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Welding Studies on WB36 for Feed Water Piping

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ABSTRACT

To increase efficiency, reduce emissions, cost and to reduce weight of boiler per MW, the power manufacturing sectors are going towards the once through technology (super critical boiler) instead of sub- critical. Once through supercritical (OTSC) technology has become a focal point for effective utilization of coal-based thermal power generation sector in India. Another main advantage of moving towards OTSC technology is reducing the weight of the boiler per MW, which can be done by going for material capable of handling higher pressure and temperature than the conventional material. So, in order to keep pace with these technologies, research on newer materials for every boilers line, which can operate at both higher pressure and temperature, has been initiated. So, in this article, we have taken one such feed water system and headers, where WB 36 steel (15 MiCuMoNiNb5) can be used instead conventional standard carbon steel like A106 grade B or C, which are usually used. For super critical, ultra super critical power plants this conventional materials like A106 grade B or C, leads to very thick piping system. V&M has developed WB 36 steel (15 MiCuMoNiNb5) for high pressure piping of boiler feed water system. This heat-resistant, copper-alloyed ferritic steel 15MiCuMoNiNb5 has been widely used in European nuclear and conventional power plants for decades for feed water system. This widespread application is due to the toughness and strength, caused by the precipitation of copper, that are exhibited even at elevated temperatures which other fine-grained structural steels have at room temperature. The aim of this project "Welding Studies on WB36 Steel for Feed Water Piping" was taken to understand the metallurgy and the behavior of the new materials under different manufacturing operations.

Keywords: *Ageing, Hardness, Mechanical properties, Preheating, Post Weld Heat Treatment, Toughness, WB36, Welding, etc.*

I. INTRODUCTION

Studies on the performance of power plant indicated that there is an optimum plant efficiency using feed water at higher temperature of around 300°C. Using conventional standard carbon steel like A106 grade B or C for feed water system results in high wall thickness. This necessitate to go for material which can retain higher strength and toughness even at 300°C. It has found that in some countries like Europe, Australia and China, it is common practice to use WB 36 for this purpose and been operating for more than 20,000 hours without any problem. This material was devolped by Vallourec & Mannesmann (V&M). WB36 is low-alloy, heat-resistant steel 15 NiCu- MoNb 5 (WB 36, material number 1.6368) is used as piping and vessel material in boiling water reactor (BWR) and pressurized water reactor (PWR) nuclear power plants in Germany. One reason for its wide application is the improved 0.2% yield strength at elevated temperatures. Conventional power plants use this material at operating temperatures of up to 450°C, whereas German nuclear power plants use the material mainly for pipelines at operating temperatures below 300°C and in some rare cases in pressure vessels up to 340°C (e.g. a pressurizer in a PWR).

The main advantages of this material is the possibility of reducing of wall thicknesses between 15 to 35% compared with for example, SA106grade C. Using thinner pipes allows in time and cost savings in material, Welding /bending operations and weight of structure and reduces problem due to thermal fatigue. As an example, Table 1 gives the results of calculation of wall thickness according to the steel grade for pipes for an application at 370 bar 320° C with an inner diameter of 480 mm.

Table 1. Comparison of wall thickness requirement for different grade steels

Operating conditions of 370 bar /320 °C	
Steel grade	**Minimum Wall thickness (mm)**
15 NiCuMoNb5- Cl.1	58.9
15 NiCuMoNb5- Cl.2	55.1
SA 106 Gr B	109.3
SA106 Gr C	90.2

This paper outlines welding studies carried out on the WB36 pipe material and its weldability testing and also studies on ageing and its effect on mechanical properties of WB36 steel and its weldments. Therefore, it mainly has three topics

- Steel properties and evaluation of test material.
- Weldability analysis and welding studies carried out on the pipe material
- Studies on heat treatment and its effect on mechanical properties of wb36 steel and its weldments

II. STEEL PROPERTIES

2.1. Chemical Composition.

The chemical composition of WB36 according to ASME is given in Table 2 along with SA 106 Gr C for comparison. Grade C belongs to the group of carbon manganese steels. The composition of WB36 differs in nickel, copper and niobium content.

Table 2. Chemical requirements of WB 36(%) in comparison with SA106 GrC

WB 36											
C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**N**	**Cu**	**V**	**Nb**
0.10-0.17	0.25-0.50	0.81-2.0	0.030	0.025	0.30	0.250.50	1.0-1.3	0.02	0.50-0.80	0.02	0.015
SA 106 Gr C											
0.35	0.10	0.29-1.06	0.035	0.035	0.40	0.15	0.40	-	0.40	0.08	

*ASME CC 2353 - Single values shown are maximum

2.2. Mechanical properties

The pipe material has been included in ASTM standard “Specification for seamless ferritic alloy steel pipe for high temperature service” under A335 P36. The specified properties for the pipe material as per ASTM (2005) are given in Table 3. WB36 composition has been optimized to achieve high yield and tensile strength values. The strengthening effect is obtained by means of grain refinement through the addition of Nb. A second effect is partial hardening by Cu- precipitates. During the development of WB36, it was found that a Cu/Ni-roughly 0.5 is needed in order to avoid red shortness during hot forming.

Table 3. Specified mechanical properties of WB36 steel

Standard	***UTS (MPa)**	***YS (MPa)**	***Elong. (%)**	**Hardness HB**	**CVN impact energy J**
Class 1, N & T Class 2, Q & T	620 660	440 460	15 15	265 Hv 265 Hv	-
EN10216-2 WB 36	610-780	440	19 long. 17 trans.	-	40 long. 27 trans
SA106 GR C	485	275	16.5	-	-

* Specified minimum

2.3. Metallurgy of steel

The specified heat treated condition leads to structure of bainite and ferrite. The proportion of both constituents depends on cooling rate from normalization temperature. Normally the bainite content lies between 40 and 60%. In the case of air cooling the bainite content varies with wall thickness. Large wall thickness therefore require water quenching in order obtain enough bainite. Since higher bainite content can increase strength, water quenching is also used to obtain class 2 material according to ASME. Transformation temperatures are determined by dilatometer measurement. Ac1 temperature was found to be approximately 725 ºC and Ac3 around 870ºC.

Figure 1 shows the CCT diagram of WB36. The steel WB 36 is used in normalized and tempered condition. For high strength or large wall thickness, water quenching is also used. The normal microstructure consists of bainite and ferrite. During tempering, copper precipitates as hardening element in from of fine particles.

