International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 10, October-2015

Investigation of Hydrogen Assisted Crack in Welding by using Y-Groove Test

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***Abstract*—— Ferritic steel with Cr and Mo as major alloying elements are used extensively in nuclear power plants, fossil power plants, and petrochemical industries where the material is exposed to temperatures in the range of 550°C to 630°C. These steels are widely used because of their high strength, good creep resistance, and low coefficient of thermal expansion. These steels have martensitic or bainitic structure in the normalized condition and hence are susceptible for hydrogen assisted cracking (HAC) during welding.**

Modified 9Cr-1Mo steel, grade 91 has been selected for steam generator of Proto type Fast Breeder Reactor (PFBER). During fabrication of steam generator component, welding is unavoidable. Indigenous design of PFBR and fabrication of components is under way. Along with development of different materials for PFBR, modified 9Cr-1Mo steel electrodes were also developed indigenously to meet the PFBR specification of impact energy of minimum 45 J at ambient temperature from Charpy V-notch impact testing. In the present study the susceptibility of the weld joint made by these electrodes to HAC has been evaluated using widely used Y-groove test.

***Keywords*—— Hydrogen Assisted Crack, Y Groove Test, 9Cr-1Mo Steel.**

I. Introduction

Under certain conditions, hydrogen can degrade the fracture behaviour of most structural alloys. Practically all metal materials can be damaged by the absorption of hydrogen, if a sufficient quantity can penetrate into the material. The sources of the hydrogen, the paths it takes to enter the material and the embrittlement mechanisms are extremely diverse. So care should be taken for each specific case with careful study to take preventive measures for reducing these effects. The hydrogen solubility in the molten metal is much higher than when it is in the solid condition. This hydrogen loading is reversible to a great extent, because it is caused mainly by the storage of the hydrogen in the interstitial positions of the lattice. Irreversible damage only occurs if the hydrogen can effuse or if it can accumulate as gas in the hollow spaces. This type of hydrogen damage is of importance in welding practice and is exhibited for instance in the development of cold cracks or fish eyes (or flakes). Even though residual stress is also found, it is believed that only diffusible hydrogen cause hydrogen embrittlement and cracking. This type of damage is also produced during casting.

Y-Groove test is a self restraint test and is best suited for real time applications. Here critical preheat temperature (temperature at which crack doesn't occur) is obtained. Two type of tests are been done namely 'Inclined' and 'Straight' Y-Groove. The reason to have two types is: originally inclined Y-Groove test is done to monitor the susceptibility in HAZ and then it is proved that these types are said to be good for studying susceptibility of parent metal. As per the literature studied Straight Y-groove types are said to be good for susceptibility study of weld metal. These tests are done as per the standard British STD EN ISO 17642-2:2005 for both 12mm and 30mm thick plates.

Specimens after testing were examined for cracking as per the standard. The fracture surface of the cracked specimens was examined under SEM. Microstructure of the weld metal was examined using optical microscope and hardness of the weld metal was measured using Vickers hardness tester. This report presents and discusses the results obtained from this study.

II. Literature Review

During welding process hydrogen is absorbed into the molten weld pool. As the weld metal solidifies, solubility of hydrogen decreases because of decrease in temperature and hydrogen present in the weld metal becomes supersaturated and diffuses away from the weld fusion zone to the heat-affected zone (HAZ) where hydrogen concentration is lower. In the HAZ, due to heating and cooling cycles, transformation products of high hardness are produced. This region of high hardness and low ductility is subjected to a relatively high tensile load imposed by the contracting weld fusion zone resulting in cracking in the presence of hydrogen (HIC) within a few hours of completion of welding operation. For hydrogen cracking, three primary independent conditions are necessary to be fulfilled: a high hydrogen level, susceptible microstructure and tensile stress acting on the weld. All arc welding processes introduce hydrogen into the weld to some extent. Hydrogen can originate from moisture that exists in electrode coatings or from the surrounding humid atmosphere. Hydrogen can also originate from hydrocarbons, grease, rust, or other organic contaminants. In general, only hard HAZ microstructures are susceptible to HIC. The risk of hydrogen cracking in the HAZ increases with hardness. Such microstructures are promoted by steel that has high carbon equivalent as proposed by Yurioka (Yurioka *et al* 1987).

