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

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ABSTRACT

The fabrication and construction of structures used in the offshore and marine industries shall be 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 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 CGHAZ of the ABS Grade A steel. Three heat input combinations 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 consists of grain boundary ferrite (GBF), Widmanstatten ferrite (WF) and pearlite (P). Significant grain coarsening was observed at the coarse grain heat affected zone (CGHAZ) of all the joints and it was found that the extent of grain coarsening at CGHAZ increased with the increase in the heat input. The results of the mechanical investigation indicate that the joints made 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 the higher the heat input, the higher the grain size of microstructure but will lead to lower hardness and impact toughness value.

ABSTRAK

Fabrikasi dan pembinaan struktur-struktur yang digunakan di dalam industri luar pesisir dan maritim mestilah dibuat mengikut keperluan kod dan piawaian antarabangsa bagi memastikan kualiti dan pemanjangan jangka hayat. Keluli ABS Gred A merupakan salah satu bahan yang biasa digunakan dalam industri marin. Pemilihan bahan yang betul mestilah dilakukan bagi memenuhi fungsi penggunaan dan menjimatkan kos. Kajian telah dilakukan bagi mengenalpasti kesan haba masukan terhadap pembahagian formasi struktur mikro serta sifat-sifat mekanikal di kawasan bijian kasar zon terkesan haba (CGHAZ) pada keluli ABS Grade A. Tiga kombinasi haba masukan yang dinyatakan sebagai haba masukan rendah (0.99 kJ/mm), haba masukan sederhana (1.22 kJ/mm) dan haba masukan tinggi (2.25 kJ/mm) telah digunakan terhadap spesimen kimpalan dengan menggunakan kimpalan arka teras lakur (FCAW). Pembentukan struktur mikro pada bijian kasar zon terkesan haba (CGHAZ) melibatkan ferit bijian sempadan (GBF), ferit Widmanstatten (WF) and pearlite (P). Bijian bersaiz kasar dapat diperhatikan pada bijian kasar zon terkesan haba (CGHAZ) pada setiap penyambungan dan ianya didapati bahawa pembesaran bijian kasar pada CGHAZ meningkat dengan meningkatnya haba masukan. Keputusan pemeriksaan mekanikal menunjukkan bahawa penyambungan yang menggunakan haba masukan rendah menghasilkan nilai kekerasan dan kekuatan impak yang rendah berbanding dengan penyambungan yang menggunakan haba masukan sederhana dan tinggi. Ianya dapat disimpulkan bahawa semakin tinggi masukan haba, semakin tinggi saiz bijian tetapi mendorong kepada penurunan nilai kekerasan dan kekuatan impak.

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LIST OF SYMBOLS AND ABBREVIATIONS

µm	-	Micrometer
α	-	Alpha
α	-	Ferrite
γ	-	Gamma
γ	-	Austenite
δ	-	Delta
A1	-	The temperature at which austenite starts to form when heated.
A3	-	In hypoeutectoid steel, the temperature at which the transformation of ferrite into austenite is completed.
AF	-	Acicular Ferrite
ASTM	-	American Society for Testing and Materials
Bs	-	Temperature where bainite starts to form
C	-	Carbon
CCT	-	Continue-Cooling-Temperature (diagram)
CGHAZ	-	Coarse Grain Heat Affected Zone
CJP	-	Complete Joint Penetration
E	-	Welding Energy
Fe	-	Iron
FCAW	-	Flux Cored Arc Welding
FGHAZ	-	Fine Grane Heat Affected Zone
FL	-	Fusion Line
GBF	-	Grain Boundary Ferrite
HAZ	-	Heat Affected Zone
HVN	-	Vickers Hardness

CHAPTER 1

INTRODUCTION

1.1 Introduction

Due to ever rising demand for oil and gas in the world today, the global offshore oil and gas industry has been growing by leaps and bounds. The rising cost of oil and gas prices holds great promises for the industry in coming years. The constructions carried out in the offshore are done in the marine environment. The offshore includes warm marine environment and arctic environment. There are several industries which carry out their production in the offshore. Companies such as the oil and gas, shipbuilding, energy companies are those found in the offshore. Activities in the offshore are dangerous.

The fabrication and construction of structures used in the offshore and marine industries shall be 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 (Pirinen, 2013). Some of the activities of the construction both in the offshore and onshore include fabrication and welding. Welding is one of the most important, versatile means of fabrication available to industry. Welding is used to join hundreds of different commercial steel or alloys in many different shapes. Many of the problems that are inherent to welding can be avoided by proper consideration of the particular characteristics and requirements of the process.

1.2 Research Background

Welding is a process that involves high temperature up to the melting point of steel. For the time being, there is an alloying method introduced in the flux or filler wire to stimulate the transformation which then improves the weld metal. However the same concept is not available for the heat affected zone (HAZ) since the area remains in solid state within the temperature range above lower critical temperature but below the melting point. The HAZ in metal can be divided into four main areas; coarse grained supercritical HAZ (CGHAZ), fine grained supercritical HAZ (FGHAZ), intercritical HAZ (ICHAZ) and subcritical HAZ (SCHAZ) (Aimin Guo *et al.*, 2010). Among these, coarse grained HAZ (CGHAZ) is the most affected area during welding process due to rapid cooling that caused hardening which in turn possible to be the main factor of cleavage fracture. It is reported that the cleavage fracture resistance of bainitic microstructures is closely related to both prior austenite and bainite packets. The formation of fine sub blocks, blocks, and high angle packet boundaries in one single prior austenite grain intimately related to the capability of bainite microstructure in halting the propagation of crack tip. At the same time, the arrangement of blocks in the grain enables the slip systems to be connected easily and reduces the accumulation of dislocations which then improves the ductility of materials (Mamat, 2012). In order to increase ductility into this area, the stimulating formation of bainitic microstructure is one of the alternatives that being conceived nowadays to produce finer microstructure.

Meanwhile, heat input is one of the crucial parameter that has to be included during preparation of welding procedure specification (WPS) and the value of it will be the determinants for decision of post weld heat treatment (PWHT). It is reported that the width of HAZ increases with an increment of heat input and grains in the fusion zone also will be coarsen (Eroglu *et al.*, 1999). Moreover, it is confirmed that heat input is the main factor for affecting the embrittlement of weld joints, when the heat input is very high, the impact toughness of the weld joints is very low. However, in order to improve the welding efficiency, the heat input is required to be high enough in actual engineering welding and the optimum value of it is worth to be investigated.

