SHARP TOOLS AWARD - 1
For Best Paper in Welding Fabrication and Practices

Detection of Hydrogen Assisted Cracking Susceptibility in Modified 9Cr-1Mo Steel Welds by Acoustic Emission Technique

Gopa Chakraborty[1*], O. Venkata Ramana[2], T.K. Haneef [1], S. K. Albert[1], Babu Rao Jinugu[2], C. K. Mukhopadhyay[1], B. P. C. Rao[1]
[1]Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamilnadu
[2]Department of Metallurgical Engineering, Andhra University, Andhra Pradesh,
*gopa_mjs@igcar.gov.in

DOI : 10.22486/iwj.v52i3.184313

ABSTRACT

Assessment of hydrogen assisted cracking susceptibility for high chromium steel weldments is extremely important to avoid damage and sudden failure of components used in fossil power plants and nuclear reactors. Acoustic emission is a novel non-destructive technique that can be successfully employed to detect crack initiation and propagation behavior of the welds during Gap – Bead on Plate test, Y-Groove and Implant test of Modified 9Cr-1Mo steel plates. The diffusible hydrogen content of AWS E9018-B9 electrode under different preheating-post heating conditions is determined by gas chromatography technique. It is observed that the percentage of crack, as determined from G-Bop, Y-Groove tests decreases with increase in preheat, post heat temperature from 100° to 150°C and no cracking is optimized at 200°C preheat- no post heating conditions. Lower critical stress calculated based on implant test data is 328 MPa for the steel welded with 200°C preheat. The diffusible hydrogen content (3.71 ml/100 gm of weld metal) is also lowest for similar welding condition. Acoustic emission time domain analysis of cumulative count shows peak shifting of waves, which confirms the crack initiation and propagation behavior.

KEYWORDS: Hydrogen assisted cracking; modified 9Cr-1Mo steel; acoustic emission technique; gap – bead on plate test; Y-groove test; implant test

1.0 INTRODUCTION

High chromium steels are extensively used in fossil power plants and nuclear reactors due of their high temperature creep strength and good oxidation resistance. Modified 9Cr-1Mo (P91) steel has been used to fabricate the steam generator of Prototype Fast Breeder Reactor (PFBR), which is under construction at Kalpakkam. For welding this steel by Shielded Metal Arc Welding (SMAW) process welding consumables have been developed indigenously as per PFBR specification. P91 steel is highly susceptible to hydrogen-assisted cracking (HAC). Presence of undetected cracks caused by HAC during fabrication can aggravate brittle fracture of the component during service. Hence, there is a need to assess the susceptibility of these welds to HAC. Earlier studies [1] have shown that the conditions for HAC to occur in steel welds are: presence of diffusible hydrogen, residual stress and susceptible microstructure in the weld and temperature in the range of ambient to 200°C. In this regard, martensitic microstructure with high hardness is most susceptible. Hence, during welding, efforts are made to reduce risk of HAC by avoiding development of a susceptible microstructure and minimizing the hydrogen levels in the welding. Probability of having a susceptible microstructure in the HAZ or weld is assessed from the composition of the base metal and weld metal, heat input and preheating (which will reduce the cooling rate of the weld) chosen for welding [2]. In order to reduce hydrogen level, low hydrogen welding consumables, proper baking of the consumables to remove moisture content in the consumables and appropriate preheating or preheating + post heating conditions that would provide more time for hydrogen to diffuse out at high temperature are chosen. Various tests are available for determining HAC susceptibility of steels. These tests are categorized as self restraint and external loaded test. The susceptibility of a weld to HAC can be quantified from implant test in terms of Lower Critical Stress (LCS), the stress below which the weld does not fracture during the test and by other conventional tests such as Gap- bead on plate and Y-grove testing. In the present work approach has been made to detect HAC by non destructive method by employing Acoustic emission (AE) technique coupled with conventional G-BOP, Y-grove and implant tests. AE technique which involves transient elastic waves generated by rapid release of energy from localized sources has been successfully used in detecting the degradation of structural integrity of materials [3-4]. Diffusible hydrogen level in the electrode is also measured using thermal conductivity based gas chromatography method.

