Mechanical, Metallurgical and Corrosion Properties of Dual Pulsed, Pulsed Gas and Shielded Metal Arc Welded AISI 310 Austenitic Stainless Steel

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Abstract. AISI 310 is a highly alloyed austenitic stainless steel used for high-temperature applications. The high chromium and nickel contents give this steel excellent oxidation resistance as well as high strength. In the present work, the material was welded using shielded metal arc welding (SMAW), Pulsed Gas Metal Arc welding (P-GMAW) and Double Pulsed Gas Metal Arc welding (DP-GMAW). A comparative study has been carried out on the basis of chemical, mechanical, metallurgical and corrosion properties of base metal and all other welded samples. SMAW process has high heat input and hence dilution effect is more prominent in this process. The mechanical properties evaluated in terms of maximum tensile strength, impact energy and hardness was obtained for DP-GMAW sample. This superior mechanical behaviour of DP-GMA welded sample was attributed to the better grain refinement occurred due to double pulsation effect. However, the DP-GMAW process showed highest corrosion rate when compared to other two welded samples.

Keywords: AISI 310, Double Pulsed Gas Metal Arc Welding, Micrographs, Corrosion rate

1. Introduction
AISI 310 is a high chromium and nickel alloyed austenitic stainless steel used for high-temperature applications. The combination of good ductility and weldability enabled its widespread usage in applications such as furnace parts, heat treatment equipment, boiler baffles, kilns, lead pots, etc. The high chromium and nickel contents give the steel excellent oxidation resistance as well as high strength at high temperatures. As the AISI 310 material has numerous applications, it is important to study the weld behaviour and corrosiveness of the material. Gas Metal Arc Welding (GMAW) is a common welding process where an externally supplied shielding gas is used to protect the arc and molten metal from oxygen and other gases in the air. A filler wire is continuously fed in to the welding through the wire feeder and welding gun. The GMAW process can be performed continuously without changing the
electrode and has the potential to improve the productivity over Shielded Metal Arc Welding (SMAW). An advancement of conventional GMAW process, named as Pulsed GMAW (P-GMAW), produces stable spray modes of metal transfer even at low average currents. All these GMAW uses constant Wire Feed Rate (WFR).

Further, Dual Pulse GMAW (DP-GMAW) was developed to avoid many problems associated with GMAW of aluminium material [1]. This welding process is a derivation of P-GMAW where a low frequency current pulsation is superimposed over the pulsed current for additional control of metal transfer and weld pool [1, 2]. The DP-GMAW process requires less operator skill as it controls the arc length and heat input together to get excellent penetration [3]. The process also ensured a better surface oxide cleaning property and bead profile with good mechanical properties [1]. DP-GMAW significantly influence the mechanical and microstructural properties of ferritic stainless steel [4].

However, it was found that very few studies reported the DP-GMAW of austenitic stainless steel [4, 5]. Also, no previous work dealt with the corrosion properties of DP-GMA welded AISI 310 steel. Hence, in this study, an attempt was made to understand the welding strength and corrosiveness of AISI 310 steel welded using DP-GMAW process. The mechanical characterisation in terms of tensile strength, Charpy impact energy, and hardness, metallographic analysis and corrosiveness were investigated. The corresponding data of AISI 310 steels welded using SMAW and P-GMAW processes were also evaluated and their comparative investigation were also performed.

2. Experimental setup

2.1. Material selection
In this study, austenitic stainless steel AISI 310 plate was used as base material. The welding was done on plate having dimensions, 10 mm thickness and 100 mm length. The important mechanical properties of AISI 310 at room temperature is shown in Table 1. The filler wires used for SMAW was E 310 and that for GMAW was E 309. The schematic of the groove preparation is shown in Fig. 1. Conventional V-groove arrangement with 70° groove angle and 1.5 mm root face and root gap was prepared for welding. This groove was designed according to the thickness of the material. The edges were prepared and cleaned thoroughly to remove oil, dust, paint and other impurities. Copper plate was used as backing plate for all the welding experiments to protect the molten metal and to avoid oxidation at root side. The multi pass deposition technique was adopted in this study and welding experiments were performed using SMAW, P-GMAW and DP-GMAW processes. The current, voltage and heat input were measured in each pass.

