Effects of pulsing current and filler materials on the mechanical and metallurgical properties of DSS 2205 weldments

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Abstract. The control of balance in austenite to ferrite ratio of duplex stainless steel (2205) during welding is critical due to not choosing the optimum heat input and cooling rate and welding processes, which leads to the development of embrittlement of intermetallic precipitates in the weldment. Further, the imbalance of austenite to ferrite ratio primes the stress corrosion cracking (ferrite < 25 %), low impact toughness and corrosion resistance (ferrite > 75 %). The pulse current gas tungsten arc (PCGTA) welding has utilized to weld the DSS 2205 using ERNiCrMo-3 and ERNiCrMo-4 fillers for better control of austenite to ferrite ratio. The tensile strength of Mo-3 weldment is 4.06 % higher than Mo-4. Besides, the Mo-3 weldment also provided the enhanced impact toughness and microhardness compared to Mo-4. The macrographs show similar weld bead width. The microstructure of both fillers Mo-3 & Mo-4 confirmed columnar structure at the weld interface and the finer equiaxed structure at weld center. The scanning electron microscope along with energy dispersive spectroscopy assured the absence of Cr2N, Chi and sigma phases. The PCGTA of DSS 2205 with Mo-3 is giving the improved properties with respect to Mo-4.

1. Introduction

Duplex stainless steel (DSS) is basically a two phased alloy which has equal amount of austenitic and ferritic structures. Typical chemical composition consists Cr-25% and Ni-5%. Cr plays an important role in increasing the strength, corrosion resistance and wear resistance. Owing to its high strength, the machinability of this grade in general is quite low. Ni helps to get an equalized microstructure in DSS as it stabilizes an austenite phase. The anticorrosive properties of DSS 2205 (better than grade 316) allow it to be used in several marine applications, both onshore and offshore. DSS has played a crucial role in making of marine structures and machinery for the last decade. Its important usage lies in constructing gas pipelines, ocean-based machinery and to contain different kinds of chemicals. DSS is a very popular material to be used where Ferritic and Austenitic grade properties are needed. When compared the yields strength of DSS 2205 is around 2-3 times greater than commercial austenitic

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stainless steel (ASS) grades. One of the economic advantages of using DSS is that, used at low thickness as compared to other grades, which in turn helps in weight reduction and the cost as well without compromising the strength of material.

The welded duplex steel has found many applications in the marine projects, heat exchangers, reactors etc. The reason behind this is that the constituents of our filler materials offer excellent strength, wear resistance and anti-corrosive properties. Vinoth Jebaraj et al. [1] studied different properties of DSS 2205 having several marine applications with reference to DSS’s machinability, surfaced and weldability. Various kinds of solid-state and fusion welding processes on joining DSS 2205 were studied. The changes occurring in the microstructure during cooling process was studied along with the transformations occurring in the heat affected zone (HAZ). These results were compared between different welding processes. Also, a comparison was made between DSS 2205 and other commercial ASS grade materials on the basis of machinability. Vinoth Jebaraj et al. [2] studied the change in microstructures effect on the weldment and base metal’s impact toughness. DSS 2205 was taken for this research. Gas tungsten arc welding (GTAW) was carried out on DSS 2205 and the ferrite to austenite ratio was assessed in the HAZ and the base metal. Changes in the impact toughness upon heat treatment processes were also studied. When heated at 1050 °C for about 1 hr, the austenite phases were found to be nucleated which in turn enhanced the value of impact toughness. But increasing the temperature beyond 1050 °C witnessed a high reduction in the value of impact toughness which was because of incomplete dissolution of the sigma phase in the microstructure observed. Elsaady et al. [3] evaluated the effects of pitting corrosion on DSS 2205 which was welded using ER 2209 filler material. The welded DSS sample went through pitting corrosion tests as well as the microstructural examination. Four critical temperatures were found for the DSS weld, with reference to pitting corrosion- Severe pitting corrosion and maximum metal loss was found to be occurring at 850 °C. Very less pitting corrosion was observed at a temperature of 1050 °C since at this temperature complete dissolution occurs. The pitting corrosion was reencountered when the heating was extended to above 1050 °C, due to ferritic structures growth. Daniela Ramminger Pissanti et al. [4] studied the microstructural changes over the welded cross section of UNS S32205 Duplex stainless steel and assess the Charpy impact toughness of various regions formed for the pipeline girth friction welding. The results showed that major microstructural changes were observed at the weld interface due to very high temperature and plastic deformation. The impact toughness drop was observed in this region because of changes in austenite morphology and enormous ferrite grain growth. Emami et al. [5] examined the microstructural evolution of SAF 2205 duplex stainless steel using friction stir welding at 50 mm/min and 400 rpm using optical microscope and scanning tunneling microscope. The observations showed refined grains and plain shear texture specimens had been formed in every constituent phase of ferrite and austenite. Also, recrystallization texture components of cube were observed in austenite phase. Shuwan Cui et al. [6] inspected the microstructure, grain boundary misorientation angle distribution (GBMAD), grain size of the duplex stainless-steel plates 10.8 mm thick welded using keyhole tungsten inert gas (K-TIG) welding to characterize the impact toughness of the weld metal. Performed Charpy tests showed that the impact absorbed energy (IAE) of the weld metal improves with the heat supply. Also, the results proved that the impact energy of the weld metal improved with the increase in austenite volume fraction.