Thus, this study aims to characterize and appraise the behavior of microstructure transformed at CGHAZ and its correlation to the heat input. The use of Flux Core Welding Process (FCAW) during sample preparation reflects to 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 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.

1.3 Problem Statement

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 made by welding procedures. Nowadays, because of high heat inputs during the joining process, the 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 influences the formation of microstructure at HAZ. The formation of microstructure especially martensite, bainite and martensite-austenite (MA) constituent potent to affect the toughness of HAZ, thus lead to HAZ cracking 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 formation of microstructure and its mechanical properties. However, there are still less studies done to the weldments itself since the previous studies are merely based on simulated HAZ.

1.4 Objective

Generally, the research objective is to study the effect of welding heat input to the microstructure at CGHAZ of ABS Grade A (A131 A Grade) steel. Whereas, the specific objectives of the research are:

a) To scrutinize the effect of welding heat input to the distribution of microstructure formation at CGHAZ.
b) To scrutinize the effect of welding heat input to the mechanical properties at CGHAZ.
c) To elucidate the correlation of heat input, microstructure, mechanical properties and its relationship with HAZ cracking.

1.5 Scope of Research

In the course of this research, an attempt has been made to understand the changes in mechanical and microstructure behavior at HAZ area of weld metal. The following scopes have been identified and carried out to achieve the research objectives.

a) Material Specimen
   ABS Grade A one of the low carbon steel (carbon content less than 0.2%) is used in this study. This steel plate is almost exclusively used in the marine and offshore industry for the hull construction and structural parts. This grade is certified by ABS – American Bureau of Shipping.
b) Welding Process
   The samples are prepared by using Flux Core Arc Welding (FCAW) method, so the influence of welding processes is outside the scope of this work. FCAW is the most popular method in structural weld. The heat input values (0.9 kJ/mm, 1.22 kJ/mm and 2.25 kJ/mm) are adopted form welding procedure specification (WPS) of Sime Darby Engineering Sdn. Bhd. This research solely looks at single V butt weld joints; fillet

welds are excluded. These specific joints were selected because they are widely used in many kinds of plate structures.

c) Microstructure Identification

Macro test is carried out to each sample to get a clear picture of the HAZ area. Then, by using OM, the average grain size is measured and analyzed to know the distribution of microstructure at the HAZ area.

d) Mechanical Test

Microhardness test and charpy V-notch impact test are carried out to all samples to investigate the mechanical properties of HAZ area.

1.6 Thesis Outline

The thesis consists of five chapters overall, which includes introduction, literature review, methodology, results and discussion and finally the conclusion. In the first chapter, it gives a rough view of the whole project. The introduction deals with research background, problem statement, objective as well as scope of research.

The next chapter which basically concerns on the output after reviewing the journal papers, reference books, articles, thesis, technical papers and also online sources. The outcome of this chapter is important as it may assist the whole research to progress smoothly.

The following chapter concentrates on the methodology of this research. It elaborates in detail the sequence of process or method to carry out the task in order to achieve the research objective.

Subsequently Chapter 4 will present the results obtained from the study. The discussion of the result is highlighted here as well. In the last chapter, which is Chapter 5, the research is summarized and recommendation of the future work is suggested.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explains about the literature review of this project. The relevant and comprehensive literature review is highlighted. The flux core arc welding (FCAW) process, heat input, heat affected zone (HAZ), the effect of heat input to the microstructure and mechanical properties are explained to give a clear picture of the project carried out.

2.2 Welding In General

Modern welding technology started just before the end of the 19th century with the development of methods for generating high temperature in localized zones. Welding generally requires a heat source to produce a high temperature zone to melt the material, though it is possible to weld two metal pieces without much increase in temperature. There are five categories of welding processes and in general they can be categorized as (Sacks & Bohnart, 2005):

a) Arc Welding

A welding power supply is used to create and maintain an electric arc between an electrode and the base material to melt metals at the welding point. In such welding processes the power supply could be AC or DC, the electrode could be consumable or non-consumable and a filler material may or may not be added. The most common types of arc welding are shielded metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), flux core arc welding (FCAW) and submerged arc welding (SAW).

b) Gas Welding

In this method a focused high temperature flame generated by gas combustion is used to melt the workpieces (and filler) together. The most common type of gas welding is oxy-fuel welding where acetylene is combusted in oxygen.

c) Resistance Welding

Resistance welding involves the generation of heat by passing a high current (1000 – 100,000 A) through the resistance caused by the contact between two or more metal surfaces where that causes pools of molten metal to be formed at the weld area. The most common types of resistance welding are spot-welding (using pointed electrodes) and seam-welding (using wheel-shaped electrodes).

d) Energy Beam Welding

In this method a focused high-energy beam (laser beam or electron beam) is used to melt the workpieces and thus join them together.

e) Solid State Welding

In contrast to other welding methods, solid state welding processes do not involve the melting of materials being joined. Common types of solid state welding include; ultrasonic welding, explosion welding, electromagnetic pulse welding, roll welding and friction welding.

2.3 Flux Core Arc Welding (FCAW) Process

FCAW was introduced in the 1950's. Technically the introduction of this process was not new. It was just a new type of an electrode that can be used on a MIG welding machine. FCAW is a process similar to GMAW welding. Both processes using continues wire feeds, and similar equipment. The power supply for a FCAW, and a GMAW welder, are the same machine. They are both considered semi automatic processes, and have a very high production rate (Sacks & Bohnart, 2005).

The main difference between FCAW and GMAW welding is the way the electrode is shielded from the air. FCAW just like the name implies, has a hollow wire with flux in the center, similar to the candy called "pixy sticks". Just as the name states, a "Flux Core". The main difference between GMAW and FCAW is, FCAW gets its shielding from the flux core, and this allows the operator to weld outdoors where it is windy. Figure 2.1 shows the schematic of FCAW process.