| Properties                        | Typical | Minimum |
|-----------------------------------|---------|---------|
| Tensile Strength, MPa             | 575     | 515     |
| Yield Stress (0.2 % offset), MPa  | 290     | 205     |
| Elongation (50mm gauge length), % | 50      | 40      |
| Hardness (Brinell)                | 156     |         |
| Endurance (fatigue) limit, MPa    | 260     |         |

2.2. Power source
The inverted type KEMPi ProMig 530 welding machine, capable of doing GMAW, P-GMAW and DPGMAW under synergic mode was used as the power source for this experimental study. The machine had a duty cycle of 60% at rated current 520A. The actual welding arrangement with different equipment used in this study is shown in Fig. 2. Commercially pure Argon shielding gas used for GMAW process. A 100% flow of shielding gas with a flow rate 15 l/min was used for all the welding process. The gas flow was measured by a flow meter connected on the gas cylinder. During the welding process the welding current was controlled by adjusting the Wire Feed Rate (WFR). Even though the WFR is set on the machine, it was found to vary during the DP-GMAW process. In DP-GMAW the main role of the
low frequency thermal pulsation (current pulsation, also referred as Inpulse, Alu-Plus, etc [1]) was to control the weld pool. The variation of the mean current between thermal base and thermal pulse was synchronized with WFR to maintain constant arc length [1]. A large variation of WFR in DP-GMAW process significantly influences the mean current and arc voltage during welding. This variation will result in arc instability leading to porosity in the weld pool. Hence, the filler wire was fed through special arrangements of rollers and torch. The carriage FRONIUS-FCU-4-RC that moves automatically adjusting to the variation in WFR was used to minimize the error in feed rate. The current, voltage and the variation of the WFR was measured directly through the digital display on the power source. The characterisation of these power source data along with standoff distance variations of the welding processes were also performed. Welding parameters in each welding passes for all the three welding processes is enlisted in Tables 2-4. WFR value was set for P-GMAW and DP-GMAW processes, and it was observed that the heat input value was lower in DP-GMAW process for same travel speed and higher wire rate.

2.3. Metallographic examination
After welding, the welded plates were cut 25mm away from the edge with help of a power hack saw machine to prepare the samples for metallurgical analysis. The specimens were then polished using the SiC abrasive papers of grade 120, 240, 320, 400, 600, 800 and 1200 grits, one after another. They were further polished with alumina and finally finished with 9µm to 0.5 µm diamond paste. After proper polishing, the specimens were deeply etched using electrolytic etching with 10 % Oxalic acid to reveal
Table 2: Welding parameters in each welding pass for SMAW process

| S. No. | Weld layer | Weld pass | Heat input (kJ/cm²) | Welding parameters | Remarks               |
|--------|------------|-----------|---------------------|---------------------|-----------------------|
| 1      | 1          | 1         | 3.7                 | 121+/-2             | 10+/-1 Root pass, GTAW Filler wire ER309 |
| 2      | 2          | 2         | 8.51                | 120+/-3             | 26+/-1 SMAW E310 φ 3.15 mm |
| 3      | 3          | 3         | 12.97               | 160+/-2             | 27+/-1 SMAW E310 φ 3.15 mm |
| 4      | 4          | 4         | 9.86                | 120+/-2             | 26+/-1 SMAW E310 φ 3.15 mm |
| 5      | 4          | 5         | 8.51                | 120+/-2             | 26+/-1 SMAW E310 φ 3.15 mm |
| 6      | 4          | 6         | 8.51                | 120+/-2             | 26+/-1 SMAW E310 φ 3.15 mm |

Table 3: Welding parameters in each welding pass for P-GMAW process

| S. No. | Weld layer | Weld pass | Heat Input (kJ/cm²) | WFR m/min | Mean current, A | Arc voltage, V | Travel speed, cm/min | Stand of distance, mm |
|--------|------------|-----------|---------------------|-----------|-----------------|----------------|-----------------------|-----------------------|
| 1      | 1          | 1         | 7.41                | 4         | 183+/-2         | 27.0+/-1       | 40                    | 15                    |
| 2      | 2          | 2         | 7.5                 | 5         | 168+/-2         | 30.3+/-1       | 40                    | 15                    |
| 3      | 3          | 3         | 7.73                | 5         | 184+/-1         | 28.0+/-1       | 40                    | 17                    |
| 4      | 4          | 4         | 7.15                | 5         | 182+/-2         | 26.2+/-1       | 40                    | 13                    |
| 5      | 4          | 5         | 7.02                | 5         | 180+/-2         | 26.0+/-1       | 40                    | 15                    |
| 6      | 4          | 6         | 7.18                | 5         | 175+/-3         | 28.2+/-1       | 40                    | 15                    |
| 7      | 4          | 7         | 7.18                | 5         | 182+/-3         | 26.3+/-1       | 40                    | 15                    |

