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# Microstructure and mechanical property relationship for different heat treatment and hydrogen level in multi-pass welded P91 steel joint

Chandan Pandey [a,*], M.M. Mahapatra [b], Pradeep Kumar [a], N. Saini [a], A. Srivastava [c]

[a] Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Uttrakhand, 247667, India
[b] School of Mechanical Sciences, Indian Institute of Technology Bhubaneswar, Odisha 751013, India
[c] BHEL, Haridwar, India

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ABSTRACT

The effect of heat treatment condition and diffusible hydrogen level on microstructure and mechanical properties of multi-pass shielded metal arc welded (SMAW) P91 steel butt joints of 18 mm thickness has been studied. Field-emission scanning electron microscope (FESEM), Mercury diffusible hydrogen measurement, Charpy test, room-temperature tensile testing, hardness measurement and energy dispersive X-ray spectroscopy (EDS) were performed to characterize the multi-pass SMAW joints in as-welded, post-weld heat treatment (PWHT) and normalizing/tempering (N&T) state. The P91 steel butt joints with low level of diffusible hydrogen exhibited higher tensile strength and toughness. Both PWHT and N&T treatment provided similar mechanical properties but a significant microstructure variation was noticed for different zones of P91 welds. N&T treatment produced the homogenize microstructure along the P91 weldments both in terms of microstructure and micro-hardness.
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## 1. Introduction

In nuclear and thermal power plants, 9–12% Cr ferritic/martensitic steels have been used as a major candidate material since the eighties. ASTM A335 P91 (also known as the modified 9Cr-1Mo steel) as a candidate material of 9–12% Cr ferritic/martensitic steel family is widely used in nuclear and thermal power plants because of improved mechanical and thermal properties in severe condition of temperature and pressure [1–3]. The P91 steel is also used in power plants for high efficiency power generation simultaneously decreasing the environment pollution by reducing the emission of $CO_2$ [4]· For out-of-core and in-core (piping, cladding, ducts, wrappers, and pressure vessel) of Gen IV reactors, P91 steel is also considered as a candidate material because of high oxidation resistance and high resistance to radiation damage [5,6]. In the 1970's, P91 steel was developed in the Oak Ridge National Laboratory (ORNL). The mechanical properties of P91 steel was mainly improved by modifying the chemical composition of plain 9Cr-1Mo (P9) steel. Compared to other steel of Cr-Mo family, P91 steel offers enhanced tensile strength, toughness, yield strength and creep rupture strength, adequate fracture toughness and stress corrosion cracking [7–9]. High thermal conductivity and low thermal expansion coefficient at higher temperature make P91 steel more reliable against creep and thermal loading [10,11].

P91 steel can be welded easily by many arc welding processes including manual metal arc welding, gas tungsten arc welding and submerged arc welding [12–14]. After the welding, post weld heat treatment (PWHT) is recommended by many researchers for tempering of the newly formed martensite [12,13]. Welding process led to lath martensitic formation in the weld fusion zone. Welding process not only affects the weld fusion zone microstructure but also affects the small area adjacent to the weld fusion line. The small heat affected area besides the fusion line is denoted as the heat affected zone (HAZ). The heating and cooling during the weld thermal cycle resulted a non-equilibrium structure formation that led to reduction of creep strength of weld metal compared to the as-received P91 base metal. On the basis of temperature experienced during the weld thermal cycle, P91 weldment is divided into weld fusion zone, coarse grained HAZ (CGHAZ), fine grained HAZ (FGHAZ), inter-critical HAZ (ICHAZ) and over-

* Corresponding author.
*E-mail addresses:* chandanpy.1989@gmail.com, chandan.pndy@rediff.com (C. Pandey), nit030078@gmail.com (N. Saini).

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**Table 1**
Chemical composition of as-received C&F P91 steel, SMAW filler rod and GTAW filler wire, %wt.

| Element | Chemical composition, wt% | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | W | S | Si | Cr | Mo | V | N | Ni | Cu | Nb | Ti |
| C&F P91 steel | 0.023 | 0.689 | 0.0258 | 0.019 | 0.193 | 8.16 | 0.710 | <0.005 | <0.02 | 0.305 | 0.034 | <0.008 | <0.02 |
| SMAW filler rod | 0.08–0.13 | 0.40–1.0 | – | max 0.02 | 0.20–0.50 | 8–10 | 0.85–1.1 | 0.15–0.30 | 0.03–0.07 | 0.4–1.0 | – | 0.04–0.08 | – |
| GTAW filler wire | 0.12 | 0.50 | – | 0.019 | 0.30 | 9.0 | 0.90 | 0.20 | <0.02 | 0.50 | – | 0.06 | <0.02 |

tempered base metal [16,17]. The HAZ experienced the austenitic transformation during heating, martensitic transformation during cooling and precipitates dissolution. The non- equilibrium structure across the weldment limits the life of P91 weldments under the high-temperature service condition. Various HAZs formed in P91 weldments does not show the optimal microstructure and precipitation characteristic as found in the as-received virgin metal for optimized mechanical properties and creep strength. To overcome the quenching stress and non- equilibrium structure gradient across the P91 weldments, PWHT is carried out just after the welding. The microstructural changes in sub-zone of P91 weldments after the PWHT has been already reported [12–16]. Author(s) [17,18] also suggested the normalizing and tempering (N&T) treatment just after the welding is quite helpful to overcome the microstructure gradient. Pandey et al. [17] had reported about the effect of N&T treatment on microstructure and tensile properties of multi-pass TIG welded P91 pipe weldments. They have been reported that the N&T treatment provides the superior microstructure and mechanical properties compared to subsequent PWHT. Abd El-Salam et al. [18] had also compared the effect of PWHT and N&T treatment on microstructure and mechanical properties of P91 weldments.