Because of the high alloy content and hardenability, the microstructure of both weld metal and HAZ are bainitic or martensitic in the as-welded condition and hence they Cr-Mo steels are highly susceptible to HIC. Systematic investigations were carried out (Albert *et al* 1993, 1996, 1997) to determine whether the diffusible hydrogen content H_D in the welds can be correlated to HIC susceptibility for these ferritic steels using UT modified hydrogen sensitivity tests. It was found that as the volume % of hydrogen in the shielding gas increases, H_D also increases and is a strong function of alloy content. As the hydrogen in the shielding gas increases, critical preheat temperature also increases. Under identical testing conditions, H_D is minimum and susceptibility is maximum for 9Cr–1Mo steel(Albert *et al* 1997). From the electrochemical permeation studies carried out for 2.25Cr– 1Mo steel and 9Cr–1Mo steel (Albert *et al* 1997; Parvathavarthini *et al* 1999, 2001), it is seen that when the alloy content is higher, solubility of hydrogen in the reversible traps is higher. Therefore susceptibility to HIC can be correlated to hydrogen present in the reversible traps.

Microscopic observation of hydrogen cracking is an important step in understanding hydrogen embrittlement and also in finding the cause of cracking. Thompson and Bernstein have discussed basic aspects of a microstructurally controlled process of hydrogen embrittlement fracture. The fracture mode of hydrogen assisted cracking includes microvoid coalescence (MVC) or dimple rupture, quasi cleavage fracture (QC), and intergranular fracture (IG).

One of the main features of the Beacham theory is the classification of fracture modes with respect to stress and hydrogen level. At relatively high stresses, hydrogen-assisted cracking can propagate by microvoid coalescence, which is normally thought of as a ductile failure mechanism. Beachmen proved that hydrogen can be responsible for microvoid coalescence by partially fracturing a sample in hydrogen, then freezing the sample in liquid nitrogen and sectioning the sample to find evidence of the process occurring ahead of the crack tip. As the stress intensity decreases, crack propagation proceeds by the lower plastic deformation processes of quasi-cleavage, and finally, intergranular separation. Increasing hydrogen concentration at the crack tip has the effect of decreasing the stress intensity at which these fracture processes occur.

Beacham suggested the interrelationship between the stress intensity factor, dissolved hydrogen content, and hydrogen assisted cracking fracture mode in a microscopically small volume of crack tip materials, The IG mode predominates as the stress intensity factor is low. This mode is the most energetically favourable process as it involves the least amount of plastic deformation compared with the MVC and QC modes. At higher stress intensity, the energetically favourable Intergranular Cleavage (IC) process is replaced by the QC and MVC processes; MVC and QC relatively faster modes of fracture compared with the IG mode.

Vasudevan et al (1981) observed that the crack mode changed from IG to QC and then to MVC as a crack propagates in an implant test, one of external restraint test. As the time passes, hydrogen accumulates at the notch tip, e.g. weld root and weld toe. When the hydrogen concentration reaches the critical level, a crack is initiated. In a self-restraint weld, residual stress is relaxed and stress intensity decreases with crack growth and then the crack eventually stops. In an external weld cracking test, however, stress intensity continues to increase and the crack growth rate is accelerated as the crack grows. The fracture mode was QC at a finer austenite grain while IG was predominant at a coarse grain size. The kinetics and morphology of growth of hydrogen assisted cracking is sensitively influenced by microstructural features and other factors including hydrogen content, strain rate, temperature and stress intensity.

For prevention of HAC, The Welding Institute, UK, developed the hardness control approach (J.F.Lancaster) in which the main emphasis was given to reduce the hardness below a critical value by reducing the cooling rate especially in the case of carbon steels where the hardness decreases with cooling rate. The cooling rate was reduced by preheating the job before welding or by varying the heat input of the welding and this would result in a weld microstructure of lower hardness, making it less susceptible to hydrogen assisted cracking. It considers four factors, namely combined thickness, hydrogen content of the electrode, carbon equivalent and weld heat input to determine suitable preheat temperature that would prevent cracking. (Grafille.B.A 1976) divided steels into three broad categories based on carbon content and CE.

Steels falling in Zone I (low carbon, low alloy content) are the least susceptible to cracking and HAC occurs only under conditions of high hydrogen content and restraint. For alloys falling in Zone II, hardness varies with cooling rate, and the hardness control can be applied to determine preheat temperature to prevent cracking. For high alloy and high carbon steels falling in Zone III, the hardenability would be too high for the hardness to vary with cooling rate in normal welding conditions.

For steels having higher CE values, the preheat temperature is usually determined by Hydrogen control approach. In this approach, cracking is prevented by reducing the diffusible hydrogen content in the weld. This is also achieved by preheating as, in addition to reducing HAZ hardness, it also helps in lowering the diffusible hydrogen content of the steel by giving more time for the removal of hydrogen at higher temperatures where diffusion is much faster than the ambient temperature. Based on this approach, (Ito and Bessyo 1968) defined a cracking parameter P_w that considers the effect of composition, hydrogen content and restraint separately.

