Influence on Weldability of P91 Steel with change in composition of Shielding Gas in GMAW Process

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Abstract

In Gas Metal Arc Welding process (GMAW), the primary function of the shielding gas is to protect the molten metal from atmospheric gases as the weld pool is being formed. The gas also promotes a stable arc and uniform metal transfer. The quality, efficiency, and overall operating acceptance of the welding operation are strongly dependent on the shielding gas as it influences the mode of metal transfer and weld bead profile.

In the present work, bead on welds were produced on 30 mm thick Modified 9Cr-1Mo (P91) steel by Gas Metal Arc Welding process with 1.2 mm solid wire (ER90SB-9) using four different shielding gas compositions – Ar+2% O_2, Ar+20% CO_2, Ar+5% CO_2 and Ar+2.5% CO_2. The resulted bead profiles, weld metal composition, inclusion level, and microstructure obtained using the shielding gas compositions are explained in the text to follow.

Key words: *Modified 9Cr-1Mo, GMAW Process, Shielding Gases*

1 Introduction:

According to the ASME Boiler and Pressure Vessel Code, Section IX, QW/QB-492, Creep Strength-Enhanced Ferritic (CSEF) steels are a family of ferritic steels whose creep strength is enhanced by the creation of a precise condition of microstructure, specifically martensite or bainite, which is stabilized during tempering by controlled precipitation of temper-resistant carbides, carbo-nitrides, or other stable and/or meta-stable phases.

The family of 9Cr-1Mo steels is creep strength enhanced ferritic steel material used for elevated temperature service in Power plant and Nuclear Industry. Compared to stainless steels, the 9Cr-1Mo material possesses lower thermal expansion and higher thermal conductivity, thus reducing thermally-induced stresses. In addition, the alloy is more resistant to stress corrosion cracking and resists sensitization during welding on exposure to elevated temperature. Compared to 2.25Cr - 1Mo steels, the 9Cr-1Mo alloy offers better high temperature strength and greater resistance to atmospheric corrosion during plant construction and outages [1]. Amongst the Cr-Mo ferritic steels, the modified 9Cr-1Mo steel developed by the Oak Ridge National Laboratory (ORNL) in USA by increasing the nitrogen content of the basic 9Cr-1Mo (P9) composition and adding small amounts of vanadium (V) and niobium (Nb) is being widely used today. Modified 9Cr–1Mo steel designated as Grade 91 or T91 (for tube) or P91 (for plate) has much improved creep resistance over 2.25Cr–1Mo (Grade 22) or 9Cr–1Mo (Grade 9) steel. This is attributed to the precipitation strengthening caused by the presence of the fine, coherent niobium and vanadium carbo-nitride precipitates in the tempered martensite matrix, which is achieved by optimizing the Nb/V ratio [2].

P91 material can be welded with various arc welding processes such as gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), submerged arc welding (SAW), etc. However, in order to reduce cost and downtime, in particular, for high thickness welds and site repairs, there is much interest in the use of other high productivity welding processes such as hot-wire GTAW, gas metal arc welding (GMAW) and flux cored arc welding (FCAW). Even though Hotwire GTAW produces high quality welds, the productivity levels are not at par in comparison with FCAW or GMAW. In case of FCAW, the flux with higher oxygen contents combined with larger weld beads, tend to give somewhat lower toughness than the well-established GTAW process. Now-a-days, GMAW-P process is being seriously considered for such applications in view of the huge potential of this process to achieve excellent productivity and quality, provided reasonable toughness values can be achieved in the weld. In GMAW, an electric arc is established between the work piece and a consumable bare wire electrode. The arc continuously melts the wire as it is fed to the weld puddle. The weld metal is shielded from the atmosphere by the flow of an inert gas, or gas mixture [3].

The present study deals with the effect of the shielding gas composition on various weld joint attributes like bead geometry, weld metal composition, inclusion level, microstructure, etc.

