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Mechanical properties and fracture characteristics of ASTM A335 P91 steel used in boiler materials.

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Abstract : Maximizing the efficiency of the power boilers generally requires operation at the highest possible temperatures and steam pressures. In turn these most aggressive operating conditions require the use of higher strength materials than were typically used for the construction of the power plants. This situation has increased the interest in the issues related to the processing andthefabrication of alloys such as 90Cr-1Mo-V steels. Of these steels, the modified 9Cr-1Mo steel known as P91/T91 or, in Europe as X10CrMoVNb9-1, has been used in a wide range of industrial applications. In addition to the improved room temperature tensile strength, the modified variant also has increased creep strength, lower ductile –brittle transitiontemperatures and higher energy. The present study concerned with the hot tensile properties of SA welded P91 material. The welding was carried out on a 406 mm diameter, 53mm thick wall pipe by using root pass of TIG welding and subsequent passes of SMAW and SAW. This study examines the effect of the tensile test temperature ranging from 400˚C to 700 ˚ C on the tensile properties of the P91 SA-weldment. The hot tensile properties of SA welded P91 compared with the SMA welded P91 steel. The fracture surfaces of the hot tensile & impact specimens were examined under Scanning electron microscope and fractographic studies were made. An attempt has also been made to evaluate the mechanical strength of the weldment and microstructural characteristics of the different regions in the weldment to correlate fractography features with tensile and impact strength.
Key words: *tensile,ductile, SMAW, SAW P91 X20.*

1. Introduction:

Cr-Mo ferritic steels are widely used infossil power plant for the structure and piping systems due to their creep strength and moderate oxidation resistance up to 650 ˚c. the 90Cr-1Mo steel is one of the best alloys in the family of Cr-Mo steels for elevated temperature applications[1,2,3,4,5]. With ever increasing the demand of high efficiency in the power generation industry, the operation temperature is steadily increasing. The modified90Cr-1Mo steel is a relatively new structural alloy that was originally developed in the steam generator industry. With minor addition of Nb & V elements in the 90Cr-1Mo steel, the long term creep strength of the steel can be further improved. P91 is primarily used in the normalized and tempered condition. During the heat treatment, a fine dispersion of Nb(C,N) and $M_{22}C_6$ is precipitated. Through the mechanism of precipitation strengthening, this gives rise to the enhanced mechanical properties. Welding of Cr-Mo ferritic steels play a crucial role in the power and the petroleum industries, and has been extensively and studied in recent years. Considerable effort went in the development of 90Cr-1Mo-V steel consumables to optimize strength and toughness of the weldment.

Welded joints are used as structural parts of boilers, pressure vessels, piping, tunings and other equipment working at high temperatures. In addition to these properties, the welded structure must be safe enough during the sudden starts or interruption of its operation. Therefore welded joints of heat resistance steels must have appropriate Impact properties and resistance against brittle failure[6,7], the stringent design, construction and operational requirements of nuclear plantsdemand consistency of the material behavior. This is reflected in the more restricted composition and property specification of the normalized and tempered 90Cr-1Mo steel currently adopted by the UK nuclear industry which meets the broader international standards [8,9,10]. The weld abilityof P91 steels is very good. Due to the high alloying content, a relatively high preheating temperature (200-350°C) must be used. The development of the suitable welding filler metal of the similar type which can employed in the SMAW, GTAE and SAW welding methods[11,12]. Current trends in the design of large pressure vessles require massive sections that operate under high stresses at high temperature. To attain good through section fracture toughness values at higher yield strength that are required for such components, the steel needed to be used must possess higher hardenability, and greater heat treatment potentials. Toughness charecterization is one of the important parameters which plays a vital role in determining the performance and life of the materials under the given service conditions. Toughness characterization is done by impact energy test, fracture toughness test(plane stress fracture toughness test) (K1C) test[15].

The present investigation has been carried out to assees hot tensile properties and fracture toughnesss characteristics of P91 weldment. SA welding was done on a 406 mm diameter & 53 mm thick wall pipe. This study examines the effect of tensile test temperatures ranging from 400 to 700 °c on the tensile properties of the SA weldment. The hot tensile properties of SA welded P91 compared with the SMA welded P91 steel. The fracture surfaces of the hot tensile and impact testes were examined by scanning electron microscope (SEM) and fractographic studies were made. An attempt has also been made to evaluate the mechanical properties of the weldment and microstructural characteristics of the different regions in the weldment.