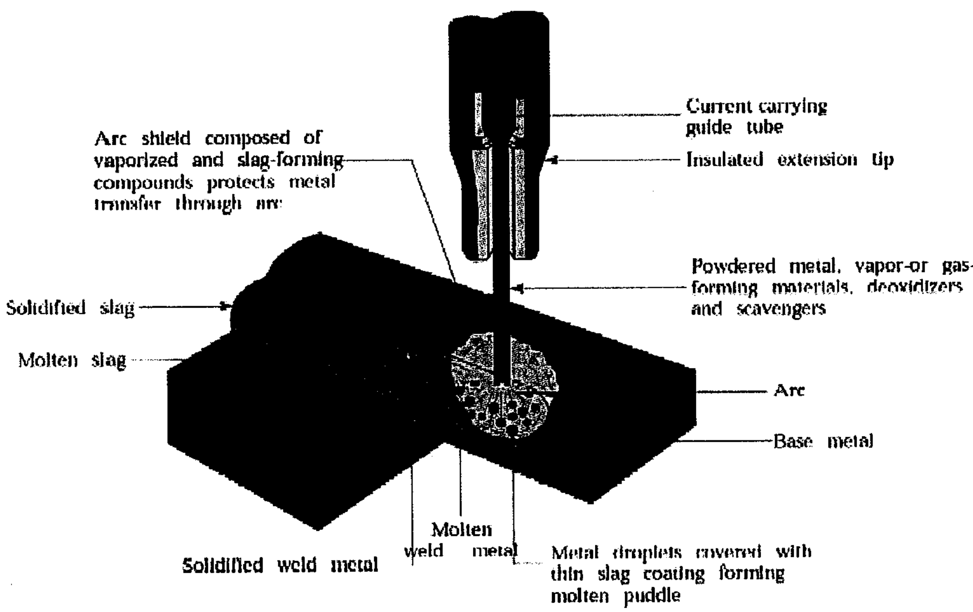

Figure 2.1: Schematic of FCAW process (Sacks & Bohnart, 2005)

FCAW power supply is also a GMAW welding power supply, they are the same machine. That is a "Constant Voltage Power Supply". Constant voltage power supplies keep the voltage near, or at the same level. Unlike a GTAW, that keeps the amperage consistent. In the FCAW the amperage is changed with the wire feed speed. The faster the wire feeds, the more contact the electrode has, producing more amperage, and heat. The voltage type used is direct current (DC) like the type current produced by a battery. The polarity used in industrial FCAW is typically DC electrode positive. This means that the handle is the positive side of the circuit, or the electricity flows from the metal to the welding handle. This is typical when larger electrodes are used. When welding with smaller electrodes and sheet metals, the polarity is changed to DC electrode negative. The electrodes used for FCAW are almost visually the same as a GMAW electrode. The difference is that FCAW electrodes are tubular, or a hollow tube with flux in the center. GMAW electrodes are solid metal.

The variety of shielding gases that may be used for FCAW is limited. In the case of dual shielding being used with a flux cored electrode the choices of shielding gasses are limited. The choices are carbon dioxide (CO_2), argon (Ar), a mixture of carbon dioxide and argon, and a mixture of argon and oxygen.

Knowledge and control of process variables are essential to consistently produce welds of satisfactory quality. The variables are not completely independent, and changing one generally requires changing one or more of the others to produce the desired results. In FCAW, some of the variables that affect weld penetration, bead geometry and overall weld quality are (Sacks & Bohnart, 2005):

a) Wire feed speed (and current)
b) Arc voltage
c) Electrode extension
d) Travel speed and angle
e) Electrode angles
f) Electrode wire type
g) Shielding gas composition
h) Polarity

2.4 Heat Input

In arc welding, energy is transferred from the welding electrode to the base metal by an electric arc. When the welder starts the arc, both the base metal and filler metal are melted to create the weld. This melting is possible because a sufficient amount of power (energy transferred per unit time) and energy density is supplied to the electrode. Heat input is a relative measure of the energy transferred per unit length of weld (Linnert, 1994). It is an important characteristic because, like preheat and interpass temperature, it influences the cooling rate, which may affect the mechanical properties and metallurgical structure of the weld and the HAZ as illustrated in Figure 2.2. Heat input is typically calculated as the ratio of the power (i.e., voltage x current) to the velocity of the heat source (i.e., the arc) as given in the Equation 2.1.

$$H = \frac{60EI}{1000S} \tag{2.1}$$

where, H is the heat input (kJ/mm), E is the arc voltage (volts), I is the current (amps) and S is the travel speed (mm/min).

This equation is useful for comparing different welding procedures for a given welding process. However, heat input is not necessarily applicable for comparing different processes (e.g., SMAW and GMAW), unless additional data are available such as the heat transfer efficiency (Linnert, 1994).

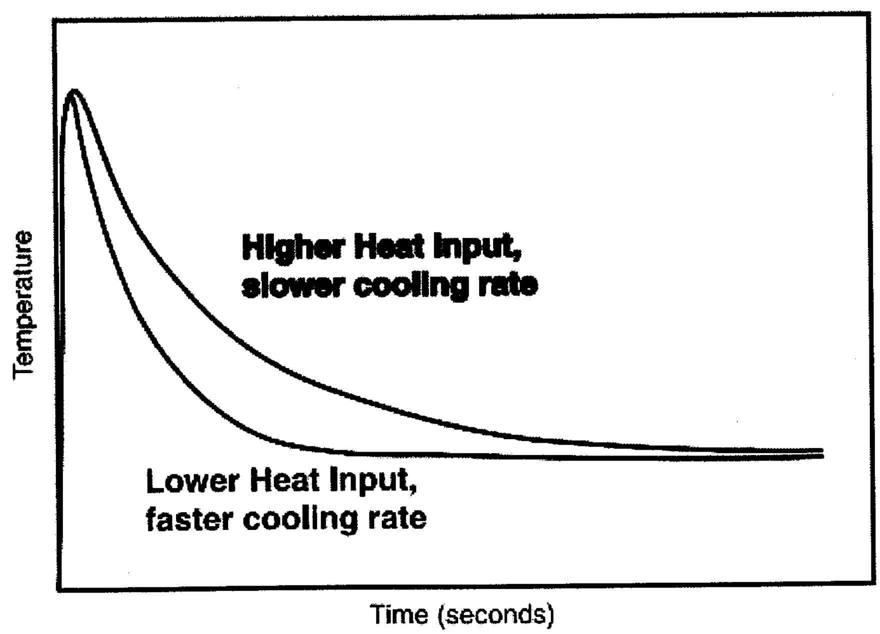

Figure 2.2: Heat input influences cooling rate (Linnert, 1994)