2.0 EXPERIMENTAL PROCEDURES

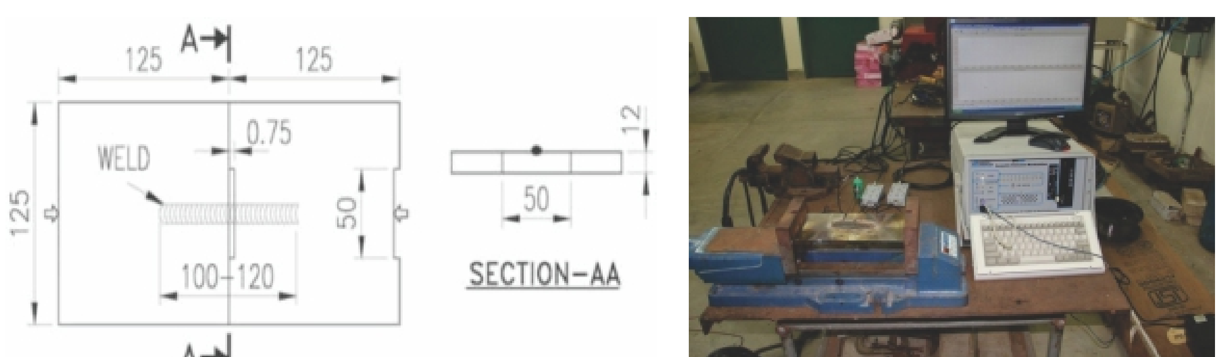
The chemical composition of the modified 9Cr-1Mo steel base metal and AWS E9018-B9 electrode of 3.15 mm diameter is given in **Table 1**. Approximate current and voltage employed during all the welding were 90A and 22V. Electrodes were baked at 300°C for 2 hours prior to welding.

2.1 Gap-Bead on Plate test

For G-Bop test, two P91 steel plates of dimensions 125mm X 125mm X 12mm were clamped together using hydraulic vise. One of the test blocks had a 0.75 mm recess machined in the center of each side for 50 mm face as shown in **Fig. 1(a)**. Before the welding the acoustic emission sensors, one frequency sensor and wide band sensor were attached to the plates with the help of wave guide. Samples were welded with different preheating conditions, i.e. without any preheat and maintaining 100°C, 150°C, 200°C preheat conditions using oxy-acetylene flame. SMAW deposition was made across the plates for a length of 100mm in such a way that the weld bead was placed over the recess. The longitudinal shrinkage stress and the stress concentration at the weld root at the notch induce a transverse crack in the weld metal if it is susceptible to HAC. Signal acquisition by AE setup was started immediate after welding. Continuous signal monitoring by AE display unit was performed for 24 hours while the test blocks remained clamed (**Fig. 1b**). At the end of the experiment, the weld above the recess was heat tinted to a dull red color. After cooling the blocks to room temperature, the weld was broken apart. Any portion of the fracture surface displaying a discoloration

Table 1: Chemical composition (wt%) of P91 base metal and AWS E9018-B9 electrode

	C	Cr	Mo	Mn	Ni	P	V	Nb	N	Al	Fe
P91	0.11	8.84	0.85	0.4	0.22	0.014	0.21	0.008	0.065	0.015	Bal
E9018-B9	0.08	8.69	0.99	0.65	0.73	0.008	0.16	0.066	0.04	0.005	Bal



(a) (b)

Fig. 1: (a) G-BOP sample and (b) test set up for AE data acquisition during G-BOP test

