6.1 Introduction

Metallographic investigation plays an important role to establish the causes of failures and the service condition of a component. These investigations provide the information regarding presence of defects, mechanical properties and response in the intended service conditions before a component can be put into use. These consist of studying the microstructure and micro-hardness. Characterization of the microstructure and fracture surface topology plays a prominent role in metallurgical analysis.

The mechanical properties and behaviour of welds are determined by the microstructure developed during the submerged arc welding process (Joarder et al. 1991). The characteristics of the weld metal also depend on size, shape and pattern of distribution of micro-constituents and inclusions. Finer and evenly distributed inclusions result in better mechanical properties (Stuck et al. 1972; Shultz and Jacson 1973).

It was suggested that the acicular ferrite provided a good toughness and tensile strength to the welds because its fine size has a higher resistance to the crack propagation (Liu and Olson, 1986). Thus, it seems to be convenient to increase the volume fraction of ferrite in welds. A method for promoting the formation of acicular ferrite consists of the additions of oxides into the flux, such as boron oxide, vanadium oxide and titanium oxide (Evnas, 1986). The oxides in the flux may contribute to different metallic element dissolution and oxygen into the weld. These elements may
react to form oxide inclusions, which are trapped into the weld and facilitate the
nucleation of acicular ferrite during the weld cooling (Dowling et al. 1986; Eijk et al.
1999).

Microstructure of a weld metal is the result of heating and cooling cycle. Also it
is directly related to the welding process and the material being welded. The properties
of the weldment can be optimized by improving the microstructure. The main factors
that determine the microstructure of a weld are: chemical composition, austenite grain
size and cooling rate (Lancaster, 1980). The chemical composition of the weld metal
attributes from the composition of base metal, electrode and flux (Davis and Bailey,
1991). In order to increase the mechanical properties of welds for low-carbon steels,
the selection of an appropriate flux composition plays a very important role to obtain a
fine acicular ferrite, which has been shown to improve the properties in this type of
welds.

The heat input directly influences the microstructures formed in weld metal
(Easterling, 1992; Svensson, 1994). The typical microstructure formed in weld metal
(WM) of low carbon steels consists of grain boundary ferrite (GBF), Widmanstaten
ferrite (side plates), acicular ferrite (AF) and microphases (a small amount of
martensite, retained austenite or degenerate pearlite depending on the cooling rate and
composition. High heat input and low cooling rate result in coarse grain structure and
consequently impart low hardness, less tensile strength, yield strength and ductile
weldment (Aklsoy et al. 1999). Low heat input and high cooling rate result in fine grain
structure and possibility of formation of martensite and consequently cause the higher
hardness, tensile strength, yield strength and, brittle weldment. Thus, the study of microstructure and micro-hardness is useful for predicting the mechanical properties and the response of the weld metal to the given service conditions.

The present work investigates the effect of different heat-input using different fluxes (developed as well as parent fluxes) on the microstructure and micro-hardness of the weld metal.

6.2 Constituents of Microstructure

6.2.1 Austenite

It is an interstitial solid solution of carbon dissolved in gamma iron and has FCC structure. The maximum solubility of carbon in austenite is 2.11% at 1147°C which decreases to 0.77% carbon at 727°C. It is normally not stable at room temperature. Under certain conditions it is possible to obtain austenite at room temperature. It is soft, ductile, malleable and non-magnetic. Its mechanical properties like tensile strength, elongation and hardness are 1035 MN/m², 10% in 5 cm and Rockwell C 40 respectively (Avner 2006).

6.2.2 Cementite

Cementite or iron carbide (Fe₃C) contains 6.67 % carbon by weight. It has a complex orthorhombic crystal structure. It is a hard, brittle interstitial compound of low tensile strength (35 MN/m²) but high compressive strength and with high hardness (1000VPN).
6.2.3 **Pearlite**

It is the eutectoid mixture containing 0.80% carbon and is formed at 727°C on very slow cooling. It is very fine platelike or lamellar mixture of ferrite and cementite. Its mechanical properties like tensile strength, elongation and hardness are 837 MN/m², 20% in 5 cm and Rockwell C 20 respectively.

6.2.4 **Bainite**

It is a phase that exists in steel microstructures after certain heat treatments. It is one of the decomposition products that may form when austenite (the face centered cubic crystal structure of iron) is cooled past a critical temperature of 723°C. Its microstructure is similar in appearance to tempered martensite.

A fine non-lamellar structure, bainite commonly consists of ferrite, carbide, and retained austenite. In these cases it is similar in constitution to pearlite, but with the ferrite forming by a displacive mechanism similar to martensite formation, usually followed by precipitation of carbides from the supersaturated ferrite or austenite.