Table 1: Chemical composition of the base material and filler material

Element (%)	C	Cr	Mo	V	Ni	Si	Mn	Al	Cu	Nb	N
Base metal	0.100	9.013	0.888	0.207	0.241	0.214	0.412	0.021	0.048	0.079	0.0452
Filler Wire	0.114	8.83	0.94	0.2	0.74	0.23	0.52	-	-	0.057	0.03

2 Experiment:

Modified 9Cr-1Mo (P91) steel plate [800 mm (length) x 150 mm (width) x 30 mm (thick)] in the normalized and tempered condition was used for the current study. Bead on welds were produced using 1.2mm dia. ER90S-B9 wire by Pulsed GMAW (GMAW-P) process. Table-1 shows the composition of the base material and filler material. The GMA welds were made using a KUKA Series KR 16 ROBO integrated with a suitable power source (Fronius TPS 5000). Figure-1 depicts the experimental setup used in the current work.

Figure 1: Experimental setup

Four types of premixed shielding gas compositions; Argon + 2%O_2, Argon + 20%CO_2, Argon + 5%CO_2, and Argon + 2.5%CO_2 were used in the study. In order to establish the range of welding parameters, initial trials were carried out on a carbon steel plate. Subsequently, two layers of weld beads were produced on the P91 plate with each of the four shielding gases in flat position (1G). Preheat (200°C) and inter-pass (300°C) temperature were monitored and maintained using thermal chalks.

Refer Table-2 for the various welding parameters employed during welding on P91 plate. In order to study the bead profile, few individual beads were also produced on the same coupon with each of the gas compositions. One part of the welded coupon was subjected to Post Weld Heat Treatment (PWHT) at 760±5°C for 4 hours.

The welds were subjected to various tests like chemical analysis, measurement of O_2 content, hardness survey of weld and HAZ before and after PWHT, etc. Transverse cross section of the weld was prepared for bead profile measurement, macro and microstructural examination. The samples were further characterized in Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray spectrometry (EDS) analysis.

Table 2: Welding parameters

Shielding gases	Current (A)	Voltage (V)	Travel speed (mm/min)
Ar+O_2	**220-240**	**26-28**	**300-320**
Ar+20CO_2	**240-260**	**24-26**	**300-320**
Ar+5%CO_2	**220-240**	**24-26**	**300-320**
Ar+2.5%CO_2	**230-240**	**24-26**	**300-320**

3 Results & Discussion

3.1 Weldability Characteristics:

Weldability characteristics were evaluated based on various factors like bead appearance, bead profile, arc stability, spatter, fume, operator comfort, etc.

Refer Figure-2 (a) to (d) for the as-welded bead appearance with various shielding gases. It was observed that the welding arc

Table 3: Weldability Characteristics

	Ar + 2% O2	Ar + 20% CO2	Ar + 5% CO2	Ar + 2.5 %CO2
Bead appearance	Not satisfactory	Not satisfactory	Satisfactory	Satisfactory
Undercut	Yes	No	No	No
Bead start/ stop location	Not satisfactory	Satisfactory	Satisfactory	Satisfactory
Spatter	yes (Moderate)	Yes (Highest)	Yes (Moderate)	Nil
Arc stability	Not satisfactory	Not satisfactory	Satisfactory	Satisfactory
Operator Comfort	Not satisfactory	Satisfactory	Satisfactory	Satisfactory
Overall Performance	**Poor**	**Moderate**	**Good**	**Excellent**

was very harsh and the beads produced were blackish in nature with the Ar+2%O_2 shielding gas. Small undercuts were also observed in the welds. With Ar+20%CO_2, considerable amount of spatters and small porosities were observed on the weld surface. The welding arc was very stable with the addition of both 2.5% and 5% CO_2 in Argon shielding gas. However, the beads produced using Ar+2.5%CO_2 gas mixture showed no signs of spatter. Based on the various factors listed in Table-3, Ar+2.5%CO_2 could be considered to be the optimum composition of the shielding gas.