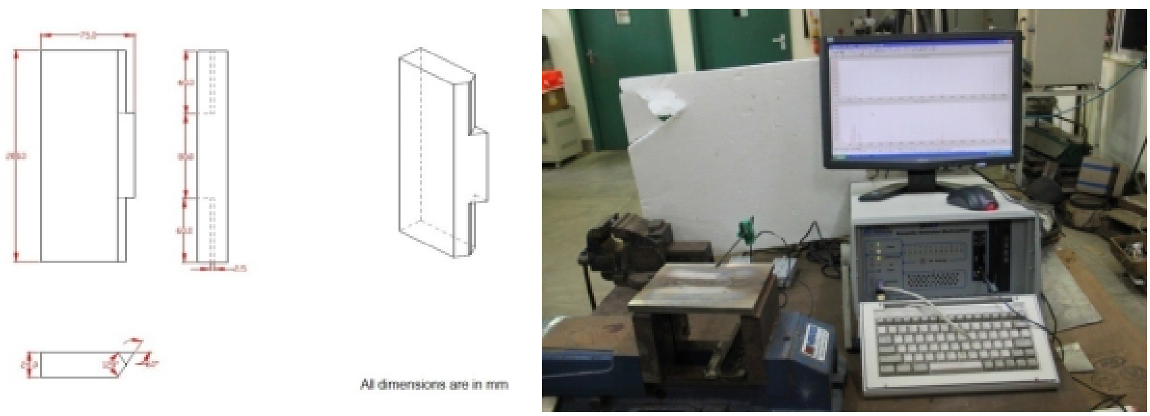
indicated occurrence of HAC. Percentage of crack to uncracked portion was estimated for each sample. Failed samples were studied under scanning electron microscope (SEM) for further studies. Similar experiments were conducted for test blocks for which 100°C, 150°C and 200°C post-heating were applied in addition to preheating. AE signals were recorded after completion of post heating. Selected samples were sectioned to observe for micro cracks.

2.1 Y-Grove test

Inclined Y-groove samples were fabricated as shown in **Fig. 2a**. Prior to actual welding, tack welding was done and the AE setup was connected to the base plates (**Fig. 2b**). Welding were performed without any preheat, with preheat only and with a combination of preheat and post-heating for 100°, 150° & 200°C. The AE signals were recorded for 24 hours and after that the samples were subjected to dye penetrant testing and microscopic examination for detection of cracks.

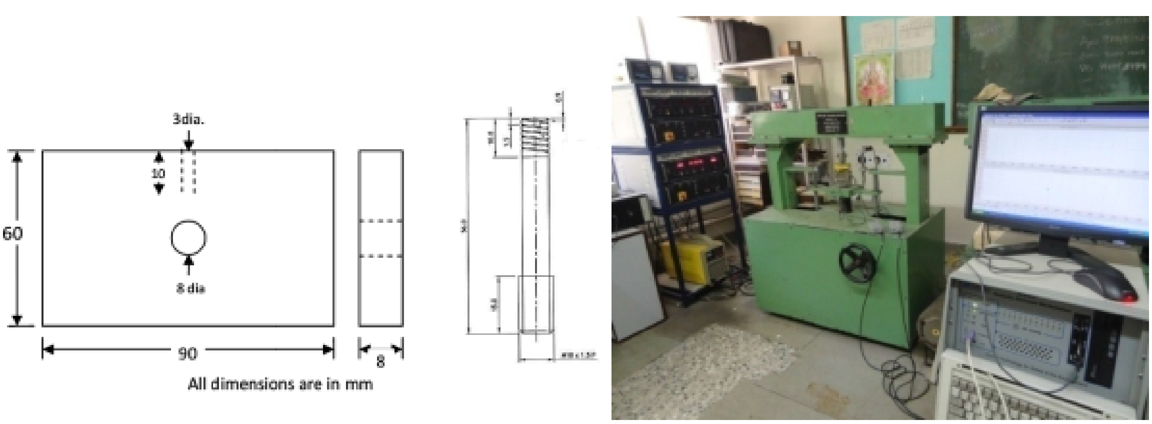
2.3 Implant test

Fig. 3a shows the schematic diagram of implant specimen and base plate, prepared as per Doc. IIW-802 guidelines [5]. The implant testing machine is a computer controlled and mechanically operated machine along with a load-cell attached to it to display the load and time duration during the testing. The specimen assembly consists of a base plate with a hole, into which implant specimen is inserted in such a way that the top surface of the implant specimen and base plate are at the same level. AE acquisition setup was attached to the base plate prior to welding for continuous monitoring of the signal (**Fig. 3b**). Single pass bead on plate welding was made on this specimen assembly in such a way that the weld bead passes over the implant specimen fusing its top surface completely with the base plate. Based on results of G-BOP and Y-frove test, the samples were welded with 200°C preheat only without application of any post-heating. A thermocouple was attached



(a) (b)

Fig. 2 : (a) Y-grove sample and (b) test set up for AE data acquisition during Y-grove test



(a) (b)

Fig. 3 : (a) Implant sample and (b) test set up for AE data acquisition during Implant test