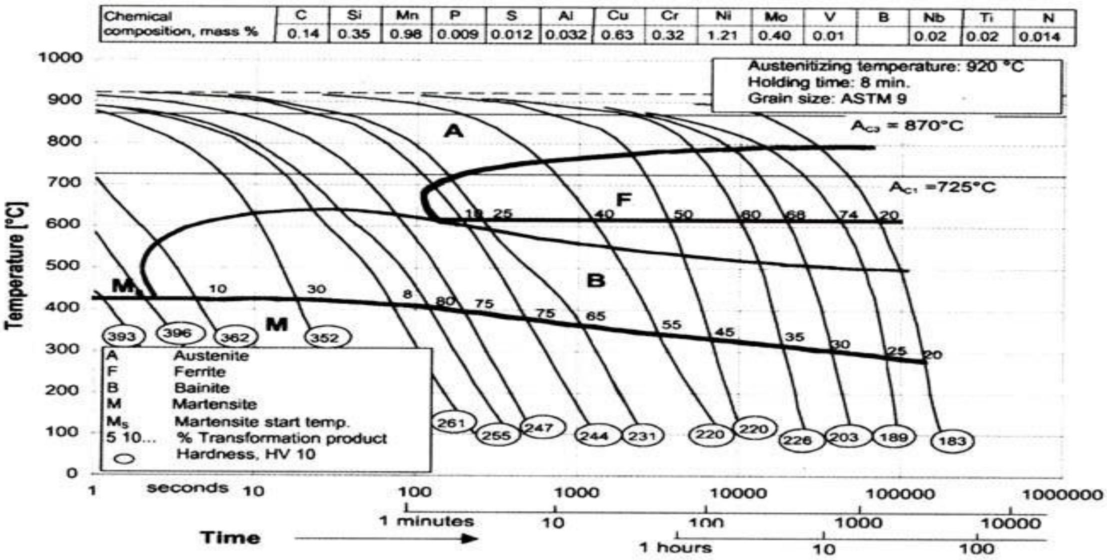

Figure 1 CCT drawing for the steel

2.4. Evaluation of material

Before we are going for weldabilty test it is necessitate to evaluate the test specimen, which was taken for consideration to conformity, whether both mechanical and chemical property as per literature and also select the welding consumable. The steel composition and mechanical properties of test specimen were tested to check the conformity to specification. The test results are shown in Table 4, 5& 6. The chemical composition of steel but for Cu, is meeting the specification requirement. With respect to Cu, Lab value was 0.35% against the specified range of 0.5 to 1.8%. The tensile properties are meeting the specification requirements. Impact toughness of the pipe material was also tested at room temp, 0°C and -25°C. ASTM has not specified the toughness value for the steel grade but EN standard require 27 J toughness at room temperature. It can be seen that the base metal has excellent toughness at room temperature. The toughness rapidly decreased at 0 and -25°C. But the values are much above the minimum required by EN standard. The toughness behavior of the material at different temperature is shown in Fig. 2.

Table 4. Chemical composition test values for the pipe steel (wt. %)

C	0.15	**Ni**	1.21
Mn	1.00	**Mo**	0.31
Si	0.39	**V**	<0.05
S	0.010	**Cu**	**0.35**
P	0.017	**Nb**	0.03
Cr	0.22	**W**	--

Table 5. Tensile test values of the pipe material

YS (MPa)	UTS (MPa)	% Elong.	% RA	Hardness HV10
579	654	27	64	212
587	658	28	64	209

Table 6. Test values of Impact toughness for pipe material

Toughness energy (J)		
Room Temperature(RT)	**0 °C**	**–25 °C**
142	127	49
179	121	89
137	118	62

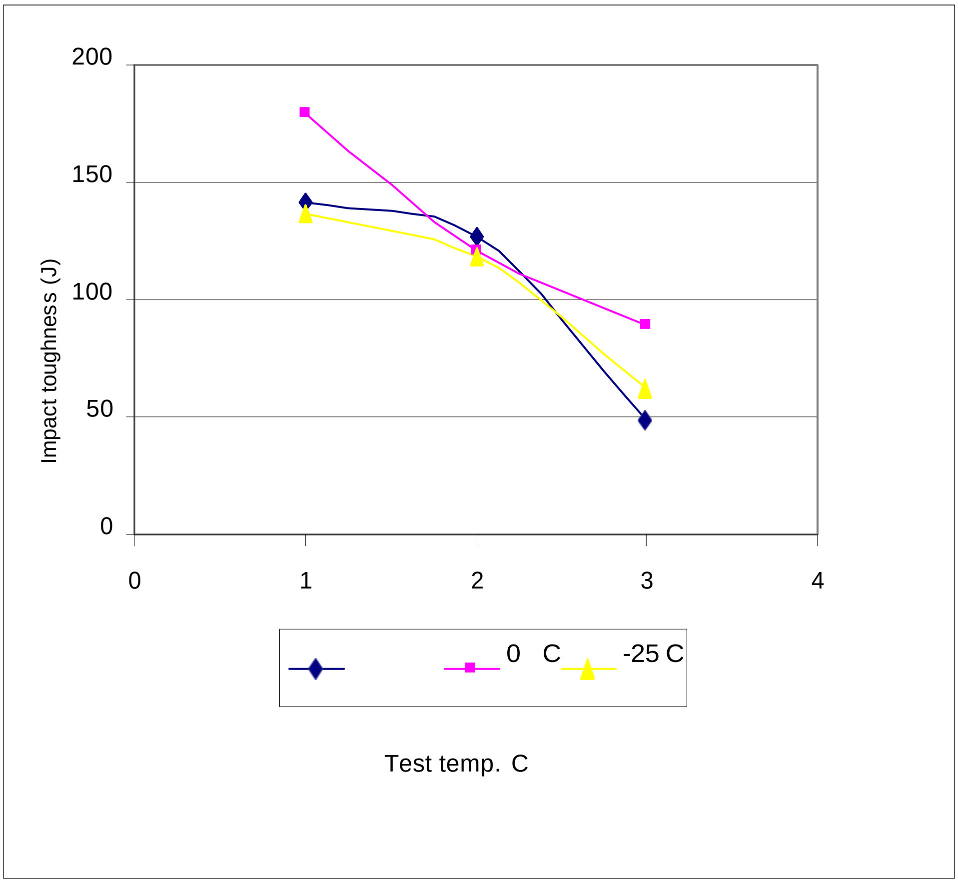

Figure 2 Toughness behavior of steel at different temperature

III. WELDABILTY OF WB36.

3.1 Welding consumables

Welding consumables for GTAW, SMAW and SAW process are supplied by number of consumable manufacturers like M/s Bohler Thyssen/ Germany, Oerlikon. M/s V & M has recommended and used the welding consumable listed in Table 7. The typical properties of the weld metal for the recommended fillers are also given in Table 8&9.

V & M has used both matching and under matched strength class fillers for welding the WB 36 steel. SH Schwarz 3K is designated under E7015Gand that of FOX EV65 under E8018GH4. For the other consumables of SMAW, the tensile properties of specified minimum matches that of base metal. The chemical compositions of the weld metals were matching /near matching to that of base metal but for Cu.

The above consumables are proprietary in nature. The ASME Sec IIC standard consumables listed in Table 10 & 11. are closer to the base metal chemical and tensile properties. Considering the base metal tensile properties, E9018 - M electrode was identified and used for welding of pipe butt joints.