Cooling time t8/5 represents the time taken for the weld to cool down from 800ºC to 500ºC. This temperature is taken as the full diffusion controlled transformation of austenite take place here. It is possible to identify the cooling time from the weld parameter as it depends on the preheat temperature and heat input. A nomogram was proposed by Inagaki and sekiguchi .

This was done with the bead on plate and T-fillet joints of MMA welds and is valid upto a thickness of 34mm. This is obtained by the tie line intersecting the cooling time which is drawn from heat input and plate thickness line. Another nomogram was proposed by Berkhout and Van Lent based on the heat flow. In addition to these nomograms, equations were also formed to predict the cooling time from the parameters. One such equation by Suzuki is given and the constants of the equation

The Cr-Mo steels are known for their high temperature strength and oxidation resistance and are widely used in power and petrochemical industries for the fabrication of steam generators and heat exchangers. Cr content in these steels vary from 0.5% to 12% and Mo from 0.5% to 1%. The carbon content is normally less than 0.2% for good weldability, as the hardenability of steel is very high. The chromium provides improved oxidation and corrosion resistance and molybdenum increases strength at elevated temperature. They are normally used in the annealed or normalized and tempered condition.

The most important property of this class of steels is the excellent creep resistance in the temperature range of 500-650°C. 2.25Cr-1Mo steel (J.Moreton 1971), the most widely used Cr-Mo steels can be used up to a temperature of 550°C and stress levels of levels of 100 Mpa. Creep properties of Cr-Mo steels can be further improved by controlled addition of elements like Nb, V, W, and N etc. New versions of this class of steels like Modified 9Cr-1Mo steels are intended to be used for temperature up to 630°C. Presence of chromium and Molybdenum in significant level leads to high hardenability. In normalized condition (R.Vasudevan 1981),
For low alloy steels the resulting microstructures are Bainite and Ferrite
For high alloy steels the resulting microstructure are martensite

For 1.0 Cr-0.5 Mo: Bainite and Ferrite
For 2.25 Cr-1.0 Mo: Bainite and Ferrite
For 9.0 Cr-1.0 Mo: Martensite

Addition of chromium, molybdenum leads to improve creep strength and oxidation resistance.

Modified 9Cr-1Mo steels was developed by (S.K.Albert 1993) Oak Ridge National Laboratory (ORNL) and combustion Engineering, Inc., (CE) for using as reactor structural material for fast breeder reactor (FBR).
It posses better creep resistance than standard 9Cr-1Mo steel.
It posses better weldability than 12Cr-1Mo-V steel.
Modified 9Cr-1Mo steels contain controlled addition of Vanadium and Niobium. In these steels tempering results in precipitation of stable Niobium and Vanadium carbides, instead of chromium and molybdenum carbides.

III. Material Specifications

The material chosen for investigation is modified 9Cr–1Mo steels. The typical chemical composition and mechanical properties are given below.

TABLE 1. CHEMICAL COMPOSITION OF MODIFIED 9Cr-1Mo STEELS

Element	Wt%
C	0.10
Mn	0.39
S	0.009
P	0.021
Si	0.50
Cr	9.50
Mo	1.00
Ni	0.14
V	0.25
Nb	0.10
N	0.065
Al	0.024

TABLE 2 MECHANICAL PROPERTIES OF MODIFIED 9Cr-1Mo STEELS

Yield Strength Mpa	Tensile Strength Mpa	Elongation %
460	650	22

TABLE 3 CHEMICAL COMPOSITION OF (AS WELDED) ELECTRODE MDN 91

Element	Wt%
C	0.100
Co	0.016
Cr	9.00
Ni	0.70
Mn	0.70
Mo	1.00
N	0.055
Nb	0.060
P	0.009
S	0.012
Si	0.240
V	0.170
Cu	<0.050
Al	<0.010
Sn	<0.005
W	<0.09

TABLE 4 WELDING PARAMETERS AND ELECFTRODE BAKING CONDITION

Consumable type	Baking Condition		Current (A)	Voltage (V)	Heat Input (KJ/mm)
	Temperature (°C)	Time (hrs)			
Midhani	300	2	80	26	0.962
Mailam	300	2	85	22	0.984

IV. EXPERIMENTAL DETAILS

A. Y Groove test

In this project British standard is followed for the experiment. The specimens (200x125) are prepared for butt welding with Y-edge preparation having 2mm root gap and a 60° groove angle. First symmetrical Anchor or constraining welds are made on both ends and then the test weld of length about 80mm is made in the central section as given in the figure: 1 and 2.