Table 4: Welding parameters in each welding pass for DP-GMAW process

| S. No. | Weld layer | Weld pass | Heat input (kJ/cm²) | WFR m/min | Mean current, A | Arc voltage, V | Travel speed, cm/min | Stand of distance, mm |
|--------|------------|-----------|---------------------|-----------|-----------------|----------------|-----------------------|-----------------------|
| 1      | 1          | 1         | 5.431               | 6         | 170+/-2         | 21.3+/-1       | 40                    | 15                    |
| 2      | 2          | 2         | 6.3                 | 6.5       | 190+/-2         | 22.1+/-1       | 40                    | 15                    |
| 3      | 3          | 3         | 5.7                 | 6.5       | 188+/-2         | 20.2+/-1       | 40                    | 15                    |
| 4      | 3          | 4         | 5.6                 | 6.5       | 186+/-3         | 20.1+/-1       | 40                    | 15                    |
| 5      | 4          | 5         | 5.64                | 6.5       | 190+/-2         | 19.8+/-1       | 40                    | 15                    |
| 6      | 4          | 6         | 5.4                 | 6.5       | 187+/-3         | 19.3+/-1       | 40                    | 15                    |
| 7      | 4          | 7         | 5.67                | 6.5       | 188+/-2         | 20.1+/-1       | 40                    | 15                    |

the fused metal zone. The macro images were taken at a 6.7X magnification, and microstructures are taken using optical microscope.

2.4. Mechanical characterization tests
The mechanical characterisation of the welded samples were performed through transverse tensile testing, charpy test, and Vickers hardness test. Transverse tensile testing was performed on all the welded samples prepared as per ASTM E8 standards [6] with weld bead at the middle of parallel length. The strain rate for the tensile testing was set to at 1 mm/min. The charpy V notch (CVN) impact testing was done after the completion of the welding. The CVN test provides information about behaviour of
metal when subjected to a single application of a load resulting in multiaxial stresses associated with a notch coupled with high rates of loading. The specimen preparation and test procedure for the CVN test was done following ASTM E23 standards [7]. Further, the hardness values of base metal, heat affected zone and weld metal was calculated using Vickers hardness method at load 10 kg.

2.5. Corrosion testing

Corrosion resistance of the austenitic stainless steel occurs due to the presence of thin chromium oxide layer on the surface of the material [8]. The corrosion testing of the welded samples were performed by two methods, namely, immersion testing and electrochemical corrosion testing. During immersion testing method, small sections of the material are exposed to the test medium and the loss of weight of the material is measured over a period of time. In the present experiment the base metal and weld metals are cut separately and are suspended into the corrosion medium. The corrosion environments selected for the study are 3.5% NaCl, 1% KOH and 1% HCl solution due broad-spectrum existence in industrial zones [8-10]. The weight losses were measured regularly and tabulated. Further, the graphs of weight loss vs duration of experiment was plotted as per ASTM G31 standard [11]. The corrosion rates (CR) were calculated from the Eq. 1 [11], where K-constant (8.76 X 10^4 for CR in mm/year), T-time of exposure in hours, A-area in cm², W-mass loss in grams and D-density in gram/cm³.

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\text{Corrosion rate} = \frac{KW}{ATD}
\]  

During electrochemical corrosion testing, the weld metal was separated from the base metal by coating paint over the base metal. The exposed area for corrosion testing is 0.36 cm². The rest potential selected was between -300mV to -600 mV. The specimen was then suspended over the solution exposing only the cross section of the weld metal with the solution. An electric potential was then applied across the welded specimen. An accelerating electrode was also placed in the solution to accelerate the electrochemical test. The solution considered were of 3.5 % NaCl, 1 % KOH and 1 % HCl. Further, the corrosion rate was calculated and compared from the Tafel plot [12].