Figure 2: Bead appearance (a)Argon + 2% O_2, (b) Argon + 20% CO_2, (c)Argon + 5% CO_2 ,(d) Argon + 2.5% CO_2

3.2 Chemical Analysis

Chemical compositions of the diluted weld with various shielding gases are as shown in Table-4. Even though the percentage of carbon in base material is 0.1 and filler material is 0.114, the weld showed a higher carbon content of 0.13 to 0.14. This higher value could be due to the carbon pickup from the shielding gas composition during welding. There is also a reduction in the chromium and the manganese percentage which can perhaps be attributed to the evaporation of elements at high welding temperature [4].

The oxygen content in the weld was measured by the wet analysis using TCH600N/O/H determinator and is shown in Figure-3. The oxygen content in the weld was found to vary between 500 to 580 ppm and was in the direct proportion of the amount of CO_2 present in the shielding gas. The weld beads produced with the Ar+2.5% CO_2 depicted the minimum O_2 content. Smaller O_2 content in weld is reported to be beneficial to obtain greater toughness [5].

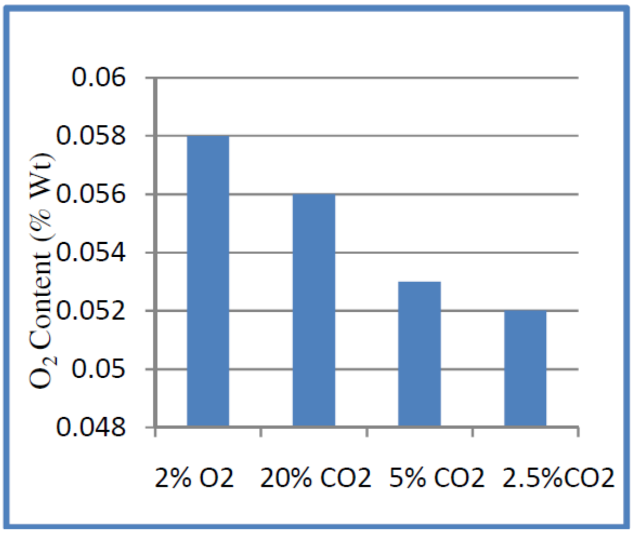

Figure 3: O2 Content for various shielding gases

In general, the amount of ferrite precipitates increases with an increase in the chromium equivalent (Cr_{eq}) and the ferrite factor (FF) resulting in reduction of the weld metal impact toughness. Equations (1) and (2) show the empirical relations for the estimation of Cr_{eq} and FF, respectively. It has been suggested to keep the weld metal Cr_{eq} and FF well under 10 and 8, respectively, to ensure minimum precipitate [6]. The Cr_{eq} and FF obtained in the weld coupons prepared with the four gas compositions are shown in Figures 4 and 5, respectively. The welds made using the Ar+2.5%CO_2 provided the minimum values of Cr_{eq} and FF.

