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RESEARCH ARTICLE

EVALUATION OF WELD ROOT CORROSION CHARACTERISTICS OF X65QT MATERIAL

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ABSTRACT

The preferential weld corrosion of X65QT pipe line steel material due to inadvertent usage of unqualified welding electrodes at site conditions and the factors influencing the corrosion resistance was examined. The resultant change in chemical composition and microstructure effects on various weld zones by LPR (LPR) and Galvanic corrosion (GC) methods under aerated condition in natural sea water was studied. Four types of commercial electrodes were used and its influence on root weld corrosion is discussed. The heat affected zone (HAZ) of all the welds resulted as more anodic than the weld and base metal. The influence of weld root hardness was found to have less significant for the electrodes used. The elements like Cr, Ni shows increased corrosion resistance. Mo in combination with Cr results in higher level of cathodic effect. Ni content is outperforming than Cr+Mo on corrosion resistance. Si equally contributes corrosion resistance compared to Ni. The type of metallurgical grain shows significant effect on corrosion characteristics.

INTRODUCTION

Preferential weld root corrosion (PWRC) of carbon steel and stainless steel is a significant concern in the oil and gas Industry. A corroded pipe in an offshore platform at the weld root (fibre optic image) is shown in Fig. 1 (Balraj 2009). PWRC describes the corrosion process at weld specific to pitting corrosion of weld or GC of carbon steel which is more electrochemically active than other base metal and HAZ. The factors influencing this effect is shown in the Fig. 2. There are many reports (Robinson, 1979; Denny, 1995; Joosen *et al*., 1996; Kushida, *et al*., 2001; Egil *et al*., 2005; Lee *et al*., 2005) published on various aspects of weld corrosion for various materials and environments. There are instances that the electrodesgets mixed up due to lack of effective consumable control at sites. Hence an attempt has been made to test the corrosion characteristics of X65QT (composition is given in Table 1) material which is preferred for pipeline construction. Any weld metal property is different from the adjacent base metal and HAZ due to the thermal cycle, chemical composition and weld microstructure involved. The weld metal properties will vary due to gas and slag-metal reactions, heat and mass transfer etc. The shielded metal arc welding (SMAW) electrodes are basic coated type which has potassium and Iron powder in the flux coating. The coating has electrical function such as ionization, thermionic emission, thermal conductivity and physical function such as positional capability, slag viscosity, coating thickness effect etc. Apart from this, carbonate decomposes into carbon di oxide during electrode melting. Hence, the function of coating is for arc stabilization, slag forming, fluxing, and provision of elements in the weld metal (Seferian, 1962). Alloys like Ni, Cr, Cu, and Mo are added in the weld metal to make the weld nobler than base metal and HAZ. The root weld is refined by hot pass and further fill passes. Some of the elements are added and some are reduced due to gas and slag - metal reactions. For X65QT material the basic coated electrodes such as E80xx-xx are used. Generally, various design and construction codes allow certain amount of defects in the weld such as undercut, porosity, inclusions etc. Any defect or imperfection may act as anodic site to initiate corrosion. It has been reported that hardness, grain size, level of aligned secondary phases and decrease in refinement of weld root by hot and fill passes are mostly responsible for preferential weld corrosion attack. During construction, there are incidents that unintentional possibility of mix up of electrodes at sites in the backing oven or holding oven or the welder overlooked the electrode specification while doing welding due to site conditions. There are two types of weld root corrosion mechanisms involved. One is flow assisted degradation and the other one is dissolution (galvanic) effects. The flow assisted degradation involves erosion corrosion and cavitation near the weld. The second one involves the selective corrosion of a part of the weld zone which depends upon the precise metallurgy at this region.