Satishkumar and Manikandan [7–9] studied the preclusion of microsegregation occurring in the aerospace grade Hastelloy X. GTAW and pulsed gas tungsten arc welding (PCGTAW) processes were used along with the filler wires ERNiCrMo-2, ERNiCrCoMo-1, and ERNiCr-3. SEM was used to study the microstructures of the weldments. The EDS analysis showed that PCGTAW was successful in removing the microsegregation caused by Cr precipitate. The XRD analysis showed that Molybdenum rich carbide phase is present in GTAW while NiCrCoMo phase was observed in PCGTAW. The tensile results of the PCGTAW samples gave better results than that of GTAW samples. Chennaiah MB et al. [10] studied the advantages of PCGTAW welding by observing the parameters on the microstructures of Aluminium 6061 alloy. Optical metallography along with micro-hardness tests were conducted for the study. The research showed that finer grains were produced in the welding when the duration of the
pulse was short keeping pulse frequency constant. Also increasing the heat input reduces the frequency of the pulse which in turn makes grains finer. Keeping the frequency of pulse as constant, lower peak currents produced finer grains as compared to that of higher peak currents. From the studies it is identified that very scarce work on the effect of heat supply on microstructure and tensile properties of PCGTA on DSS have been reported. Hence it is considered to be important and current study would be beneficial in gaining the performance of welded plates using various inputs. In this study, welding has to be carried out using two different filler materials such as ERNiCrMo-3 and ERNiCrMo-4 and main aim is to study the weldment’s mechanical properties so that the welded material can be used accordingly. The project aims to investigate the welding properties of Duplex stainless steel (DSS 2205) by using PCGTA welding to evaluate the mechanical, metallurgical properties of the weldment.

2. Materials and Methodology

Initially the plates were cut using Wire cut EDM (Electrical discharge machine) machine with dimensions 150 mm x 100 mm x 4 mm. The elemental composition of DSS 2205 is displayed in Table 1. The plates were then cleaned using Acetone and V grooves were made at the edges at an angle of 45°. The PCGTA Welding was performed using the filler wires ERNiCrMo-3 and ERNiCrMo-4 using KEMPPI 400 machine. The process parameters for the welded joint are pulsed currents between 90-130 A. Argon was used with the supply of 13 L/min for shielding. The peak current and base current as set in welding process were 130 A and 90 A. The total heat input (Equation 1) for ERNiCrMo-3 filler is 1.906 kJ/mm and for ERNiCrMo-4 is 1.817 kJ/mm (Table 2). The microstructure sample along with the tensile and impact samples were cut using the Wire Cut EDM Machine. The microstructure ample was mounted for microstructural examination. To reveal the microstructure an etchant made of Oxalic acid was used and electrolytic etching was performed. The sample was examined using the Optical microscope, scanning electron microscope (SEM), and change in microstructure was observed at the weldment region. Tensile test (ASTM E8), microhardness (E384) were performed then to gauge the strength of the weldment and determine the place of failure. Impact test (ASTM E23) was conducted using Charpy machine to find the impact energy of different specimens and further compare them to that of the base material.

\[
HI = \eta \times \frac{I_m \times V}{S_w} \left( \frac{kJ}{mm} \right)
\]  

(1)