2. Experimental details:

In the current investigation, joining of SA 335 P91 by SMA welding process was carried and the resultant weldment subjected to mechanical and metallurgical studies. This study examines the effect of the tensile test temperatures ranging from 400 to 700 °c on the tensile properties of SAW and SMAW welded P91 steel. Fractographic studies were done by Scanning electron microscope to know the characteristics of the fracture surface. The impact testing of SAW weldment was done. Also the microstructural evaluation of the weldmentas hardness testing was carried out.

2.1 Materials Used:

The material chosen for investigation is SA 335 P91, low alloy ferritic steel. The original dimension of the pipe was ø460 mm × 53 mm ×300 mm and welded by SAW. The dimensions of the pipe used for SMAW was ø 120 mm ×12 mm thick.

2.2 Chemical analysis:

Chemical analysis was carried out on the material chosen for investigation (P91) as per standardization of ASTM E-1086. The experimental result shows that composition of the chosen material matches the ASTM standard chemical composition value. The table gives the chemical composition (%) of the P91 as per the ASTM standards and also the experimental analyzed result.

Table 1:chemical composition SA 335 P91.

	C	Mn	P	S	Si	Cr	Mo	V	Nb	Ni	N	Al
Standard	0.08 -0.12	0.30-0.60	0.02 max	0.01 max	0.50 max	8.00 -9.50	0.85 -1.05	0.18 -0.25	0.06 -0.10	0.40 max	0.03 max	0.03 max
Analyzed (ϕ 120, 12 mm thick pipe)	0.08	0.42	0.02	0.01	0.3	8.24	0.9	0.21	0.05	-	-	-
Analyzed (ϕ 460, 53 mm thick pipe)	0.09	0.42	0.01 max	0.01 max	0.26	8.39	0.86	0.21	0.05	-	-	-

Table.2:Chemical composition of SAW welded P91.

	C	Mn	P	S	Si	Cr	Mo	V	Ni	Cu
Analyzed (SAW)	0.12	0.72	0.01 max	0.01 max	0.21	8.19	0.82	0.19	0.75	0.10 max

2.3 Welding consumables:

The following table gives chemical composition of the welding consumables available for SMAW,GTAW and GMAW.

Table 3. Chemical composition of welding consumables.

Consumables	C	Mn	P	S	Si	Cr	Mo	V	Nb	Ni	N	Al
E9018-B9 (SMAW)	0.08-0.13	1.25	0.02 max	0.01 max	0.30	8.00 -10.50	0.85-1.20	0.15-0.30	0.02-0.10	1.0	0.02-0.07	0.04
E B9 (SAW)	0.07-0.13	1.25	0.01 max	0.01 max	0.30	8.0-10.0	0.80-1.10	0.15-0.25	0.02-0.10	1.0	0.03-0.07	0.04

2.4 Welding flux:

Flux, marathon 543 is a highly basic agglomerated flux specially designed for SAW with AWS E B9 wire. When used in combination with AWS EB9, Marathon 543 yields a weld deposit that is chemically balanced to insure optimum mechanical properties, including creep resistance. Welding characteristics are excellent with good wetting and easy slag removal. Marathon 543 is metallurgical neutral.

2.5 Welding joint details:

The single 'U' edge preparation was used for SA- welding of ø 460 mm, 53 mm thick pipe. The single 'V' edge preparation was used for SMA-welding of ø 120 mm, 12 mm thick pipe.