The factors known for PWRC are electrical properties of the material and any corrosion cell formation around the weld joint, water phase liquid film thickness, conductivity, temperature and tendency to form corrosion products, flow induced shear stress and weld joint metallurgy. Weld has three primary regions- base metal, weld metal and HAZ as shown in the Fig. 3[3]. The possible degradation mechanisms are shown in the same in this Fig. A wide range of HAZ microstructures can be produced, close to the fusion boundary, the HAZ transformation on heating to melting point and cooling. The resulting transformation may be a ferrite-pearlite, bainetic or martensitic microstructure, depending on the material composition, peak temperature, and cooling rate. A carbon steel weld which failed by preferential weld corrosion is shown in Fig. 4[3]. This phenomenon has been observed in a wide range of aqueous environments. Preferential HAZ corrosion in seawater was reported and attributed to the presence of low-temperature transformation products such as martensite, lower bainite, or retained austenite[4]. Therefore, elements which are favouring increased hardening of the metal (e.g., increase in manganese content) may lead to increased localized corrosion. It has been reported that there is microstructural dependence for increased corrosion as HAZ shows appreciably more severe when the material composition and welding parameters are such that hardened structures are formed. It has been known for many years that hardened steel may corrode more rapidly in acid conditions than fully tempered material,

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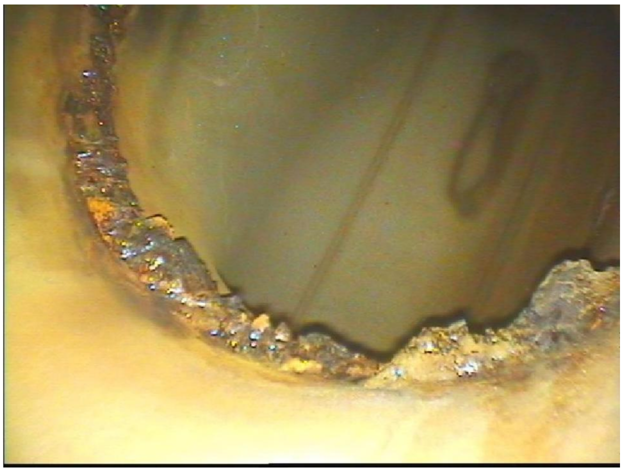

Fig.1. Preferantial Weld Root Corrosion [1]

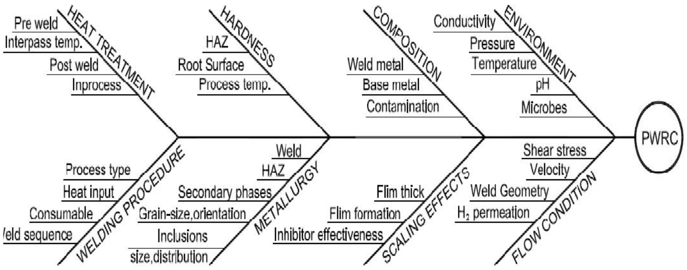

Fig.2. Factors Influencing Weld Root Corrosion

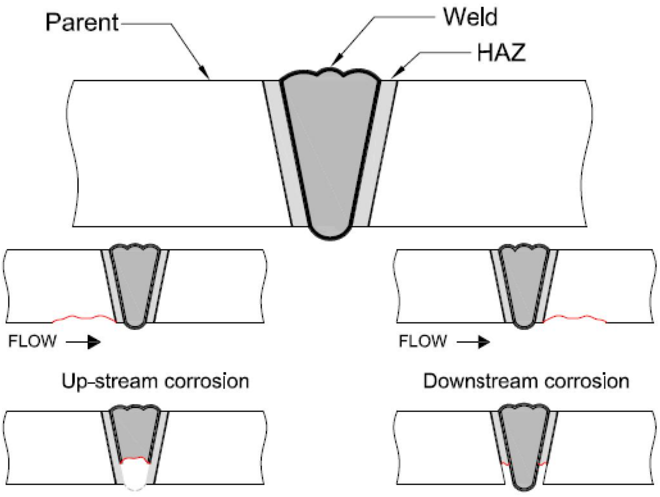

Fig.3. Different forms of Weld Corrosion

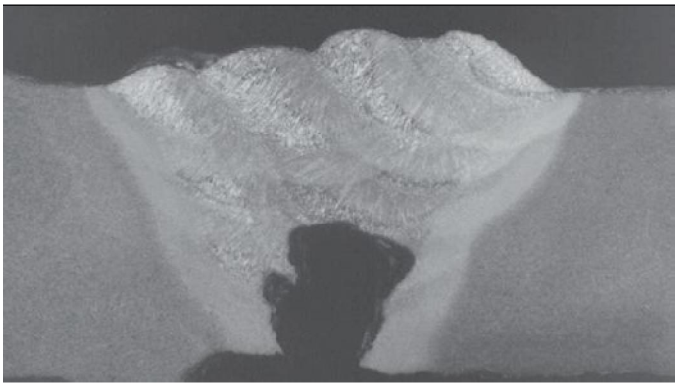

Fig. 4. Carbon Steel Weld Root Corrosion (Photo courtesy ESR Tech.)[3]