2.4.1 Measuring Heat Input

Heat input cannot be measured directly. However, it can be calculated from the measured values of arc voltage, current and travel speed (Funderburk, 1999).

a) Arc Voltage

In determining the arc voltage (*E*), the voltage should be measured as close to the arc as possible, as opposed to the valued displayed on the welding machine voltmeter. Measuring the voltage across the arc provides the actual voltage drop across the welding arc. The welding machine voltmeter reading is always higher than the arc voltage due to the resistance of the welding cables. The machine voltage, therefore, can be used only for approximate calculations and, in the case of significant voltage drops, may lead to heat input calculation errors.

b) Current

The welding current (*I*) is measured with either an inductance meter (tong meter) or a shunt with appropriate metering equipment. The current is never fixed with respect to time, especially on microsecond level. With SMAW, the current is also a function of the arc length, which is dependent on the welder's skill. Therefore, the current used in the heat input calculations should be the average value.

c) Travel Speed

The travel speed (*S*) is the forward velocity of the arc measured in either inches per minute or millimeters per minute. Only the forward progress contributes to the travel speed. If a weaving technique is used, only the forward speed counts, not the oscillation rate. For vertical welding, only the upward or downward speed of the arc is used. The travel speed must be in terms of minutes and not seconds for the dimensions to balance in the heat input equation. When the travel speed is measured, the arc should be established for an amount of time that will produce an accurate average speed. A continuous welding time of 30 seconds is suggested. If this is not possible for the production joint (e.g., short welds), a test weld should be run on a mockup joint that will provide a sufficient length to determine the travel speed. The travel speed accuracy with manual or semi-automatic welding is dependent on the welder. However, with automatic welding, the speed is set on the motor controlled travel carriage.

2.4.2 Effect of Heat Input

According to Funderburk (1999), varying the heat input typically will affect the material properties in the weld. Table 2.1 shows how the listed properties change with increasing heat input. An arrow pointed up, ↑, designates that the property increases as heat input increases. An arrow pointed down, ↓, designates that the property decreases as heat input increases. Next to the arrow is the approximate amount that property changed from the minimum to the maximum value of heat input tested.

Other than notch toughness, all of the mechanical properties show a monotonic relationship to heat input, that is, the mechanical property only increases or decreases with increasing heat input. Notch toughness, however, increases slightly and then drop significantly as heat input increases. The change in notch toughness is not just tied to the heat input, but is also significantly influenced by the weld bead size. As the bead size increases, which corresponds to a higher heat input, the notch toughness tends to decrease. In multiple pass welds, a portion of the previous weld pass is refined, and the toughness improved, as the heat from each pass tempers the weld metal below it. If the beads are smaller, more grain refinement occurs, resulting in better notch toughness, all other factors being even. Tests have been conducted with SMAW electrodes and procedures that provided heat inputs varying from 0.59 kJ/mm to 4.33 kJ/mm) (Evans, 1997). This represents a very large heat input range, which encompasses most applications of SMAW.

If the changes in heat input are relatively small, as opposed to those of the previous table, then the mechanical properties may not be significantly changed. In another study, no significant correlation between heat input and mechanical properties was established for submerged arc welding (SAW) with typical highway bridge fabrication heat input levels of 1.97 kJ/mm to 3.54 kJ/mm (Medlock, 1998). In this case, the tests results did show varying properties; however, no discernable trends were established.

Table 2.1: Mechanical properties affected by heat input (Funderburk, 1999)

Property*	Change
Yield Strength	↓ 30%
Tensile Strength	↓ 10 %
Percent Elongation	↑ 10%
Notch Toughness (CVN)	↑ 10%, for 0.59 kJ/mm $<$ H $<$ 1.97 kJ/mm ↓ 50%, for 1.97 $<$ H $<$ 4.33 kJ/mm
Hardness	↓ 10%

*SMAW with a heat input range of 0.59 kJ/mm to 4.33 kJ/mm

2.5 Basic Metallurgy of Fusion Welding

A typical fusion welded joint varies in metallurgical structure from the fusion zone to the base material with consequential variations in mechanical properties. This is because of the fact that fusion welding processes result in melting and solidification with very high temperature gradient within a small zone with the peak temperature at the center of the fusion zone (Sacks & Bohnart, 2005). In general, a weld can be divided into four different zones as shown schematically in Figure 2.3.

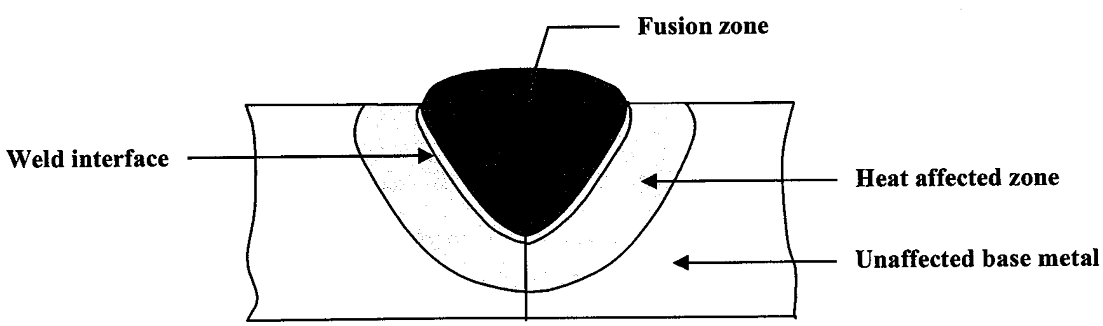

Figure 2.3: Schematic presentations of several zones in a fusion welded joints (Sacks & Bohnart, 2005).

The fusion zone (referred to as FZ) can be characterized as a mixture of completely molten base metal (and filler metal if consumable electrodes are in use) with a high degree of homogeneity where the mixing is primarily motivated by convection in the molten weld pool. The main driving forces for convective transport of heat and resulting mixing of molten metal in weld pool are buoyancy force, surface tension gradient force, electromagnetic force and friction force. Similar to a casting process, the microstructure in the weld fusion zone is expected to change significantly due to remelting and solidification of metal at the temperature beyond the effective liquidus temperature.