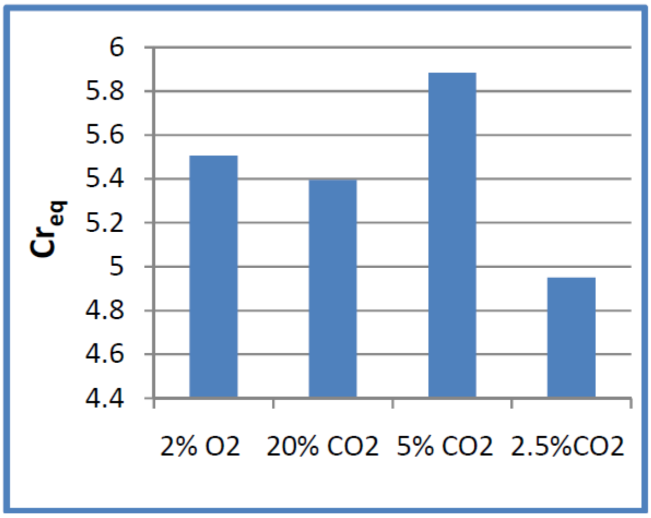

Figure 4: Chromium Equivalent (Creq) for various shielding gas

Cr_{eq}= Cr + 6Si + 4Mo +1.5W +11V + 5Nb +1.2Sol.Al + 8Ti - 40C - 2Mn - 4Ni - 2Co - 30N -Cu(mass %) .... (1)

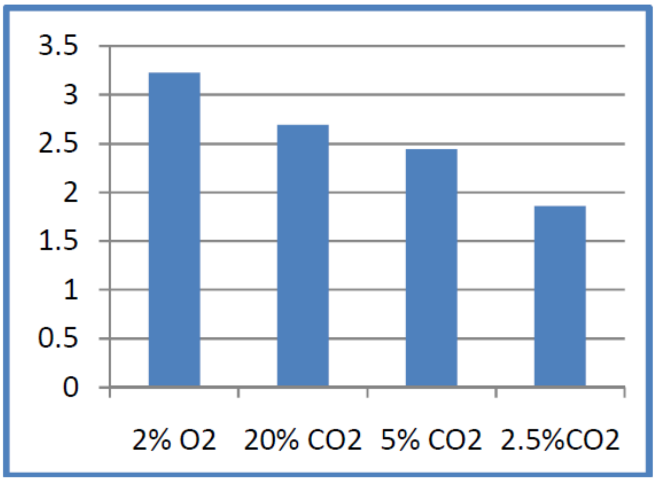

Figure 5: Ferrite factor for various shielding gas

FF = Cr + 6Si + 4Mo + 8Ti + 2Al + 4Nb - 2Mn - 4Ni - 40 (C + N) …. (2)

Table 4: Chemical composition of diluted weld metal

Element (%)	Ar + 20% CO_2	Ar + 2.5% CO_2	Ar + 2% O_2	Ar + 20%CO_2
C	0.14	0.13	0.13	0.13
Mn	0.45	0.45	0.42	0.42
Si	0.2	0.24	0.25	0.2
Cr	8.76	8.69	8.56	8.56
Ni	0.8	0.72	0.69	0.7
Mo	1.05	1.04	1.07	1.07
V	0.19	0.19	0.18	0.18
Nb	0.052	0.053	0.048	0.04
N	0.056	0.092	0.063	0.067

In general, manganese and nickel contents in the filler material are restricted to control the Ac1 transformation temperature to be higher than the intended PWHT temperature. When the AC_1 temperature of the weld metal is lower than the intended PWHT temperature, the martensite (the normal of the as welded high-Cr weld metal) can transform partially into resulting in possible reduction in the creep rupture strength of the weld metal [7]. The AC_1 temperature can be calculated empirically with the following equation.

$AC_1 = 854.5 - 43.9\,(Mn + Ni) - 9\,(Mn + Ni)^2$ .... (3)

In the current case, the Ac1 temperature was found to vary between 784°C to 795°C which is well above the intended PWHT temperature of 760°C (Refer Table 5).

Table 5: AC_1 Temperature calculation

Shielding gas	Mn+Ni	AC_1
Ar+O2	1.11	794.6
Ar+20CO2	1.12	794
Ar+5%CO2	1.25	785.5
Ar+2.5%CO2	1.17	790.8

3.3 Bead profile study

In order to study the bead profile, the weld samples were prepared by standard metallographic procedures and etched with the Vilella's reagent consisting of 1 g of picric acid, 5 ml of HCl and 100 ml of alcohol. Figures 6(a) to (d) show the bead profiles produced by various shielding gases.