Along the non- equilibrium microstructure formation across the P91 weldments, hydrogen-assisted cracking (HAC) is also a serious issue in P91 weldments. HAC in P91 weldments has been reported by many Author(s) [19–21]. Pandey et al. [22] had also studied the effect of diffusible hydrogen level on the tensile and flexural performance of single pass SMAW deposited metal on P91 steel. They had reported that increase in diffusible hydrogen in deposited metal decreased the tensile and flexural strength of joint. Pandey et al. [23] had also reported about the hydrogen induced cold cracking of P91 steel for different diffusible hydrogen levels in deposited metal. Due to lack of techniques for measurement of diffusible hydrogen in multi-pass, it is difficult to measure the diffusible hydrogen in multi-pass weld. Hence, a rough estimation has been made for multi-pass welds as electrode having high level of diffusible hydrogen in single pass will provide much more diffusible hydrogen for the multi-pass weld.

In current research work, P91 weldments have been produced by using the SMAW process for four different hydrogen level and two different heat treatments (subcritical PWHT, normalizing/tempering). The effect of heat treatment and diffusible hydrogen have been studied on microstructure and mechanical properties (tensile properties, Charpy toughness) of multi-pass welded P91 steel plate. Conclusion are reached regarding the preferred weld consumable condition and heat treatment which produce optimal microstructure that might lead to the optimum combination of tensile properties and Charpy toughness.

## 2. Experimental details

### 2.1. Material and welding procedure

The P91 steel plate was supplied in cast and forged (C&F) condition by Bharat Heavy Electricals Limited (BHEL) as a plate of thickness 20 mm and width 200 mm. The chemical composition of C&F P91 steel was analyzed using Optical Emission Spectrometer (Make: Metavision, model: 1008i) in the laboratory. The chemical composition and mechanical properties of P91 plate in as-received condition are shown in Tables 1 and 2. For the welding purpose, plate of dimension 150 × 90 × 18 mm was machined from the as-received C&F P91 plate. Plate after the groove preparation is shown in Fig. 1(a). The bevel angle, root face height and root gap were 37.5°, 1.5 mm and 1.5 mm, as shown in Fig. 1(b). The plates were preheated at 300 °C before the welding. To minimize the distortion, the plate was tack welded from the both sides, as shown in Fig. 1(c). The root pass was carried out using the GTAW process with AWS ER90S-B9 (9CrMoV-N) filler wire of diameter 1.6 mm for all the welds. Fig. 1(d) and (e) shows the plate after root pass on top and bottom side, respectively. SMAW process was used for filling pass using the welding consumable rod of diameter 4 mm and designated as 9CrMoV-N (AWS E9015-B9). Chemical composition of SMAW filler rod and GTAW filler wire are given in Table 1. The plate after complete welding is shown in Fig. 1(f). For case I, the welding process parameters used for the GTAW root pass (top and bottom side) and SMAW filler pass is depicted in Table 3. The heat transfer efficiency is considered 0.60, 0.80 for root pass (GTAW) and filler pass (SMAW), respectively. The heat input is given by Eq. (1) [24];

$$Q = \frac{\eta \times V \times I}{TS} \quad (1)$$

where Q is heat input (kJ/mm), η is heat transfer efficiency, V is voltage (volts), I is current (amp) and TS is travel speed (mm/sec).

The welding was carried out in four different condition of weld consumable as depicted in Table 4. The number of filler passes used for the welding for case I, case II, case III and case IV were 14, 13, 14 and 14. The plates for different cases, after the completion of welding is shown in Fig. 2.

After the completion of welding, the weld joints were subjected to post-weld heating at temperature of 280 °C for 60 min. The one weld joint for different diffusible hydrogen level was allowed to cool down to room temperature after the post-weld heating. The second one from each condition was subjected to subsequent post-weld heat treatment (PWHT). The third weld joint from each condition was allowed to normalizing and tempering (N&T) heat treatment. The PWHT temperature range recommended is below than the critical temperature (Ac1 ≈ 815 °C). For large size spec-

**Table 2**
Mechanical properties of C&F P91 steel in as-received state.

| Mechanical properties | Yield strength (MPa) | Tensile strength (MPa) | Elongation (%) | Hardness (HV) | Impact toughness (Joules) |
|---|---|---|---|---|---|
| Grade 91 steel | 455 ± 10 | 655.5 ± 6.36 | 22.08 ± 0.247 | 231 ± 5.38 | 96 ± 5 |
| Min. required [25] | 450 | 650–750 | 15 | – | 30 |

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