The weld interface, which is also referred to as mushy zone, is a narrow zone consisting of partially melted base material which has not got an opportunity for mixing. This zone separates the fusion zone and heat affected zone.

The heat affected zone (HAZ) is the region that experiences a peak temperature that is well below the solidus temperature while high enough that can change the microstructure of the material. The amount of change in microstructure in HAZ depends on the amount of heat input, peak temperature reached, time at the elevated temperature, and the rate of cooling. As a result of the marked change in the microstructure, the mechanical properties also change in HAZ and, usually, this zone remains as the weakest section in a weldment (Jeffus, 2003).

The unaffected base metal zone surrounding the HAZ is likely to be in a state of high residual stress, due to the shrinkage in the fusion zone. However, this zone does not undergo any change in the microstructure.

The fusion zone and heat affected zone of welded joints can exhibit very different mechanical properties from that of the unaffected base metal as well as between themselves. For example, the fusion zone exhibits a typical cast structure while the heat affected zone will exhibit a heat-treated structure involving phase transformation, recrystallization and grain growth. The unaffected base metal, on the other hand, will show the original rolled structure with a slight grain growth.

2.6 Heat Affected Zone (HAZ)

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 (Mamat, 2012).

Generally, the HAZ is the base metal underlying the weld which has been heated to temperatures above the iron – iron carbide (Fe – FeC_3) metastable phase diagram A1 line (723 °C) temperature and below the solidus temperature, typically 1495 °C as shown in Figure 2.4. However, with higher heat input processes, such as submerged arc or electroslag welding, the HAZ includes peak temperatures below the A1 line temperature. This is because spheroidization of the pearlite iron carbide plates occurs as a result of tempering. The longer the base metal is exposed to temperatures just below the A1 line, the greater the spheroidization.

2.6.1 HAZ Regions and The Fe – Fe Carbide Metastable Phase Diagram

As shown in Figure 2.4, weld area can be defined as the area that includes weld metal and heat affected zone (HAZ). The HAZ in metal can be divided into four main areas; coarse grained supercritical HAZ (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 possible to be the main factor of cleavage cracking (Mamat, 2012).

The peak temperature represents the maximum temperature seen by the unaffected base metal as a result of a welding thermal cycle. The peak temperatures define the size of each region. This is shown by extending the 0.15 % C line vertically and intercepting it with the lines dividing the phases on the phase diagram. These intercepts are then projected horizontally until they intersect the temperature gradient curve in the figure to the left. This second intercept is then extended vertically and downward to the weldment to reveal the "relative" width of each HAZ region. In practice, the HAZ size is very small in relation to the weld size.

The partially melted zone has been subjected to peak temperatures where the base metal is transformed to delta ferrite and liquid (between the solidus and liquidus temperatures). This zone is very narrow, perhaps a grain diameter or two in thickness. Since high peak temperatures occur in this zone, large grains result as in the coarse-grained supercritical.

The coarse-grained supercritical is adjacent to the fusion boundary of weld and has been subjected to peak temperatures (above the recrystallization temperature, typically 1000 °C and below the solidus temperature, typically 1495 °C) which promote rapid austenite grain growth (large grains). This region also includes base metal which has been exposed to temperatures below the solidus, where austenite and delta ferrite both exist. In practice, this region is rarely seen because of the very narrow temperature zone in which austenite and delta ferrite exist. In practical terms, the thickness of this region is usually less that a grain diameter.

The fine-grained supercritical is adjacent to the coarse-grained supercritical and has been subjected to peak temperatures below the recrystallization temperature but above the Ac_3 temperature (the equilibrium cooling temperature at which some of the austenite transforms to ferrite). Since the peak temperature is below the recrystallization temperature, rapid austenite grain growth does not occur. In practice, aluminum (Al) killed carbon steels which have been agitated with nitrogen during steel making, precipitate aluminum nitrides in this temperature zone. The aluminu nitrides are extremely small and precipitate at the base metal grain boundaries. Their presence at the grain boundaries helps prevent the grain boundaries from moving; hence, the high peak temperatures do not result in large grain growth.

The intercritical is adjacent to the fine-grained supercritical and has been subjected to peak temperatures between A3 and A1, where the base metal ferrite and carbides begin to transform to austenite. Grain refinement occurs at these peak temperatures. A normalizing heat treatment of the base metal occurs in this region.

The subcritical is between the intercritical and unaffected base metal and has been subjected to peak temperatures below the A1. At temperatures just below the A1, the pearlite carbide plates begin to spheroidize. A tempering heat treatment of the base metal occurs in this region, however, the pearlite does not completely spheroidize since the weld thermal cycle is too short for this to happen.