Table 4: Details of edge preparation

Parameters	SAW	SMAW	Parameters	SAW	SMAW
Type of edge preparation	Single 'U'	Single 'V'	Root face width	1.6 mm	1.5 mm
Wall Thickness	53 mm	12 mm	Root gap	1.6 mm	1.5 mm
Outside Diameter	406 mm	120 mm	Groove angle	10°	70°

2.6 welding procedure:

Table 5: GTA welding parameters for root pass (Weld metal deposit 2.5 mm)

Parameter	Value	Parameter	Value
Current	100 A	Electrode Tip configuration	60°
Voltage	20 V	Electrode Type & dia.	EWTh-2, Ø 2.4 mm
Polarity	DCEN	Welding position	2G
Shielding gas	Argon (99.9%)	Method	Manual
Gas flow rate	8 lit/min	Preheating Temp.	220°C
Filler wire	ER90S-G	Technique	stringer
Filler wire dia.	2.4 mm	Number of passes	1

Table 6: SMA Welding Parameters for further two passes (Weld metal deposit 10mm)

Parameter	1st Pass	2nd pass	Parameter	1st Pass	2nd pass
Current	120	150	Electrode (length)	350 mm	350 mm
Voltage	28	30	Welding position	2G	2G
Polarity	DCEP	DCEP	Welding Speed	250 mm/min	300 mm/min
Electrode	E 9010-D9	E 9018-B9	Tech. (weaving/ stinger)	Stringer	Stringer
Electrode dia.	3.2 mm	4.0 mm	Interpass Temp.	230-350 °C	230-350° C

Table 7: SA welding parameters

Parameter	Value	Parameter	value
Current	400 A	Welding position	1G
Voltage	30 V	Welding Speed	450 mm/min.
Polarity	DCEP	Preheating Temp.	220°C
Filler wire	E B9	Interpass Temp.	230-350°C
Filler wire diameter	3.2 mm	Tech.(weaving / stinger)	Stringer
Electrode stick out	30 mm	Number of passes	63
Type of flux	Marathon 543 (Basic agglomerated flux)		

The two pipes were preheated and checked with thermal chalks to achieve a minimum temperature of 100 ˚ C. GTAW process was used for tackling the pipes and weld deposit thickness was 2.5 mm. particular attention was paid to the quality of tack weld welds were dressed by grinding to facile proper fusion where the root run completed. Back purging by argon was done to prevent oxidation inside the pipe. The SMAW process was used for the further two passes and the weld metal deposit was 10 mm. the SMAW stick electrodes after baking were stored in a portable oven at 150˚C.preheating was done using producer gas burners for temperature of 220˚C and was maintained before and during the course of the welding. The temperature was checked using thermal chalks. Inter pass temperature was controlled between 230˚- 350˚C and when temperature exceeded the maxiumum, welding was stopped and resumed afterafter the temperature dropped to 230˚C. further passes were done by using the SAW. Preheating and interpass temperature were manited as same. On completion of welding the joints were given post heating at 300˚C/2 hours by enclosing thermal blankets. Radigraphic inspection was done after welding, then gring of capping passes. Then the weld metal was subjected to PWHT of 750˚C for 260 minutes. Preheating and PWHT procedure is given in fig 3.3

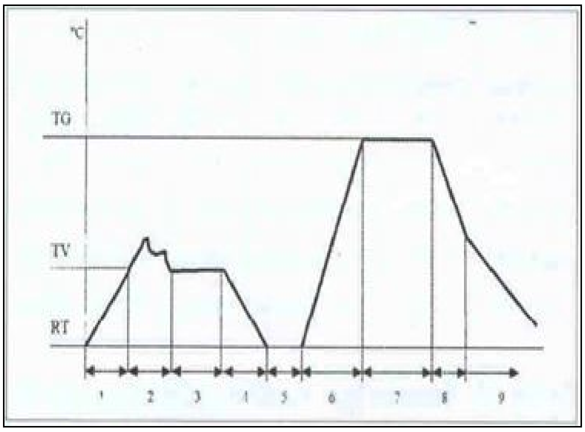


Fig 3.3 : Preheating and PWHT Procedure

Table 8: Heat treatment Procedure (Preheating and PWHT

Operation	TEMP. °C	Rate of Heating / Cooling	Operation	TEMP. °C	Rate of Heating / Cooling
1.Preheat (TV)	220	100 °C /hr	6.Heating to PWHT	Reach 760 +/-10°C	140 °C/hr max)
2.Welding by GTAW & SMAW	220-350	—	7.Soaking at PWHT Temp. (TG)	760 +/-10°C at 2.5 minutes/mm. (260 minutes. minimum)	
3.Post Heat	220-280/2 Hrs	—	8.Cooling	Cooling to 350 °C.	150 °C/hr max.
4.Cooling	Room Temp.	100 °C /hr	9.Cooling	Cooling to Room Temp.	—
5.Hold at Room temp for 72 hrs.max. before PWHT			—	—	—

3. Testing:

3.1 Tensile Testing:

Both the base metal and weldment were subjected to tensile testing. ASTM E8M was used for the base metal tensile testing. The transverse tensile specimens of weldment were prepared in the following dimensions 20 X 20 mm as per the standard AWS B4.0-98. All weld metal tensile test was also done as per the standard. Two specimens of transverse tensile were taken from the face side of the weldment. Also two specimens were taken from the root side for tensile testing.

