Abstract:
The present investigation revolves around evaluation of fracture toughness of welded API X65 steel plate. API X65 is a high strength low alloy (HSLA) steel which is used in line-pipes for transporting oil and natural gas. In the above application, catastrophic failure due to fatigue is reported to cause sudden damage and loss to human-life as well as property. Hence, from end application point of view, knowledge on fracture toughness especially in welded plates is of immense importance. Through the present work, an effort has been made to add to the limited number of reports on the above subject. In this work, first, the selected steel was characterized in terms microstructure, hardness and tensile properties. Thereafter, the welding of steel plates was performed with sub merged arc welding (SAW) with root pass of shielded metal arc welding (SMAW). The micro hardness profile in base material (BM), heat affected zone (HAZ), weld zone (WZ) and weld nugget were evaluated along with microstructural characterization of the above zones using optical and transmission-electron microscopy. The fracture toughness of various zones of welded plate, was evaluated in terms of J-R curve following the concept of EPFM. The samples for fracture toughness tests were prepared as per ASTM E1820. Fractography of the failed specimens were also carried out. The evaluation of fracture toughness of welded API X65 plates indicates that, JQ value of heat affected zone was slightly lower than the base material, but for the weld zone it dropped significantly by 53% due to the non-uniform crack front and crack propagation. The phenomenon is attributed to presence of different defects in the weld region. JQ value for fusion line samples showed significant scatter with an average reduction of 40% in JQ value as compared to base material. The scatter in fusion line value can be attributed to error in precise placement of notch or deviation of crack path during testing. Presence of Nb and V imparts precipitation hardening effect to the API X65 steel, such that it has a satisfactory combination of strength and toughness parameters fulfilled by API service requirements.

Keywords: Sub merged arc welding (SAW); Shielded metal arc welding (SMAW); Base material (BM); Heat affected zone (HAZ); Weld zone (WZ); Fracture toughness.

I. INTRODUCTION

1.1 Background and motivation

Over the past few years, production of oil and gas increased enormously and due to this, the transport of such oils and gasses require development of improved line-pipe steels. The usage of high strength low alloy steels (HSLA) in line-pipe brings in the advantage of cost reduction by virtue of reduction in wall thickness of pipelines [1]. Manufacturing of HSLA line-pipe steel for oil and gas transmission follows the API 5 L standards [2]. The desired properties in these steels are high mechanical strength, good weld ability, high fracture toughness, strain tolerance, resistance to environmental degradation such as stress corrosion cracking. The aim of steel suppliers is to develop all the above properties at a reasonable price. These steels were first introduced in early 1930’s which was followed by years of research to achieve optimum structure-property combination. The micro alloying elements like niobium, vanadium and titanium were added in certain amounts as low as 0.005-0.010 percent in early steels. These HSLA steels were firstly used in ship plates, beams, bridge steels, reinforcing bar and heat treated forgings and was not introduced into line-pipe steels until 1959 [3]. However due to the predominant changes in the metallurgical approaches and development of different kinds of rolling techniques these HSLA steels came into existence with the escalating technological demands of high pressure line-pipe steel. In this work, a special grade of HSLA steel developed at TATA Steel Ltd., Jamshedpur, India, was characterised. It was specially aimed to develop a suitable combination of strength and toughness for the steel owing to different microalloying additions. The study also compares the properties of the steel and its weldments.

1.2 Objectives of the current work

The primary objective of the present investigation is to study and evaluate the fracture toughness of the welded high strength line-pipe steel. The major scope of the work is briefly summarised as follows:

(I) To characterize the steel for its chemical composition, its microstructure in base metal and weld regions and to determine the hardness and tensile properties.

This section consists of (a) chemical composition analysis of the steel specimens (b) microstructural examination at various zones i.e. parent material, heat affected zone, weld zone and grain size measurement (c) determination of their hardness and tensile properties.

(II) To study the fracture toughness property of the welded API X65 steel.

The major experiments to fulfil this objective are (a) pre-cracking of the sample under fatigue (b) examination of the fracture toughness at various zones by J-R curve approach.
Fractographic examinations on the fractured sample using (SEM) scanning electron microscope. Fractographic examinations of fractured surface using SEM to study the various features and understand the type of failure in the fractured sample.

II. LITERATURE REVIEW

High-strength low-alloy steel (HSLA) were firstly introduced in early 1930’s. The elements like niobium vanadium and titanium were added independently in amounts of about 0.005 to 0.010 in early steels, however as strength increased with adding them in combination and the metallurgical approaches got more refined. The overriding melting methods at early days was Siemens-Martin open hearth process, the steels were ingot casted and brought to the required shape by the use of Thermo mechanical controlled process (TMCP). HSLA steels were firstly used in ship construction, bridges, reinforced bars but not introduced into line-pipe application until 1959 [3].