Where, \( I_m \) = Mean Current (A), \( V \) = Voltage (V), \( \eta \) = Efficiency, \( S_w \) = Feed rate (mm/sec)

| Table 1. Chemical composition of DSS 2205 and filler materials |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Materials       | Cr  | Ni  | Mn  | Mo  | Fe  | W   | Nb  | Si  | N   | P   | S   | C   |
| DSS 2205        | 22.1| 5.2 | 1.8 | 3.4 | 66.3| -   | 0.8 | 0.2 | 0.03| 0.02| 0.03|
| ERNiCrMo-3      | 22.2| 64.1| 0.5 | 8.8 | 0.2 | 3.55| 0.5 | -   | 0.02| 0.015| 0.1 |
| ERNiCrMo-4      | 16.3| 56.9| 0.7 | 15.9| 5.7 | 3.5 | 0.08| -   | 0.04| 0.03| 0.02|
Table 2. Heat calculations of DSS 2205 weldment by PCGTAW

| Weldments   | Pass | Current (A) | Voltage (V) | Welding Speed ($S_w$) (mm/sec) | $I_m$ (A) | Heat Input (kJ/mm) | Total Heat Input (kJ/mm) |
|-------------|------|-------------|-------------|-------------------------------|----------|-------------------|--------------------------|
| PCGTA ERNiCrMo-3 | Root | $I_p = 130$ , $I_b = 90$ | 10.46       | 1.02                          | 110      | 0.0789            | 1.906                     |
| PCGTA ERNiCrMo-3 | First | $I_p = 130$ , $I_b = 90$ | 10.46       | 0.721                         | 110      | 0.1116            |                          |
| PCGTA ERNiCrMo-4 | Root | $I_p = 130$ , $I_b = 90$ | 10.6        | 1.064                         | 110      | 0.0767            | 1.817                     |
| PCGTA ERNiCrMo-4 | First | $I_p = 130$ , $I_b = 90$ | 10.6        | 0.777                         | 110      | 0.105             |                          |

3. Results and Discussion

3.1. Weld quality examination

The micrograph of the weldment joined by PCGTA welding technique with ERNiCrMo-3 and ERNiCrMo-4 is displayed in figure 1 (a & b). It has been confirmed from the figure that welding defects like solidification and liquation cracks, inclusion, porosity and lack of penetration are not found in weld zone as well as weld interface region. This confirmed optimum process parameters in both the filler wire condition. Further, both the weldment revealing the similar weld bead profile which is due to the larger thermal gradient and quicker cooling rate observed during welding.

3.2. Microstructure examination

The microstructure of the DSS 2205 metal is displayed in figure 2. It is clearly showing the presence of equal amount of austenite ($\gamma$) and ferrite ($\alpha$) element throughout the structure. The microstructure of DSS 2205 weldment joined with PCGTA ERNiCrMo-3 is displayed in figure 3 (a & b) and PCGTA ERNiCrMo-4 is displayed in figure 3 (c & d). The type of structure observed after welding is totally different from the base metal microstructure. The use of Ni enriched filler such as ERNiCrMo-3 and ERNiCrMo-4 produced the balanced microstructure. Vinoth jebaraj et al. [1] also reported the similar structure. Both ERNiCrMo-3 and ERNiCrMo-4 weldments are confirmed the columnar structure at the weld interface and equiaxed structure at the weld centre and. It also revealed no liquation cracks in the HAZ region. The similar kind of results are also observed by others [1,11].

Figure 1. Macrograph of DSS 2205 weldment; (a) PCGTA ERNiCrMo-3 (b) PCGTA ERNiCrMo-4
Figure 2. Microstructure of DSS 2205 (base metal)

Figure 3. Micrograph of DSS 2205 weldment by; (a) PCGTA ERNiCrMo-3 – Weld Centre (b) PCGTA ERNiCrMo-3 – Weld Interface (c) PCGTA ERNiCrMo-4 – Weld Centre (d) PCGTA ERNiCrMo-4 – Weld Interface
3.3. SEM/EDS analysis

The occurrence of the austenite and ferrite phases in the weldments are confirmed with SEM/EDS analysis. The results of both ERNiCrMo-3 and ERNiCrMo-4 fillers are displayed in figure 4. The occurrence of austenite phases in the grain boundaries of ferrite matrix at both weld centre and interface region. Also, the EDS composition at the dendritic core region of both ERNiCrMo-3 and ERNiCrMo-4 fillers at weld centre confirmed the more amount of Fe and less amount of Ni when compared to interdendritic region of the weldments (figure 4 (i-vi)). Further, the presence of more amount of Ni at interdendritic region confirmed the occurrence of austenite phase and similarly, the higher Fe elements in the dendritic region confirmed the ferrite phase. The sigma phase (tetragonal unit cell) occurs when Cr is more than 25 % and Mo of more than filler material and base metal but, in this study no sigma phase is found in all the specimens. The chi phases (cubic unit cell) occurs when Mo is more than 15 %, but this phase also not formed in the weldments. The similar kind of conclusion also stated by Elsaady et al. [3]. The presence of N in both filler materials are absent and this controls the development of Cr₂N phase in the weld centre and interface. This also confirmed with EDS values.