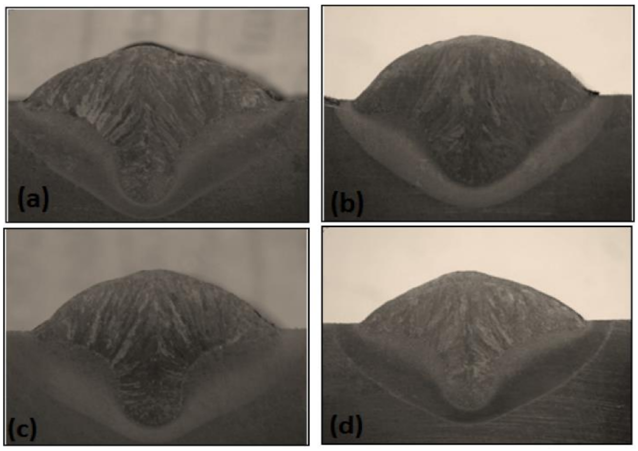

Figure 6: Bead profile (a) Argon + 2% O_2, (b) Argon + 20% CO_2, (c) Argon + 5% CO_2, (d) Argon + 2.5% CO_2

It has been reported that weld cross-sections with greater depth than the width promotes growth of the solidifying grains in the direction perpendicular to the steel surface and their mutual intersection in the middle of the cross-section. To inhibit the same and avoid resulting solidification cracking, the width to depth ration has been recommended to be in the range of 1:1 to1.4:1 [8]. The width to depth ratio in the welds obtained in the present work was in the range of around 2.5 (Fig. 7) indicating relatively better resistance to solidification cracking.

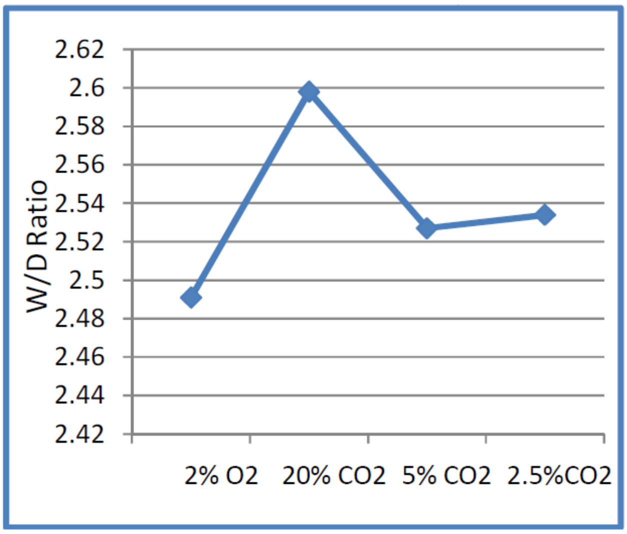

Figure 7: W/D Ratio for various shielding gas

3.4 Microstructure

The microstructure study of the weld before and after PWHT was carried out using scanning electron microscopy (SEM). Figures 8(a) to (d) and 9(a) to (d) show the welded micrographs. The as-welded microstructure showed untempered martensite with little precipitates along the prior grain boundary. Fine carbide particles distributed both along the previous austenite grain boundaries and throughout the matrix were observed after PWHT (760 x 4 hrs.).

The optical micrographs of all four welds are shown in Figs 10(a) to (d). Spherical inclusions in the welds can be observed in Figs 10(a) to (d). The size and distribution density of these inclusions showed direct correlation with the percent amount of CO_2 in the shielding gas. Accordingly, the size and distribution of the inclusions were found to be the least in welds prepared using Ar+2%O_2 gas mixture followed by the welds prepared using Ar+2.5%CO_2. The SEM and EDS analyses of the inclusion showed significant presence of silicon (Refer Fig.10).

