Improvement of Weld Characteristics by Variation in Welding Processes and Parameters in Joining of Thick Wall 304LN Stainless Steel Pipe

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Various properties of weld joints of 25 mm thick wall 325 mm O.D, 304LN austenitic stainless steel pipe prepared by using different welding process and conventional V-groove as per AWS specification have been compared. The welding was carried out by commonly used shielded metal arc welding (SMAW), gas metal arc welding (GMAW) and pulsed current gas metal arc welding (P-GMAW) processes. In P-GMAW process the influence of pulse parameters have been studied by considering their summarized influence defined by a dimensionless hypothetical factor \(\phi=[(I_b/I_p)f \cdot t_b]\) where, \(t_b=[(1/f)\cdot t_p]\). The characteristics of weld joints with respect to their metallurgical, mechanical, corrosion and fracture mechanics properties as well as residual stresses have been studied and compared. Welding of thick wall stainless steel pipe by P-GMAW process significantly improves the tensile properties, reduces the inclusion and porosity content, increases initiation fracture toughness and lowers residual stresses of weld joint in comparison to those observed of SMA and GMA weld joints. The influence of \(\phi\) on properties of P-GMA weld joints is primarily attributed to the reduction in severity of weld thermal cycle and refinement of microstructure of weld deposit.

KEY WORDS: austenitic stainless steel; SMAW; GMAW; P-GMAW; pulse parameters; residual stresses; inter granular corrosion; microstructure; mechanical properties; fracture toughness.

1. Introduction

Nitrogen added austenitic stainless steel is a prospective material for the reactor vessels and piping systems primarily due to its good inter granular corrosion resistance along with desired mechanical and fracture mechanics properties. The use of such a material may provide comparatively longer life with enhanced safety of any component requiring higher stress for a rapid crack propagation indicating more resistance to brittle fracture.\(^1-8\) The austenitic stainless steel being a readily weldable material, the fabrication of its components and structures in various applications is largely carried out by using different welding processes and procedures. However, the quality of weld joints of this class of steel primarily depends upon thermal behavior of the welding processes employed with or without involvement of fluxes.

The weld joint is a mechanically heterogeneous body composed of base metal, weld metal and heat affected zone (HAZ). These different regions of the weld joint leads to heterogeneous mechanical and metallurgical properties of the material along with considerable development of harmful tensile residual stresses. These difficulties resulting from heterogeneity of weld get further compounded in case of heat-sensitive materials like austenitic stainless steel (ASS), especially of thick sections, due to its lower thermal conductivity and higher coefficient of thermal expansion in comparison to those observed in structural steel.\(^5-8\) The considerably low thermal conductivity makes the HAZ of arc weld of ASS more prone to sensitization while its significantly high coefficient of thermal expansion develops considerable stresses in the weld. Hence the proper selection of welding process and procedure by considering efficient energy distribution in the welding arc leading to comparatively low heat built-up in the weld pool is imperative to reduce the amount of damage produced in different zones of weld joint due to heterogeneity in their properties. Such a control in arc characteristics can be primarily achieved by using gas metal arc welding (GMAW) and possibly more appropriately by employing pulsed current gas metal arc welding (P-GMAW) processes. This is because the use of P-GMAW with proper selection of its simultaneously interactive pulse current parameters that includes pulsed current \((I_p)\), base current \((I_b)\), pulse time \((t_p)\), pulse off time \((t_o)\) and pulse frequency \((f)\) may provide a comparatively low heating welding process.\(^9-12\) The criticality of selection of pulse parameters in this regard is well addressed by considering its summarized influence defined\(^3,14\) by a hypothetical factor \(\phi=[(I_b/I_p)f \cdot t_b]\) where, \(t_b=[(1/f)\cdot t_p]\). But hardly any systematic work is reported so far considering the influence of welding processes on characteristics of the weld joint of thick wall pipe of 304LN.
stainless steel requiring multipass weld deposition.

In view of the above an effort has been made in the present investigation to carry out a comparative study on the characteristics of conventional V-groove welds of 304LN SS pipe prepared by using shielded metal arc (SMA), GMAW and P-GMAW processes. The P-GMA weld joints have been further compared by considering the influence of pulse parameters in reference to variation in $f$. The characteristics of weld joint have been analysed primarily with respect to the distribution of longitudinal and transverse residual stresses at the top and root of the weld joints and the microstructure of the weld and HAZ. In order to understand their utility the weld joints are also briefly characterised by studying their mechanical, fracture mechanics and corrosion properties.