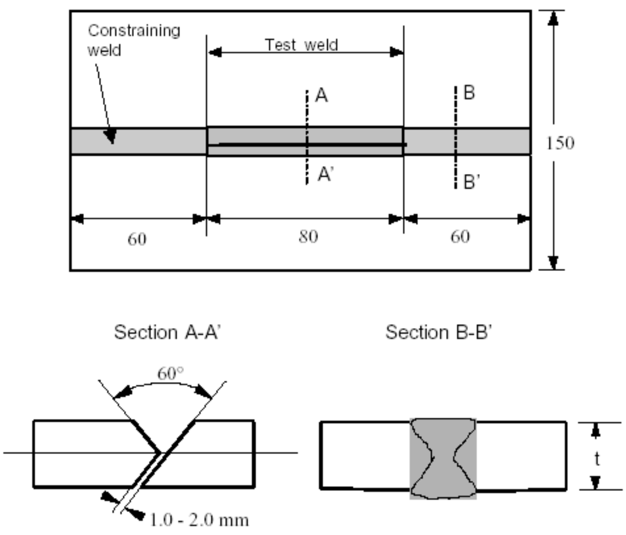
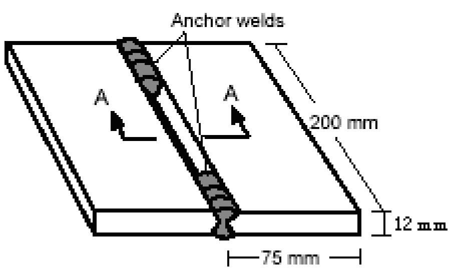


Fig:1 Schematic representation of Inclined Y-Groove.



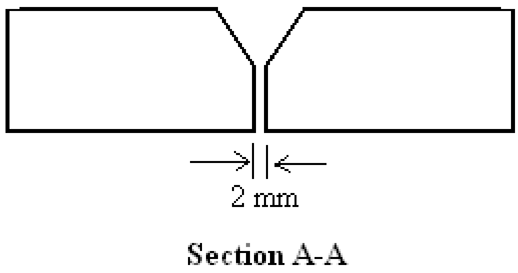


Fig:2 Schematic representation of Straight Y-Groove.

B. Preparation of the test piece:

The test materials are machined by Sawing, Milling or Grinding and made sure that surface to be weld are milled and ground finished as given in the figure: 1 & 2. When the pieces are fitted, principal rolling direction of the plate is determined and kept accordingly parallel to the welding direction. The surfaces to be welded are made clean and checked for any scale, rust, oil, grease etc.

C. Anchor Welds:

This weld is the one giving the restraint to the test weld. So the anchor weld is made with the welding consumable whose Yield strength equal to the yield strength of the test material. The weld is deposited with the standard procedure as pre-heating (250˚ C), interpass heating and post heating to avoid hydrogen cracking. All consumables are dried in accordance with the manufacturer's recommendations to have lowest possible hydrogen levels. PWHT (300˚C) is also done accordingly with the standard recommendations. This is done in order to relive the residual stress.

D. Test Welds:

1) Preheating:

The test piece is heated with the flame for sufficient time to obtain thorough heating for the required preheat temperature. The temperature is monitored with thermocouple, which was welded to that side of the joint fit up which was preheated. Heating is done till the plate reaches slightly above the required temperature and allowed for cooling. This is done as uniform temperature can be obtained only at the time of cooling. Welding is done at the time when it reaches the required temperature.

2) Deposition:

The welding is carried out in the 1G position as per given in the figure. Welding is carried out in the single pass. Heat input is calculated accordingly to maintain it at the same.

E. Metallographic examination:

This is done as per EN1321 Std as given in the Figure: 3. Five sectioning cuts are made as the positions nearest to the starting point where the width of bead becomes constant and the Centre of the bead crater, and the positions quartering the distance as shown in the figure. The prepared faces are polished and checked for cracks with stereomicroscope (Minimum at 10X and maximum of 50X) and scanning electron microscope.

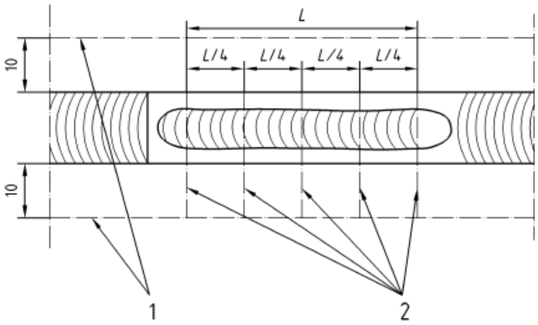


Fig: 3 Crack Examining Position at the test weld.

1- Cutting in the width direction.
2- Examining section position.
L- Cutting length of the test weld for crack examination.

