

Pulsed current gas metal arc welding of P91 steels using metal cored wires



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ABSTRACT

A detailed experimental study was undertaken to examine the suitability of pulsed current gas metal arc welding of 12 mm thick P91 steels in groove joint configurations with metal cored filler wire. Both the single and multipass welds showed satisfactory bead morphology, tensile strength and toughness especially at higher groove angles of 60° and 75° for the selected range of welding current and speeds. The weld metal compositions showed considerably high presence of Ni, Mn and Si with little loss of other alloying elements. The weld properties were primarily affected by the heat input per unit length of weld and the groove angle. The maximum ultimate tensile strength and toughness of the welds were found to be around 845 MPa and 125 J, respectively, for a heat input of 1.38 kJ/mm and a groove angle of 75°. The use of metal cored filler wires could enhance the welding speed by 20% and filler wire deposition rate by 42% compared to that with the solid wires. Overall, the present study showed that the pulsed current gas metal arc welding of medium to high thickness P91 steels using metal cored filler wires could provide higher deposition rate and welding speed, and enhanced weld bead properties in comparison to solid wires.

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1. Introduction

Modified 9Cr–1Mo steels, designated as P91 steels, were developed by modifying the composition of 9Cr–1Mo steels with minor additions of niobium, vanadium and nitrogen to provide superior creep resistance over the normal 2.25Cr–1Mo or 9Cr–1Mo steels (Arivazhagan et al., 2009). Although P91 steels were increasingly preferred for high temperature components in the power generation and petrochemical industries, their weldability remained a major concern during fabrication and use of the real-life components. Loss of alloying elements due to vaporization (David et al., 2013), formation of delta ferrite in weld fusion zone (Shanmugarajan et al., 2011) and consequent deterioration of weld joint mechanical strength had been common problems in arc welding of P91 steels. Susceptibility of welds in P91 steels to type IV in-service creep cracking had been another critical challenge as reported by Abson and Rothwell (2013) and Francis et al. (2009). David et al. (2013) and Arivazhagan et al. (2009) reported the welds in P91 steels to be prone to hydrogen induced cracking due to air hardenable martensitic structure and would require systematic

weld schedules involving preheat and postweld heat treatments to improve the toughness.

Although gas tungsten arc welding (GTAW) was commonly used for joining of P91 steels, slower welding speed and reduced rate of filler wire deposition were practical concerns in GTAW as explained by David et al. (2013) and Coleman and Newell (2007). Shielded metal arc welding (SMAW), submerged arc welding (SAW) and flux cored arc welding (FCAW) improved the rate of filler wire deposition but the resulting welds showed non-metallic inclusions, loss of toughness and greater oxygen content e.g., 400–800 ppm compared to around 100 ppm as reported in GTAW by Sireesha et al. (2001) and Arivazhagan et al. (2009). Conventional gas metal arc welding (GMAW) was rarely attempted due to susceptibility to selective loss of volatile alloying elements, lack of fusion defects and inconsistent weld quality (David et al., 2013).

In recent times, several advanced processes such as GTAW with activated flux (A-TIG) and externally fed preheated filler wire, laser and electron beam welding, and friction stir welding (FSW) were attempted for P91 steels. Aravinda et al. (2014) reported enhanced rate of filler wire deposition in GTAW with preheated filler wire but the weld metal toughness deteriorated due to increased heat input. Kamal and Vishvesh (2015) and Vasudevan et al. (2010) reported enhanced penetration in single pass welding of P91 steels using GTAW with activated flux but these studies were limited only up

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to a plate thickness of 6 mm. Shanmugarajan et al. (2011) observed the presence of δ -ferrite phase in autogenous laser beam welds of P91 steels and attributed it to the increase in the heat input. Kundu et al. (2013) reported high tensile residual stresses in single pass electron beam welds of thick P91 steels. Divya et al. (2014) and Albert et al. (2005) highlighted the need to reduce the HAZ width in laser and electrode beam welds of P91 steel to minimize the in-service creep failure. Thomas et al. (1999) used friction stir welding (FSW) to join ferritic steels although the premature failure of FSW tools when welding such stronger and thicker materials had been by far the major problem (Bhadeshia and DebRoy, 2009). In summary, appropriate control of the heat input to ensure consistent weld toughness and adequate filler wire deposition rate to achieve the target productivity remained as a key challenge in welding of P91 steels especially for thicker sections.

In comparison to several conventional arc welding processes, pulsed current gas metal arc welding (GMAW-P) could provide a more controlled heat input (Devakumaran and Ghosh, 2010), higher rate of filler wire deposition (Kapal and Surjya, 2011) and better performance in positional welding (Devakumaran and Ghosh, 2010; Ghosh et al., 2010). GMAW-P could reduce the spatter and weld porosity (Kapal and Surjya, 2011), lack of fusion (LF) defects, and width of HAZ (Krishnan et al., 2015a,b). In particular, Krishnan et al. (2015a,b) carried out detailed studies on single and multipass bead-in-groove trials in 12 mm thick P91 steels using GMAW-P with solid filler wires. The authors could achieve fairly acceptable bead profiles, weld metal compositions and tensile properties at higher welding speeds and deposition rates in comparison to that with GTAW (Krishnan et al., 2015a,b). However, the weld metal toughness (70–90 J) with the GMAW-P was not at par with those reported with GTAW (>150 J) that was attributed to marginal loss of alloying elements coupled with high oxygen content of the welds obtained using GMAW-P (Krishnan et al., 2015a,b). In contrast to the solid filler wires, GMAW-P with metal cored filler wires could improve weld metal toughness and rate of wire deposition as the cored filler wires allowed deposition of requisite alloying elements for specific applications (French and Bosworth, 1995). Ramini et al. (2005) reported the important role of welding position and sequence to achieve satisfactory weld joint properties in GMAW-P with metal cored wire. Arivazhagan and Kamaraj (2013) could reduce the weld metal inclusion level using GMAW-P with metal cored filler wires.

