all space within austenite grain boundary. When crystals or grains joined together, the crystal lattice couldn’t complement each other’s crystal and caused a grain boundary exists. Figure 8 shows atoms forming crystal grains and crystal grain boundary. The grain boundary of crystalline solids was very thin and might have one or two atoms. The grain boundary would have either low or high grain boundary, due to the selection that occurred during the transformation.

Figure 8. Grain boundary: Black circles represent atoms forming crystal grains, and white circles represent atoms located at crystal grain boundaries [12].

3.3. Variant selection

Variant selection is a phenomenon when certain variant within austenite grain boundary express more than other variants during the phase transformation. Single austenite consists of 24 variants; when variant selection occurs during the transformation there will be less than 24 variants present within the austenite grain boundary. Within the austenite grain boundary, the preferable and selected variant will
be in bigger size and the unpopular variant transform into smaller size and some of them vanish due to time and space constraint.

Figures 9 – 11 show the CGHAZ Inverse Pole Figure (IPF) images of variant distribution of low carbon steel under low, medium and high heat input. The IPF images show different color and each color represent different variant however the variant with maroon color was the biggest variant that occurred within the CGHAZ grain area. The preferable or selected variant for low carbon steel were V16, V15 and V1 for low, medium and high heat input, respectively. The biggest variant presence indicated the occurrence of the variant selection. Phase transformation without variant selection would have the number of variants the same as the number of variants before the transformation occurred. Moreover, the variant for phase transformation without variant selection mostly were in the same size. However, for phase transformation with variant selection, the selected or preferable variant would grow or express more during the phase transformation which led other unpreferable variants to have less time and space to grow and this caused some variant to vanish. In contrast, the phase transformation with variant selection would have less variant number than the original variant number before transformation occurred. Based on the Figures 9 – 11, the variant size kept decreasing with the increase of heat input. This shows that heat input had slight effect on variant sizes.

Figure 9. CGHAZ low carbon steel under low heat input. (a) IPF variant distribution and (b) 001 α pole figure of V16 location.
4. Conclusion

It was found that variant selections had occurred during the transformation. Based on significant data on variant grain diameter and high angle, it showed that heat input did affect variant selection at CGHAZ of low carbon steel. The result showed that by increasing the heat input, CGHAZ of low
carbon steel hardness had decreased. This research proved that heat input affected variant selection and mechanical properties at CGHAZ of low carbon steel.

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