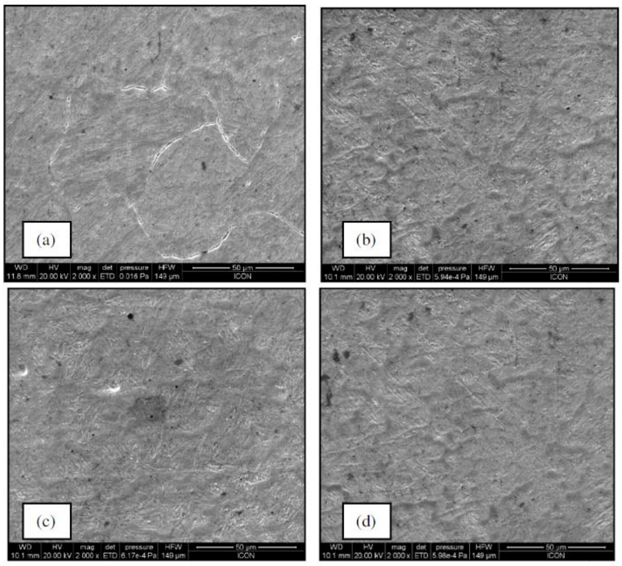

Figure 8: SEM image Before PWHT (a) Argon + 2% O_2, (b) Argon + 20% CO_2, (c) Argon + 5% CO_2 (d) Argon + 2.5% CO_2

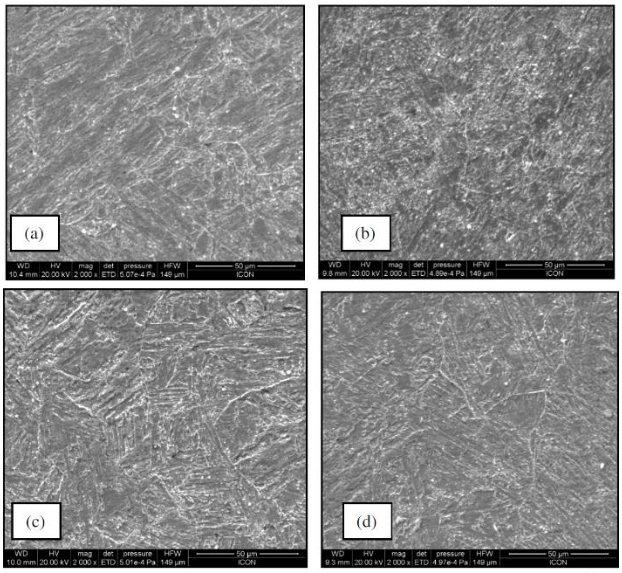

Figure 9: SEM image After PWHT (a) Argon + 2% O_2, (b) Argon + 20% CO_2, (c) Argon + 5% CO_2 (d) Argon + 2.5% CO_2

3.5 Hardness Survey

The hardness distributions across the welds in the as-welded and heat-treated conditions for the different shielding gases used are given in Figures 12(a) to (d). After PWHT, the hardness of P91 weld metal is lowered as a result of the tempering reactions, which include a reduction in dislocation density, lath break-up and development of a polygonized structure, reduction in solid solution strengthening due to the precipitation, and the coarsening of the precipitates [9]. From the results it can be inferred that the shielding gas composition has no significant effect on the hardness values. It was also observed that fusion zone hardness found approaching that of the base material.