2. Experimentation

2.1. Welding of Pipes

The welding of 25 mm thick wall and 325 mm outer diameter AISI 304LN stainless steel pipe has been carried out using GTAW autogenously and in consecutive two root passes followed by filling passes using SMA, GMA and P-GMA welding processes at conventional V-groove confirming the ASME Section IX of Boiler and Pressure Vessel Code. Schematic diagram of the weld groove as well as the consumable root insert used of matching composition with filler metal have been shown in Figs. 1(a) and 1(b) respectively. The multipass welding was performed by using appropriately designed welding procedure specifications (WPS) resulting in a practically sound weld with respect to lack of fusion. The welding was carried out in 1GR position by holding the pipes in a rotating table with the help of three jaw clamping system. The GTAW was carried out using water cooled torch with 7 mm diameter gas nozzle and 3.2 mm diameter 2% thoriated tungsten electrode under the shielding of commercial argon of 98.95% purity at a flow rate of 12 L/min. The GMAW and P-GMAW passes were carried out by newly designed narrow GMA welding torch nozzle using 1.2 mm diameter solid austenitic stainless steel filler wire of specification SFA-5.9-ER308L. The GMA weld deposition was carried out under commercial (99.98%) argon gas shielding at a flow rate of 18 L/min using direct current electrode positive (DCEP) at an electrode extension of 12–14 mm. Whereas the SMAW passes were carried out with basic coated 4.0 mm diameter SFA5.4 E 308L-15 electrodes at the electrode polarity of DCEP. The P-GMA weld deposition was carried out at a given heat input by varying $f$ at two different levels of 0.05 and 0.25. During welding all the conventional welding parameters were recorded with WMS 4000 software installed in a computer while pulse parameters were recorded with the help of a transient recorder appropriately connected to the electrical circuit of the welding power source. The welding parameters used in the preparation of SMA and GMA weld joints are shown in Table 1, and the pulse parameters used in preparation of P-GMA welds at two different $f$ of 0.05 and 0.25 are shown in Table 2. The heat input per pass of the SMA and GMA welding was estimated as follows.

\[ \text{Heat input (kJ/cm)} = \frac{\text{Welding current (A)} \times \text{Arc voltage (V)}}{1000 \times \text{Welding speed (cm/s)}} \]

However in case of P-GMAW the heat input was estimated by using mean current instead of welding current of Eq. (1). Characteristics of the weld joints prepared by different welding processes were correlated to the average heat input per pass estimated as mean value of heat input employed in its multiple filler passes. During welding the dye penetration test of weld deposit was carried out intermittently after each weld pass and finally the weld joints were tested by 100% X-ray radiography.

2.2. Measurement of Shrinkage and Residual Stresses

The transverse axial shrinkage after each pass of multipass weld deposition was estimated by measuring the difference between two center punched points axially located across the joint marked before welding at a known distance. After completion of weld joint the residual stresses at its top and the root were measured by placing three-element strain gauge rosette system in the desired location and using blind centre hole drilling technique on it. The measurement of residual stresses has been carried out at different locations in weld and HAZ adjacent to the fusion line (FL). Prior to fixing the strain gauge at different locations selected for measurement of residual stresses, the required surface area was mechanically flattened with smooth finish.

**Table 1.** Welding parameters used in the preparation of SMA and GMA weld joints.

| Process | Layer (s) | Electrode/Filler wire size (mm) | Passes | Welding current (A) | Arc Voltage (V) | Welding speed (cm/min) |
|---------|-----------|---------------------------------|--------|---------------------|----------------|------------------------|
| GTAW    | I         | Root Autogeneous                | 90     | 11-13               | 3-5            |                        |
| GTAW    | II        | Root                             | 120    | 12-14               | 5.7            |                        |
| GTAW    | III       | Filler                           | 140    | 12-14               | 6.6            |                        |
| SMAW    | IV        | Remaining                        | 120    | 22-25               | 8-10           |                        |
| SMAW    | Cap Pass  | Filler passes                    | 160    | 24-28               | 9-12           |                        |
| GMAW    | Remaining | Filler                           | 160    | 27-30               | 9-12           |                        |
| GMAW    | Cap Pass  |                                  | 230    | 21-23               | 20             |                        |
| GMAW    | Cap Pass  |                                  | 220    | 23-25               | 20             |                        |

**Table 2.** Pulse parameters used in the preparation of P-GMA welds.

| Process | Layer (s) | Electrode/Filler wire size (mm) | Passes | Pulse parameters | Arc Voltage (V) | Welding speed (cm/min) |
|---------|-----------|---------------------------------|--------|------------------|----------------|------------------------|
| GTAW    | I, II and III | Welding parameters are same as those mentioned in Table 1 |
| P-GMAW  | Remaining | Welding parameters | 0.05 | [60|58|52.5|3.0|11.1] | 21-23 | 20 |
| P-GMAW  | Cap Pass  | Welding parameters | 0.05 | [60|58|52.5|3.0|11.1] | 21-23 | 20 |
| P-GMAW  | Remaining | Welding parameters | 0.25 | [70|12|90|2.0|125] | 21-23 | 20 |
| P-GMAW  | Cap Pass  | Welding parameters | 0.25 | [70|12|90|2.0|125] | 21-23 | 20 |
and cleaned by acetone. The experimental set up used for drilling operation at the top and the root side of the weld joint has been shown in Figs. 2(a) and 2(b) respectively. The measurement of residual stresses and their estimation was carried out in accordance to the procedure ASTM E-837. After the hole drilling operation the joint surface was metallographically polished and etched to reveal the precise location of drilling with respect to weld fusion line.