3.4. Tensile test analysis

The tensile testing has been carried out in three trails in order to obtain the repeatability and results are displayed in Table 3. PCGTA ERNiCrMo-3 is giving 3.90 % higher ultimate tensile strength value (UTS) compared to PCGTA ERNiCrMo-4. This is due to the presence of more amount of Ni and less amount of Fe in ERNiCrMo-3 filler stabilize the austenite phase than ferrite phase whereas, high Fe and low Ni in ERNiCrMo-4 stabilizes the ferrite phase than austenite. The failure occurred at the weld region for all the specimens. The presence of high austenite improves the tensile properties of PCGTA ERNiCrMo-3 compared to PCGTA ERNiCrMo-4. The ductility of both the weldments are more or less similar each other. The same observation also concluded by other researches [7,8].

| Table 3. Tensile strength analysis of DSS 2205 weldment by PCGTA |
|------------------|------------------|------------------|------------------|
| Weldments        | Trail            | UTS (MPa)        | Mean UTS (MPa)   |
|                  |                  |                  | Elongation (%)   | Mean Elongation (%) |
| Base Metal       | Trail 1          | 815              | 49.8             |                    |
|                  | Trail 2          | 818              | 45.9             | 45.9               |
|                  | Trail 3          | 813              | 41.9             |                    |
| PCGTA ERNiCrMo-3 | Trail 1          | 747              | 14.5             |                    |
|                  | Trail 2          | 746              | 16.2             | 14.1               |
|                  | Trail 3          | 743              | 14.6             |                    |
| PCGTA ERNiCrMo-4 | Trail 1          | 714              | 13.9             |                    |
|                  | Trail 2          | 729              | 14.5             | 15.3               |
|                  | Trail 3          | 714              | 14.4             |                    |
Figure 4. SEM Photographs of DSS 2205 weldment by: (a) PCGTA ERNiCrMo-3 – Weld centre ((i) EDS dendritic core, (ii) EDS interdendritic) (b) PCGTA ERNiCrMo-3 – Weld Interface ((iii) EDS interdendritic) (c) PCGTA ERNiCrMo-4 – Weld Centre ((iv) EDS dendritic core, (v) EDS interdendritic) (d) PCGTA ERNiCrMo-4 – Weld Interface ((vi) EDS interdendritic)
3.5 Impact toughness and microhardness measurement

The results of impact toughness and microhardness of both PCGTA ERNiCrMo-3 and ERNiCrMo-4 is mentioned in Table 4. It is come to know that, the PCGTA ERNiCrMo-3 is providing 24.32 % and 6.94 % higher impact toughness and microhardness than PCGTA ERNiCrMo-4 respectively. The high austenite makes the material harder and increase the impact strength where ferrite makes the weldment to more ductile and decrease the impact toughness and microhardness of the weldments [12,13]. This is the reason for higher toughness and microhardness in PCGTA ERNiCrMo-3 than PCGTA ERNiCrMo-4. Many others suggested the similar results [1–3].

| Table 4. Mean microhardness and impact toughness of DSS 2205 weldment by PCGTAW |
|----------------------------------------|----------|----------|----------|----------------|----------------|
| Weldments | Impact energy (J) | Microhardness (HV) | | | |
| Base Metal | Trail 1 | Trail 2 | Trail 3 | Mean | Mean |
| PCGTA ERNiCrMo-3 | 35 | 39 | 37 | 37 | 288 |
| PCGTA ERNiCrMo-4 | 25 | 31 | 29 | 28 | 268 |

4. Conclusions

1. The welding of DSS 2205 has been successfully performed using ERNiCrMo-3 and ERNiCrMo-4 filler in PCGTA welding condition.
2. The macrostructure revealed the similar weld bead size in both the weldment and it is due to low heat input provided in both weldments.
3. The microstructure confirmed the presence of ferrite and austenite structure in both weldments.
4. SEM/EDS analysis confirmed the more ferrite phase in weld dendritic core region compared to weld interdendritic region which shown higher austenite phase. Further, the presence of sigma, chi and Cr2N phases are not found in all the weldments.
5. The PCGTA ERNiCrMo-3 filler is giving 3.90 %, 24.32 % and 6.94 % higher tensile strength, impact toughness and microhardness than PCGTA ERNiCrMo-4 respectively. The presence of high austenite in PCGTA ERNiCrMo-3 is the reason for higher strength.

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