3.2 Hardness Testing:

Hardness survey was done by using Vickers hardness tester with 10Kg load, The indents were made in Base material, weld metal and Heat affected zone.

$VHN=1.85P/L^2$

Where, P – Load in Kg, L – diagonal length in mm.

The impression appears as a dark square on a light background. The measurements are taken across the diagonals of the square, and the hardness value corresponding to the readings is obtained from a chart or calculated by a simple formula.

3.3 Impact Testing:

This test measure the resistance of the metal to fracture in the presence of a sharp notch also called notched-bar impact test. Minimum impact values are specified in many codes and specifications for ferritic steels, because some of them fail by brittle fracture in service, even though they exhibit normal properties as determined from the standard tensile test. Even failure is especially severe when the material used in a notched condition.

Notched conditions include restraint due to deformation in directions perpendicular to the major stress, multi-axial stress, and stress concentrations. The energy values determine the variation of impact strength with temperature and arriving at the transition temperature. They are not useful for engineering design calculations. There are several impact tests among which charpy-V notch, is well known. To carry out the test, the specimen is paced in a vice of an impact testing machine. A pendulum, swinging on ball allowed to strike the specimen. The striking energy is absorbed in fracturing the specimen, is indicated by pointer. The impact test values are expressed in joules(J). in this present investigation, impact specimens were taken from the face side and root side of the weldment.

3.4 Side Bend Testing :

The bend test is a simple and inexperience quantitative test that can be used to evaluate both the ductility and soundness of the material . the bend test coupon was prepared according to AWS specification. This test was conducted on UTM with 6.66t material at 180^o bend. The transverse side bend test is good at revealing lack of side wall fusion. The test coupon is said to pass only when it does not have discontinuity in weld.

3.5 Hot Tensile Testing:

This study examines the effect of temperature ranging from 400 to 700^{o}C on the tensile test properties of a SAW weld of modified 9Cr-1Mo ferric steel. Hot tensile testing was performed in an UTN-60 testing machine. Isothermal tensile test on SAW welded transverse tensile specimens of the six of 12.5 X 6 mm were carried out at the temperature of 400^{o}C, 500^{o}C, 600^{o}C, and 700^{o}C. the specimens were selected from both the face and root side of the weldment. The present investigation also aims on studying the SMAW welded P91 in the temperature range of 400 to 700^{o}C.

3.6 SEM Analysis of Fracture Surface:

SEM examination of the fracture surfaces of all the hot tensile and impact tested specimens were carried out then the fractographs were compared together.

4. Results and Discussion:

4.1 Tensile Resting:

The transverse tensile tensiletest results of the weld joint by SAW, all weld tensile and tensile test results of the base metal are shown in the table 9 and 10. Two test coupons of the weld were evaluated as per standard. The investigated values of all tension test results are within the requirements of ASTM A213. In each case of face side transverse tensile the failure was observed in wed metal and the reason behind the failure is because of the coarse martensite and δ ferrite in the weld metal. Weld metal side failures were observed in root side tensile test because less strength of the root pass weld metal of 21/4 Cr 1Mo. Because the tensile strength of P22 material was less than that of the P91 base material and the weld metal. The investigated values of all the transverse tensile test results are within the requirements of ASME SEC-IX.