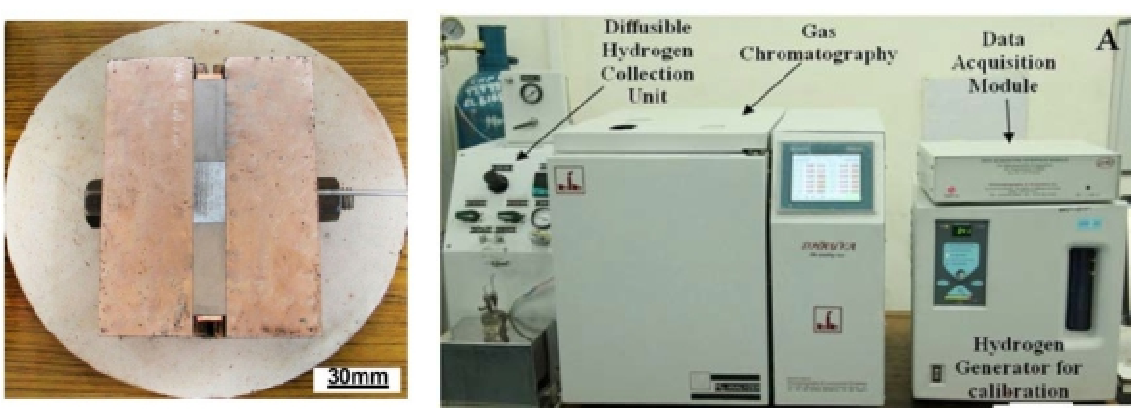
to the base plate to monitor the temperature and loading was done when the assembly cools down to 100^{0}C. A series of tests with first specimen loaded at 1500 kg were conducted. Subsequently, loading was increased to 2000 kgin steps of 100 kg till failure of the sample. Two tests were repeated for each loading condition.

2.4 Diffusible Hydrogen Measurement

For diffusible hydrogen measurement, P91 steel samples are fabricated as per ISO 3690 specification. The specimen of size 30 mm x 15 mm x 10mm is fixed in a copper jig with run-on and run-off pieces each of size 40 mm x 15 mm x 10mm (**Fig. 4a**). Bead on plate welding was carried out with 3.15 mm diameter grade E9018-B9 electrode, baked at 300^{0}C for 2 hours prior to welding. Samples were prepared without any preheat, with preheat only and with a combination of preheat and post-heating for 100^0, 150^0 & 200^{0}C. Immediately after completion of the welding the specimens for diffusible hydrogen measurement were immersed in ice cold water for 5s and kept inside liquid nitrogen to cool to subzero temperature till they were taken out for hydrogen extraction and measurement. The HE_GCTCD set up used for diffusible hydrogen measurement consists of a diffusible hydrogen collection chamber, a heater to heat the chamber and a gas chromatograph (GC) (**Fig. 4b**). The specimen is kept inside the chamber at 400^{0}C for 30 minutes for extraction of diffusible hydrogen from the test specimen. Hydrogen collected in the chamber is transported to a GC with a thermal conductivity detector using Ar as carrier gas and the signal is recorded. Prior to measurement, GC is calibrated using known volumes of hydrogen injected into the GC and from this; volume of hydrogen evolved from the weld specimen and collected in the chamber, is estimated. Using the weight of the deposited metal in the weld, the volume of diffusible hydrogen is calculated in milliliters per 100 gm of deposited weld metal. For each condition three tests were performed and average of the data is reported.