3. Results and discussion

3.1. Chemical composition

The chemical composition of base metal, filler wire and weld joint prepared by SMAW, P-GMAW, DP-GMAW determined through vacuum emission spectroscopy are tabulated in Table 5. It was found that the chemical composition of SMA welded region and the E310 filler wire were similar. The loss of composition due to the vaporization effect was compensated by the diffusion effect because of high heat input in SMAW process. Even though the electrode used for P-GMAW and DP-GMAW processes were of same composition, the DP-GMAW process showed low values of Cr and Ni equivalent. This observation was also attributed to the vaporization effect during welding process. The high heat input dilution effect occurred for P-GMAW process whereas heat input was lower in case of DP-GMAW process. Hence, it was concluded that the dilution effect had insignificant role in the modifying chemical composition of the weld.

3.2. Macrographs and micrographs of weldment

Radiographic testing of all the three welded samples were taken, and corresponding macro images are shown in Fig. 3. The figures indicated that all the welded samples are free from any defects. The micro images of the base metal at different magnifications shown in the Fig. 4a shows the number of twin lines in the base metal regions. Figs 4b, c, and d shows the typical weld metal microstructure formed for SMAW, P-GMAW and DP-GMAW processes, respectively. The microstructure images with lower magnification is also shown as inset for reference. It was observed that P-GMAW and DP-GMAW process showed more refined grain structure compared to the SMAW process. The dendrite refinement
Table 5 Chemical composition test results

| Materials     | C   | Si  | Mn  | Cr  | Ni  | P   | S   | Cr eq | Ni eq |
|---------------|-----|-----|-----|-----|-----|-----|-----|-------|-------|
| Base Metal    | 0.026 | 1.284 | 1.489 | 25.06 | 19.746 | 0.025 | 0.01 | 26.986 | 21.271 |
| Electrode/    | 0.042 | 0.620 | 1.650 | 25.51 | 19.740 | 0.025 | 0.01 | 26.44  | 22.965 |
| Filler Metal  | 0.05  | 0.350 | 1.804 | 24.505 | 13.913 | 0.023 | 0.01 | 25.03  | 16.315 |
| SMAW          | 0.04  | 0.614 | 1.637 | 25.498 | 19.194 | 0.024 | 0.01 | 26.498 | 22.173 |
| P-GMAW        | 0.025 | 0.345 | 1.806 | 24.345 | 13.923 | 0.023 | 0.01 | 24.863 | 15.576 |
| DP-GMAW       | 0.04  | 0.302 | 1.72  | 22.662 | 12.977 | 0.023 | 0.01 | 23.662 | 15.037 |

**Figure 3** Macro images of (a) SMAW, (b) P-GMAW and (c) DP-GMAW weld

was uniformly distributed throughout the weld joint for DP-GMAW process, whereas dendrite refinement occurs in some areas in case of P-GMAW process. Also, the dendrite refinement was much lower for P-GMAW process. A finer grained microstructure was observed for DP-GMAW sample as the thermal pulsation induced frequent stirring of weld pool during the welding process (Fig. 4d).

### 3.3. Mechanical Testing

The tensile samples after testing is shown in Fig. 5 demonstrates the failure locations for each welded samples. During the tensile testing, the SMAW specimen failed in the weld metal whereas base material failure was observed for P-GMAW and DP-GMAW specimens. The ultimate tensile strength (UTS) obtained and Charpy impact energy for all the welded samples are compared in Table 6. The highest value of UTS (560 MPa), and impact energy (49 J) was recorded for DP-GMAW sample. Moreover, the Vickers hardness profile across the weld shown in Fig. 6 also revealed the better hardness trend of DP-GMAW sample. The increased values of mechanical parameters evaluated were attributed to the fine grained microstructure in DP-GMAW (Fig. 4) as compared with P-GMAW and SMAW processes [13].

### 3.4. Corrosion behavior of the welds

The laboratory immersion corrosion rate values using different medium, i.e. 3.5% NaCl, 1% KOH and 1% HCl solutions, are shown in the Fig. 7a, b and c respectively. The plots of potentiodynamic polarisation (PDP) behaviours of the AISI 310 (base metal), SMAW, P-GMAW and DP-SMAW welds under different corrosion testing medium are also given in the Fig. 8. The corresponding Icorr and corrosion rate for three weld sample are tabulated in Tables 7. It was observed that the corrosion rate was maximum for DP-GMAW sample for all the three corrosion medium whereas it was almost same for both base metal and SMAW sample. In laboratory immersion testing, the corrosion rate was minimum for base metal in 3.5% NaCl solution and the maximum value was 0.32 mm/year for DP-GMAW sample. For 1% KOH solution, corrosion rate was maximum for DP-GMAW process with a maximum value of 0.15 mm/year. Minimum corrosion in this solution occurred for base metal. The
Figure 4 Micro images at lower magnification (200X, shown as inset) and higher magnification (500X, main image) of (a) base metal, and weld obtained after (b) SMAW, (c) P-GMAW, and (d) DP-GMAW processes