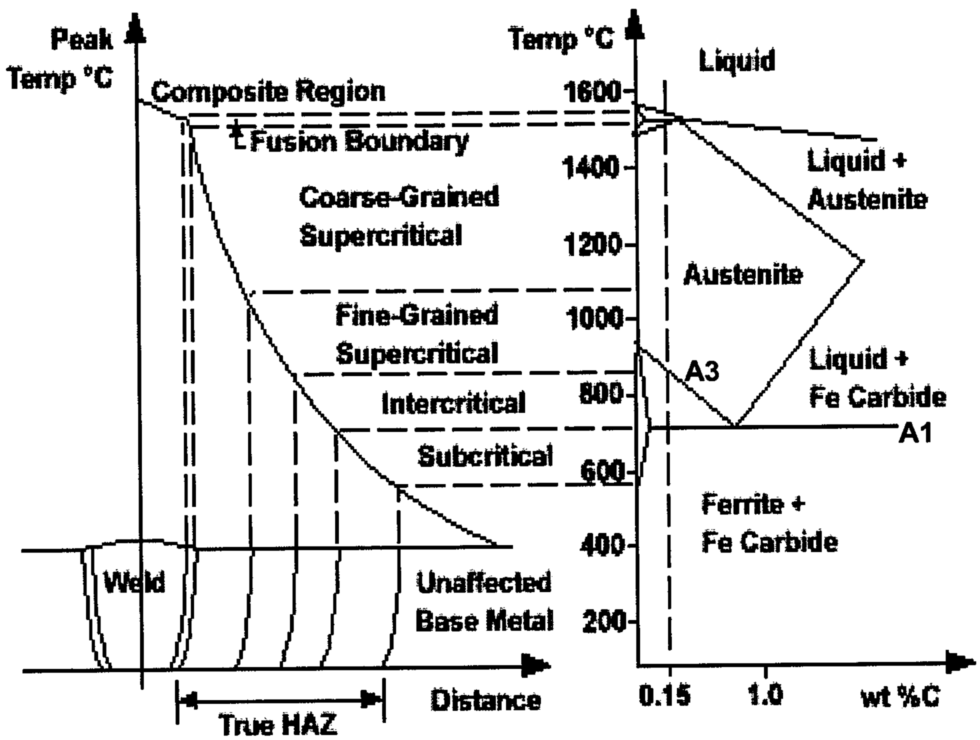

Figure 2.4: Relation between heat affected zone and corresponding temperature (Mamat, 2012)

2.7 ABS Grade Steel

ABS Steels are types of structural steel which are standardized by the American Bureau of Shipping for use in shipbuilding and marine environment. ABS steels come many grades in ordinary strength and two levels of higher-strength specifications. All of these steels have been engineered to be optimal long-lived shipbuilding steels. ABS does permit the use of other steels in shipbuilding, but discourages it, and requires more detailed engineering analysis. All ABS steels are standard carbon steels. As with other grades of steel, they have a specific gravity of 7.8.

Ordinary strength ABS shipbuilding steel comes in a number of grades, A, B, D, E, DS, and CS. On certified steels, the plates are marked with the grade and a preceding "AB/", e.g. AB/A etc. Yield point for all ordinary-strength ABS steels is specified as 235 N/mm^2, except for ABS A in thicknesses of greater than 25 mm which has yield strength of 225 N/mm^2, and cold flange rolled sections, which have yield strength of 205 N/mm^2. Ultimate tensile strength of ordinary strength alloys is 400-490 N/mm^2, except for ABS A shapes and bars with 400-550 N/mm^2, and cold flanged sections with 380-450 N/mm^2. The various grades have slightly differing alloy chemical ingredients, and differing fracture toughness.

Higher strength ABS shipbuilding steel comes in six grades of two strengths, AH32, DH32, EH32, AH36, DH36, and EH36. The 32 grades have yield strength of 315 N/mm^2, and ultimate tensile strength of 440-590 N/mm^2. Meanwhile, the 36 grades have yield strength of 355 N/mm^2, and ultimate tensile strength of 490-620 N/mm^2.

2.8 Microstructure in General

Microstructures suitable to resist high magnitude of stress, are usually composed of, or a combination of, martensite, bainite, retained austenite and acicular ferrite. Prior to these final constituents, the weld metal will have undergone complex changes and transformations as it cools from its liquid form when deposited. This may be clearly seen in the basic phase diagram of steel showing the iron - carbon system as presented in Figure 2.5.

However, one must bear in mind, that there are a few characteristic differences between the microstructure of weld metals and those of wrought steels. Once wrought steel is formed, various types of heat treatment may be performed in order to adjust both the microstructure and the mechanical properties. However, with weld metals this is not normally the case, and in many circumstances it is not possible. Weld metals are cast materials and their cooling conditions are very different in comparison to that of steel that has undergone forging or rolling. Other characteristic differences between the two are the frequent presence of non-metallic inclusions within weld metals and also segregation. The occurrence of interdendritic segregation must always be kept in mind when investigating the weld metal microstructure. Basically there is a difference incomposition between the core and the other portions of the dendrite that formed during solidification. As alloying is increased it plays a more important role in determining the microstructural transformations that take place and it may lead to different phases in the dendrite-core and in interdendritic regions. Microsegregation allows the formation of microstructures that are hard to produce in any other metallurgical process. This can be beneficial when it is properly controlled but can create a lot of difficulties with for example cracking when not. When weld metals are deposited in multi runs or if they are heat treated, part of the previous bead is reheated to a high temperature and the bead is no longer in the "as deposited" condition. Microsegregation can be partially removed, however, a long annealing time is needed to remove it completely (Noren & Pfeifer, 1999).