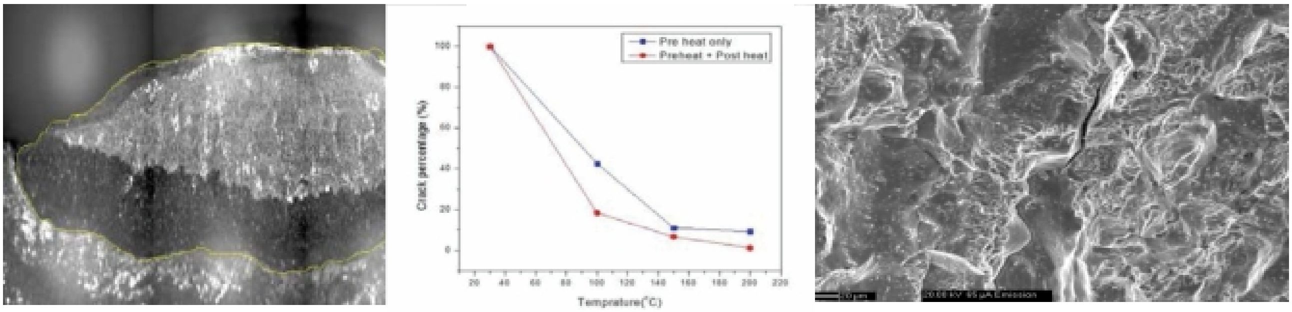
3.0 RESULTS AND DISCUSSION

In G-BOP test the percentage of crack is estimated from the ratio of the area of the bead up to which the crack has propagated to the total bead area (**Fig. 5a**) with the help of image processing software and the same is plotted in **Fig. 5b**. The sample tested without any preheat or post heat is fully cracked. SEM image of the cracked sample is shown in **Fig. 5c**. The cracking percentage has reduced from 42.86% to 3.28% with increasing preheat temperature from 100^0 to 200^{0}C. With application of preheat and post heat both, the crack percentage further reduces and it is 1.25% for 200^{0}C pre +post heat. Preheating decreases cooling rate of the solidified weld pool thereby reducing hardness of the resultant micro-structure. Post heating is helpful in reducing residual stresses of the weld joint, also it allows more time for residual hydrogen to diffuse out. Thus, these two factors contribute to lower down cracking tendency of the P91 weld during G-BOP test. AE data is filtered to 50dB to remove signals generated due to post heating of the sample. It is noted from AE results (**Fig. 6**) that without preheat weld metal is fully cracked within 300 seconds, which indicates higher severity of cracking. With 100°C & 150°C preheats cracking occurs by 500, 1000 seconds, which indicates some time for propagation of the crack.



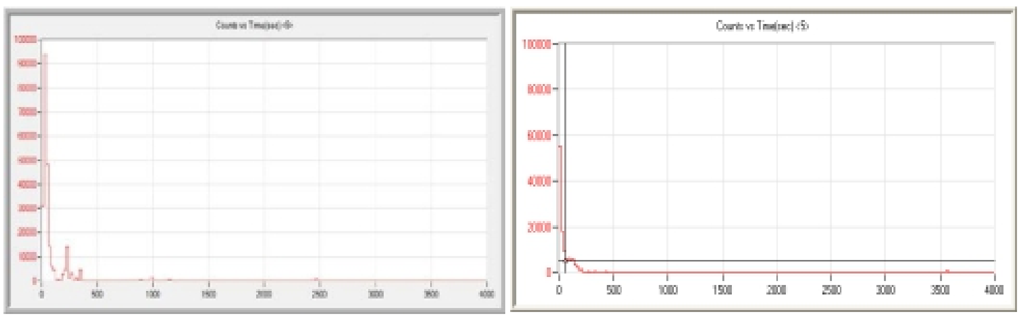
(a) (b)

Fig. 4 : (a) Diffusible hydrogen measurement sample and (b) test set up for hydrogen measurement



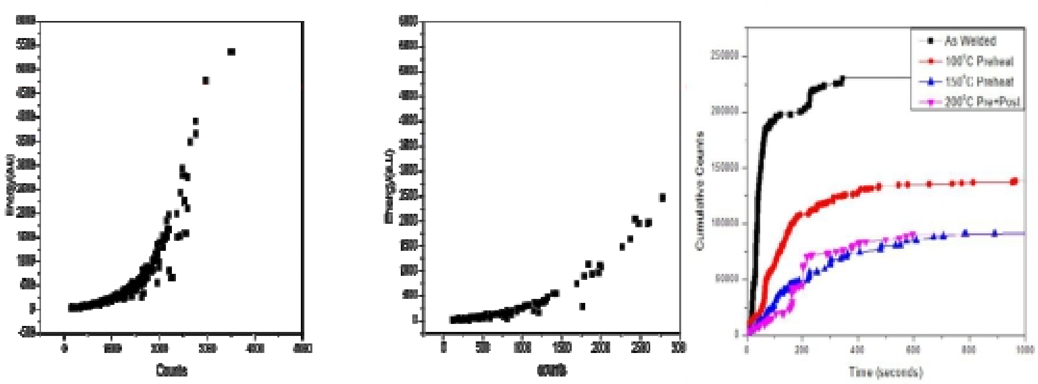
(a) (b) (c)