Then after the boom in the technology has brought to the application into line-pipe steel with rapid evolution of HSLA technology since then. HSLA is a type of alloy steel that provides very good mechanical properties and are very highly resistant to corrosion than carbon steel. HSLA steels are different from other steels that these are not made to meet the specific chemical composition, however to meet the specific mechanical properties depending on the application by varying the micro alloying elements accordingly. These steels will have a very less carbon content varying from 0.05 to 0.025% to respond easily during forming and welding operations.

Other alloying elements are added approximately up to 2.0% manganese and very little amounts of copper, niobium, nickel, vanadium, titanium, chromium, nitrogen, molybdenum or zirconium [4, 5]. Cu, Ti, V and Nb are added for strengthening purposes [5].

These elements are deliberately added to alter the microstructure of carbon steels, which is generally the amalgamation of ferrite-pearlite, to produce a very fine scattering of alloy carbides in an almost pure ferrite matrix [6].

Mostly used in cars, cranes, trucks, bridges and other structures where huge amounts of stress has to be handled and excellent strength to weight ratio is required. However, these steels are good at strength to weight ratio their cross sections and structures are lighter by 20 to 30% compared to carbon steels with same strength [7].

HSLA steels are more resistant to corrosion than most carbon steels due to lack of pearlite – and fine layers of ferrite (almost pure iron) and cementite in pearlite. HSLA steels usually have densities of around 7800 kg/m³ [8].

Classification of HSLA steel

HSLA steels include many standard grades covered by ASTM standards designed to provide particular strength, toughness, formability, weldability, and to withstand corrosion depending on the application of the material. HSLA steels are not the alloy steels even though some amount of alloying elements are added to the steels to meet the requirement. Particularly these are separate steels which are similar to as-rolled carbon steels with improved mechanical properties by adding the alloying elements and special rolling techniques such as controlled rolling and rapid cooling techniques which are explained briefly later. Because of this they are priced at the base price of carbon steels not at the base price of the alloy steels which will be a bit expensive compared to the carbon steels. However these steels are sold with minimum mechanical properties with the specific alloy content left to the discretion to the steel producers. These steels are classified into six categories [8, 9] weathering steels, microalloyed steels, rolled pearlitic steels, acicular ferrite steels, dual phase steels, inclusion-shape-controlled steels.

Effects of alloying elements

Manganese is one of the vital elements in the pipe steels which plays a major role because it will merges with Sulphur to form MnS. Which will cause hot shortness in steels? Therefore, the addition of manganese with Sulphur and formation will vulnerable of steel to hot shortness [10]. It is added to steels to not only improve the hot working Chapter 2 Literature review 5 properties of the steel, but it also improves the strength, toughness, hardenable. Iron sulphide has lower melting point than MnS, which tends to form at the austenite boundaries in the absence of manganese there are chances of increase in potential crack growth sites during hot working [11]. With little amount of carbon with high amount of manganese (Mn 0.8-0.15%) in steel design is depends on manganese leads to solid solution strengthening [11]. Silicon is one of the deoxidizer used in steel making. Silicon exhibits properties like increase of solid solution hardening on ferrite and used to improve the strength and toughness [10].