Table.9. Transverse tensile test result of P91 SAW weldment

Specimen location	Thickness mm	Width mm	CSA mm^2	Tensile load kN	UTS N/mm^2	Position of fracture
Face side	20.9	19.03	403.4	262	649	WELD
Face side	19.7	19.2	378.2	242	640	WELD
Root side	20.2	19.1	385.8	242	627	WELD
Root side	19.8	19.2	380.2	240	631	WELD

Table.10. Tensile test result of P91 base metal

Material	σ_y (MPa)	UTS (MPa)	Elongation(%)
P91 base metal	591	650	27

4.2 Hardness test:

Testing standard – ASTM E92
Equipment – Vickers harness test
Load – 10 kg
Testing temperature -27°C.

The results (Table-11) show that the hardness values of the weld metal is very high because of fine martensitic structure. The formation of δ ferrite in the weld metal microstructure restricts the grain growth and grain size. The presence of α ferrite has the stronger effect on hardness. The HAZ also showing higher hardness because of the finematensite structure compare to the base metal. The investigated value of all the hardness values are within the requirements.

4.3 Impact test:

Testing standard – ASTM E23
Equipment – Tinius Olsen
Specimen size- 10× 10 × 55 mm
Test temperature- room temperature
Type-CVN 2mm depth at Weld Centre

Table.12: Impact values of P91 base metal and weld metal

Location	Impact Energy (in Joules)
BM	273, 293, 282
WM-FACE SIDE	131, 146,130
WM-ROOT SIDE	79, 70, 76

Impact test were carried out for the base metal and welded samples are given in table 12. The face side SAW weld metal showing the very high impact energy of 146 J compare to the root side weld metal. The reason behind the less impact energy is fully martensic structure of root side. The weld metal shows nearly half the impact energy of base metal. This may be due to the carbides and carbonitrides in the weld metal.

4.4 Side bend test:

The test results to the given in the table-13. No open discontinuity was observed in all the four test specimens and meets the requirement of ASME SEC-IX.

Table.13: side bend test result of P91 SAW weldment.

Test specimens	Observation	Remark
SB1, SB2, SB3, SB4	No open discontinuity	passed

4.5 Hot tensile test :

The hot tensile are shown in table 14 &15. The sudden drop in tensile value was observed at temperature of 700°c because this P91 material is developed to play a role upto 640°c . A coarse grain structure of the austenite is the main reason for less tensile value at 700°c. in each case of face side transverse hot tensile testing the failure was observed in weld metal. Root side tensile results are slightly higher than face tensile values at all the temperatures, due to the large amount of the δ ferrite in the sub arc welded region. The SMA weldment shows the higher tensile value at all the temperature compared to the SA- weldment. The reason behind the higher tensile value is due to the less δ ferrite in the weld metal and also failure was observed in base metal region.

Table .14: Hot tensile test result of SA-welded P91 weldment

Sl.No	Specimen location	Test tempe rature °C	Specimen size in mm	UTS in Mpa	Position of fracture
1	Face side	400	12.60X6.26	515	Weld
2		500	12.76X6.10	454	Weld
3		600	12.60X6.20	432	Weld
4		700	12.66X6.10	284	Weld
5	Root side	400	12.55X6.20	491	Base
6		500	12.60X6.06	451	Base
7		600	12.68X6.28	429	Base
8		700	12.60X6.08	266	Base

Table.15: Hot tensile test results of SMA-welded P91 weldment

Sl.No	Test temp.°C	Specimen size in mm	UTS in Mpa	Position of fracture
1	400	12.02X7.62	535	Weld
2	500	12.44X7.60	457	Weld
3	600	11.96X7.60	447	Weld
4	700	11.64X7.44	307	Weld

4.6 Microstructural characterization:

The P91 base metal consists of tempered martensitic metal consists of tempered martensitic structure and finely distributed carbides and carbonitrides

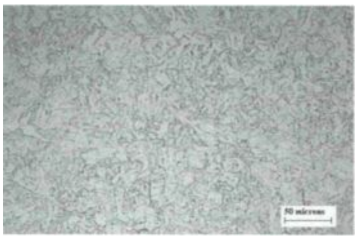


Fig .1: Micrograph of the P91 base metal at 340 X

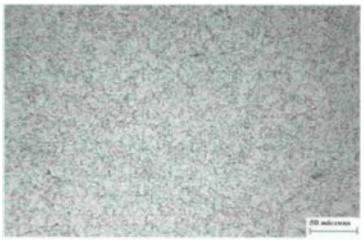


Fig.2:Micrograph of HAZ at 340 X

(figure.1.). Figure.2 shows the HAZ microstructure of fine martensite with finely distributed carbides. The precipitates of these regions are probably $M_{23}C_6$ and QX (Nb-V Carbonitrides).