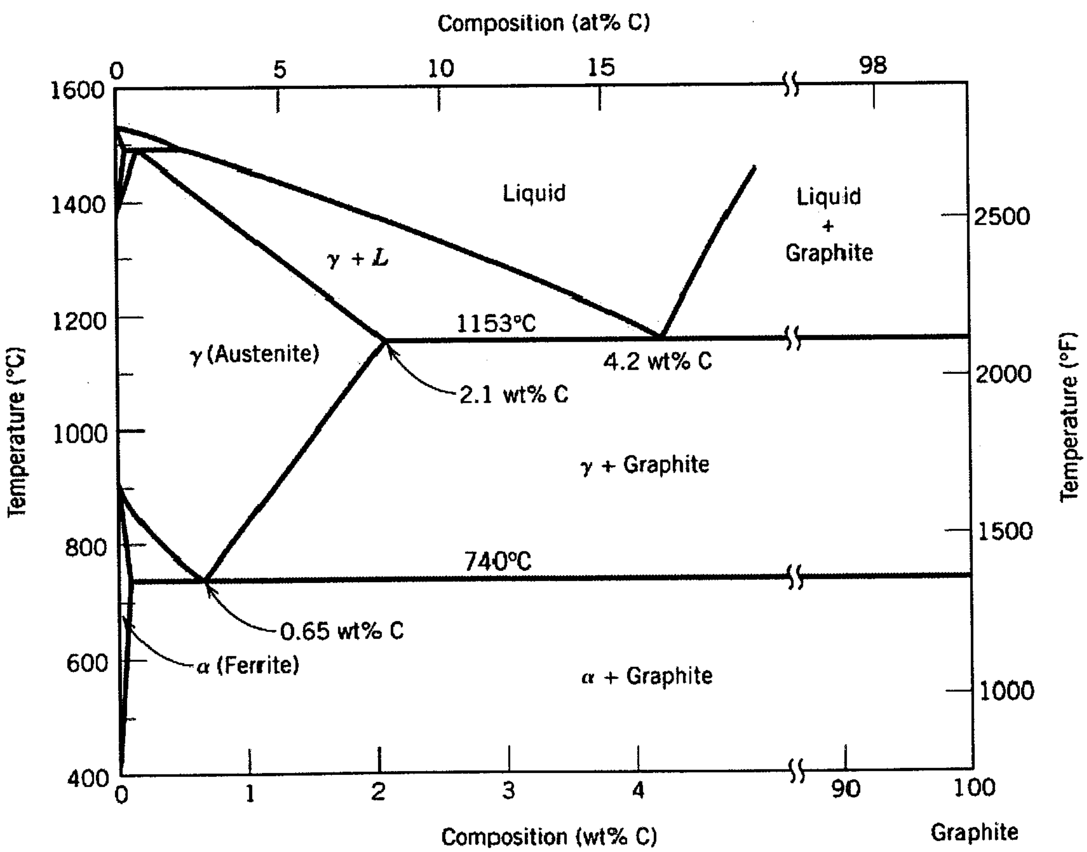

Figure 2.5: The iron-carbon phase diagram (Keenda, 2004)

2.8.1 Solidification and The Decomposition of δ-Ferrite

When welding in particular material with similar or the same composition as the molten weld metal, epitaxial growth rather than nucleation occurs. Epitaxial growth is where the molten liquid solidifies and develops new grains directly from the solid in the underlying material. Solidification generally occurs along the maximum thermal gradient towards the weld centre resulting in a columnar solidification structure. The width of the columns are usually related to the size of the grains in the underlying bead. It is normally expected that the grains increase in size and are expected to be wider than the underlying grains. Grains separated by high angle boundaries are called the primary grains and it is usually found that there is a substructure divided by low angle grain boundaries within the primary grains. The substructure develops in different ways depending on the solute content, the thermal gradient and the solidification velocity. Four different modes are usually found; planar front, cellular, cellular dendritic and dendritic. In this particular work the mode of cellular dendritic was applicable which is a combination of cellular and the dendritic growth mechanisms. Growth occurs from the motion of an unstable solidification front and dendrites develop sometimes with a slight deviation from the maximum thermal gradient direction following the easy growth direction of <100>.

Most steel weld metals begin their solidification with the formation of δ-ferrite and in the majority of cases it is accompanied by nucleation of austenite on the δ-δ ferrite grain boundaries as shown in Figure 2.6. The δ-ferrite grains that form on solidification are reported to have an elongated or columnar structure (Keenda, 2004). When δ-ferrite forms, two major solid phase transformations occur on cooling to room temperature. The first occurs at high temperatures with δ-ferrite (Body Centered Cubic, BCC) transforming to austenite, (Face Centered Cubic, FCC) approximately between 1400°C and 1500°C. The austenite is reported to grow from side to side across the δ-ferrite grains with some uncertainty about the exact mechanism as it is generally not possible to clearly see the former austenite boundaries after transformation has taken place at lower temperatures (Keenda, 2004). In any case, the formation of austenite happens very quickly and its grain size is a very important factor. The austenite grain size has an influence on the γ to α-ferrite transformation (next section), and on the final mechanical properties.

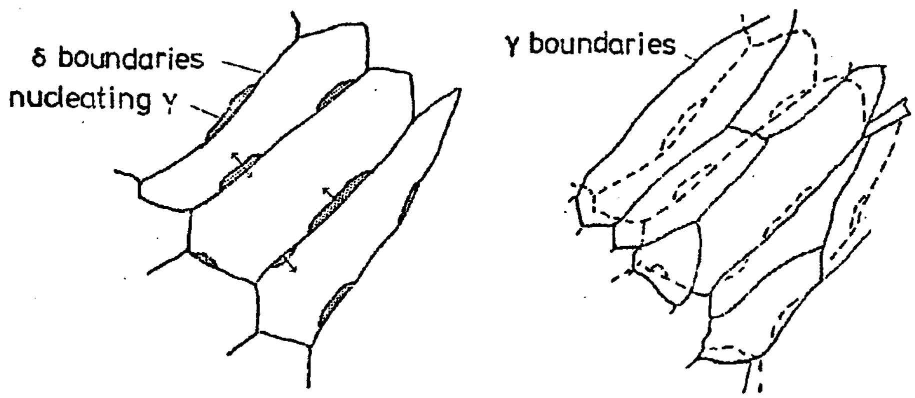

Figure 2.6: Schematic diagram showing the development of columnar austenite grains from the primary δ-ferrite solification structure (Keenda, 2004)

The formation of δ-ferrite may be prevented entirely by fast cooling, increasing carbon content or with additions of manganese or nickel (Keenda, 2004). When austenite forms directly from the molten weld metal the austenite grain size is expected to be larger than if it were formed from the decomposition of δ-ferrite. Additonally, only one major solid phase transformation takes place on cooling to room temperature.

2.8.2 The Decomposition of Austenite

The second solid transformation, the decomposition of austenite, takes place below 800 °C and the exact temperature depends on cooling rate and alloying content, with austenite (FCC) transforming to α-ferrite (BCC). The decomposition of austenite is generally shown in the form of a continuous cooling transformation (CCT) diagram such as that in Figure 2.7. Understanding the reactions and factors that control these curves has been the focus of metallographic investigations for decades within steel research.