The strengthening rate of low carbon steels by Si was higher in coarse grain region compared to that of the fine grain region. But, silicon decreases the prior austenite grain size which leads to a fine ferrite grain size [12]. Increasing the amount of silicon will results in decrease in the rate of recrystallization and increase the strength of austenite due to the solid solution hardening [13]. Molybdenum also has a great effect on increasing the high temperature strength and retarding grain growth at temperatures just above the critical temperatures of steel [10]. It increases the steel harden ability and shows very good resistance to hydrogen embrittlement and stress corrosion cracking in high Sulphur content steels [14]. It has also been reported that adding molybdenum to Microalloyed steels results in the slowing down of the bainitic transformation which results in a fine bainitic region [15]. It is the most important element in the micro alloying elements to stabilize the carbon and has very adverse effect on austenite recrystallization and hardenability [10]. The rate of initial transformation of austenite to high ferrite niobium steels is reduced by the solute drag effect of niobium and pinning effect of the Nb(CN) precipitates [16]. Vanadium is used to interfere the austenite grain growth at peak temperatures results in fine grain therefore achieves good toughness and strength [10]. But, steels that are hardened by precipitation hardening with vanadium carbide exhibits poor wear resistance than vanadium free steels. Vanadium and Silicon has a vital role in the microstructure and hardness. Microalloying with Titanium results in the deceleration of austenite recrystallization along with precipitation strengthening of ferrite. Titanium amalgamates with carbon and forms titanium carbides, which are highly stable and difficult to dissolve in austenite. Titanium subsequently improves the weldability and resistant to HAZ cold cracking due to TiC precipitate particles which acts as the effective traps for hydrogen atoms [17]. Chromium is added to
increase the corrosion resistance of the steels. It also increases the harden ability and wear resistance of the steels. Chromium amount more than 4 weight % in steels increases the corrosion resistance. However there will be a subsequent decrease in the weld ability. Chromium can form Cr3C2 by this the wear resistance increases enormously [10]. Chromium polarizes the cathodic polarization curves of line-pipe steels which helps in uneven corrosion rate in the line-pipe weldments [18]. Nickel improves oxidation and corrosion properties of steels along with this it also improve toughness, impact resistance and solid solution strengthening. Nickel also helps in forming of very finer pearlite as pearlite is very strong and tougher results in very high toughness and has no adverse effect on welding [10]. Aluminium is added as a deoxidizer to steels. But adding this in excessive amount will results in decrease in toughness and the deoxidizing function ends i.e. at weight% greater than 0.05. Aluminium likely to form aluminium nitride (AlN) which has a very severe effect on hot ductility of different grades. If weight % of aluminium increases by 0.02 it promotes precipitation of AlN rather than vanadium nitride [21]. Copper is regarded as the dangerous element as it causes hot shortness which reduces ductility of the material at temperatures 1100-1300°C. It also causes surface defects during hot processing and it has been reported [20]. But, it increases the corrosion resistance and tensile properties of steels. It is usually the element which causes embrittlement in low alloy steels.

This promotes grain boundaries to segregate and reduces the toughness property. It increases the tendency to cracking while welding because of the embrittlement property present in it so due to this reason the amount of phosphorous should be low as 0.015 weight%.

But when it is present in phosphate form it reduces the hydrogen uptake. Sulphur is a harmful element in steels which form sulphide inclusion with manganese and reduces the toughness properties in steels. Sulphur will separate the grain boundaries which causes intergranular fracture [11].

Nitrogen it has been considered as one of the vital and low cost alloying additions to steels. Nitrogen will be present in the interstitial atoms as nitrides of iron, titanium, vanadium, aluminium, niobium and other alloying elements.

Depending upon the form it can be treated as harmful or beneficial to physical and mechanical properties of the steels. Because it is a small atom like carbon can easily diffuses in the steels and causes surface hardening.

**Processing and manufacturing of line-pipe steels**

An important factor affecting strength and toughness of the material was rolling process involved in the manufacturing of HSLA steels they are:

1. Thermomechanical Controlled Rolling (TMCR)
2. Thermomechanical controlled process (TMCP)

The TMCR consists in rolling slabs into plates in three main steps.

- First, rolling in temperatures of austenite recrystallization (around 1250°C).
- Second, rolling in austenite non-recrystallization temperatures (around 1050°C).
- Third, finishing rolling in austenite – ferrite Ar3 temperature(910°C) (or even at lower temperatures depending on the carbon content and on the mechanical resistance aimed)
- Finally air cooled.

The TMCP is similar to TMCR process for first three steps followed by accelerated cooling i.e. with water after the third step of the controlled rolling [22, 23]. However, there is a difference between both TMCR and TMCP processes, the final rolling pass temperature.

In the TMCR process this temperature is lower because, as this process does not have accelerated cooling, the mechanical properties should be guaranteed during the final rolling pass. Reducing the temperature in this third step of the process TMCR gives the material micro textures in the steel microstructure.

These textures have different orientations through steel plate’s thicknesses, which causes the development of residual stresses in the as rolled material and which allows the appearance of separations.

**HSLA steels applications**

HSLA steels are widely used in automotive industry, in oil and gas industry where fluids or gases with very high pressure has to be transferred for huge distances, in earth movers and heavy off road vehicles, industrial equipment, construction of bridges, trusses, storage tanks, power transmission lines, in civil constructions etc. these are the additional applications of this steels.

The choice of particular kind of steel depends on the application in which it is going to be used depending number of application requirements like thickness, corrosion resistant, formability, and weldability.

Mostly in selection process of steels strength to weight ratio of HSLA compared with normal low carbon steels. These characteristics of HSLA leads to the application of line-pipes also [8].

**HSLA steels in line-pipe applications**

HSLA techniques in line-pipe steels were firstly used in Mannesmann, Europe in normalized API Grade X-52 vanadium grades around 1952. Then later in 1953and 1962 further extended to API Grade X-56 and X-60 [24, 25]. Then in North America in the year 1959 hot rolled steel utilizing HSLA concepts came up into existence [3] and this replaced the normalising process completely in Europe by 1972 [24, 25, 26].