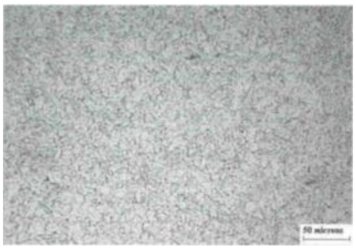


Fig .3: Micrograph of the face side weld metal (SAW) at 170X

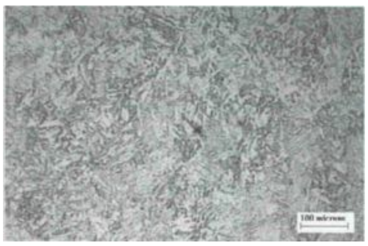


Fig.4: Micrograph of the weld metal (SAW) 2 mm from the top at 170X

Micrograph of the SAW-weld face (figure.3) shows the martensite with δ- ferrite with finely distributed carbides.

Figure.4 shows the finer martensitic structure which has taken in SAW welded region of -4 mm away from the weld top. Finer martensite formed due to grain refinement of the multipass welding. The formation of δ-ferrite in the weld metal microstructure during the solidification restricts the grain and grain size. However, martensite gradually losses its acicular feature because of the PWHT.

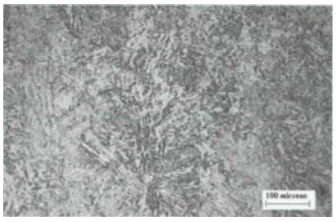


Fig.5: Micrograph of the weld meal (SMAW) at 170 X

Fig.6: The interface between GTAW & SMAW WM at 170 X

The SMAW weld metal structure(figure.5) exhibits fine martensitic structure compare to the SAW weld metal, this may be because of the low heat input which can accelerate the fast cooling rate.

Figure.6 shows the interface between TIG and SMAW.TIG weld metal consists of acicular ferrite structure due to the multipass welding effect. The figures 7 & 8 below micro photographs show the interface weld metal. The SAW shows the wider fusion boundary compare to the SMAW fusion boundary.

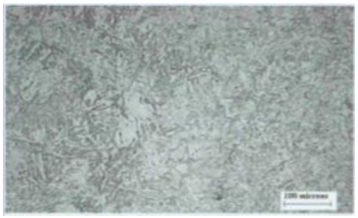


Fig. 7: The interfaces of SAW weld metal at 170 X

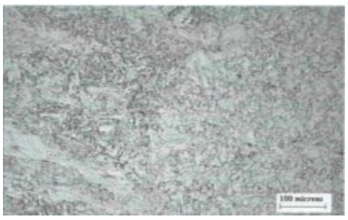


Fig.8: The interface SMAW weld metal at 170 X

Also coarse grain structure of HAZ is observed in the SAW welds side.

4.7 Fracture characterization studies:

The fracture appearance of SAA-welded face side hot tensile specimen fractured at 400°C that had tensile

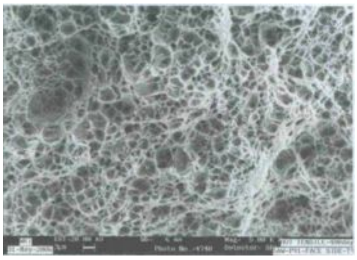


Fig.9: SEMfractograph of SA-welded face side hot tensile at 400°C

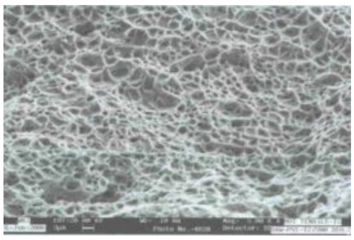


Fig.10: SEM fractograph of SA-welded face side hot tensile test at 500°C

Strength of 515 MPa exhibits extensive dimple fracture with micro voids as shown in figure 9. The fracture surface of the fracture surface of the SA-welded face side hot tensile fractured at 500°C,