Table 7. Welding consumable used by M/s V & M

Process	Producer	Trade Name
SMAW	Bohler Thyssen Welding	SH Schwarz 3K E 7015 G SH Schwarz 3KNi E 9018 G FOXDMOKb FOXEV60 FOXEV65 E8018GH4
SMAW	Oerlikon	Tenacito 65R E9018G-H4
SAW	Bohler Thyssen Welding	Bohler 3NiMo1-UP/BB24 Union S3NiMo1/UV 420TT (R)
GTAW	Bohler Thyssen Welding	DMO-1G Union 1 Mo

Table 8. Typical Chemical composition of weld for recommended fillers by M/s V & M

Brand Name	**C**	**Mn**	**SI**	**Cr**	**Cu**	**Ni**	**Mo**	**Nb**	**N**
Base metal	<0.012	0.80 1.20	0.25 0.50	-	0.50 0.80	1.0 1.30	0.25 0.50	0.015 0.045	<0.020
SH Schwarz 3K	0.06	0.90	0.35	-	-	-	0.45	-	-
Fox DMO kb	0.07	0.80	0.40	-	-	-	0.50	-	-
SH Schwarz 3k Ni	0.06	1.25	0.30	0.20	0.08	1.0	0.40	-	-
Fox EV 65	0.06	1.20	0.30	-	-	0.80	0.35	-	-
Union S3NIMo1/UV 420	0.08	1.55	0.25	-	-	0.90	0.55	-	-
Union 1 Mo	0.10	1.15	0.60	-	-	-	0.50	-	-

Table 9. Typical mechanical properties of weld joint for recommended fillers by V & M

Brand Name	**YS (MPa)**	**UTS (MPa)**	**Elong. (%)**	**Toughness (J)**
Base metal	410 440	590 780	>16	O ºC / 27
SH Schwarz 3K	U- 490 S- 480	U-570 S-550	U-20 S-21	RT – 120 RT-120
Fox DMO kb	U - 480 S - 470	U-560 S-560	U-22 S-22	RT > 120 RT > 120
SH Schwarz 3k Ni	U - 540 S - 500	U-620 S-590	U-20 S-21	RT > 140 RT > 140
Fox EV 65	U - 550 S - 530	U-630 S-620	U-20 S-20	RT > 130 RT > 130
Union S3NIMo1/UV	U - 560 S - 550	U-680 S-660	U-22 S-22	RT -140 RT - 140
Union 1 Mo	U -480	U-570	U-23	RT -81

U- As welded; S- After PWHT 580- 560 ºC

Table 10. Chemical Composition of Weld metal for identified fillers

Electrode	**C**	**Mn**	**Si**	**P**	**S**	**Ni**	**Cr**	**Mo**	**V**
E8016C4	0.10	1.25	0.60	0.03	0.03	1.10 2.00	-	-	-
E9018M	0.10	0.60 1.25	0.80	0.03	0.03	1.40 1.80	0.15	0.35	0.05
E8016C3	0.12	0.40 1.25	0.80	0.03	0.03	0.80 1.10	0.15	0.35	0.05

Table 11. Specified mechanical properties of weld metal for identified fillers

Filler	**YS (MPa)**	**UTS (MPa) Min.**	**Elongation (%) Min.**	**PWHT condition**
	470-550	550	24	
E8016C4	460	550	19	AW
E9018M	540-620	620	24	AW

AW- ASWELD

3.2 Preheating.

In order to evaluate hydrogen cracking susceptibility of steel and to determine the optimum preheat temperature for welding, implant method of hydrogen cracking test was employed. Cracking test was planned at nil preheat, 100, 150, 200ºC preheats at two stress levels of 500 & 570 MPa. Fracture has not occurred at a stress level of 570 MPa for 100 ºC and at a stress level of 500 MPa even for nil preheat, indicating extremely high resistant of the steel to HAZ hydrogen cracking. The test results are presented in the Table 12. A conservative preheat of 100 ºC can be used for safe welding of the steel.

Table 12. HAZ hydrogen cracking test by Implant test

Material		**WB36**		**Electrode**		**E 9018 -M**		
Dia. of electrode		**4.0 mm**		**Electrode baking**		**300 ºC/hr**		
Process		**SMAW**		**Preheating**		**As given below**		
Pre heat (ºC)	I max (amps)	V (Volts)	Hi max (kJ/mm)	Load (kg)	Spmn. dia (mm)	Stress (MPa)	*Test result	Rupture time
RT	110	22	0.75	1250	4.89	653	B	8 mts
RT	110	22	0.75	1280	4.94	655	B	15 mts
75	110	22	0.74	1210	4.81	653	B	50 mts
75	110	22	0.73	1210	4.82	650	NB	24 hrs
125	110	22	0.74	1230	4.85	653	NB	24 hrs
125	110	22	0.75	1230	4.85	653	NB	24 hrs
175	110	22	0.74	1340	5.07	651	NB	24 hrs
100	110	22	0.94	1350	5.08	653	NB	24 hrs
100	110	22	0.75	1130	4.66	650	NB	24 hrs

*B-- Specimen ruptured; NB -- Specimen not ruptured during test duration, RT- Room temp.

3.3 Hot cracking test

The steel susceptibility to hot cracking was evaluated. Various test methods are available in the literature: among them, varestraint test developed by Lundin was more popular for evaluating fusion zone cracking susceptibility of the steel. The hot cracking test was performed using a moving torch TIG-A-MAG model LT 1100 varestraint-testing machine. Here a TIG welding torch was used to deposit a melting run on the specimen surface. In all cases, at a specific instant a pneumatically actuated ram applies a bending moment on the specimen and the movement of the torch is also arrested. As the bending strain is applied on the solidifying weld metal, hot cracks develop in the latter. The strain applied is controlled by the diameter of the ram and is given by Percentage strain= (t/2R) x 100, Where t is specimen thickness and R is Radius of the Die or ram. The batches of P 36 grade materials were tested at two different strain levels viz 2% and 4%.