HSLA steel was still used in Europe till the mid 1990’s and the applications and research work on this different kinds on API 5L grades is going on till date.
III. EXPERIMENTAL PROCEDURES:

Introduction
The aim of the present investigation is to study the fracture toughness of welded high strength line-pipe steel in which the material chosen for investigation was API X65. To achieve this particular objective various tests were conducted which are discussed in this chapter. A brief overview of the tests conducted were determination of chemical composition of the selected steels, measurement of grain size and volume fraction of phases, determination of mechanical properties of the selected steel, microstructural characterization using optical and in transmission electron microscope in order to find out the second phases and precipitates respectively at various zones of the sample i.e. parent material, heat affected zone and weld zone. Harness profile of the sample was done in all the regions and in different welds as well which will be explained with the help of a stereo microscope image for better understanding, experiments related to fracture toughness, study of fractured surfaces in scanning electron microscope.

Material selection and chemical composition
Material used in this investigation was 10 mm thick hot rolled plates pertaining to API X65 grade where API stands for American petroleum institute. Plates of API X65 were received after rolling at Tata Steel limited. The chemical composition of the received plates was determined using optical emission spectrometer (ARL 3460).

Welding of the material
Pieces of dimensions 100 x 25 x10 mm were taken for welding. The welding was done with single bevel groove weld where different types of welds has been planned to be incorporated in this investigation. SMAW or conventional weld or stick weld fir root run followed by fill up of the joint by SAW. The cross sectional view of the sample is shown below in order to get a clear understanding of how the weld has been done Figure which has been captured with LEICA M165C stereo microscope (Figure). The weld parameters along with consumables are discussed in the results and discussion. As the welds were not visible directly, some part of the sample was cut at the weld zone into 25x10 mm sample. The samples were prepared which will be explained briefly later in the microstructural examination.

Figure.1. Evolution of line-pipe grade steel

Figure.2. Cross sectional image of the material after weld

Figure.3. LEICA M165C Stereo microscope
TEM Analysis

In order to get better understanding of the second phases and precipitates present in the material TEM analysis has been done for the material. Thin samples of about 0.08 mm or 80 μm have been prepared by mechanical thinning process wherein care was taken not to introduce any bend in the samples. Thinned samples were etched with Nital in order to reveal the various zones on the sample. Punching of the sample has been done because the sample diameter is only 3mm that can be accommodated in sample holder of TEM equipment. The samples were punched in such a way that in all the different zones at least two samples can be obtained. After punching, electro polishing of the sample were done before loading the sample into the TEM. The process of electro-polishing has been explained briefly with the help of the Figure 3.8. For example, Figure shows the image of the sample after punching: Figure shows the equipment used for electro polishing (Tenopol-5 product of STRUERS) and Figure shows the image of the samples after electro-polishing. Different parameters used while electro polishing are as follows: current: 30-40 milli amper, voltage: 16V for first cycle for 30 sec followed by 19V for second cycle for 30 sec. Samples were cleaned with methanol before placing into the solution for electro-polishing i.e. Acitic acid 90% + Percolic acid 10%.

IV. CONCLUSION AND FUTURE SCOPE

CONCLUSIONS

The aim of this investigation was to evaluate the fracture toughness of welded API X65 steel plates keeping in view the limited number of reported works on the subject. The selected steel was characterized in terms microstructure, hardness and tensile properties. The welding of steel plates was performed with submerged arc welding (SAW) with root pass of shielded metal arc welding (SMAW). The micro hardness profile in base material (BM), heat affected zone (HAZ), weld zone (WZ) and weld nugget were evaluated. The microstructural features of the above zones were revealed using optical and transmission electron microscopy. The fracture toughness of the above zones of welded plate was evaluated in terms of J-R curve following the concept of EPFM. Major conclusions are:

The evaluation of fracture toughness of welded API X65 indicates that, JQ value of heat affected zone was slightly lower than the base material, but for the weld zone it dropped significantly by 53% due to the non-uniform crack front and crack propagation. The phenomenon is attributed to presence of different defects in the weld region. JQ value for fusion line samples showed significant scatter with an average reduction of 40% in JQ value as compared to base material. The scatter in fusion line value can be attributed to error in precise placement of notch or deviation of crack path during testing. Presence of Nb and V imparts precipitation hardening effect to the API X65 steel, such that it has a satisfactory combination of strength and toughness parameters fulfilled by API service requirements.

V. REFERENCES


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