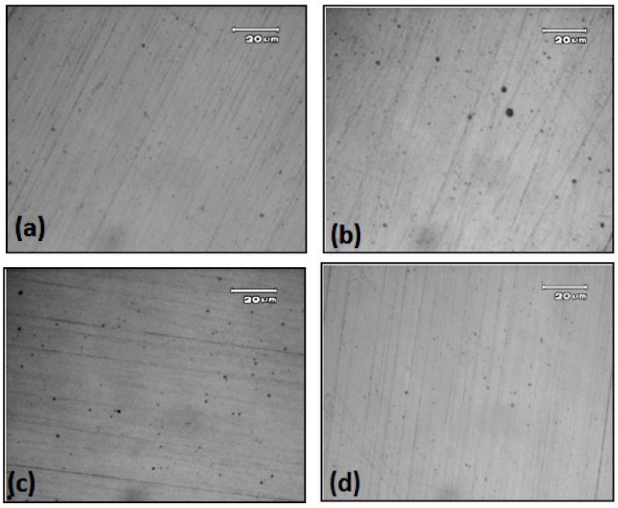

Figure 10: Weld inclusion (a) Argon + 2% O_2, (b) Argon + 20% CO_2, (c) Argon + 5% CO_2 (d) Argon + 2.5% CO_2

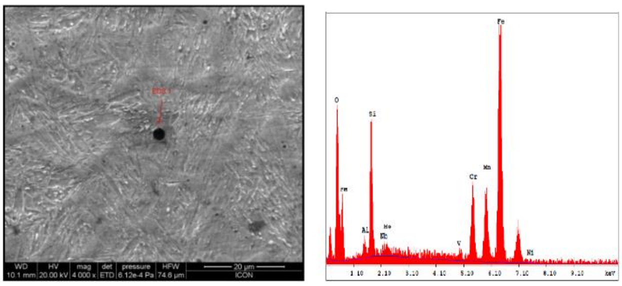

Figure 11: SEM image and Spot EDS of weld metal inclusion

4 Conclusion

1.) Bead appearance and the other weldability characteristics were studied for P91 steels using GMAW process with four different shielding gas mixtures. The Ar+2.5%CO_2 mixture provided the optimum performance.

2.) The chemical analysis of the welded coupons showed increase in carbon content and reduction in both manganese and chromium content with all the welded samples.

3) The O_2 level in the weld metal was found to be in the range of 520 to 580 ppm as against 700-800 ppm in the case of SMAW & SAW as reported in the literature [5]. In the present work, the weld samples prepared using the Ar+2.5%CO_2 mixture depicted the least O_2 level.

4) The chromium equivalent and the ferrite factor of the welded samples were found to be well under 10 and 8, respectively, indicating little chance to form delta ferrite in the welds.

5) The width to depth was found to be greater than two with all the weld samples indicating better resistance to solidification cracking.

6) The inclusion (SiO_2) level was found proportional to the CO_2% and almost negligible in the case of shielding gases with 2.5% CO_2 and 2% O_2.

7) No significant difference in the weld and HAZ hardness pattern were observed in the welded samples.

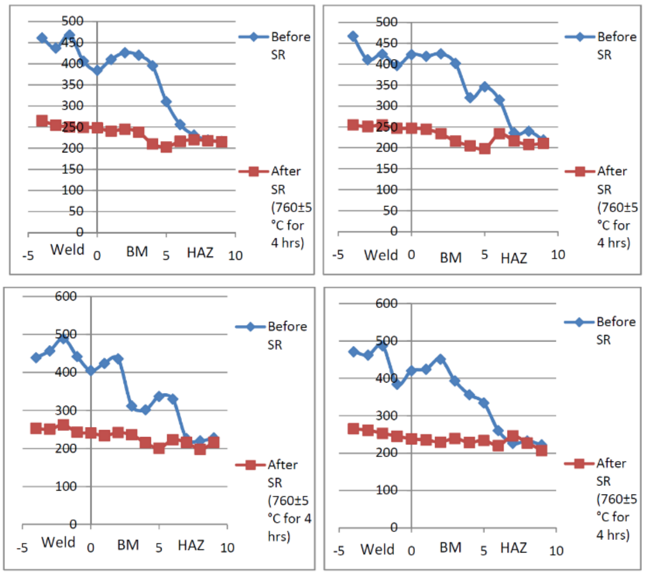

Figure 12: Hardness survey before and after PWHT (a) Argon + 2% O_2, (b) Argon + 20% CO_2, (c) Argon + 5% CO_2 (d) Argon + 2.5% CO_2

5 References

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