Bainite manifests as aggregates, termed sheaves, of ferrite plates (sub-units) separated by retained austenite, martensite or cementite. While the sub-units appear separate when viewed on a 2-dimensional section they are in fact interconnected in 3-dimensions and usually take on a lenticular plate or lath morphology. The sheaves themselves are wedge-shaped with the thicker end associated with the nucleation site. The temperature range for transformation to bainite is between those for pearlite and martensite. When formed during continuous cooling, the cooling rate to form bainite is
higher than that required to form pearlite, but lower than that to form martensite, in steel of the same composition.

6.2.5 Martensite

It is a very hard form of steel crystalline structure that is formed by displacive transformation. It includes a class of hard minerals occurring as lath or plate-shaped crystal grains. When viewed in cross-section, the lenticular (lens-shaped) crystal grains appear acicular (needle-shaped). The martensite is formed by rapid cooling (quenching) of austenite which traps carbon atoms that do not have time to diffuse out of the crystal structure.

6.2.6 Alpha ferrite

Alpha ferrite is commonly called ferrite. It is an interstitial solid solution of carbon in alpha iron and is thus having BCC structure. The maximum solubility of carbon in ferrite is 0.02% at 727°C, which decreases with the fall in temperature to negligible amount at 0°C. It dissolves only 0.008% C at room temperature. It is soft and ductile. Its average mechanical properties are tensile: tensile strength, 245 MN/m², elongation, 40% in 5cm and hardness less than Rockwell C 0.

6.2.7 Delta ferrite

Delta iron is an interstitial solid solution of carbon in delta iron having BCC structure. It has maximum solubility of carbon of 0.09% at 1495°C. It is a high
temperature phase and is a high temperature manifestation of alpha ferrite. It is paramagnetic.

6.2.8 Acicular ferrite

It is a microstructure of ferrite that is characterized by needle shaped crystallites or grains when viewed in two dimensions. The grains actually three dimensional in shape and have a thin, lenticular shape. This microstructure is advantageous over other microstructures because of its chaotic ordering, which increases toughness. Acicular ferrite is formed in the interior of the original austenitic grains by direct nucleation from the inclusions, resulting in randomly oriented short ferrite needles with a 'basket weave' appearance. This interlocking nature, together with its fine grain size (0.5 to 5 um with aspect ratio from 3:1 to 10:1), provides maximum resistance to crack propagation by cleavage. Acicular ferrite is also characterized by high angle boundaries between the ferrite grains. This further reduces the chance of cleavage, because these boundaries impede crack propagation.

6.2.9 Widmanstatten ferrite

When a coarse austenite grained steel due to high temperature heating is cooled fast but less than critical cooling rate, the typical microstructure then developed is called Widmanstatten structure. In this structure, the proeutectoid phase separates not only along the grain boundaries of austenite, but also inside the grains after certain crystallographic planes and direction in the shape of plates or needles, forming mesh
like arrangements. Widmanstatten structure is characterized by its low impact values and low percentage elongations (Svensson, 1994).

### 6.2.10 Polygonal ferrite

Polygonal ferrite occurs in the form of coarse ferrite islands inside the prior austenite grains. Its presence reduces the toughness of the weld metal. Its amount decreases with the increase in carbon and chromium content of the weld metal. Its amount increases with the increase in heat input during welding and decreases with the increase in carbon and chromium content of the weld metal.

### 6.2.11 Grain boundary ferrite

Pro-eutectoid ferrite forms along the austenite grain boundary when the weld metal is cooled in the stage of austenite-ferrite transformation. Elongated or granulated, this grain boundary ferrite grows into the austenite grain on one side of the boundary. This reaction is known as ferrite veining due to its branching aspects throughout the weld metal (George 1986).

### 6.3 Effect of Alloying Elements

#### 6.3.1 Carbon

Carbon exerts the most profound and significant effect on the allotropy of iron. Carbon is austenite stabilizer. As the carbon content increase, it increases the range of austenite formation, expands greatly the austenite field and also decreases the fields of ferrites (BCC). The much larger phase field of austenite compared to alpha ferrite
reflects the much greater solubility of carbon in gamma iron than in alpha iron. Flick (1986) and Surian et al. (1995) observed that mechanical properties of the weld metal increased with the increase in carbon content. They also observed that the ratio of yield to ultimate tensile strength of the weld deposit increased with the increase in carbon content. Its higher content reduces the weldability and oxygen level and hence the inclusion rating of the weld metal. In other words the higher the carbon content the more likely special procedures such as preheating, interpass temperature control and post heating are necessary. Heuskal (1969, 1973) also reported the decrease in toughness with the increase in amount of weld metal carbon.