apparently because local micro cathodes on the hardened surface stimulate the cathodic hydrogen evolution reaction. The rate of corrosion is usually governed by the cathodic (reduction) rate when other limiting factors are not present, and therefore, it is a factor in acidic environments but less so in neutral or alkaline conditions. In some cases, the HAZ was attacked, while in other cases, the weld metal was preferentially corroded. Where enhanced HAZ corrosion was observed, the composition was more influential than the microstructure (Savage, 1996). However, hardened transformed microstructures suffered increased corrosion (John Wiley and sons, 2000).

Experimental Work

Four types of SMAW electrodes-E7018, E8018G, E8018B2 and E8018B6 were used in this work. The welding parameters were chosen within the limits of the qualified welding procedure. Experiments were conducted using 60.3mm diameter pipe of grade *API 5L- X65QT* material with a wall thickness of 8.7mm. The weld base metal and weld metal composition are given in Table 1. Hardness level was measured as per *NACE MR 0175* and the average values are given in Table 2. The pH of sea water was measured as 7.7. The dissolved oxygen content was tested as 6mg/lit under aerated condition at room temperature (23^{o}C). Repeated experiments were conducted as per the guidelines for three electrode technique as described in *ASTM G5 and G59* along with the procedure of 5B (Neil and Thompson, 1998) for polarization resistance testing to determine the general corrosion rate and procedure 5A for galvanic current measurements to ascertain the composition effects. The samples were prepared as per the guidelines given in *ASTM G1.* Ag / AgCl reference electrode and the base metal as counter electrodes were used. The weld zones were masked leaving the zone of interest exposed to the medium by epoxy resin. The instantaneous corrosion rate was determined using LPR technique. This method involves changing the potential of the working electrode and monitoring the current which is produced as a function of time. The polarization resistance is defined as the slope of the potential-current density (E Vs i) at the corrosion potential E_{corr}. This method is based on Tafel slope, developed by Stern (Denny and Jones 1995). The procedure used for measuring the polarization resistance (Rp) has been applied to polarization curves which go through E_{corr}. The sweep rate was set at 0.125mv/sec. The corrosion rate was calculated using the data logger and computer inbuilt software. The Tafel constants βa and βc were considered as 0.12 V/decade for calculations purposes (Neil and Thompson 1998). The mathematical derivations are explained in many publications (Neil and Thompson 1998; Denny and Jones 1995).

RESULTS AND DISCUSSION

The weld metal metallurgical properties are mainly influenced by heat input, cooling rate, the type of consumable. The types of consumable and the respective weld metal compositions are presented in Table 1. Every element is having its own property to influence the characteristics like corrosion resistance, ductility, machinability etc. The distinct difference on the influence of corrosion resistance has been observed with Cr, Ni, Cu and Mo. Some of the elements influence the grain size, final microstructure, weld hardness such as Al, Ti, V, Boron etc. The elements like Cu, Al and V assist in the formation of protective film. PWRC describes selective attack of the weld root surface which is exposed to the operating medium. Weld metals are usually more electronegative than the base metal with corresponding Si content. But generally, Si content helps for weld metal fluidity. This forms SiO_2 inclusion which may act as sites for the initiation of corrosion. Hence, addition of this element should be made with caution though it helps the weld to become cathodic. It has been reported that certain level of Si also has the detrimental effect which may initiate preferential corrosion (Egil *et al*., 2005). The HAZ is associated with hardened microstructure. But the precise microstructural /electrochemical influence for the enhanced local activity of the HAZ is not fully clarified yet (Korb *et al*., 2006). It is considered that there are microanodic sites formed on the surface in the HAZ area which