2.3. Chemical Analysis
The chemical analysis of different samples was carried out under spark emission optical spectroscopy at a spot size of 3 mm diameter on solid specimens. The analysis was performed at polished transverse section of the weld joint by locating the spot on weld metal and base metal. Similarly the analysis was also carried out on the mechanically flattened filler metal used in various welding processes. However the nitrogen content of base metal and weld deposit was analyzed under CHN infrared analyzer using a 10 mm long pin sample of 5 mm diameter.

2.4. Measurement of Inclusion and Porosity Content
The inclusion and porosity content of the base metal and weld deposit was measured with the help of image analyser software used during optical microscopic studies on the metallographically polished unetched transverse section of weld joint. The software analysis was carried out on at least 21 randomly captured images of different locations of the matrix viewed at a magnification of ×100. The analysis was made by measuring the area fraction of practically round shape black spots observed on the matrix of weld deposit considered as porosity or a void containing inclusions in it. The volume fraction of the spots present in the matrix was estimated by assuming it as a linear function of their measured area fraction.

2.5. Inter Granular Corrosion Test
In order to study acceptability of weld joint with respect to its susceptibility to IGC, a rapid oxalic acid electrolytic etch test was carried out as per ASTM E262 Practice A on the metallographically polished transverse section of weld joint by dipping it into a solution containing 100 g reagent grade oxalic acid (H₂C₂O₄·2H₂O) in 900 ml distilled water and using a current density of the order of 1–0.1 A/cm². The susceptibility of base metal IGC was also tested by following the same procedure. The inter granular corrosion attack on the weld joints were examined under a optical microscope at a magnifications of 250× and 500× in the locations of weld and HAZ respectively by evaluation of the etched structures developed under the test exposure. The evaluation was primarily made on the basis of identification of isolated ferrite and interdendritic ditches in weld deposit and the presence of step structure, dual structure and ditch structure in the HAZ as specified in the said ASTM standard.

2.6. Studies on Microstructure
Various features of microstructures of the weld joints revealed under the rapid oxalic acid electrolytic etch test was also studied in detail under the optical microscope. The studies were carried out on the multi-pass weld deposit and HAZ adjacent to the fusion line. Microstructure of the multipass weld has been analysed by measuring its columnar or coaxial dendrite content. Dendrite fraction measurement was carried out, with the help of Axio Vision software based image analyser facility installed in a computerised optical microscope. The image analysis was carried out on minimum 21 randomly selected spots on the SMA, GMA and P-GMA welds. The grain size of HAZ within 0.1 mm from the fusion line (FL) on either side of weld joint was also measured by using the image analyser software at 6–10 randomly selected spots located at various parts of HAZ adjacent to the SMA, GMA and P-GMA filler weld deposits.

2.7. Testing of Mechanical Properties
2.7.1. Tensile Test
The tensile testing was carried out by using round tensile specimens confirming the ASTM E8M specification and the properties are reported as an average of test results of at least three specimens. The tests were carried out at a strain rate of 0.003/s. The tensile specimens of the base material and weld joint of pipes were machined out from both of their longitudinal and circumferential directions. The longitudinal tensile specimens of the base metal and weld joint (axial weld) were having 50 mm gauge length whereas the circumferential (all weld) tensile specimens were having 25 mm gauge length. The diameters of the two types of specimens within their gauge lengths of 25 and 50 mm were 5 and 10 mm respectively. The yield strength was estimated at 0.2% offset strain.
2.7.2. Hardness Test

The hardness of the base metal as well as across the weld and HAZ of the weld joint was measured by Vickers micro-hardness testing at a load of 100 g. The distribution of hardness around weld joint was studied with reference to centre and fusion lines of each weld as revealed in its metallographically prepared and etched transverse section. The relatively low load was used in order to get a small indentation giving rise to a more effective study on the characteristics of different locations of HAZ.