1) *Metallography:*
The tested specimens were subjected to metallographic examination. The Villela's reagent (1 gm picric acid + 5ml HCl + 95ml propanol) used as etchant. The etching time is 90 seconds.

2) *SEM Analysis*
Fracture surface analysis was carried out for the broken specimen by using scanning electron microscope. The fracture modes were analyzed and studied at various locations.

V. RESULTS AND DISCUSSIONS

A. *Restraint intensity*

The restraint intensity plays a major role in HIC. Restraint intensity for Y-groove is estimated as follows.

$R_f = F / (2\Delta w * l_w)$ ………………………………. (1)[4]

Where

F= force required to contract the root gap.
l_w = Length of the weld.
$2\Delta W$ = is elongation due to tensile of force in both sides as shown in the fig: 4.

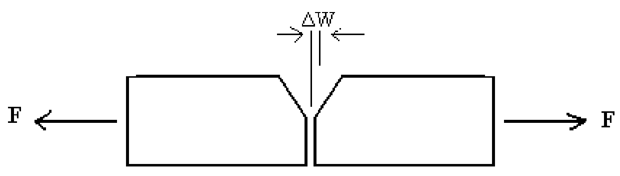


Fig:4 Restraining force and Elongation ΔW

Assuming the condition to be Elastic,

E= Stress/Strain = $f / \acute{\varepsilon} = FW / (2\Delta WA)$

Then $F / 2\Delta W = AE / W$……………………… (2)

It is considered as Restraint is taking place in both anchor welds and test weld. This condition is considered as the anchor weld gives enough resistance for the test weld to prevent contraction. When this condition is applied, then the equation (2) becomes

$F / 2\Delta W = (2l_a *h + l_w*h_w) E / (W)$.

Substituting this equation in (1) we get

$R_F = (2l_a *h + l_w*h_w) E / (W*l_w)$.

Where
l_a = length of the anchor weld (60x2 = 120 mm),
h_w = test weld height (3 mm, measured from actual specimen)

The restraint values for 12mm and 30mm plate are given in the table

Table:5 Restraint Intensity values for both type of plates

Plate Thickness (mm)	Root Opening (mm)	Restraint Intensity (Kgf/ mm.mm)
12	2.0	3545
30	2.0	8104

This Restraint Intensity given in the table may seem to be higher and is because the area in which restraint force acting considered here is larger. So the force obtained will also be more for preventing the contraction, thus inducing more restraint.

B. *Y-groove Test results*

Results of cracking tests are presented in the Table 6.

Table:6 Crack Detail of the Y-Groove Test

Type of joint	Electrode used	Pre-heat temperature (°C)	Crack / No crack (Yes/No)
Inclined Y-groove (16 mm)	Midhani	35 (ambient)	Yes
		75	No
		100	No
	Mailam	35(ambient)	Yes
		75	No
		100	No
Straight Y-Groove (16 to >30mm)	Midhani	35(ambient)	Yes
		75	Yes
		100	No
	Mailam	35(ambient)	Yes
		75	No
		100	No
Straight Y-Groove (30 mm plate)	Midhani	35(ambient)	Yes
		75	Yes
		100	Yes
		125	Yes
		150	No

From the results presented above it may be noted that the Electrodes produced by M/s Mailam is more resistant to cracking than those produced from M/s Midhani. This can be attributed to slightly lower diffusible hydrogen content in the Mailam electrodes (3.2 ml/100g) than in the later (3.7 ml/100g). Even for Midhani electrodes, susceptibility to HAC is not very high. Cracking was arrested with a preheat of 100°C for tests conducted at 12 mm thick plates and at a preheat of 150°C for tests conducted using 30 mm thick plates.

Results presented in the Table 6 also indicate cracking was more in straight Y-groove specimens than the inclined Y-groove specimens. As already mentioned, straight Y-groove tests are suitable to reveal susceptibility of the weld metal for cracking while the other one for HAZ cracking. In all the specimens tested, including inclined Y-groove specimens, cracking was confined to weld metal indicating higher susceptibility of weld metal to cracking than the HAZ.

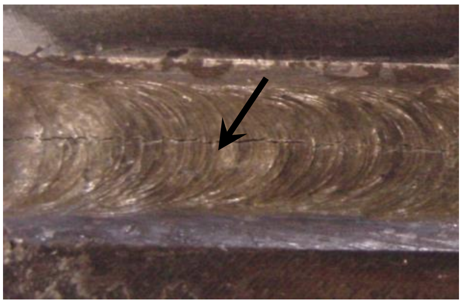


Fig: 5 Photograph showing Crack occurred at No pre-heat temperature for both Straight and Inclined Y-Groove with both the electrode.