Table 1. Chemical Composition of Base Metal and Welds

Electrode Spec.	Elements									
	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	V
E7018	0.044	1.101	0.680	0.014	0.004	0.060	0.100	0.049	0.090	0.009
E8018G	0.026	1.409	0.313	0.200	0.005	0.080	0.920	0.023	0.020	0.003
E 8018-B2	0.054	0.981	0.387	0.020	0.005	0.980	0.100	0.512	0.050	0.005
E8018-B6	0.078	1.062	0.297	0.012	0.007	4.626	0.050	0.516	0.056	0.002
BM	0.1	1.32	0.29	0.013	0.003	0.07	0.17	0.01	-	-

Table 2. Welding and Corrosion Test Results

Sample ID	Heat Input (kj/mm)	Hardness-Avg(HV10)			Corrosion Rate (mm/y)	
	Root weld	BM	Weld	HAZ	Weld	HAZ
E7018	1.82	192	204	175	0.844	2.666
E 8018-G	1.95	192	204	215	0.787	4.369
E 8018 - B2	1.35	212	226	208	9.4×10^{-8}	5.134
E 8018-B6	1.8	182	175	299	1.172	3.164
Base Metal	-	-	-	-	1.271	-

initiates the corrosion process. In general, the significant elements like Ni and Cr possess increased resistance to oxidation and corrosion. Mo tends to help the steel to resist from softening at high temperatures and increase the creep strength. There are conflicting reports on the influence of various elements by laboratory tests. Another example of the thermal cycle effect on corrosion is ring worm corrosion in HAZ (Joosen *et al*., 1996). Hence, welding parameters significantly contribute to the thermal cycle, chemical composition, the microstructural transformation which in turn on corrosion characteristics. It is a proven fact that upto 1% of Ni content increases the corrosion resistance and beyond it enhances the preferential corrosion. This limit is also emphasized by *MR-0175* but the limit is some what arbitrary (Joosen *et al*., 1996). Though this is satisfactory for many applications, there are instances when severe preferential weld corrosion has been reported in sweet environments under certain conditions even at less than 1% Ni level (Kushida, *et al*., 2001). Ni alloyed weld reported to reduce the risk of PWC but only in low conductivity environment (Egil *et al*., 2005). Ni is an austenite stabilizer and depresses ferrite and martensite formation temperatures. Hence, changes in any one of the conditions like environment, base metal composition, deposited weld metal composition and the welding procedure (thermal cycle) may influence the corrosion characteristics either way. In SMAW process the weld metal is deoxidised by the flux coating. The slag and gas metal reaction promotes acceptable weld metal properties by increasing or decreasing the content of various elements. The oxide inclusion in combination with Mn and Si can lead to corrosion attack. It has been reported that Si also is equally detrimental like more than 1%Ni (Lee *et al*., 2005).

Solution resistance also influences the local corrosion rates. This limits the anodic area to a narrow band adjacent to the weld bead. The LPR test results are shown for base metal and weld zone for 8018G electrode in the Fig. 5 and 6. The calculated corrosion rate is given in Table 2 along with weld heat input and the hardness level. The heat input had been maintained from 1.35 to 1.95kj/mm as per the qualified welding procedure. The hardness levels of various zones are given in Table 2. The base metal revealed Bainetic microstructure. Weld metal of 7018 (0.1% Ni) electrode resulted in coarse columnar grain structure of ferrite and pearlite. The electrode 8018G (0.92% Ni) also revealed coarse columnar grain structure. The microstructures for base metal and 8018G electrode weld zone are shown in Fig.7. Electrode 8018B2 (0.98%Cr+0.52% Mo) resulted with fine columnar structure. The electrode 8018B6 (4.6%Cr+0.516% Mo) revealed uniformly distributed grain of bainite and fine acicular bainite. The weld corrosion rate of electrodes 7018 and 8018G show almost same level though the chemical composition has little variation except the Ni content of 0.92%. The Si content of 7018 electrode weld is almost double that of 8018G weld which would be contributing to this effect.