Figure 5 Photographs showing the fracture location of weld joint after tensile testing of (a) SMAW (b) P-GMAW and (c) DP-GMAW samples

Table 6 UTS and position of fracture from tensile test and Charpy impact test results

| Process/Metal | UTS in MPa | Position of fracture | Impact energy in Joules |
|--------------|------------|----------------------|------------------------|
| SMAW         | 490        | WM                   | 44                     |
| P-GMAW       | 516        | BM                   | 44                     |
| DP-GMAW      | 560        | BM                   | 49                     |
| Base metal   | 515-550    | ----                 | 34                     |

corrosion behaviour under 1% HCl solution was the same as that of the 3.5% NaCl and 1% KOH solution, and the maximum value of corrosion rate (0.27 mm/year) was observed for DP-GMAW sample. As observed from Fig. 7, the corrosion rate was maximum between 48 to 72 hours in all the medium which was due to the breakage of primary layer which resists the initial corrosion. The PDP test using conventional electrochemical setup and using different electrolytes also revealed similar result as that of laboratory immersion testing. The Icorr value was minimum for base material when compared
Figure 6 Vickers hardness profile across the weld for different welding processes.

Table 7 Electrochemical data for base metal and weld metal at 3.5% NaCl, 1% KOH and 1% HCl

| Solution/Samples | BM   | SMAW | P-GMAW | DP-GMAW |
|------------------|------|------|--------|---------|
| (a) 3.5 % NaCl   |      |      |        |         |
| Icorr (mA/cm²)   | 0.01992 | 0.03922 | 0.12376 | 0.20137 |
| Corr. Rate (mm/year) | 0.21313 | 0.41966 | 1.324 | 2.1547 |
| (b) 1% KOH       |      |      |        |         |
| Icorr (mA/cm²)   | 0.33727 | 0.46379 | 0.56657 | 0.69313 |
| Corr. Rate (mm/year) | 3.6088 | 4.9625 | 6.0623 | 7.4165 |
| (c) 1% HCl       |      |      |        |         |
| Icorr (mA/cm²)   | 0.24053 | 0.31719 | 0.59931 | 0.63978 |
| Corr. Rate (mm/year) | 2.5737 | 3.3939 | 6.4126 | 6.8457 |

Figure 7 Graph of corrosion rate (mm/year) vs duration in (a) 3.5% NaCl, (b) 1% KOH, and (c) 1% HCl solutions
Figure 8 Potentio-dynamic polarization curves recorded in (a) 3.5 % NaCl, (b) 1% KOH, and (c) 1% HCl solutions to the welded specimens under all three electrolytes. The maximum Icorr value was observed for DP-GMAW process in all the three electrolytes. As per the chemical analysis in Table 5, DP-GMAW process has the minimum Chromium and Nickel content. There was a reduction 9.56 % chromium content DP-GMAW welded sample as compared to base material. Also, this process has the lower heat input as compared to P-GMAW process. Both these effects resulted in higher corrosion rate of DP-GMAW sample than P-GMAW and SMAW samples.

4. Conclusion
In this work, AISI 310 Plate were welded using SMAW, P-GMAW and DP-GMAW welding processes. The mechanical, metallurgical and corrosion properties of the base material and all the three welded samples. The major conclusions derived from are listed below.

a. Chemical analysis of the welded samples shows that there is 9.56% lowering of Chromium content in DP-GMAW process in compared to base material because of the thermal pulsation and vaporization effect.

b. The metallurgical analysis using optical microscopy shows that the DP-GMAW process has the fine grained microstructure compared to other welded samples and base material because of the thermal pulsation that induced a stirring action on the molten weld pool.

c. Hardness profile and Charpy impact testing results showed that the DP-GMAW process was superior to other welding processes because of the development of finer grains.

d. Even though DP-GMAW has excellent in mechanical properties, laboratory immersion testing and PDP results shows that it has a higher corrosion rate when compared to other two welding processes because of relatively low Chromium content and heat input.
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