Fig: 6 Photo showing Crack occurred with 75°C Pre-heat temperature for Straight Y-Groove Test with Mailam Electrode.

For specimens prepared at 35°C and 75°C, cracking was complete throughout the length and thickness of the test weld bead, resulting in complete fracture of the weld. Figure6 and 7 shows the cracks as seen from the top side of the weld bead. However, for 30 mm thick specimens prepared at 100 and 125°C preheat, the cracks did not extend to the top surface of the test bead for full length. Figure 7 shows the specimen prepared at 125°C preheat after DP check. However, cracks were not confined to these locations alone and under bead were present in other locations, which were revealed after cutting the specimen as per the recommended practice and observing weld cross section in the microscope. One such crack observed in the same weld at a location far away from that shown in Fig 7. This crack was not continuous through out the length as it was not observed in the other locations taken for observations. This indicates that it is not a single crack that initiated and propagated throughout the weld, but multiple cracks initiated at different locations in the weld.

Fig 7. Photograph showing the DP check for specimen with preheat temperature of 125°C

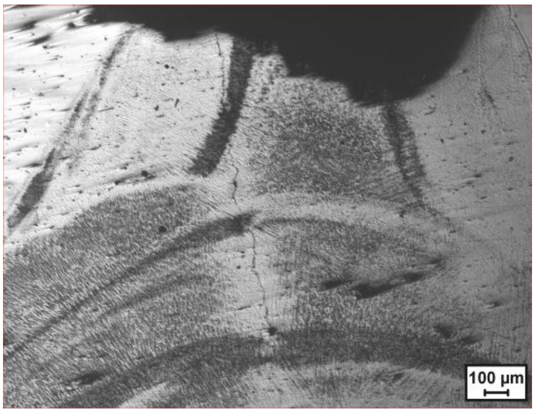
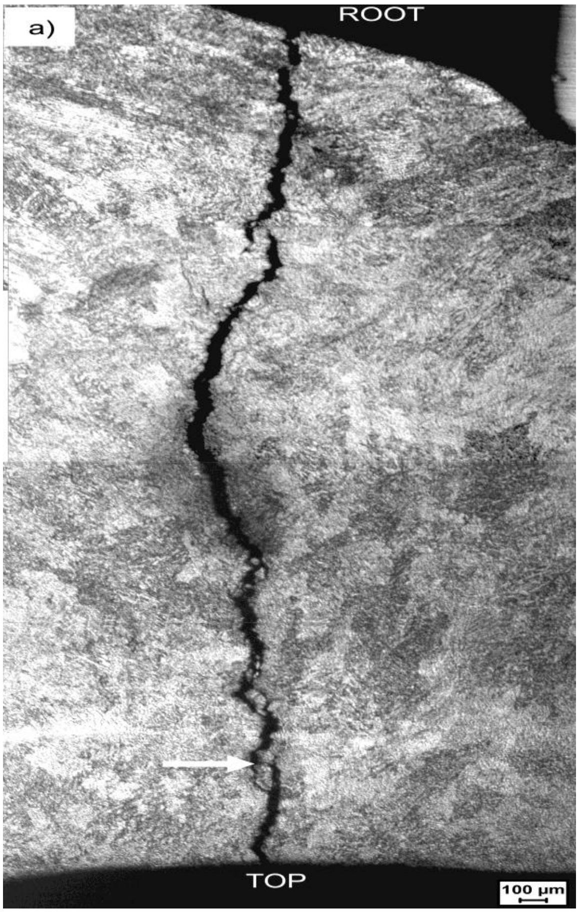


Fig 8. Showing under bead crack in the specimen of 125°C

As the specimens were sectioned to check for cracks only after 24 hours of welding, it was not possible to study the time delay for initiation of the crack as a function of preheat temperature or restraint. However, from the time taken to observe the cracks on the bead surface, it could be assumed that with increase in preheat temperature there was a delay in cracking.

Figure 9a shows the full view of the crack from root side to the top surface of the test bead. The nature of the crack indicates the crack propagation is not continuous and many secondary cracks are present along with the main crack. Secondary crack originating from the main crack is shown in Fig. 9 b. This is the enlarged view of the location marked by arrow in Fig 9a.



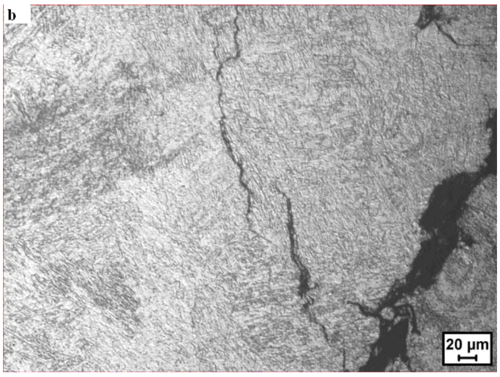


Figure 9. showing for specimen with preheat temperature of 100°C (a) the full crack from the root to top of the specimen, (b) the secondary crack of the same specimen and the place is shown by arrow in fig (a).