Sl No.	**Sample ID**	**Strain %**	**Total No. of crack**	**Length of cracks (mm)**			**TCL Ave. (mm)**
				Min	Max	Total (TCL)	
1	WB36B arrested	2%	8	0.08	0.40	1.66	1.36
2	WB36 arrested	2%	6	0.08	0.42	1.06	
3	WB36 through	4%	18	0.12	0.62	6.10	4.83
4	WB36 arrested	4%	16	0.06	0.46	3.56	
5	WB36 through	4%	12	0.14	0.44	2.59	2.44
6	WB36 through	4%	13	0.10	0.36	2.28	
7	P91 Base metal	2%	12 11	0.10 0.12	0.42 0.46	3.02 2.60	2.86
8	P91Base metal	4%	27 18	0.08 0.20	0.33 0.70	5.20 6.28	5.74

Table 13. Varestraint test results

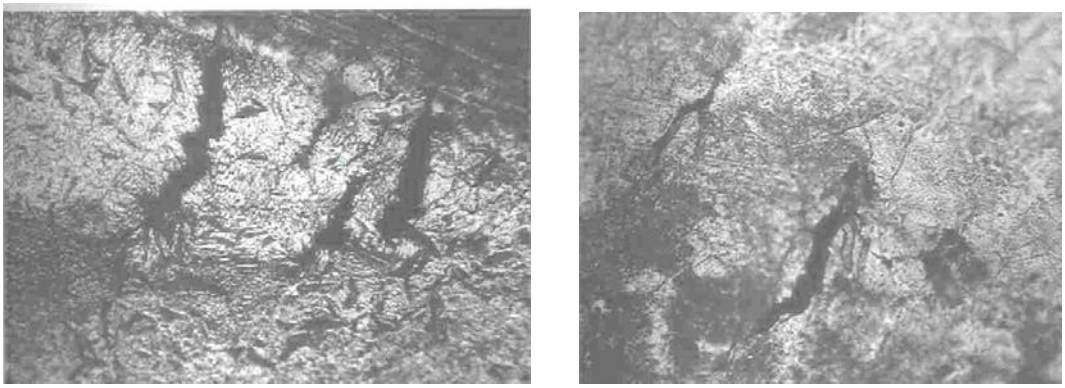

Figure 3 & 4 Varestraint test showing crack at 2% strain in fusion zone

After removal from the test jig, the specimen surfaces were examined under a microscope and the length of individual cracks (Fig. 3 & 4) was measured. These data are given in Table 13. The table shows the length of the shortest and the longest cracks and also the total length of all the cracks for each specimen. The average values of total cracks length and the maximum crack length for each strain level of an individual batches are also given. The behavior of the fusion zone under strain and resistance to cracking is better to P91 steel which is used currently in fabrication of high temperature components.

3.4 Pipe butt welding tests

Pipe butt joints were made with the welding conditions shown in Table 14. Preheat of 100 ºC was used for welding the steel. After welding pipe butt joints were given PWHT. V & M has recommended PWHT of 570 ºC/ 2.5h. Heating rate of 35 and cooling rate of 50 ºC /h maximum is recommended. Two pipes joint were welded and post weld heat treated at 570 ºC. The heating and cooling rate was varied. In one case it was 50 ºC/h maximum and in the other 100 ºC /h was maximum. Soaking time of 2.5 hr was maintained for the pipe size of 273 X 32 mm.

Table 14. Welding conditions for pipe butt welding

Process		**SMAW**		**Consumable**	**300/2hrs**	
Consumables		**E9018M**		**Preheat**	**150 ºC**	
layer	**pass**	**I max (Amps)**	**V max (Volts)**	**Time (minutes)**	**Heat input Max .(J/mm)**	**Interpass temperature (ºC)**
1	1	110	24	10.0	2368	220
2	2	110	24	9.78	2243	190
3	3	110	24	9.0	1991	200
4	4a	110	24	8.0	1710	220
	4b	110	24	8.3	1774	200
5	5a	110	24	8.0	1654	180
	5b	110	24	10.0	2067	210
6	6a	110	24	8.0	1601	190
	6b	110	24	10.0	2002	190
7	7a	110	24	9.0	1746	170
	7b	110	24	12.0	2328	170

After completion of above process, pipe weld joint properties were tested as required in ASME Sec IX. The tensile strength of the weld joint was 670 and 675 and the values are higher than that specified for the base metal. All the bend samples could be bent to 180 º without fissures or opening out. The tensile and bend test results are shown in Table 15. Hardness measurements show a maximum of 264HV in the HAZ and 236 Hv in weld metal. The weld and HAZ hardness ranges are in order and the results are shown in Table 16. Impact toughness of weld and HAZ of the weld joint was tested at 0 & 25 ºC. and test results are shown in Table 17. Both the weld and HAZ have shown good toughness properties.

The short term tests have shown that the joint welded using E 9018M consumables could meet the procedure qualification requirements. In order to check the matching of weld and base metal properties at operating temperatures, tensile tests at high temperatures were also carried out. The results (Table 18.) show that the weld metal tensile strengths at 300, 400 & 500 ºC are much above that of the base metal at the corresponding temperatures.

Table 15. Tensile and bend test results

ID	UTS (MPa)	ID	Bend test results
JA	732	JA1	No open discontinuity observed
JB	670	JA2	No open discontinuity observed
JB	675	JA3	No open discontinuity observed
--	--	JA4	No open discontinuity observed

Table 16. Hardness measurements (Hv) on WB36 weld joint

Identification*	Base metal	HAZ	Weld metal.
JA	215	228	227
	215	264	221
	215	251	221
	218	224	215
JB	215	251	236
	221	258	233
	215	254	224
	215	233	221

*JA PWHT 570 ºC; rate of heating 50 ºC/h, JB PWHT 570 ºC; rate of heating 100 ºC/h

Table 17. Impact toughness of WB36 weld joint

Specimens tested at RT(25C)				Specimens tested at RT(0 ºC)			
Identification *	Impact energy (J)	Identification *	Impact energy (J)	Identification *	Impact energy (J)	Identification*.	Impact energy (J)
JA	164	JB	139	JA	142	JB	134
JA	160	JB	164	JA	127	JB	133
JA	173	JB	138	JA	173	JB	135

* JA toughness at HAZ, JB toughness at weld

Table 18. Tensile properties at high temperature

Temp (ºC)	UTS (MPa)	Elongation (%)
300	604	17
300	609	12
400	611	19
400	629	16
500	601	18
500	563	19

3.5 Hot bending of pipes

To check the forming characteristics of the pipe material, hot bending of pipe was carried out. Hot ductility testing was carried out at different temperature to check if there is any ductility dip at the hot bending temperature range. The test results are shown in Table 19. Percentage reduction in area is more reliable indicator of high temperature ductility. As seen from RA values, the steel has good ductility at elevated temperature. Generally hot bending is carried out above the critical temperature. Based on the test results, the bending temperature was fixed at 930 - 950 º C.

Table 19. Hot ductility of P36 Pipe material

Sl.No.	Temp °C	YS N/mm²	TS N/mm²	%E on 5d	%RA
T2	700	144	167	28	90
T3	750	109	125	50	80
T4	800	93	146	48	76
T5	850	86	147	48	78
T6	900	69	145	45	81
T7	950	60	108	48	88

After fixing the temperature range, sample specimen of WB36 pipe having diameter 273mm and 32 thick is bended to 90° having bend radius of 381mm in the hot bending temperature range 930 - 950 º C in PB 600 incremental bending machine, the facility available in shop as shown in figure 5. After completion of bend, it is subjected to normalizing in furnace at 900°C; 1mm/min air cool and tempering in furnace at 630°C; 2mm/min air cool.