6.3.2 Nickel

It is highly soluble in ferrite and does not form carbides or oxides, and thus increases the strength and toughness without decreasing ductility. It also acts as an austenite stabilizer. The addition of nickel in the weld imparts corrosion resistance, high and low temperature strength (Kane 1999). Combination of nickel and chromium is used to improve the mechanical properties of the weld metal.

6.3.3 Manganese

Manganese is soluble in alpha and gamma iron. Manganese acts as a deoxidizer and an austenite stabilizer. Manganese contributes markedly to strength and hardness of the weld metal, but to lesser degree than carbon. Like nickel, it reduces the eutectoid temperature and carbon content of the weld metal (Lekthi 1998). It is weak carbide
former and has a moderate effect on hardenability. It counteracts the effects of sulphur. It refines the microstructure and promotes the formation of acicular ferrite in the weld metal.

Higher content of manganese decreases the ductility and weldability of the weld metal. The mechanical properties of weldment increase with the increase in manganese content (Surian and Boniszewski 1992). Heuskel (1973) reported that the toughness decreased with the increase in manganese content of the weld metal.

6.3.4 Silicon

It is one of the common deoxidizing agents. It dissolves in ferrite and its higher content imparts increased hardness and decrease in fracture-toughness of the weld metal (Mohandas and Reddy, 2001). A properly balanced combination of manganese and silicon produces steel with unusually high strength with good ductility and toughness.

6.3.5 Molybdenum

Molybdenum is a relatively expensive alloying element, has a limited solubility in gamma and alpha iron, and is strong carbide former. It has a strong effect on hardenability and results in the retention of a great deal of toughness. It finds its greatest use with other alloying elements such as nickel, chromium or both.
6.3.6 Chromium

The addition of chromium results in the formation of various carbides of chromium which are very hard. Chromium also refines the grain structure so that these two combined effects result in both toughness and increased hardness. It is soluble up to 13% in gamma iron and has unlimited solubility in alpha ferrite. It acts as ferrite stabilizer. It also increases the strength at high temperature, hardnability, abrasion and wear resistance of the weld metal. Evans (1989) has noticed that chromium promotes an increase in the percentage of acicular ferrite.

Some investigations conducted on base metals and on single and multipass welds by Jorge (1993) showed that an increase in chromium content promotes a higher volume fraction of martensite–austenite (M/A) constituents, up to a level that depends on the chemical composition. Consequently, an impairment of impact toughness is expected for higher chromium contents.

6.3.7 Copper

The addition of copper in the weld metal improves resistance to atmospheric corrosion.

6.3.8 Phosphorous

Phosphorous dissolves up to 1.2% in alpha iron, but the solubility decreases with the increase in carbon. Phosphorous, when present as solid solution in ferrite, distorts the crystal lattice resulting in increase in tensile strength and yield point, but reduces the ductility and toughness.
6.3.9 Sulphur

It is an undesirable impurity in steel because it forms iron sulphide, which results in cracking. Its presence reduces the strength, ductility, toughness and weldability. It induces the temper brittleness of the weld metal. Therefore, its content should be as low as possible.

6.4 Micro-hardness

Measurement of hardness plays a considerable role in the acceptance or rejection of a weldment. The integrity of the weld metal can be determined by micro-hardness of the weld bead along with the study of its micro-structure. Micro-hardness depends on composition, grain size, presence of micro-constituents and its size and distribution. These factors in turn depend on composition and grain structure, types of consumables used like electrode, flux and thermal cycle of the weldment.

6.5 Experimental Procedure

Welding was performed in the flat position by SAW process and only one pass was deposited with the aim of producing a structure containing only columnar grains. The bead-on-plate welds were laid on the steel plate at the different heat-inputs using the acidic and basic fluxes, developed as well as parent fluxes. The parameters were varied as per Table 6.1. The chemical compositions of the welding wire and base plate is same as has been reported in Table 5.1 of chapter-5. After cleaning the weld bead, samples were cut from the middle of the plate and subsequently the samples were prepared by standard metallurgical procedures for micro-hardness survey and metallurgical studies of the weld metal. The samples were etched with 2% Nital. For
metallurgical studies, micrographs of the welds were recorded at 400X magnifications. The micrographs are shown in Figs. 6.1 to 6.12.

Micro-hardness (HV 500g) was measured, as shown in Table 6.2 and 6.3 at the cross-section of the welds starting after leaving 1mm from the top of the bead along the downward vertical line at an interval of 0.5 mm. The machine used was Microhardness Vicker Tester-II, Make-Image Tech. (India). The graphs between downward vertical distance from the top of the weld and micro-hardness were drawn and shown in from Figs. 6.13 to 6.16.

