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Effect of Cooling Rates on Microstructures and Properties of API X65 Pipeline Steel during Saw

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Abstract: *The API 5L specification are suitable for use in conveying gases, water or oil under high pressure and at low temperature and also sometimes below Sub-Zero temperature in some cold countries. Apart from high Strength and Weldability, Toughness is much important for such application.*

In this paper, the formation of Micro-structure in sub-regions of HAZ's that is caused by the Thermal effects of Welding were investigated. The earlier study suggests that a large number of failures of such materials were initiated through the circumferential cracks development in the HAZ's due to Microstructural changes taking place. Present investigation aims at the Microstructural changes and its effect on Mechanical properties like variation in Hardness, Toughness across HAZ's, Weld Metal, and Base Metal. Metallographic analysis as well as Micro and Macro-Hardness characterization were carried out across the Weld in order to co-relate the different Mechanical properties and to get precise study of properties variations. Results reveals that, there is Toughness loss in sub-regions of HAZ's. And also this deleterious Toughness loss in CGHAZ is comparatively more than other sub-region of HAZ. The FGHAZ shows good combination of Strength and Toughness.

Keywords*: HAZ's, Toughness, Hardness, Weldability, Micro-structure, Weld Metal, Base Metal, API 5L X-65, SAW.*

I. Introduction

Energy companies currently make wide use of different grades of pipeline steels such as API X60, X65, X70 and X80 to transport crude oil and natural gas over long distances. Increasing demand for oil and natural gas has forced the energy industries to seek these resources in harsh and freezing environments [1,2] so they will expect pipeline steels to function well in severe Arctic conditions under High Pressure. Currently, North America, and especially Canada, is facing a crucial challenge on the safety of buried pipeline steels with regard to failure causing oil leakage onto agricultural lands. So in order to sustain this harsh condition with high pressure, High strength and high toughness are the essential property needed for the pipelines steels to have adequate energy to resist fracture [2]. The strength of pipeline steels can be altered by varying the chemical compositions but the attainment of High Impact toughness is a difficult task as it depends mainly on Heat input and Cooling Rate achieved during the time of Welding of pipeline steel [1].

Therefore, the attainment of toughness for API grade steel on the effect of weldability of steels receiving the considerable attention of discussion because welding thermal cycles will significantly change microstructures and in turn changes mechanical properties.

Generally during the welding process, three regions forms in a joint named as Base Metal Zone, Heat Affected Zones (HAZ's) and Weld Metal Zone. The properties of Base Metal Zones and Weld Metal Zone can be altered by changing the Chemical Composition as well as types of Electrodes used during Welding. But the properties of HAZ's depends on the Heat input as well as cooling rate achieved during Arc Welding. Higher heat Input with higher Cooling rate leads to the formation of the Local Brittle zone as well as different Microstructures in Sub-region of HAZ's.

Local brittle zones such as martensite-austenite (MA) islands can affect toughness properties of pipeline steel and welds in oil and gas pipelines. Austenite nucleates and grows preferably in enriched areas (such as regions of bainite or pearlite containing elevated carbon and manganese) and a long prior austenite grain boundaries. Upon cooling, the austenite will transform to hard MA regions [3]. Al- though MA has been widely studied in recent decades, the effect of cooling rate on its volume fraction remains ambiguous [3]; where some research has shown that increased cooling rate will increase fraction of MA, while other work suggests a decrease in MA with increase of cooling rate. Gonzalez et al. reported an increase in MA percentage with the increased cooling rate for X80 pipe steel during heat treatment. In contrast, Moeinifar et al. examined the HAZ of tandem submerged arc welded X80 pipeline using Gleeble simulation(heat treatment)and reported a decrease in MA percentage with increased cooling rate.

Therefore the aim of this study is to understand the effect of cooling rates on microstructures and Co-relation of Microstructure with Mechanical properties of API X65 pipeline steel during Submerged Arc Welding Technique.

II. Materials And Experimental Procedure

An API X65 linepipe steel was used to investigate the effect of cooling rate on Microstructure formation and the corresponding effect on Mechanical properties. Due to the limitation of test material, Mild steel plates were used for SAW (taking into account the density, the thermal conductivity and the specific heat capacity are, identical as API 5L X65) Mild steel plates of 300*150*10 as well as API 5L X65 plates of 350*150*11 were taken in the form of rolled plate. The chemical composition of material was analyzed by DRS method as reported in Table 1.