Following checks were done for conformity of our Post Bend Heat Treatment temperatures (PBHT). Dimension measurements of the pipe were taken before and after bending. It is found that the minimum thickness measured on the outer surface of the bend was 27.77 mm and the corresponding maximum thinning was 10.42 %. The wall thickness on the intrados has increased to a maximum of 26.19 %. In order to check the microstructure development at different stages of processing as shown in figure 6, two spots on the pipes were polished using field polishing kits and microstructure was replicated on cellulose acetate tapes. The spots were located such that they come on the extrados of the pipe bend. Hardness measurements on bend after PBHT were also performed using portable equo-tip hardness tester found that it was in the range of 173- 178 Hv. LPI and ultrasonic testing was carried out on bend portion to check for any macro cracks. Replica examination was also performed to check for any micro fissures. No macro, micro fissures were seen in NDT and Metallography examinations.

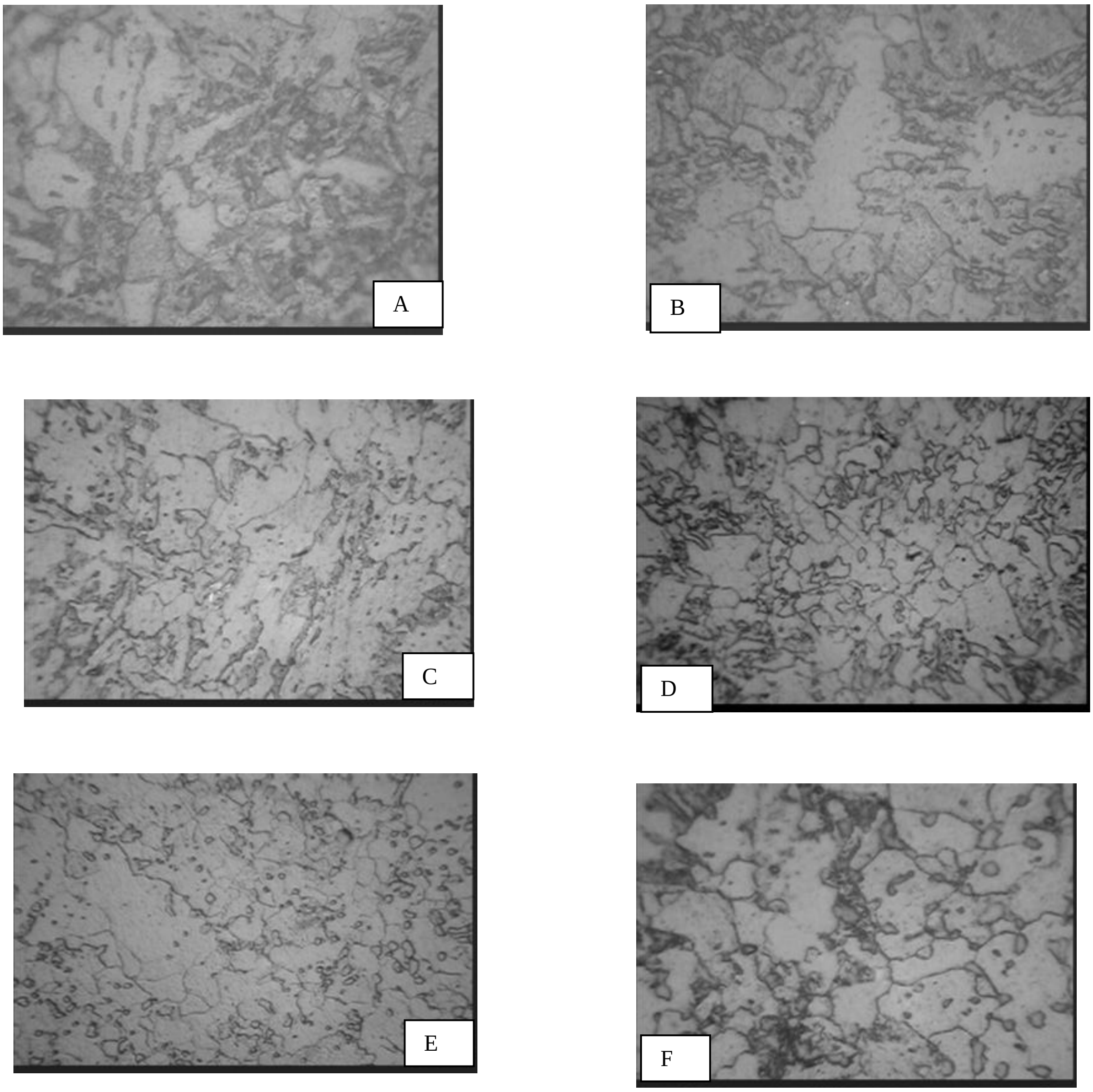

Figure 6. Microstructures of pipe material Mag 500X.
A & B - before bending, C & D- after bending, E & F- after PBHT

IV. HEAT TREATMENT

4.1 Effect of Aging heat treatment on hardness and toughness of the base metal and HAZ of the weld joint

Base metal and HAZ of weld joint samples were subjected to ageing treatment at 350 ºC for 550 and 1000 hours of duration. Hardness and toughness tests were carried out after ageing. The average hardness of base metal in the as received condition was 198Hv. After ageing at 350 ºC for 550 and 1000 hours of duration, the average hardness increased to 210Hv and 221Hv respectively as shown in table 20. and same is shown pictographically in figure 6. Welded samples that were post weld heat treated at 570 ºC for 2 hrs were also aged at 350 ºC and hardness of HAZ was tested as shown in table 21. and same is shown pictographically in figure 7. The average hardness of HAZ in the post weld heat treated condition was 230 Hv. After ageing at 350 ºC, the average hardness increased to 235 Hv and 251 Hv for 550 hours and 1000 hours of duration respectively. Ageing at a slightly higher temperature of 400 ^{0}C was also carried out on base metal for 10 hours and 100 hours .The hardness averages were 200 Hv and 209Hv respectively.