Shows dimple fracture with more number of micro voids (fig.10). Larger sizes of voids are observed in the fracture surface of SA-welded face side hot tensile specimen tested at 700°C exhibited a dimple appearance characteristic of micro void coalescence with grain boundary facets with smaller number of dimples(Fig.12). The facture surface of SAW root side hot tensile specimen tested at 400°C shows a dimple

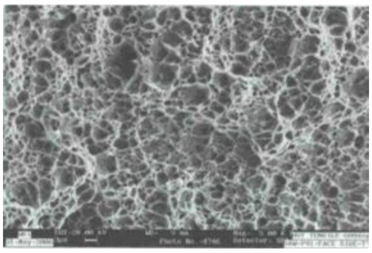


Fig.11 SEM fractograph of SA-welded face hot tensile test at 600°C.

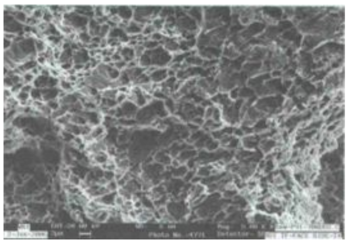
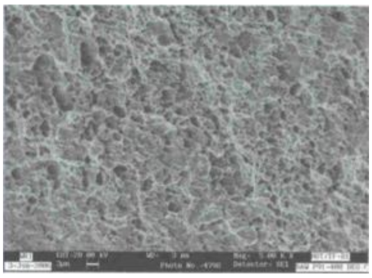


Fig.12.SEM fractograph of SA-welded face side hot tensile at 700°C



Fig(13). The fracture appearance of SAW root side hot tensile specimen tested at 500 °C