Table 1: Chemical composition of API X65 pipeline steel (wt. %):

Grade	X65
C	0.13
Si	0.45
Mn	1.65
P	0.014
Al	0.03
Ti	0.06
V	0.09
Ni	0.16
Cr	0.02
N	0.0071
Nb	0.055
Ceq	0.512

In the present work, Two Mild steel plates of 10 mm thickness and 300 mm in length and 150 mm of width in the form of flat plates were taken. The chemical composition of the filler material and base metal were almost identical so as to obtain better properties of the weld on the job piece and to minimize the HAZ welding regions. A single half V- butt junction with root face 4 mm and included angle 45° is used for the task of welding. Three thermocouples were spot welded with the help of UCD welder (SR80) to the specimen at 05 mm, 06 mm and 07 mm from the center that measures the temperature at different point in order to predict exact cooling behavior ($t_{8/5}$) in sub-regions of HAZ's. Because of the experimental limitation these thermocouples could not be inserted very close to the center line of the weld as shown in Figure 1.

Figure 1: Indicating the Thermocouple weld at different location

These thermocouples are connected with the computer module, which measures the temperature variation by lab view program with the help of DAQ (National Instrument). The process parameter for SAW test welding at ambient temperature (T_O) of 25^0 C are given in the Table 2.

Table 2: Indicating optimum process parameter of SAW

Parameters	Optimum value
Current	40 ampere
Voltage	330 volts
Trolley speed	240 mm/min
Heat input	3.3 Kj/mm

The data captured by lab view program at variable distance from the center tag were used to generate the temperature profile against the number of sample. These data are shown as a plot in the figure 2.

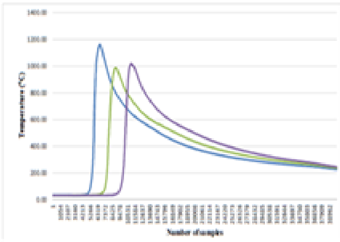


Figure 2: Indicating the three thermocouple temperature during SAW
(Blue-6mm, Violet-7mm, Green-8mm)

Based on captured data by DAQ with lab view program, the complete Microstructure of API X65 plate welding once again generated on a bigger sample by the help of Gleeble Simulator 3800 in order to perform Testing and characterization. Metallographic samples were prepared from Base plate as well as from simulated sample using standard polishing techniques, with final polishing using 1 mm diamond particles, while etching was performed using 2% nital solution for 10–15sec to reveal the microstructure. A second etchant known as Lepera's reagent was used to reveal the MA in the microstructure. When using Lepera etchant, the sample surface turns to a uniform gold color and MA appears white [18,19]. To ensure successful etching by the Lepera solution, it was found that the best results were obtained by first etching with a 2% nital solution and subsequently removing the excess etching by product using light diamond polishing before using Lepera. The Lepera etchant does not work if some nital etching by product remains on the surface. Microstructures were observed using was LEICA DM2500M microscope. The micro hardness was measured using a LEICA VMHT with 50gm load and Macro hardness using a LEICA METCO with 50kg load, which was in accordance with ASTM E 384-10 with 15s dwell time. Mechanical testing was performed as per E8/E8M standard. Charpy impact testing was performed by cooling full size impact specimens (10*10*55 mm) at -80^0 C by holding it in the cryogenic oil for 30 minutes to stabilize the temperature and then promptly tested following removal from the oil. A large number of simulated Charpy specimen were made under different heat input and cooling rate. The notch was made through thickness of pipe steel such that the fracture propagates along the axial direction of the pipe. At least three tests were performed at each temperature and the average was calculated.

III. Results And Discussion

3.1 Microstructure

The optical micrograph of the API 5L X65 base metal (BM) represents major portion of fine grained ferrite-degenerate pearlite in line pipe steel. The base metal consists of about 70-80 % volume fraction of primary ferrite. **The microstructure of BM as well as Sub-regions of HAZ’s are shown in figure 5**.The microstructure characterization of actual SAW welded sample etched under 2% Nital solution were observed as upper and lower Bainite along with some amount of Acicular Ferrite and Ferrite. The actual weld sample microstructure were compared with the actual simulated zone microstructure and observed that simulated zone microstructure is totally similar with the actual SAW welded sample. **All the SAW welded samples microstructures are shown in figure 6.** Within the sub-regions of HAZ i.e. in CGHAZ which is very close to molten weld joint, grain growth occurred with small amount of upper as well as lower Bainite and some secondary phase Martensite located prior to austenite grain boundary (PAGB) .The FGHAZ consists of Polygonal ferrite (PF), Irresolvable pearlite (IP),intergranular ferrite (IGF) and some secondary phase Acicular ferrite (AF) which play the most important role in improving the toughness of API grade steel. The FGHAZ **is shown in figure 4.4**. The ICHAZ is somewhat also same like CGHAZ which consists of Upper Bainite and Pearlite phase but the toughness is slightly better than CGHAZ. The ICHAZ **is shown in figure 4.5**.

3.2 Charpy Impact Toughness

Impact energy vs. different regions of HAZ plots at low heat input (LHI), medium heat input (MHI) and high heat input (HHI) at -80^0 C is shown in Figure 3 respectively. The BM CVN sample have the highest impact energy of about 470 J.