Fig. 5 : (a) Total bead area of G-BOP tested sample (b) effect of temperature on crack percentage and (c) SEM micrograph of sample welded without any preheat-post heat



(a) (b)

Fig. 6 : AE counts (arbitrary unit)-vs-time (seconds) signals recorded for G-BOP tested samples (a) without any preheat-post heat and (b) with 2000C preheat +postheat

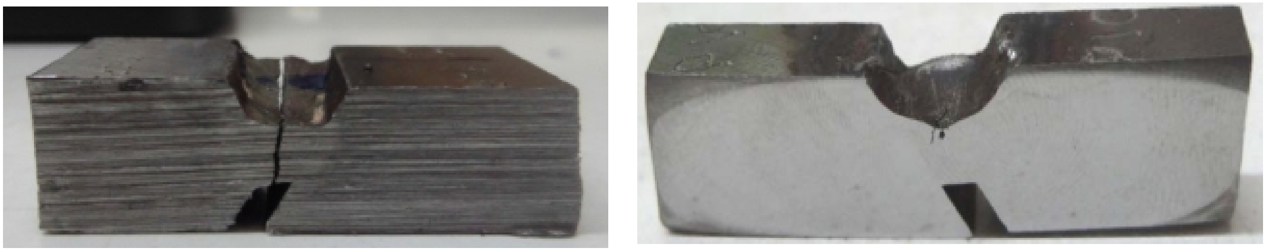


(a) (b) (c)

Fig. 7 : Correlation between AE Counts vs Energy for sample tested (a) Without preheat/post heat (b) 200°C preheat +postheat and (c) relation between Cumulative count vs time of different preheat conditions

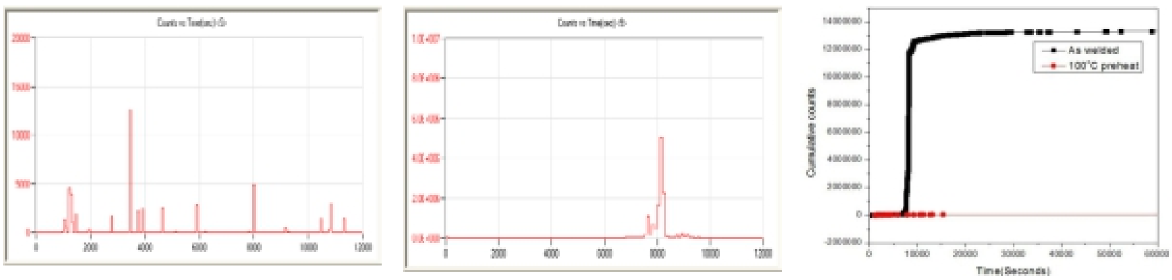
Fig. 7 reveals that higher energy counts for weld without preheat than that of 200°C preheat +post heating because as cracking tendency increases energy counts also increases. Thus, this AE parameter can be used to correlate HAC cracking.

Under Y-grove test P91 steel weld is fully cracked without application of any preheat, post heat (**Fig. 8a**). With 1000C preheat cracking tendency is less (**Fig. 8b**) and no crack is detected for rest of the test conditions. The cracking tendency under Y-grove test is less as compared to G-BOP test. This may be due to lesser restraint offered by the Y-grove test setup. In this case also AE signals can detect the time of start of cracking and energy counts for crack propagation (**Fig. 9**).



(a) (b)

Fig. 8 : Photographs of Y-grove test welds (a) without any preheat (b) with 100°C preheat