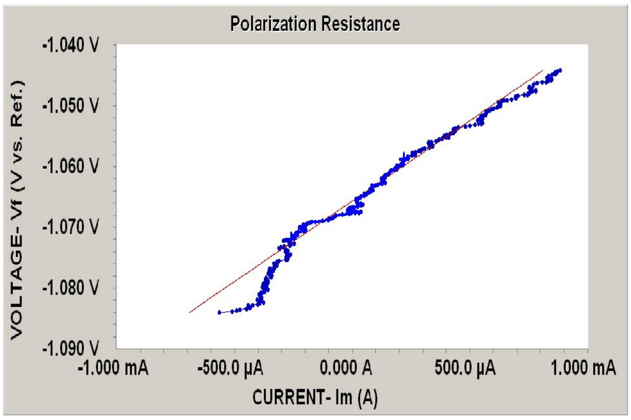

Fig .5. LPR results for Base Metal (E Vs i)

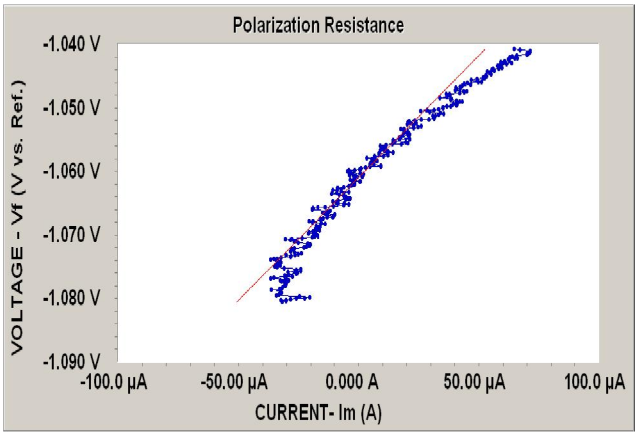

Fig. 6a. LPR results for E8018G Weld (E Vs I)

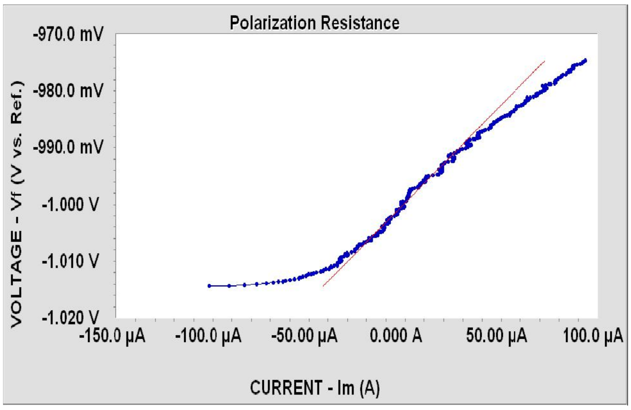

Fig.6b. LPR Results for E8018G Weld HAZ (E Vs I)

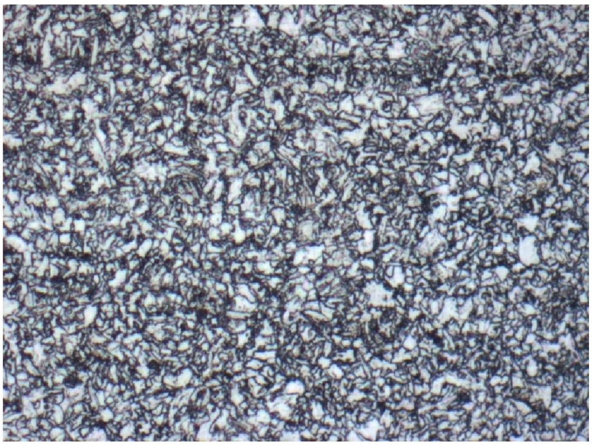

Fig.7a.Base Metal (X65QT) microstructure (Bainetic-200x)

Fig.7b.Electrode 8018G-Weld microstructure (Coarse columnar- 200x)

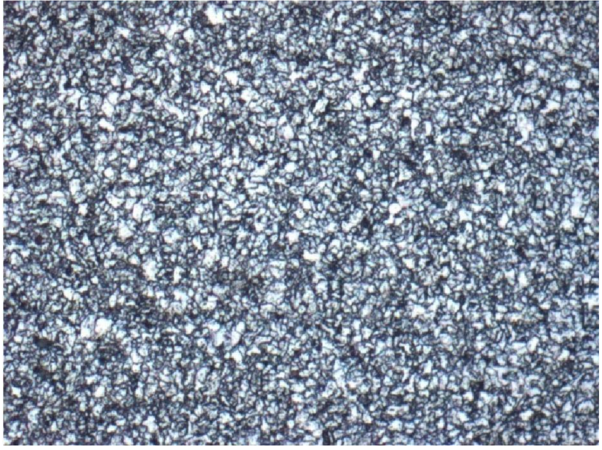

Fig.7c.Electrode 8018G-HAZ Microstructure (Mixed Grain with Acicular Ferrite-200x)