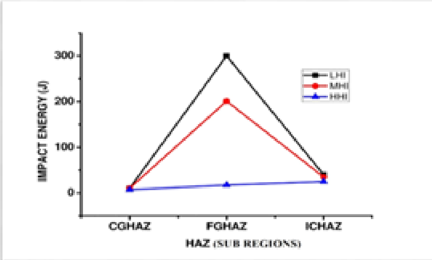


Figure 3: Impact energy vs. different regions of HAZ plots at different heat input (-80^0 C).

3.3 Hardness

The macro hardness across the weld joint i.e. BM, HAZ, and FZ were determined by hardness tester with a diamond indenter of 50kg force transverse load. The hardness variation across the weld **is shown in figure 4**. The weld zone or fusion zone shows the maximum hardness in weld metal. It may be due to acicular ferrite present in the sample.

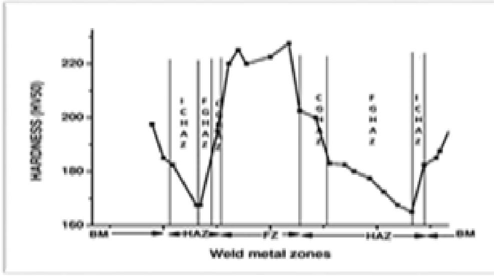


Figure 4: Hardness variation across the Welded metal

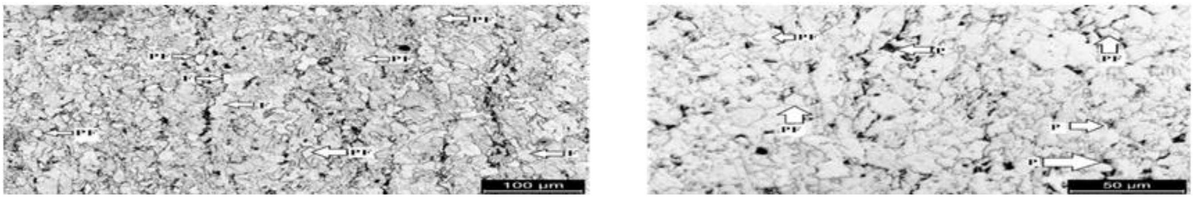
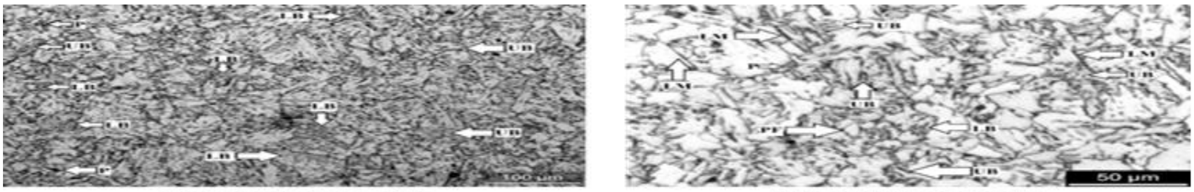
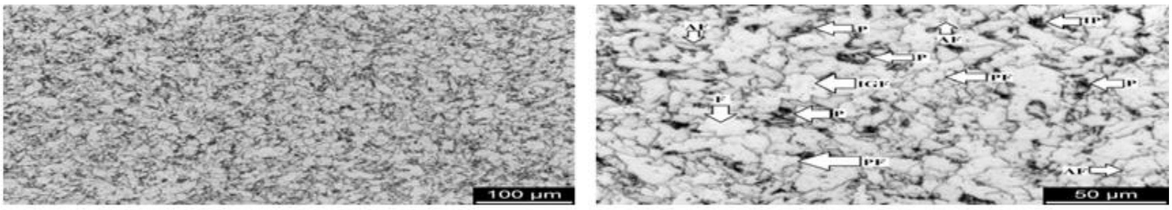