2.8. Fracture Mechanics Test

The $J$-integral fracture toughness tests was carried out using the C(T) specimens (ASTM E-813-89 and E-1820-01) of the base metal as well as the SMA, GMA and P-GMA welds. In case of the studies on both the base material and weld centre line the orientation of notch was kept in L-C (longitudinal–circumferential) direction. Prior to $J_{IC}$ fracture toughness test, all specimens were pre-cracked by fatigue, upto a crack length of about 30 mm, giving a crack aspect ratio of $a/W=0.6$. The pre-cracking was carried out by decreasing $\Delta K$ method at a stress ratio ($R$) of 0.1 and cyclic frequency of 10 Hz. The crack length was measured by compliance method using high speed data acquisition and processing system connected to COD gauge. The loading criterion was kept in accordance with the ASTM specifications confirming the initial maximum load ($P_{max}$) in the range of 0.20–0.25 $P_{L(CT)}$, where the $P_{L(CT)}$ was estimated as follows.

$$P_{L(CT)} = \left( B h_0^2 \sigma_y / (2W + a) \right)$$

Where, $B$ is thickness of the specimen (mm), $W$ is width of the specimen (mm), $h_0$ is initial uncracked ligament (mm), $\sigma_y$ is effective yield strength of the specimen (N/mm$^2$) given by $(\sigma_{YS} + \sigma_{TS})/2$, $\sigma_{YS}$ is 0.2% offset yield strength (N/mm$^2$), $\sigma_{TS}$ is ultimate tensile strength (N/mm$^2$).

During $J_{IC}$ fracture toughness testing the specimen was statically loaded by bending under displacement control mode at a loading ramp rate of 1 mm/min. The test was carried out at the initiation of slow stable crack growth in accordance with ASTM E 813-89. The evaluation of elastic–plastic $J$-integral fracture toughness ($J_{IC}$) was carried out by using single specimen technique with the help of $J_{IC}$ software at an INSTRON universal testing machine. A plot of $J$-integral vs. crack extension ($\Delta a_p$) was obtained as the crack resistance $J$–$R$ curve. The $J_0$ value was derived from the intersection of the $J$–$R$ curve with 0.2 mm offset line parallel to the blunting line.

3. Results and Discussion

3.1. Weld Quality

The X-ray radiographs of the weld joints show that the welds are sound enough with respect to presence of any discontinuity defects as per ASME section III. It confirms that the welding procedure specifications used for preparation of the SMA, GMA and P-GMA welds are to a large extent appropriate. The macro photographs of the SMA and GMA weld joints as revealed in their transverse sections are shown in Figs. 3(a) and 3(b) respectively. Similarly the macro photographs of the transverse sections of the P-GMA weld joints prepared at different $\phi$ of 0.05 and 0.25 are as shown in Figs. 4(a) and 4(b) respectively. The figures
also depict that the welds are practically free from any defects as lack of welding or root fusion.

3.2. Shrinkage and Residual Stresses

The total number of passes (N), overall cumulative transverse shrinkage (S) along with average heat input in filling passes (H.I) observed during joining of SMA, GMA and P-GMA weld joints are also shown in Table 3. The table depicts that in order to produce a sound weld the average heat input along with overall cumulative transverse shrinkage can be considerably reduced by using P-GMAW process in comparison to the GMAW and SMAW processes. It is further noticed that during P-GMA welding the cumulative shrinkage of the weld joint further reduces with a variation of f from 0.25 to 0.05. Thus it can be assumed that the use of P-GMA welding with a lower f of 0.05 may be beneficial in reducing the induction of strain especially at the root of the pipe weld in comparison to that obtained in case of the GMA and SMA welding of pipe, which may consequently minimise the residual stresses in weld joint.

Table 3. Heat input and transverse shrinkage observed in SMA, GMA and P-GMA weld joints.

| Process       | f   | N | H.I (kJ/cm) | S (mm) |
|---------------|-----|---|-------------|--------|
| SMAW          | -   | 15| 24.3        | 6.04   |
| GMAW          | 14  | 15.5| 5.68       |        |
| P-GMAW        | 0.05| 15| 11.0        | 5.30   |
|               | 0.25| 15| 11.5        | 5.44   |

The longitudinal and transverse residual stresses present at different locations on top of the weld in reference to the centre and fusion lines of the various SMA, GMA and P-GMA weld joints are shown in Figs. 5(a) and 5(b) respectively. Similarly the longitudinal and transverse residual stresses in different locations at root of the weld with respect to the centre and fusion lines of the said weld joints are shown in Figs. 6(a) and 6(b) respectively. The figures show that at the top and root of the weld, longitudinal residual stress reduces by 20–30% and 30–40% with the use of GMAW and P-GMAW processes respectively in comparison to that observed in case of using the SMAW process. The transverse residual stress has also been found to follow a similar trend but having a magnitude comparatively lower than the longitudinal residual stress of the weld joint as it is also commonly observed in earlier works.