A systematic experimental study to examine GMAW-P of P91 steels with metal cored filler wires in single pass and multipass joints was therefore required but currently scarce in literature. A detailed experimental investigation was undertaken here to study the effect of three key welding variables e.g., welding current, speed and groove angle on the weld metal composition and morphology, and mechanical properties in single pass and multipass GMAW-P of 12 mm thick P91 steel with metal cored filler wire. The transient nature of the current and voltage were monitored to realize the actual heat input and deposition rate. The weld joints were characterized to realize the effect of the key welding variables on the loss of alloying elements, weld microstructure and mechanical properties.

2. Materials and experimental procedure

Single pass and multipass bead-in-groove welding were performed on 12 mm thick P91 steel plates using GMAW-P with metal cored wire at different groove angles as shown in Fig. 1. The single pass welds were made with a groove angle of 30° (Fig. 1a) and the multipass welds were made using groove angles of 45°, 60° and 70° (Fig. 1b). The base material was received in normalized (1080 °C) and tempered (750 °C, 1 h) condition with the impact toughness,

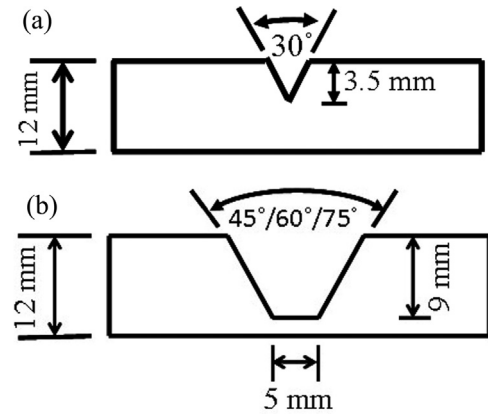


Fig. 1. Schematic representation of weld groove geometry for GMAW-P of P91 steels using metal cored wires for (a) single pass and (b) multipass.

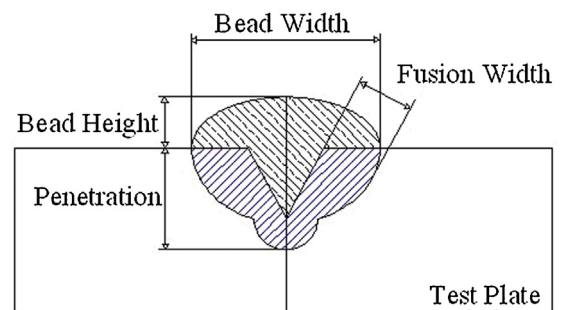


Fig. 2. Schematic representations of measured weld bead geometry parameters.

ultimate tensile strength and yield strength respectively as 185 J, 700 MPa and 560 MPa at room temperature. Table 1 indicates the chemical compositions of base metal and filler wire (E 90C-B9). The ranges of the welding conditions were selected based on a set of initial trials. The sample welds were made in flat (1G) position using a microprocessor controlled, inverter type synergic GMAW-P power source in direct current electrode positive (DCEP) mode. A 4-channel transient recorder (Graphtec made-model no. GL 900-4) was used for the real-time monitoring of the current and voltage transients at a sampling rate of 0.1 MHz. The corresponding time-averaged current (I_{AV}), voltage (V_{AV}) and heat input (q) were estimated as

$$I_{AV} = \frac{I_P t_P + I_B t_B}{t_P + t_B} \quad (1)$$

$$V_{AV} = \frac{V_P t_P + V_B t_B}{t_P + t_B} \quad (2)$$

$$q = \frac{I_{AV} V_{AV}}{v} \quad (3)$$

where I_P , I_B , V_P , V_B , t_P and t_B referred respectively to the peak pulse and base current, peak and base voltage and the corresponding time durations in a current/voltage cycle, and v was the welding speed. The variability in the time-averaged current and voltage for a given welding condition were estimated over twenty current pulses. Table 2 shows I_P , I_B , t_P and t_B and the corresponding time-averaged current and heat input for different welding conditions considered in this work.

The weld bead profiles were measured over transverse sections as shown in Fig. 2 after polishing and etching by Vilella's reagent (1 g $C_6H_3N_3O_7$, 5 ml HCl, 100 ml CH_4O). The welds were subjected to PWHT for stress relieving at 760 °C (± 10 °C) for 4 h (Dey et al., 2014). The microhardness distribution was measured across the weld cross-sections, as shown in Fig. 3, with a load of 1 kg for 10 s on a

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