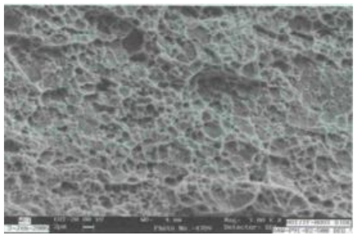


Fig.14.SEM fractograph of SA-welded root side hot tensile at 500°C

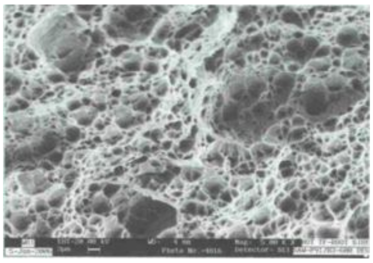


Fig.15 SEM Fractograph of SA-welded root side hot tensile at 600°C

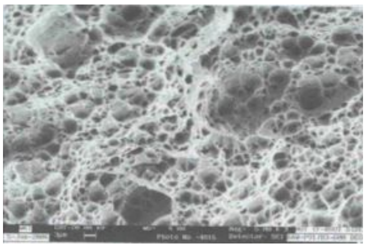


Fig.16.SEM fractograph of SA-welded root side hot tensile at 700°C

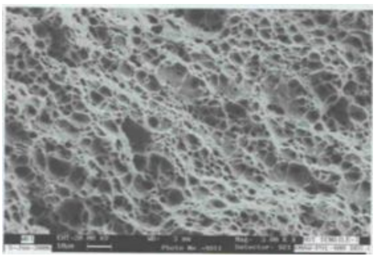


Fig.17. SEM fractograph of SMA-welded hot tensile at 400°C

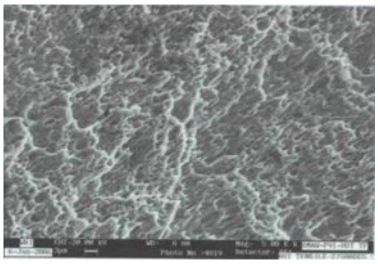


Fig.18.SEM fractograph of SMA-welded hot tensile at 500°C

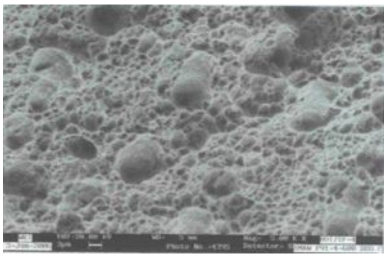


Fig 19.SEM fractograph of SMA –welded hot tensile at 600°C

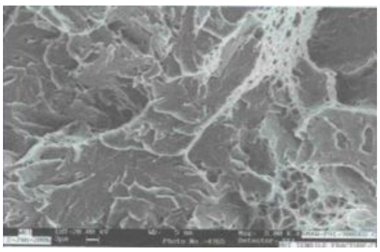


Fig .20.SEM fractograph of SMA-welded hot tensile at 700°C

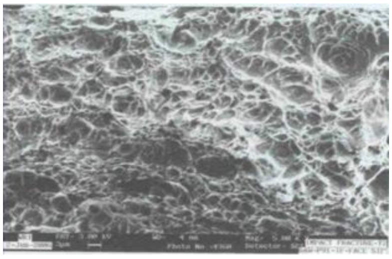


Fig.21.SEM Fractograph of SAW welded face side impact specimen at RT.

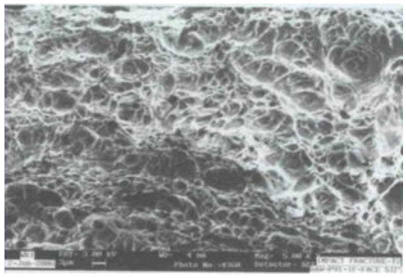


Fig.22.SEM fractograph of SAW welded root side impact specimen at RT

Fracture with some cleavage facets(Fig.13).The fracture appearance of SAW rootside hot tensile specimen tested at 500°C exhibits dimple fracture and micro voids with some cleavage facets (fig.14).Dimple fracture with micro voids coalescence is observed in the fracture surface of hot tensile tested at 600°C (fig.15).

The fracture surface of hot tensile fractured at 700°C shows mainly cleavage dominated fracture with some dimple fractured area (fig.16). Dimple fracture with some cleavage facets are observed in SMA-welded hot tensile specimen fractured at 400°C and 500°c (fig.17 and 18). Dimples and micro void coalescence with grain boundary facets are observed in SMA-welded hot tensile tested at 600°C (fig.19). Cleavage facets dominated with small amount of dimples are observed in hot tensile specimen tested at 700°C (Fig.20).(Fig.21 and 22) show SEM fractographs of impact-fractured specimens. The fracture appearance of a SA-welded face side fractured impact specimen that had impact energy of 131 j exhibits dimple fracture with some cleavage facets.But root side fractured impact specimen that had impact energy of 79 J exhibits completely cleavage facets.

5. Conclusion:

Major conclusions drawn from this study relating to the evolution of the microstructures, hot tensile tests and fracture characteristics of 9Cr-1Mo-V weldment are given below:

The base metal evolution has shown that the P91 steel chosen for the work has the composition within the specific limit. The mechanical properties, tensile strength, impact toughness and hardness are also meeting the requirements.

Welding procedure or P91 pipe with root pass welding of GTAW and subsequent passes of SMAW and SAW were developed qualified as per the standard ASME SEC-IX.

The tensile properties of P91 weldment were measured at room temperature and temperature ranging from 400°C – 700°C. Root side tensile results are slightly higher than face side tensile values at all the temperatures, due to the coarse martensitic and $^{\delta}$ ferrite in the sub arc welded region. The SMA-weldment shows the higher tensile value at all the temperature compare to the SA-weldment, because of fine martensitic structure with carbides in the weld metal.

From impact testing, it was observed that the base metal exhibits the highest toughness compared to weld metal of both root side and face side due to tempered martensite and globular carbides in the base metal microstructure.

From the hardness testing of the weldment, the weld zone registered the highest values ranging from 228-236 HV_{10}. Intermediate hardness values were observed in the HAZ region. The parent metal registered the hardness value of 206HV_{10}.

Microstructural analysis using light optical microscope reveals the coarse martensite and carbides with $^{\delta}$ ferrite in the weld region. Base metal microstructure consists of tempered martensitic structure and finely distributed carbides, and HAZ consists of martensite with finely distributed carbides.

Hot tensile specimens fractured ay 400°C – 700°C exhibits dimple fracture with micro voids. Some small amount of cleavage facets were observed in the specimen fractured at 700°C. the fracture appearance of a SA-weldment face side fracture impact specimen that had impact energy of 131 J exhibits dimple fracture with some cleavage facets and root side fracture-impact specimen that had impact energy of 79J exhibits completely cleavage facets.

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