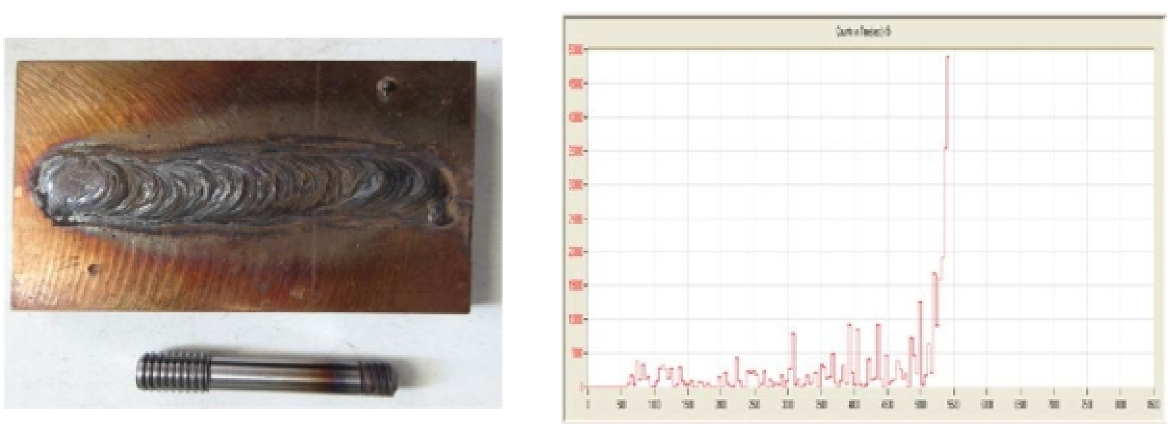


(a) (b) (c)

Fig. 9 : AE Counts vs Time (seconds) of (a) without preheat, (b) 100°C preheat (c) relation between Cumulative count vs time of as weld and 100°Cpreheat condition

Table 2 : Implant test data for LCS calculation

Pre-heat Temperature (°C)	Load (kg)	Failed or not		Lower critical stress (LCS) MPa
		1st Trial	2nd Trial	
`	1800	Failed after 01 hr 27 minutes	–	
200	1700	Failed after 2 hr 20 minutes	Failed after 51 minutes	328.6
	1600	Not failed	Not failed	



(a) (b)

Fig. 10 : (a) Photograph of Implant test sample failed at 1800 kg load (b) AE signal for the sample

Implant test was done to determine lower critical stress of sample welded with 200°C preheat. **Table 2** indicates that at 1700 Kg load the sample is partially cracked whereas at 1800 kg load the sample fails completely (**Fig. 10**). Thus, the lower critical stress calculated for the weld with 200°C preheating is 328.6 MPa, below which no failure of the weld is expected.

The diffusible hydrogen content of the welding consumable is measured (**Table 3**) with and without application of preheat-post heating. The hydrogen content of the weld is 4.73 ml/100gm which decreases to 3.71 ml/100 gm with 200^{0}C preheat and to 0.67 ml/100 gm with 200^{0}C pre+post heat. Thus, preheating and post heating can successfully reduce diffusible hydrogen content of P91 weld.

Table 3: Diffusible hydrogen content for different pre and post heating temperatures

Temperature condition (OC)	Average Diffusible hydrogen (ml/100gm)
Without any preheat-post heat	4.73
100°C preheat	4.33
150°C preheat	3.98
200°C preheat	3.71
100°C preheat +post heat	3.46
150°C preheat +post heat	2.28
200°C preheat +post heat	0.67

4.0 CONCLUSIONS

The HAC susceptibility of P91 steel weldments is determined by G-BOP, Y-grove, implant testing. It can be concluded from the present study that acoustic emission technique, coupled with G-BOP, Y-grove, implant testing can be successfully employed for detection of crack initiation and propagation tendency of P91 steel weldments due to HAC.

REFERENCES

1. Dickinsons DW and Ries GD (1979); Implant testing of medium to high strength steel - a model for predicting delayed cracking susceptibility, Welding Research Supplement, pp. 205s-211s.
2. Padhy GK and Komizo Yu-ichi (2013); Diffusible hydrogen in steel weldments - a status review, Transactions of JWRI, pp.39-62.
3. Wadley HNG, Scruby CB and Speake H (2013); Acoustic emission for physical examination of metals, International Metals Reviews, pp41-64.
4. Mazal P, Vlasic F and Koula V (2015); Use of acoustic emission method for identification of fatigue micro-cracks creation, Procedia Engineering, pp.379-388.
5. Albert SK, Ramasubbu V, Sunder Raj SI and Bhaduri AK (2011); Hydrogen assisted cracking susceptibility of modified 9Cr-1Mo steel and its weld metal, Welding in the world, pp.7-8.