C. *Fractography*

Examination of fracture surface under SEM revealed that in general, the mode of fracture was brittle, with typical cleavage morphology. However, islands with ductile mode of fracture were also occasionally visible. Figure 10 shows a typical location of the fracture surface of the specimen prepared at 100°C preheat where cleavage mode of fracture is observed.

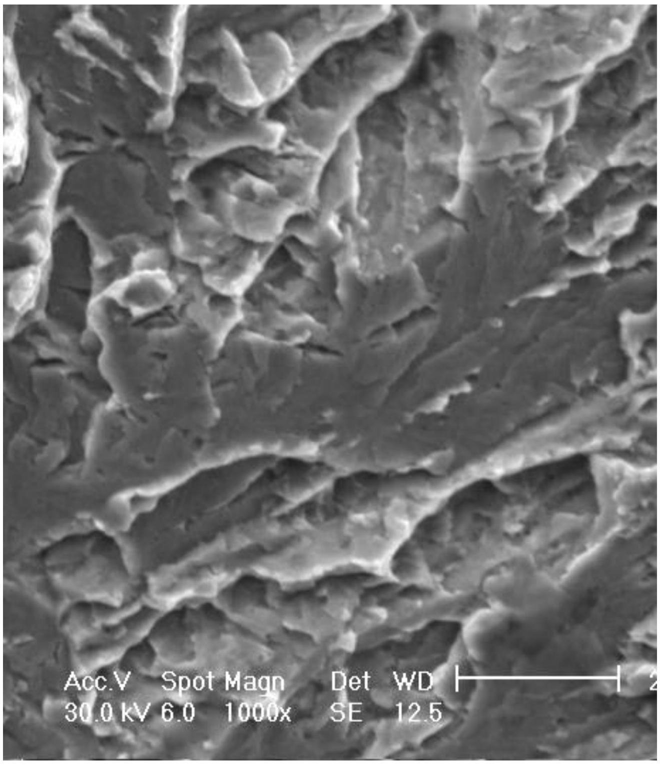


Figure 10. Showing the Cleavage fracture from specimen with preheat of 100°C

Fracture surface also revealed presence of many secondary cracks. Figure 11 shows one such secondary crack. It may also be noted that the mode of fracture is predominantly ductile on one side of the secondary crack.

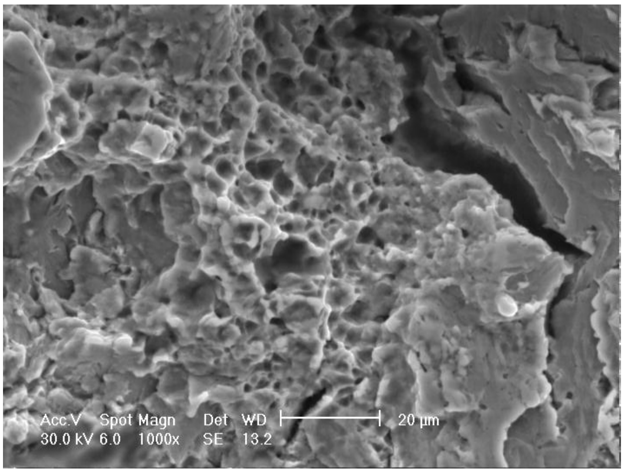


Figure 11 showing the ductile mode predominantly one side of secondary crack shown by arrow.

A comparison of the fracture surfaces of the specimens tested at 100 and 125°C preheat (Fig 12 and 13) indicates that there is some difference in their fracture morphologies. The fracture mode appears to be more ductile at higher preheat temperature than at lower preheat temperature.