In comparison to SMAW the GMAW and especially the P-GMAW process has been found advantageous with respect to reduction in residual stresses in ASS pipe joint primarily due to its relatively less severity of thermal effect (Table 3). The magnitude of residual stress distribution further marginally lowers with the variation in pulse parameters reducing the factor f from 0.25 to 0.05 indicating a further control on reduction in severity of weld thermal cycle. Except that observed in Fig. 5(a), the longitudinal residual stresses at the top and root of the GMA and P-GMA welds (Figs. 5 and 6) are generally found consider-
ably lower than the corresponding residual stresses of the SMA weld. At the root of all kinds of welds (Fig. 6) both the longitudinal and transverse residual stresses are found to be reduced from its maximum at weld centre as one goes away from it all the way beyond the fusion line. However, the distribution of residual stresses has been found relatively different at the top of the welds (Fig. 5). Here the distribution of longitudinal residual stresses in P-GMA weld behave in a fashion similar to that of the weld root (Fig. 5) but, the distribution of the longitudinal residual stresses of the SMA and GMA welds and the transverse residual stresses of all the SMA, GMA and P-GMA welds behave in a different manner showing their magnitude maximum at certain locations in between the weld centre and fusion line of the joint. However, the maximum intensity of residual stress depends upon welding process as it is relatively marked lower in case of the GMAW and P-GMAW than SMAW. The dual peak of residual stresses with a depression of stress at weld centre has been observed at the top of the weld, but not at the root, due to its narrowness causing difficulties in multiple spot analyses within it. The presence of dual peak of residual stresses distributed in either side of weld centre line in weld joint of austenitic stainless steel arising out of interactions of shrinkage and quenching stresses has also been reported by earlier workers.18–21) However, almost in all the cases the residual stresses at the weld centre are found relatively higher at the root than top of the weld.

3.3. Metallurgical Characteristics

3.3.1. Chemical Composition and δ-ferrite Content

Chemical compositions of the base metal, filler metals and weld deposits are given in Table 4. Delta ferrite content estimated as per WRC-92 diagram proposed by Siewert et al.15) and measured by ferrite scope for the various weld deposits is also shown in Table 4. The chromium and nickel equivalents were estimated by the following equations proposed in WRC-92 diagram.15)

\[
Cr_{eq} = Cr + Mo + 0.7Nb
\]

(3)

\[
Ni_{eq} = Ni + 35C + 20N + 0.25Cu
\]

(4)

The table depicts relatively lower carbon and higher chromium content in GMAW filler wire in comparison to SMAW electrode. It also shows that irrespective of the welding process used for weld deposition, the dilution of base metal introduces nitrogen of the order of 0.1 wt% to the weld and thus reduces its δ-ferrite content by stabilizing the austenite phase as per WRC-92 Siewert diagram.15) It has been further observed that the GMA and P-GMAW weld deposits have 7–8% of δ-ferrite content indicating ferrite-austenite (FA) mode of solidification in contrast to the austenite–ferrite (AF) mode of solidification observed in case of SMA weld deposits in presence of practically negligible quantity of δ-ferrite in it (Table 4). In SMA weld, AF mode of solidification also results from a considerable loss of chromium caused by oxidation during metal transfer along with base metal dilution. Hence it can be inferred that GMA and P-GMA welds prepared at relatively lower heat input (Table 3) having 7–8% δ-ferrite content (Table 4) are comparatively less prone to solidification cracking1,16,17) with respect to the SMA weld joint.

3.3.2. Inclusion/Porosity Content

Inclusion content observed in the base metal and the weld deposits of the SMA, GMA and P-GMA weld joints has been shown in Table 5. It has been primarily observed that the GMA and P-GMA weld deposits have 75–80% lower inclusion or porosity content in comparison to that of the flux covered SMA weld joints. The increase in inclusion content of the SMA welds may have primarily happened due to slag entrapment. However in most of the cases, the inclusion and porosity contents of the GMA and P-GMA welds has been found marginally higher than that of the base metal indicating the occurrence of significantly low atmospheric contamination. It is further observed that with the reduction in φ from 0.25 to 0.05 the inclusion or porosity content of the weld considerably reduces by almost 50%.