Table 20. Hardness of base metal subjected to ageing at 350ºC for 550 and 1000 hours

Base metal in "as received condition"	**Base metal aged at 350ºC for 550 hrs**	***BM aged at 350ºC for 1000 hrs**	
199	217	226	223
214	208	226	229
221	198	218	229
208	215	221	223
198	203	229	227
203	195	227	220
195	221	230	200
205	217	226	209
198	218	220	215
195		229	215
198		221	212
194		226	203
		230	217
		226	211
		227	204
		224	
Avg=198 Hv	Avg = 210 Hv	Avg = 221 Hv	

*Two sets of experiments conducted

Table 21. Hardness of HAZ of weld joints subjected to ageing at 350ºC for 550 & 1000 hours

HAZ not aged	HAZ of weld joint aged at 350ºC for 550 hours	HAZ of weld joint aged at 350ºC for 1000hours
224	218	243
242	254	272
187	243	243
215	226	274
253		232
226		258
220		230
218		262
229		
236		
226		
233		
227		
260		
233		
260		
Avg = 230 Hv	Avg = 235 Hv	Avg = 251 Hv

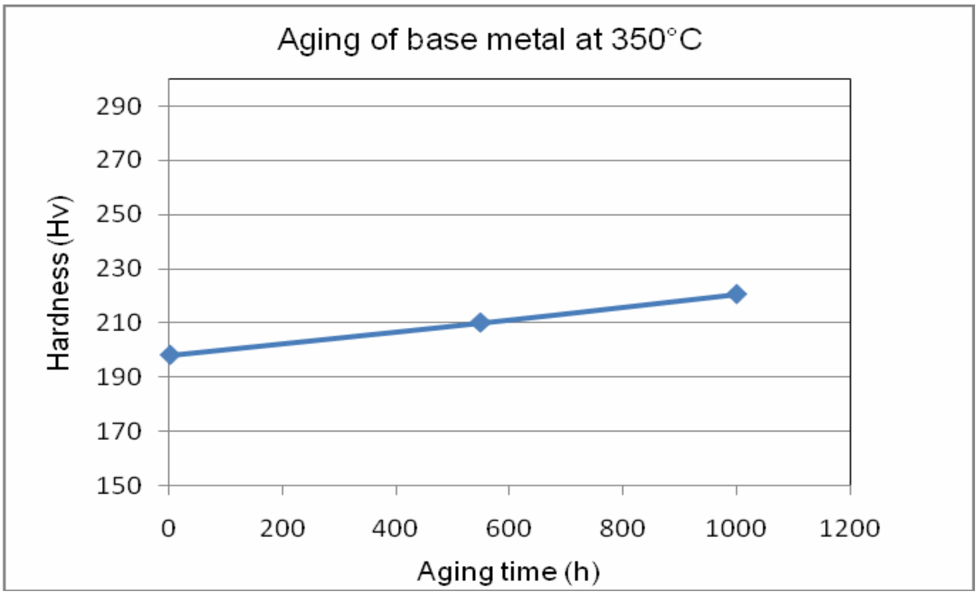

Figure 6. Hardness of base metal after ageing at 350^{0}C

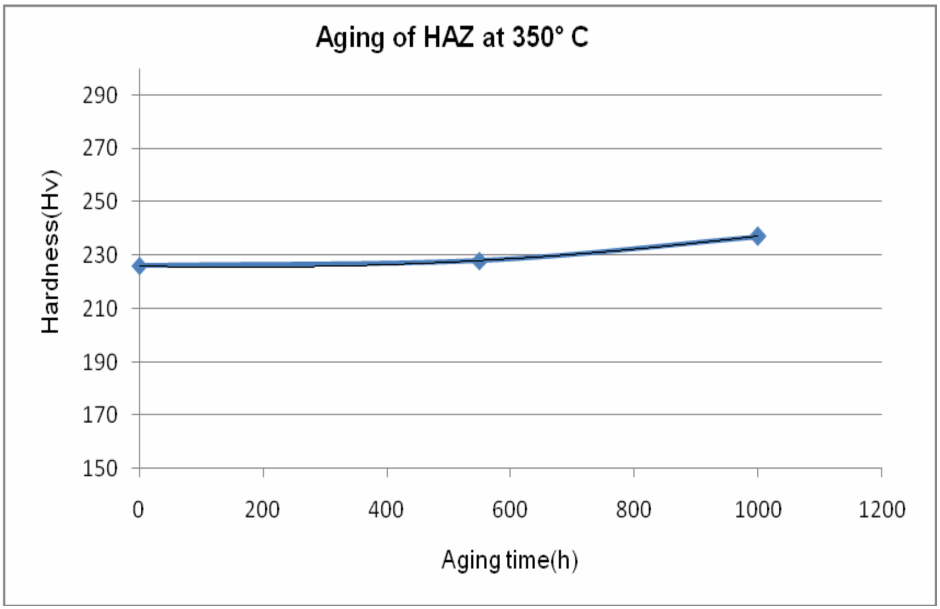

Figure 7. Hardness of HAZ after ageing at 350^{0}C

In their data book on WB 36 steel, V & M reported increase in hardness on ageing at 350 °C. The data points were read from the graph and re-plotted as shown in Figure 8 and the trend equation given below was obtained.
Y = 6.164ln(x) + 172.0 --- 1, where X is ageing time in hours, Y is hardness
Using the above equation, the hardness of the steel estimated for 100,000 hours of operation was found to be 243Hv.

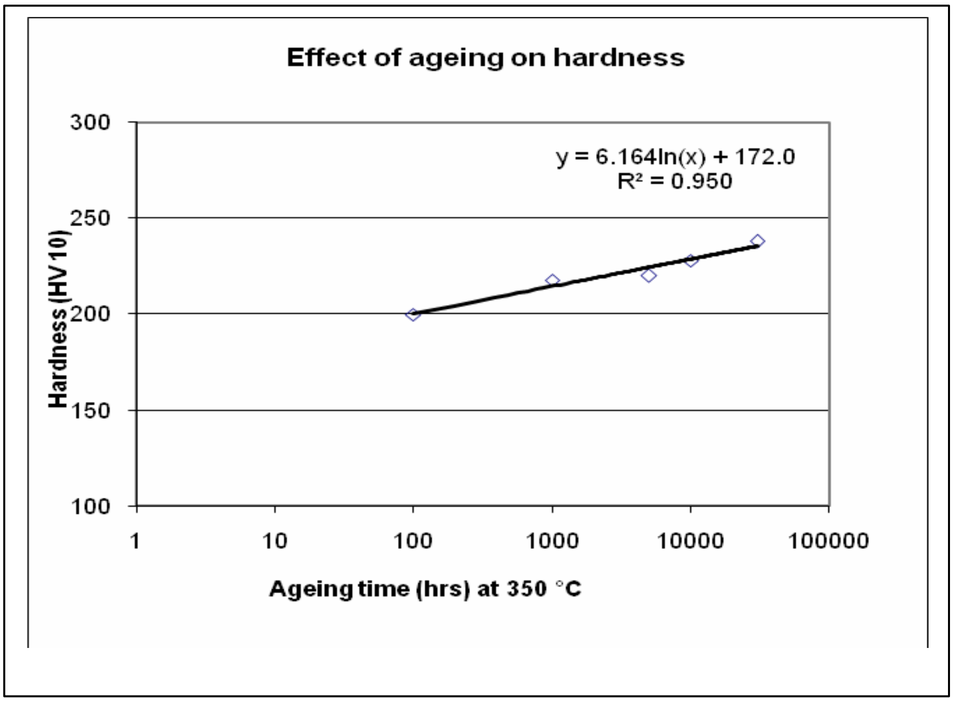

Figure 8. Hardness after ageing – V & M data

The trend equation obtained on our tests is Y= 3.027 ln(x) + 196 --- 2 and the estimated hardness after 100,000 hours of operation is 230 Hv. From the above, it is seen that the final hardness of the steel at the end of 100,000 hours of operation is not very high.