This shows that the effect of Si content is comparable to the effect of Ni. In addition, microstructure for both the electrodes were found coarse columnar type and there seems to be less difference on corrosion rate. Hence, in case the 7018 electrode got mixed up with 8018G, only the strength (particularly toughness) of the weld will be a concern. But the Si content may vary in various commercial electrodes of same specification *AWS A 5.1* to 0.75% maximum. Hence, the same level of Si content cannot be expected in all the commercial electrodes of same specification. There is general acceptance that increases in Ni content increases the corrosion resistance. Hence, the observed corrosion rate difference should be due to increased Ni content. The higher corrosion rate in HAZ of all the welds proves that HAZ is anodic to nearby weld and base metal zones. The effect of weld root hardness seems to be less significant on corrosion rate under this experimental condition as the differences in hardness levels are not much significant. This would be due to the control of heat input. During welding the root side is exposed to atmosphere and hence normalizing effect will be prsent. The hardness cannot be directly measured on the root surface under as welded condition due to ripples/roughness etc. Hence, the hardness was measured as close as possible inside the root in the cross sectioned weld as per *NACE MR 0175*. Though the HAZ is having bainetic structure like base metal, weld zone reflects distinct difference in corrosion rate. A clear difference is observed in the polarization resistance curve (Fig.8) with 8018B2 electrode compared to other electrodes. The corrosion current was very less even at aerated condition (in peco amps) and almost constant.

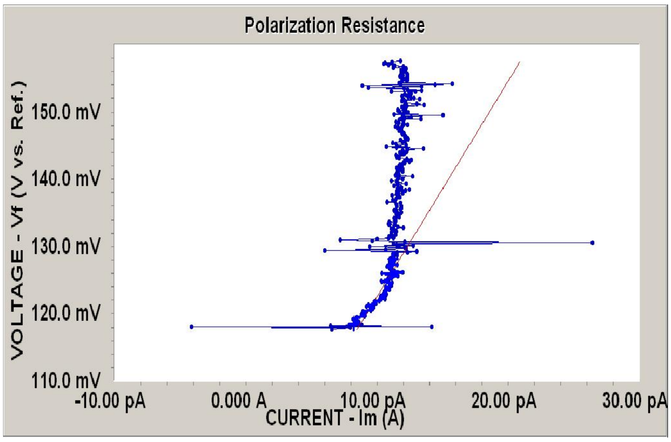

Fig. 8. LPR Results for E8018B2 Weld- (E Vs I)

Though little noise had been observed, the slope is almost zero at Ecorr. To get closer approximation on corrosion rate, a tangent was drawn as shown in the Fig. which is a common practice to find a slope other than Ecorr location. The major difference in weld microstructure between 8018B2 and 8018B6 electrodes is, fine columnar grain for B2 and B6 electrode has bainite structure. In addition the chromium content is almost four times higher than B2 electrode while all other elements are almost same level. Hence, the lowest weld corrosion behaviour is attributed by the combined effect of and overall composition. The welds with 7018 and 8018G are cathodic and HAZ of all the welds are more anodic to base metal. The weld with 8018B2 is more cathodic compared to all other welds. A clear difference can be observed between the welds which has 1% Cr with less Ni and 1%Ni +very less Cr. The weld with Cr is more anodic than Ni content weld. Another interesting observation is higher Cr (4.6 %) content is more anodic than 1% Cr.