Figure 5 a): Indicating the microstructure of API 5L X65 at (a) 20X (b) 50X



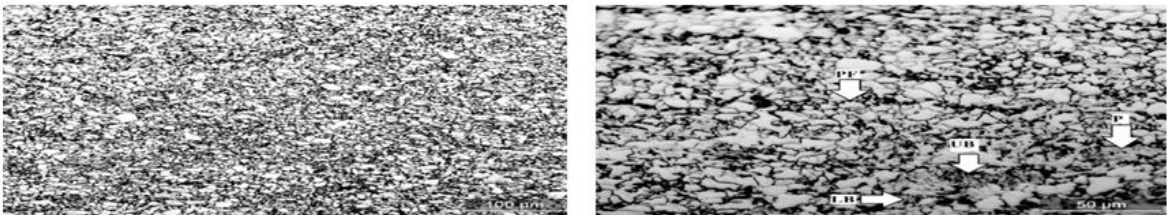
a) CGHAZ at 20X b) CGHAZ at 50X

Figure 5 b): Indicating the microstructure of CGHAZ



a) FGHAZ at 20X **b) FGHAZ at 50X**

Figure 5 c) Indicating the microstructure of FGHAZ



a) ICHAZ at 20X **b) ICHAZ at 50X**

Figure 5 d) Indicating the microstructure of ICHAZ

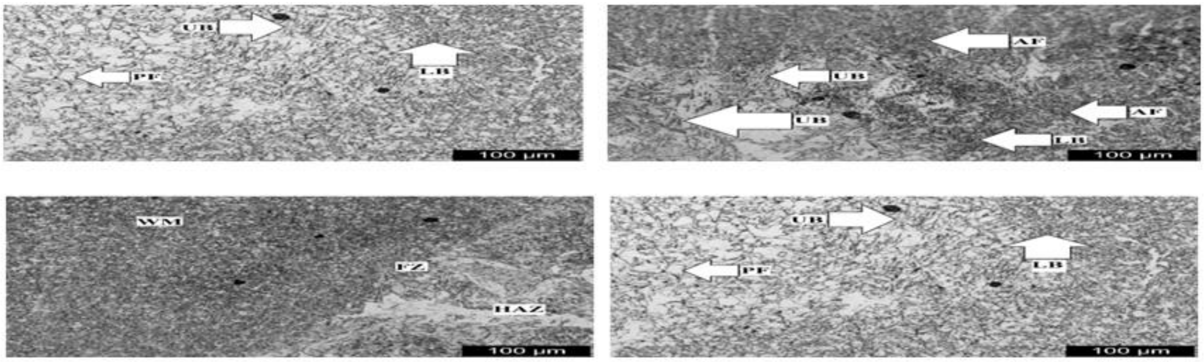


Figure 6: SAW welded samples microstructures

Micro hardness values were measured at different regions on simulated sub-regions of HAZ for all the three conditions i.e. LHI, MHI and HHI are shown in figure 7.

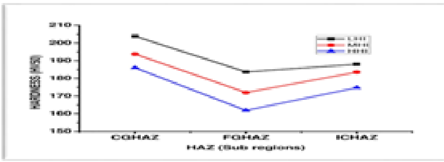


Figure 7: Plot between Vickers Hardness (HV50) vs different sub-regions of simulated HAZ.

The simulated HAZ samples were showing variation in the toughness than the BM at -80^{0} C. Suggesting that there is more toughness loss in CGHAZ as compared to FGHAZ or ICHAZ. The Toughness value of ICHAZ, FGHAZ and CGHAZ regions are inversely proportional correlated with the measured respective hardness value of corresponding regions [4]. The formation of grain boundary ferrite or upper and lower bainite is detrimental to HAZ toughness because these microstructures provides easy crack propagation paths. The increase in toughness of FGHAZ due to presence of Acicular ferrite and decreases of coarse secondary phases such as pearlite and martensite, phases that compromise low-temperature toughness, led to a decrease in crack propagation paths. The maintained of good toughness for the HAZ regions in API grade steel at low temperature can be partially attributed by the formation of acicular ferrite (AF) [5].

The hardness-toughness trajectory shows that higher toughness correlated with lower hardness which is shown in figure 8.

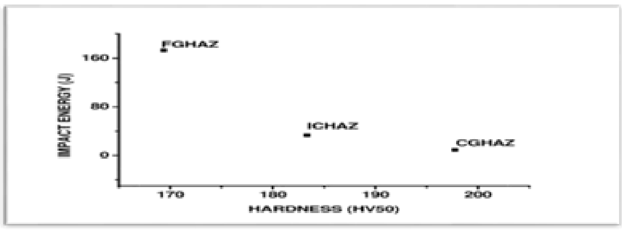


Figure 8: Plot between impact energy and Macro Hardness.

IV. Conclusions

After SAW process, the study of sub-regions of HAZ, microstructural characterization and mechanical investigation following conclusions were drawn:

1. The highest toughness is exhibited by FGHAZ where as low toughness is exhibited by CGHAZ at low temperature (-80^0 C).
2. The average measured hardness has a maximum value of 197.75 HV50 in the CGHAZ which is very nearest to FZ and minimum hardness of 169.375 HV50 in the FGHAZ.
3. Higher toughness value is co-related with minimum Hardness which is totally resembling with the CGHAZ.
4. The Upper and Lower Bainite, Lath Martensite were formed which contribute to lowest toughness of CGHAZ at lower temperature.
5. Acicular ferrite contribute to highest toughness of FGHAZ which is revealed by micro hardness characterization.
6. From all these study we can say that acicular ferrite microstructure is having good combination of strength and toughness which is very necessary for the pipeline industry to use pipeline below (Zero) 0^{0}C.

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