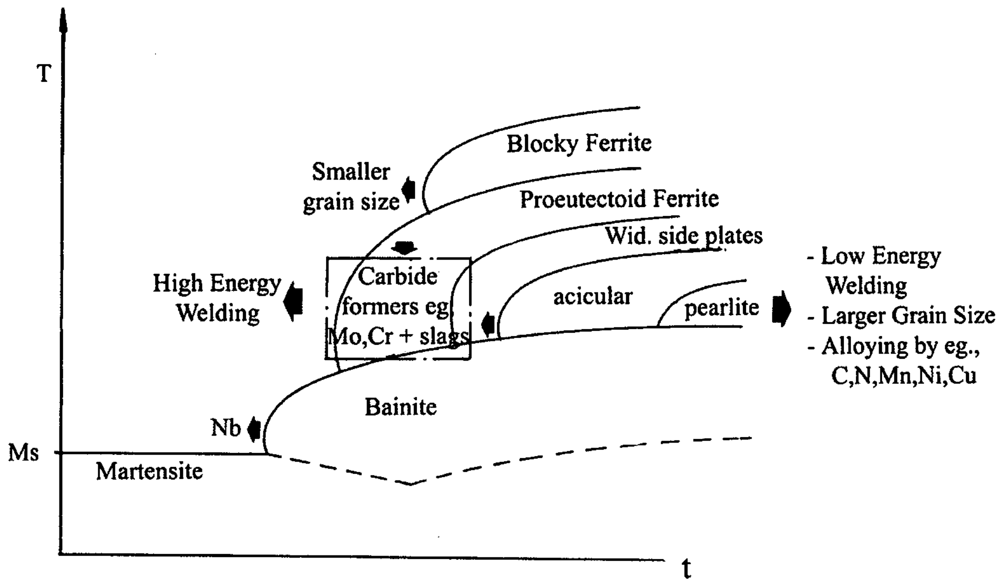

Figure 2.7: CCT diagram for steel weld metal, summarising the possible effects of microstructure and alloying on the transformation products for different weld cooling times (Keenda, 2004)

The microstructural transformations that take place are largely dependent on both the cooling rate and the composition. In steel, it was reported that austenite transformed to ferrite on cooling between 910 °C and 723 °C in iron – carbon alloys (Keenda, 2004). At fast cooling, the transformation temperature may be depressed below the region of 690 °C with austenite transforming to upper bainite. At even higher cooling rates transformation can take place in the region of 500 °C or lower, i.e. the martensite start temperature (Ms) (that depends on alloying) (Keenda, 2004).

2.8.3 Ferrite

There are three main ferritic constituents that form in weld metals; allotrimorphic ferrite, Widmanstätten side plates and acicular ferrite. Acicular ferrite is gerenally found to be positive for impact toughness. It is called acicular due to its needle shape in two dimensional sections. In three dimensions it is found to be in the form of lenticular plates with dimensions in the order of 5 μm to 10 μm in length and around 1μm in diameter. It nucleates on inclusions inside the austenite grains. In literature it is sometimes described as an intragranularly nucleated bainite. Arguments put forward to designate it as bainite were the shape change accompanying the transformation which is an invariant-plane strain with a large shear component, a similar stored energy of transformation of around 400 J/mol, no bulk partioning of substitutional alloying element on formation, the orientation relationship between it and the parent austenite and finally "the incomplete – reaction phenomenon" where the degree of reaction tending towards zero as the transformation temperature approaches the bainite start (Bs) temperature. The big difference between classical bainite and acicular ferrite is the fact that it nucleates intragranularly in the form of isolated plates radiating from a point nucleation site rather than the sheaf morphology of classical bainite which nucleates at austenite grain boundaries (Keenda, 2004).

2.8.4 Pearlite

The pearlite is a common constituent of a wide variety of steels and provides a substantial contribution to the strength. A pearlite colony consists of two interpenetrating single crystals of ferrite and cementite (Fe_3C), which are primarily ordered as alternating plates. Pearlite that consists of fine plates is harder and stronger than pearlite that consists of coarse plates. This morphology of pearlite is largely determined by the evolution of the austenite/pearlite phase transformation during the production process. Control of the pearlite phase transformation kinetics is thus of vital importance for the production of tailor-made steels.

The nucleation mechanism of pearlite involves the formation of two crystallographic phases. In hypo-eutectoid steels the pro-eutectoid ferrite nucleates first and continues to grow with the same crystallographic orientation during the pearlite formation as part of a pearlite colony (Sacks & Bohnart, 2005). In this case the cementite nucleation is the ratelimiting step in the formation of pearlite. In hypereutectoid steels the roles of ferrite and cementite are reversed and in perfectly eutectoid steel the pearlite nucleation is assumed to take place at the austenite grain corners, edges, and boundaries.

2.8.5 Bainite

Bainite was first discovered in the early 1930's by Davenport and Bain, who were investigating the isothermal transformations of austenite. It was called "Bainite" by the staff at the United States Steel Corporation Laboratory after E.C. Bain who had initiated the studies. From the early days it was known that there were two types of bainite; upper bainite formed at high temperatures and lower bainite formed at low temperatures. A schematic of both is shown in Figure 2.8.

At transformation temperatures in the region of, or less than 690 °C, carbon doesn't have time to diffuse into austenite as ferrite nucleates on the austenite grain boundaries (Keenda, 2004). To cope with this, the carbon concentrates and redistributes at the phase boundary since the solubility of carbon in bainitic ferrite is low (< 0.02 wt. %). As the carbon content increases at the phase boundary it may reach a high enough concentration at which cementite is able to nucleate and grow. Depending on the level of carbon, cementite may be in the form discrete particles (at low concentrations), or as continuous layers separating the ferrite plates (at high concentrations).

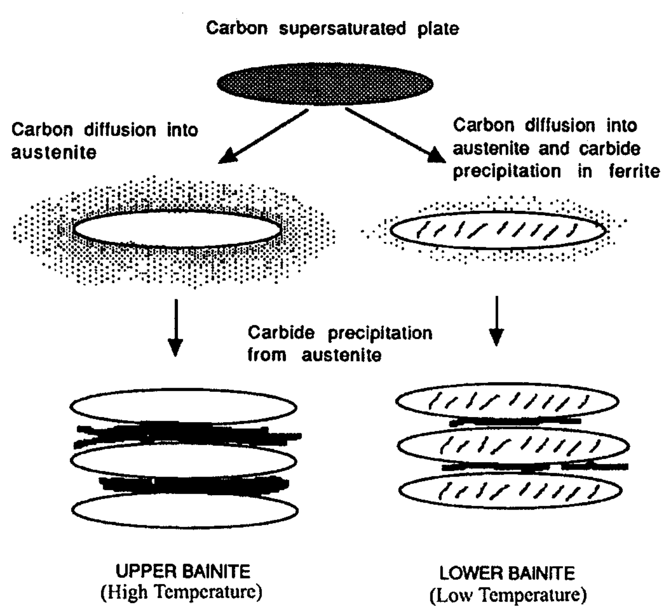

Figure 2.8: Schematic of the transition path to both upper and lower bainite (Keenda, 2004)

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