Toughness of base metal and HAZ after ageing at 350^{0}C for 550 hours was tested at 50,25, 0, -25 & -50^{0}C and the same is shown in Table 22 & 23 and Figure 8. Toughness of base metal after 1000 hours of ageing was checked at room temperature and the results are shown in Table 24 along with that for 400^{0}C aged condition. The base metal has not shown any degradation of toughness after ageing for 1000 hours. In the case of HAZ after the ageing for 1000 hours, the CVN energy reduced from 161 J to 128 J.

Table 22. Charpy toughness of Base Metal subjected to ageing at 350 ºC for 550 hours

Test temperature 50 ºC		**Test temperature 25ºC**		**Test temperature 0ºC**		**Test temperature -50ºC**		**Test temperature -25ºC**	
Identification	Impact energy Joules	Identification	Impact energy Joules	Identification	Impact energy Joules	Identification	Impact energy Joules	Identification	Impact energy Joules
7	161	4	125	5	93	2	36	3	89
9	159	8	136	10	109	6	29	1	50
Avg = 160		Avg = 131		Avg = 101		Avg = 32.5		Avg = 70	

Table 23. Charpy toughness of HAZ aged at 350ºC for 550 hours

Test temperature									
50ºC		**25ºC**		**0ºC**		**-50ºC**		**-25ºC**	
Identification	Impact energy Joules	Identification	Impact energy Joules	Identification	Impact energy Joules	Identification	Impact energy Joules	Identification	Impact energy Joules
20	138	22	139	23	185	24	27	21	193
28	233	25	222	25	145	26	140	27	171
Avg = 185		Avg = 181		Avg = 165		Avg = 84		Avg = 182	

Avg - Average

Table 24. Toughness of base metal and HAZ aged at 350ºC and 400ºC

Base metal not aged	**Base metal aged at 350ºC /1000h**	**Base metal aged at 400ºC /10h**	**Base metal aged at 400ºC /100h**	**HAZ not aged**	**HAZ aged at 350ºC /1000h**
142,179,137 Avg.153	184,136,180, 131,136,137 Avg.151	124,148 Avg.136	137,135,129 Avg.134	251,177,182, 138,185,128, 143,134,111 Avg.161	147,157,118, 114,104 Avg.128

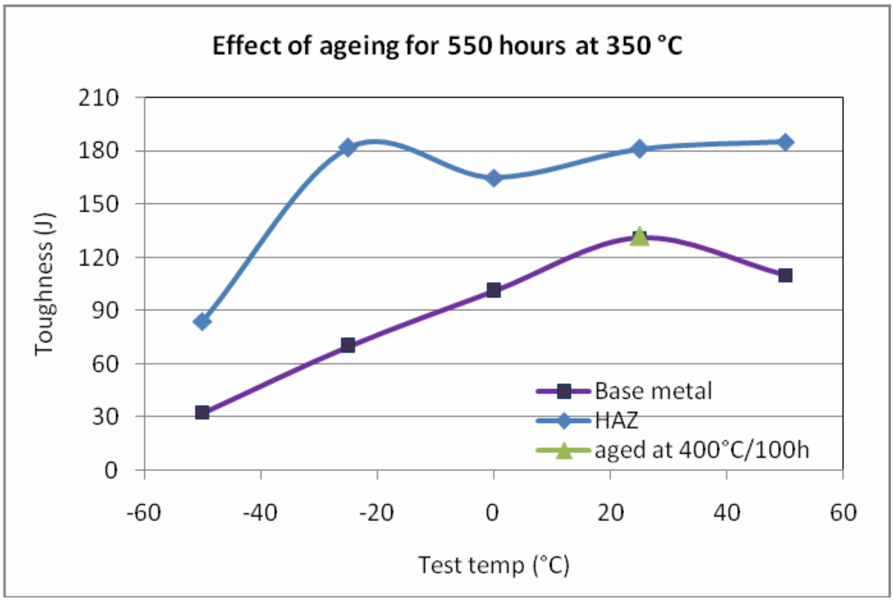

Figure 8. Toughness of base metal and HAZ after ageing at 350^{0}C

Micro structure of the base metal was also checked after the above ageing treatments. With the optical microscope, no significant differences have been noted in the microstructure as shown in Fig.8 & 9.

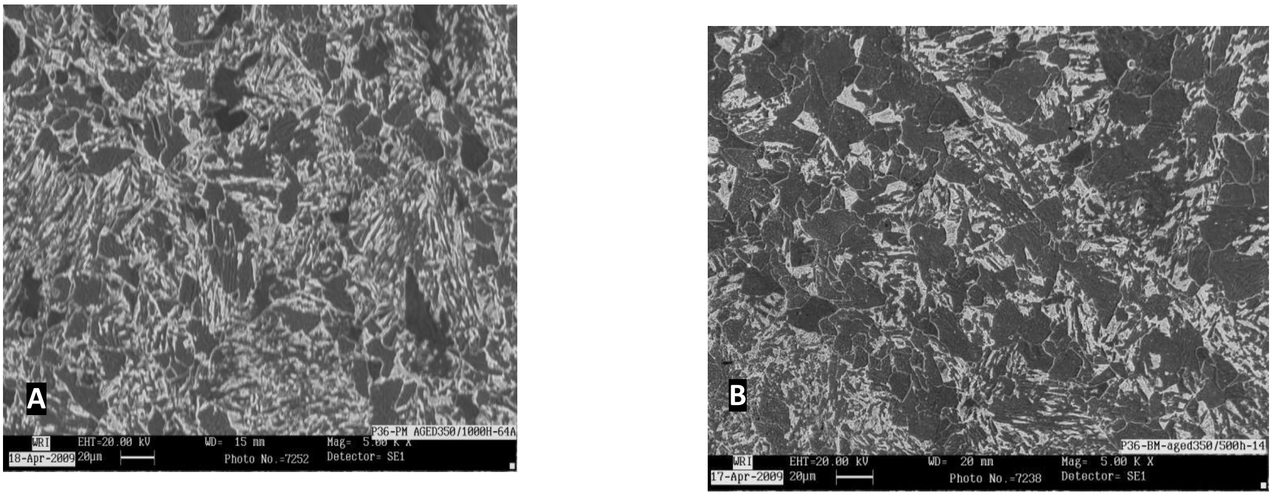

Figure 8 A- Microstructure of base metal aged at 350^{0}C-550h; B- Base metal aged at 350^{0}C-1000h