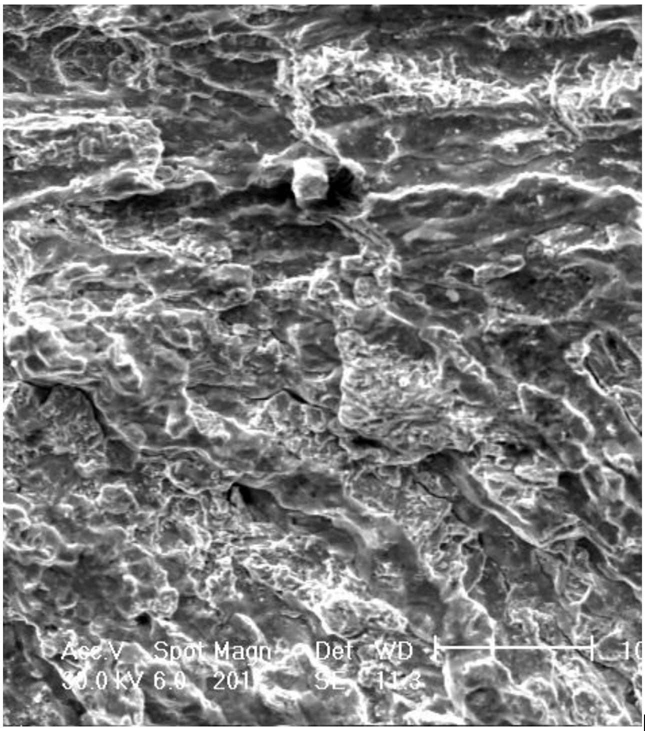


Figure 12 showing brittle mode fracture for specimen with the preheat temperature of 100°C.

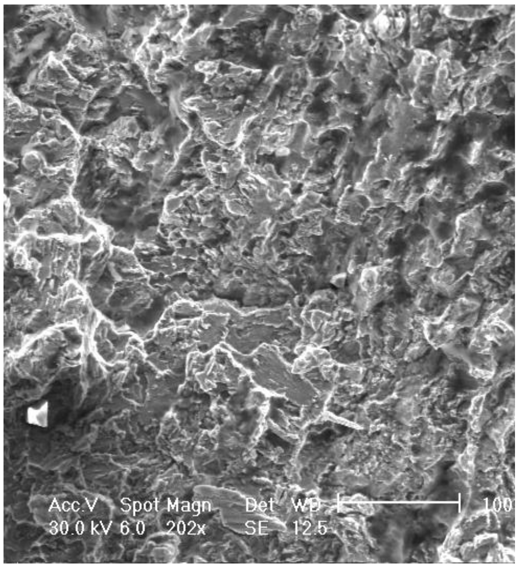


Figure 13 showing the slight ductile mode on specimen with preheat temperature of 125°C than specimen with preheat of 100°C.

D. Hardness

Hardness measurements carried out on the weld metal and base metal of the 12 mm thick specimens made using Midhani electrodes showed that weld metal is harder than the base metal HAZ. The weld metal hardness have been consistently above 450VHN and while that of the HAZ have been in the range of ~420VHN. Hardness of the unaffected base metal is in the range of 200 VHN.

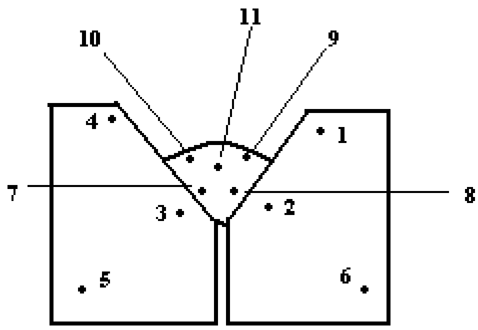


Figure 14 showing the points where hardness are measured and details are shown below in the table 15

Table 7 showing the hardness values measured along the cross section of the specimen tested with Midhani electrode.

Si No	1	2	3	4	6	7	8	9	10	11	12
Midhani HV 10Kg	413	417	420	428	228	219	459	450	459	468	438

VI. CONCLUSION

Some of the conclusion may be given from the present study are as follows:

1) Modified 9Cr-1Mo steel is highly susceptible to HAC even with the low hydrogen electrodes even with the low level of 3.2ml/100g (unbaked condition) of weld metal but can be avoided by preheat temperature of 150°C even for higher restraint.
2) Only Weld metal is more susceptible for cold cracking than the HAZ or Base metal. And also it can be concluded that Straight Y-groove test is more suitable for HAC study on weld metal.
3) Greater thick steel gives good result for studying HAC perfectly restraint is also the major parameter for HAC study.
4) Fracture mode shows highly Cleavage type but slight ductile fracture is also at higher preheat temperature favoring Beacham's theory. Secondary crack is also present after predominant microvoid type.
5) It can be suggested that use of sophisticated NDT techniques makes HAC study (especially Y-Groove) to have better results and research.

A. SCOPE OF THE FUTURE WORK:

In the present study exact delay time for crack is not measured and this may give enhanced scope for the research. Implementation of NDT techniques is necessary for measuring the delay time and even other necessary parameters. This exact measurement would make a good path to study the correlation between restraint, preheat temperature and diffusible hydrogen content. Further higher restraint also needed for good scope of the study. Above mentioned areas are much to be concentrated and will be proceeded as future work.

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