3.3.3. Inter Granular Corrosion (IGC) Test

The typical susceptibility of base metal to inter granular corrosion primarily associated with precipitation of chromium carbide at the grain boundary has been shown in

### Table 4. Chemical compositions and δ-ferrite content of the base metal, filler metals and weld deposits.

| Material/Process      | φ  | Chemical analysis of weld metal (Wt.%) | Equivalent δ-ferrite content (%) |
|-----------------------|----|--------------------------------------|---------------------------------|
|                       |    | C  Cr  Ni  Mn  N  Mo  Si  Cu  S  P  Cr$_{eq}$  Ni$_{eq}$  Est.  Obs. |
| Base metal (304LN)    |    | 0.023 0.19 0.91 1.82 0.16 0.019 0.570 0.300 0.0029 0.02 19.2 13.2  -  - |
| SMAW electrode (E308L-15) | 0.024 | 0.18 0.011 0.91 1.78 0.18 0.012 0.450 0.120 0.0060 0.020 13.7 2-4  -  - |
| GMAW filler wire (ER308L) | 0.020 | 0.23 1.89 0.95 1.62 0.12 0.580 0.25 0.01 0.02 19.0 13.3 10-12  -  - |
| SMAW                  |    | 0.027 0.18 0.11 1.28 0.10 0.04 0.370 0.140 0.0130 0.02 18.2 14.0  Nil  Nil |
| GMAW                  |    | 0.024 0.19 0.94 1.60 0.14 0.14 0.350 0.140 0.130 0.02 19.3 12.3 6.8 7.0 |
| P-GMAW                | 0.050 0.509 0.19 0.95 0.14 0.01 0.660 0.10 0.02 0.02 19.0 13.4 6.8 8.0 |

### Table 5. Inclusion and porosity content of base metal and different weld joints.

| Process | φ | Inclusions rating | Inclusion and porosity content, (Vol. %) |
|---------|---|------------------|----------------------------------------|
|         |   | Category       | Severity level |                           |
| Base Metal                     | -  | B thin/D.thick  | 0.5-1.5           | 0.20                      |
| SMAW                         | D thin/D.thick | 3.5-5.0        |                          |
| GMAW                         | -  | B thin/D.thick  | 0.5-1.5           | 2.34                      |
| P-GMAW                       | -  | D thin/D.thick  | 2.5-4.0           | 0.75                      |
|                                | 0.05 | D thin/D.thick  | 3-0.45            | 0.18                      |
|                                | 0.25 | D thin/D.thick  | 3-0.45            | 0.38                      |
The microstructures of HAZ adjacent to fusion line of the SMA and GMA welds and the P-GMA welds of two different $\phi$ of 0.05 and 0.25 are shown in Figs. 8(a)-8(d) respectively. The typical appearance of the matrix of weld deposit after the rapid oxalic acid etching of the above mentioned welds have been shown in Fig. 9.

The nitrogen added ASS is comparatively less susceptible to intergranular corrosion (IGC) attack associated with grain boundary precipitation of chromium carbide due to lowering of chromium diffusivity into the matrix in the presence of nitrogen and thereby retardation of nucleation and growth of carbides improving the passivity. However
due to a limited corrosive attack on the matrix the microstructure of base metal primarily shows step structure with no ditches at grain boundaries. In HAZ of SMA, GMA and P-GMA weld joints, some minor ditches in addition to steps exist only at some grain boundaries resulting in dual structure as per ASTM 262 practice A. Whereas, in the weld deposit of the above mentioned joints (Fig. 9) presence of interdendritic ditches could not be appreciably marked in coaxial and refined dendritic region. Hence it largely indicates that the weld and HAZ of all the weld joints have passed the acceptability test of the oxalic acid etching with respect to their susceptibility to IGC attack.

### 3.3.4. Microstructure

The microstructures presented in Fig. 9 show that the SMA, GMA and P-GMA welds are having different features of multipass weld deposition. The P-GMA weld deposit primarily shows considerable refinement in microstructure along with scarcely distributed coaxial dendritic structure, whereas the SMA and GMA welds largely show conventional behavior of multipass weld that significantly consists of both the coaxial dendritic and reheat refined regions. The refinement of microstructure increases with the lowering of factor \( \phi \) from 0.25 to 0.05 in P-GMA weld primarily due to variation in thermal shock during solidification through interruption in metal deposition imparted by the pulse. Whereas in the conventional SMA and GMA weld deposits refined region primarily results from partial reheat refinement of coaxial dendrite of earlier deposited weld bead due to severity of weld thermal cycle imparted by the subsequent passes. Such a difference observed in weld microstructure was further characterized by analyzing the distribution of coaxial dendritic and refined region in SMA, GMA and P-GMA weld deposits as shown in Table 6. In agreement to the above mentioned observations the table shows that the use of GMAW and more effectively the use of P-GMAW significantly reduces the coaxial dendritic region in the weld with respect to that observed in SMA weld, where in case of P-GMAW the use of comparatively lower \( \phi \) becomes more appropriate in this regard.

The microstructure of HAZ adjacent to fusion line (Fig. 10) of the SMA, GMA and P-GMA welds show certain extent of grain coarsening. The grain size of this region has been compared in Table 7. The table shows that the GMA and P-GMA weld joints have comparatively less grain coarsening than that observed in case of the SMA weld joint. This may have primarily happened due to considerable reduction in severity of weld isotherm arising out of the heat of weld deposition adjacent to the groove wall. However in P-GMA welds grain coarsening have been reduced.