This result is contradicting the general understanding of Cr effect (Guenter Schmit *et al*., 2006). Since the Cu level is low and almost equal compared to other influencing elements, it`s influence on corrosion rate could not be verified. The galvanic current recording is shown for the weld made with 8018G electrode is shown in Fig. 9. The corrosion current (general and GC) for various weld zones and composition is shown in Fig.10 a and b. The GC current has been increasing about an hour and then started decreasing due to slow down of the corrosion process due to scaling effect as shown in the Fig. Wherever, surface defects (like undercut, lack of penetration etc.). Corrosion product found more compared to other weld surface. It this shows that the corrosion activity had initiated at those surface defect locations. This GC test was conducted for all the welds including the base metal and HAZ. The significant low level of total corrosion current was observed with high chromium level electrode- 8018B2. The Fig.10b. shows the corrosion current level of various weld zones. HAZ resulted in significant level of higher corrosion current. The corrosion current of weld made with high Cr content is significantly low which is shown in this Fig. The galvanic current test for E8018B2 shows negative (below zero) and the weld corrosion is almost zero. The weld zone resulted as cathodic with this weld.

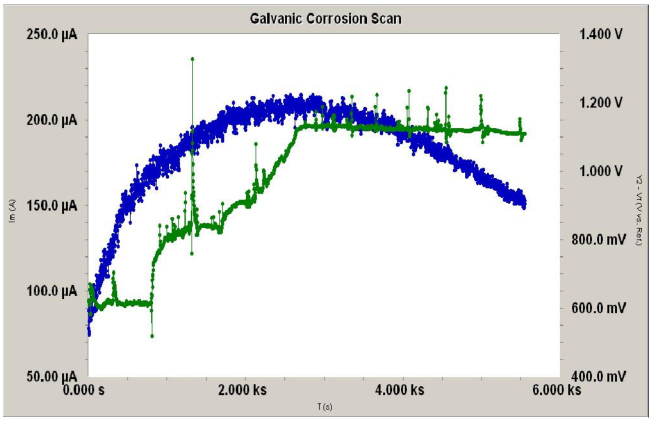

Fig. 9. GC traces for 8018G Electrode Weld

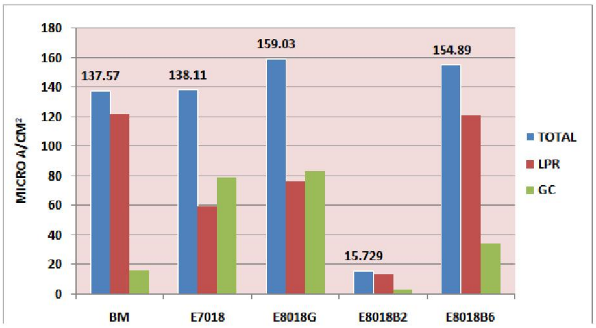

Fig. 10a. Corrosion Current for Various Electrodes

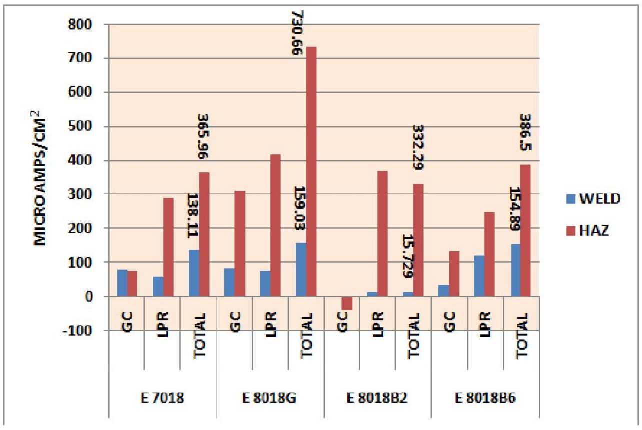

Fig.10b.Total Corrosion Current for Various Electrodes

Conclusions

- The weld hardness levels are less significant on the corrosion rate compared to other weld metal properties.
- HAZ which has bainetic structure, shows almost three times higher corrosion level compared to other zones. Hence, apart from composition, other metallurgical properties of this transition zone like type of grain etc. also influence the corrosion characteristics.
- The Si content has significant corrosion resistance comparable to Ni effect. However, Si has the tendency to form inclusions which may change these protective characteristics.
- The weld with more Cr content behaves more anodic than Ni content. Also higher Cr level exhibit more anodic than lower Cr level. Hence, there is an optimum level of elements to be determined for better corrosion resistance.
- The corrosion rate of bainetic structure of different zones with different types of metallurgical grain promote significant changes in corrosion rate.
- The overall results confirm that the weld composition effect is the primary factor on corrosion resistance.

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