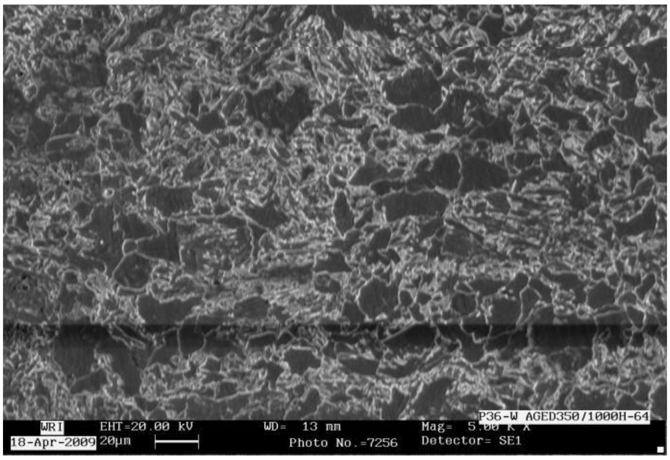

Figure 9. Weld metal ageing condition

4.2 Effect of PWHT temperatures on mechanical properties of weld joints

Mechanical properties of weld joints made with E9018-M electrodes were evaluated for one post weld heat treatment temperature. Viz 570 ^{0}C. In the literature, PWHT of weld joints at 540 and 600 ^{0}C was also reported. Hence the same was included in the scope of this project. Joints were made and subjected to the above PWHT temperatures. The test results of tensile, impact hardness and bend test results are shown in Table 25 to 27.The tensile strengths of the weld joints for the three PWHT temperatures are 679, 697 and 698 MPa and meet the specified minimum of ASME Sec IX. The average CVN energy values for the weld metal for the PWHT temperatures of 540^{0}C, 570^{0}C and 600 ^{0}C were 95, 101 and 98 J respectively. Toughness of HAZ was slightly higher for PWHT temperatures of 540^{0}C and 570 ^{0}C. In general, the hardness averages of HAZ and weld metal are slightly more than the base metal. Hardness ranges of 215-223, 211-229 Hv were observed respectively for HAZ and weld metal. The differences in hardness values of weld and HAZ between the three PWHT temperatures were not significant. The bend ductility of weld joints post weld heat treated at 540^{0}C,570^{0}C and 600^{0}C was satisfactory .The test samples could be bent without any fissures and meet the requirements of ASME sec IX.

Table 25 Tensile strength and notch *toughness of weld joint subjected to different PWHT

Identification	**U.T.S (MPa)	HAZ toughness* (J)	Weld metal toughness* (J)
AIB (540ºC)	698	104,118,130 /avg. 117	94,104,97 /avg.98
AJA (570ºC)	697	143,137,111/ avg. 130	75,96,113 /avg.95
AIA (600 ºC)	679	120,63,111 /avg. 98	102,98,104/ avg.101

*at room temp. ** Fracture in base metal

Table 26 Bend test results of weld joints subjected to different PWHT

Identification	Side Bend	Remarks
AIA	1mm open discontinuity observed	Passed
AIA	No open discontinuity observed	Passed
AIA	No open discontinuity observed	Passed
AIA	No open discontinuity observed	Passed
AIB	No open discontinuity observed	Passed
AIB	No open discontinuity observed	Passed
AIB	No open discontinuity observed	Passed
AIB	No open discontinuity observed	Passed
AJA	No open discontinuity observed	Passed
AJA	No open discontinuity observed	Passed
AJA	No open discontinuity observed	Passed
AJA	No open discontinuity observed	Passed

Table 27 Hardness of pipe joint subjected to different PWHT

Location	AIB (540ºC)	AJA (570ºC)	AIA (600ºC)
Base Metal	198,203,199,205 Hv avg. 201 Hv	199,214,221,208 Hv avg. 210 Hv	212,212,192,212 Hv, avg- 207 Hv
HAZ	198,218,189,212, 251, 230,233,240 Hv avg. 221 Hv	224,242,187,215, 253,226,220,218 Hv avg. 215 Hv	227,221,214,209, 251,240,220,202 Hv avg. 223 Hv
Weld metal	224,212,206,203 Hv avg 211 Hv	209,209,223,215 Hv avg. 229 Hv	233,238,206,212 Hv avg. 222 Hv

V. CONCLUSION

From this paper it is found that

- The steel has adequate resistance to HAZ hydrogen cracking at preheat of 100 ºC.
- The steel has excellent toughness properties at room temperature.
- Toughness of steel decreases at lower temperatures. However at -25°C, the toughness level of base metal is much higher than that specified for base metal in EN standard.
- Welding consumables of both under matched and matched strength were used by the steel supplier. However, in this work, matching strength filler was used for pipe butt welding and joint properties were tested.
- Weld joint tensile and bend test properties are meeting the specification requirements.
- Weld and HAZ toughness properties are good and comparable to base metal.
- The pipe material could be hot bent in incremental bender to R/D ratio of 2.19 without any problem of cracking.
- The pipe material P36 has been welded in SMAW process, using the recommended welding materials and post weld heat treated at the temperatures of 570^{o}C and 600^{o}C meets the requirements for weld procedure qualification.
- The hardness and toughness tests carried out on the base metal subjected to ageing treatment at 350^{o}C for limited duration of 1000 hours has not shown any embrittlement.
- The differences in hardness values of weld and HAZ between the three PWHT temperatures were not significant. The bend ductility of weld joints post weld heat treated at 540^{o}C, 570^{o}C and 600^{o}C was satisfactory. The weld joints can be post weld heat treated at temperature between 540^{o}C-600^{o}C.

From the above we can formulate Guidelines for welding and bending of WB36.

Guidelines for Welding and bending of WB36 to WB36 pipes	
Welding joint design	Single V groove
Welding fillers TIG & SMAW	UNION I MO & E 9018M
Electrode baking	300-350 °C / 2hrs
Purging for root welding	Not required
Preheat	100-150°C
Interpass temperature control	300°C max.
Bead technique	Stringer and Weave
Preheat maintenance	Nil
Thermal treatment immediately after welding	Can be cooled to room temp.
Time duration between welding completion and PWHT	Not critical
PWHT	570°C / 2.5 hr,
Bending temp.	930-950 °C
Time duration between bending and PWHT	Not critical
Post bending Heat treatment Normalizing & Tempering	900 º C, 1 mm/ min & 630 º C, 2.5 mm/ min

VI. ACKNOWLEDGEMENT

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REFERENCES

[1]. Hahn, B.; Vandenberghe, B.; Vaillant, J.C.; Bendick.W.: The WB 36 Book, 2002; Vallourec & Mannesmann Tubes.

[2]. ASME BPVC IX (2010), Boiler & Pressure Vessel Code, Section IX, Welding and Brazing Qualifications, as required by the States of Colorado, Connecticut, Delaware, Indiana, Minnesota, Nevada, North Carolina, Oklahoma, Rhode Island, Tennessee, et. alia.

[3]. Indian Boiler Regulation-2010 guide

[4]. Welding Engineering,2012; Welding Research Institute, Bharat Heavy Electricals Limited, Tiruchirappalli.

[5]. Schick, M., 1996. Veroffentlichte Untersuchungen zum Werkstoff WB36, MPA Stuttgart, 1990 bis 1996.