### Table 6. Dendrite measurement at various locations in SMA, GMA and P-GMA weld deposit.

| Process   | \( \phi \) | Coaxial dendritic region (%) | Refined region (%) |
|-----------|------------|------------------------------|--------------------|
| SMAW      | -          | 83.8                         | 16.2               |
| GMAW      | -          | 81.4                         | 18.6               |
| P-GMAW    | 0.05       | 23.4                         | 76.6               |
| 0.25      | 31.7       | 68.3                         |                     |

### Table 7. Grain size measured in HAZ adjacent to fusion line in SMA, GMA and P-GMA weld joints.

| Process   | \( \phi \) | Avg. Grain dia. \( \pm \) S.D. (\( \mu m \)) | ASTM No |
|-----------|------------|----------------------------------------------|----------|
|           |            | A                             | B         | A & B    | A   | B   | A & B |
| SMAW      | -          | 29 \( \pm \) 6               | 27 \( \pm \) 4 | 28 \( \pm \) 5 | 7.5   | 7.5   | 7.5   |
| GMAW      | -          | 19 \( \pm \) 3               | 19 \( \pm \) 3 | 19 \( \pm \) 3 | 8.5   | 8.5   | 8.5   |
| P-GMAW    | 0.05       | 18 \( \pm \) 4               | 18 \( \pm \) 5 | 18 \( \pm \) 4 | 9.0   | 9.0   | 9.0   |
|           | 0.25       | 18 \( \pm \) 3               | 15 \( \pm \) 10 | 17 \( \pm \) 5 | 8.5   | 9.5   | 9.0   |

S.D. is Standard deviation, A and B are either side of weld joint.

**Fig. 10.** Typical microstructures of heat affected zone adjacent to fusion line observed in (a) SMA and (b) GMA weld deposits in comparison to those observed in P-GMA weld deposit at a given (c) \( \phi =0.05 \) (d) \( \phi =0.25 \).
found of similar magnitude at both the $\phi$ of 0.05 and 0.25. Such a characteristic of HAZ may improve the resistance to stress corrosion cracking susceptibility of the GMA and P-GMA weld joints in comparison to that of the SMA weld joint.

3.4. Tensile Properties

The tensile properties of the base pipe in its circumferential and longitudinal directions are shown in Table 8. Similarly the tensile properties of the SMA, GMA and P-GMA weld joints of the pipes along their longitudinal (axial weld having joint at centre of the specimen) and circumferential (all weld metal) directions are shown in Table 9 and Table 10 respectively.

The dimensionless material constant ($\alpha$) and strain hardening exponent ($n$) was estimated during tensile testing of the specimens from the base metal and weld joint using Romberg Osgood expression as follows

$$\frac{\varepsilon}{\varepsilon_0} = \left(\frac{\sigma}{\sigma_0}\right)^n + \alpha$$

Where, $\sigma$ is the nominal stress at any instant, $\varepsilon$ is the strain at $\sigma$, $\sigma_0$ is the flow stress estimated as $(\sigma_u + \sigma_y)/2$, and $\varepsilon_0$ is estimated as $\sigma_y/E$, wherein $E$ is the modulus of elasticity, $\sigma_u$ is the ultimate tensile strength and $\sigma_y$ is the yield strength at 0.2% offset strain.

The Table 8 shows that the base metal is having comparatively higher yield strength in circumferential direction in comparison to that observed in longitudinal direction. The Tables 8 and 10 also show a similar behaviour where the all weld deposit (circumferential direction) has been found to depict comparatively higher yield strength than that of the longitudinal weld joints fracturing from the weld. However, the ratio of yield strength ($\sigma_y$) to ultimate tensile strength ($\sigma_u$) of the base metal has not been found to vary significantly with the change in direction from the circumferential to axial one. Whereas, unlike base metal, it is observed that the $\sigma_u$ to $\sigma_y$ ratio of weld joints significantly increased from 0.5 to 0.76 with a considerable sacrifice in elongation. It has been further interestingly observed that the P-GMA welds have shown significantly higher tensile properties than the GMA and SMA weld joints in both the longitudinal and circumferential directions primarily due to comparatively more refined homogeneously distributed dendritic microstructure (Fig. 9) across the weld region along with a considerably lower inclusion and porosity content (Table 5).