Table 6.1 Welding parameters

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Voltage (A)</th>
<th>Current (B)</th>
<th>Welding Speed (C)</th>
<th>Heat-input H=AB/1000C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volts</td>
<td>Amperes</td>
<td>mm/sec</td>
<td>KJ/mm</td>
</tr>
<tr>
<td>1</td>
<td>32</td>
<td>375</td>
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</tr>
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<td>1.9</td>
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<td>3</td>
<td>38</td>
<td>425</td>
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<td>2.15</td>
</tr>
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</table>

6.6 Results and Discussion

The micrographs of the weld, laid with different heat-input using developed basic and acidic fluxes are shown in Figs. 6.1 to 6.6. at 400X magnification. These show that ferrite veining (elongated fine grain boundary ferrite), acicular ferrite and polygonal ferrite are present in the weld. However, on comparison of the micrographs shown in these Figs. of developed and parent fluxes, it can be observed that the amount of grain boundary ferrite and polygonal ferrite increases and amount of acicular ferrite decreases with the increase in the heat-input. It can be attributed to the coarsening of the ferrite at the higher heat-input.
Similarly, the micrographs of the weld, laid with different heat-input using parent basic and acidic flux are shown in Figs. 6.7-6.12. at 400X magnification. It also shows that ferrite veining (elongated fine grain boundary ferrite), acicular ferrite and polygonal ferrite are present in the weld metal. On comparison of all these micrographs, it can be observed that the amount of grain boundary and polygonal ferrite increases and amount of acicular ferrite decreases with the increase in heat-input.

Similarly, the average micro-hardness values of the weld metal laid with the parent and developed fluxes at the heat input of 1.6 kJ/mm, 1.9 kJ/mm and 2.15 kJ/mm are shown in Tables 6.2 and 6.3. This trend of higher values of micro-hardness of the weld metal laid by acidic flux and lower heat-input is attributed to the higher carbon equivalent and the higher amount of acicular ferrite in the weld metal.

![Micrograph at 1.6 KJ/mm heat-input using developed acidic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400](image)

Fig.6.1
Fig. 6.2 Micrograph at 1.6 KJ/mm heat-input using developed basic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400

Fig. 6.3 Micrograph at 1.9 KJ/mm heat-input using developed acidic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400
Fig. 6.4 Micrograph at 1.9 KJ/mm heat-input using developed basic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400

Fig. 6.5 Micrograph at 2.15 KJ/mm heat-input using developed acidic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400
Fig. 6.6 Micrograph at 2.15 KJ/mm heat-input using developed basic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400

Fig. 6.7 Micrograph at 1.6 KJ/mm heat-input using parent acidic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400
Fig. 6.8 Micrograph at 1.6 KJ/mm heat-input using parent basic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400
Fig. 6.9 Micrograph at 1.9 KJ/mm heat-input using parent acidic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400

Fig. 6.10 Micrograph at 1.9 KJ/mm heat-input using parent basic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400
Fig. 6.11 Micrograph at 2.15 KJ/mm heat-input using parent acidic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400

Fig. 6.12 Micrograph at 2.15 KJ/mm heat-input using parent basic flux: AF-acicular ferrite, GBF-grain boundary ferrite, PF-polygonal ferrite. Nital etch X400
Fig. 6.13 Micro-hardness at different position in weld metal laid with developed acidic flux

Fig. 6.14 Micro-hardness at different position in weld metal laid with parent acidic flux
Fig. 6.15 Micro-hardness at different position in weld metal laid with developed basic flux

Fig. 6.16 Micro-hardness at different position in weld metal laid with parent basic flux
Table 6.2 Micro-hardness of the weld metal laid by basic flux at different heat-input

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Downward distance from top (mm)</th>
<th>Micro-hardness (500g HV)</th>
<th>Parent Basic Flux</th>
<th>Developed Basic Flux</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Heat -input 1.6 KJ/mm</td>
<td>Heat -input 1.9 KJ/mm</td>
<td>Heat -input 2.15 KJ/mm</td>
</tr>
<tr>
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<td>0.5</td>
<td>324</td>
<td>296</td>
<td>265</td>
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<td>Average</td>
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<td>298</td>
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Table 6.3 Micro-hardness of the weld metal laid by acidic flux at different heat-input

<table>
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<th>S.No.</th>
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<th>Micro-hardness (500g HV)</th>
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<td></td>
<td></td>
<td>Parent Acidic Flux</td>
<td>Developed Acidic Flux</td>
</tr>
<tr>
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<td></td>
<td>Heat -input 1.6 KJ/mm</td>
<td>Heat -input 1.6 KJ/mm</td>
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