3.5. Hardness

The hardness of base material has been found of the order of 220–280 VHN. The hardness across the SMA and GMA and P-GMA welds of two different $\phi$ of 0.05 and 0.25 are compared in Fig. 11. The hardness of both the weld deposit and HAZ of the GMA and P-GMA weld joints has been found significantly higher than that of the base metal. However, the ratio of yield strength ($\sigma_y$) to ultimate tensile strength ($\sigma_u$) of the base metal has not been found to vary significantly with the change in direction from the circumferential to axial one. Whereas, unlike base metal, it is observed that the $\sigma_u$ to $\sigma_y$ ratio of weld joints significantly increased from 0.5 to 0.76 with a considerable sacrifice in elongation.

The P-GMA welds have shown significantly higher tensile properties than the GMA and SMA weld joints in both the longitudinal and circumferential directions primarily due to comparatively more refined homogeneously distributed dendritic microstructure (Fig. 9) across the weld region along with a considerably lower inclusion and porosity content (Table 5).

3.6. Fracture Toughness

The initiation fracture toughness properties of the base metal, SMA, GMA and P-GMA weld deposits in $L-C$ direction are given in Table 11. The typical $J-R$ curves of the base metal, SMA, GMA and P-GMA weld deposits in $L-C$ direction have been compared in Fig. 12. In the figure the comparatively stiffer vertical progress of $J-R$ curve of the base metal indicates (higher regression line constants) high multipass weld deposit in the former one (Fig. 3) containing larger number of different kinds of zones of microstructure having dendrite and coarse and fine grain reheat refinement. However, inspite of large number of deposit in it (Fig. 4) the P-GMA weld joint shows relatively low scattering of hardness distribution in weld deposit with respect to that of the GMA weld primarily due to large scale refinement of dendritic microstructure in the former one (Table 6).
plasticity at crack front in transverse direction resulting in tunneling of specimen. This is in agreement to the high ductility of the base metal as given in Table 8. The Fig. 12 also shows that the P-GMA welds are having significantly higher \( J_{\text{Q}} \) value with respect to those observed in GMA and SMA weld joints. In P-GMA weld joints the \( J_{\text{Q}} \) value significantly increases with the decrease of \( \phi \) from 0.25 and 0.05. In case of the P-GMA welds the \( J_{\text{Q}} \) observed are not valid \( J_{\text{IC}} \) value as they do not satisfy the criterion as thickness \( B>25 \frac{J_{\text{Q}}}{\sigma_y} \), where \( \sigma_y \) is the effective yield strength according to the ASTM E813 standard. The maximum load (\( P_{\text{max}} \)) and the corresponding physical crack extension (\( \Delta a \)) observed in P-GMA welds are considerably greater than that observed in GMA and SMA weld joints.

From the above observations it may be inferred that the P-GMA welds especially with a comparatively lower \( \phi \) of 0.05 have significantly superior initiation fracture toughness properties than that of the GMA and SMA welds. However, the initiation fracture toughness properties of the base metal and P-GMA welds cannot be satisfactorily analysed by elastic–plastic fracture mechanics concepts due to their significant ductility.

### Table 11. Fracture toughness properties of base metal and SMA, GMA and P-GMA weld joints.

| Material/Process | \( P_{\text{max}} \) (kN) | \( \Delta a \) (mm) | Initiation fracture toughness through mechanical testing | Regression line constants | \( J_0 \) (kJ/m²) |
|------------------|----------------|----------------|-------------------------------------------------|------------------------|-----------------|
| Base             | 31.53          | 0.57           | 392 1564 0.98 1334 No                           | \( C_1 \) \( \times \) \( C_2 \) \( R^2 \) |
| SMAW             | 30.29          | 0.14           | 292 131 0.98 300 Yes                            |                        |
| GMAW             | 30.73          | 0.76           | 443 863 0.96 538 Yes                            |                        |
| P-GMA            | 0.05           | 36.35          | 936 692 0.99 1035 No                           | \( C_1 \) \( \times \) \( C_2 \) \( R^2 \) |
| P-GMA            | 0.25           | 16.81          | 286 446 0.99 667 No                            | \( C_1 \) \( \times \) \( C_2 \) \( R^2 \) |

# Coefficient of corelationship

4. Conclusion

The observations of the present investigation indicate that the P-GMAW and GMAW processes are comparatively better option for welding of 25 mm thick wall austenitic stainless steel pipe than conventionally used SMAW process primarily due to their ability to produce relatively faster, cleaner and continuous weld deposit. Further the homogenously distributed, considerably refined microstructure resulting in the use of P-GMA welding than in conventional GMA and SMA welding for multipass deposit significantly improves the initiation fracture toughness (\( J_{\text{Q}} \)) of the weld. The P-GMA welds prepared at \( \phi \) of 0.05 in comparison to 0.25 develops considerably lower residual stresses at the top and root of the weld, as well as improves fracture toughness and tensile properties of the weld having significantly reduced inclusion and porosity content.

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