Improvement of hot corrosion resistance of dissimilar weldments by current pulsing in a simulated power plant environment

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Abstract. Hot corrosion studies are of utmost importance for welded components in the power plant industry as well as for industries which deal with exposure to the high-temperature corrosive environment. The failure of welded components at high temperatures has often led to the reduced service life of a component and catastrophic disasters. This has been a significant engineering challenge in the design of welded components. It is generally seen that the failure of the welded sections mostly occurs because of the deposition of molten salt over the weldments which accelerate the hot corrosion reactions. In this present research work, two dissimilar base materials, AISI 4340 and AISI 304L have been welded with two different welding processes namely continuous current gas tungsten arc welding (CCGTAW) and pulsed current gas tungsten arc welding (PCGTAW) while making use of ERNiCr-3 as filler material. A comparative study of the dissimilar welded plates was carried out by simulating a molten salt environment at 600°C involving hot corrosion behavior. By analyzing the microstructure and thermo-gravimetric data, it is concluded that the pulsed current gas tungsten arc welding process has superior corrosion resistance properties while using ERNiCr-3 as the filler material as compared to the continuous current gas tungsten arc welding process.

Keywords: Dissimilar weldments; Weldment corrosion; Hot corrosion; Thermogravimetric analysis

1. Introduction

AISI 304L austenitic stainless steel has electric industrial applications in power plants, aerospace and chemical industries owing to its excellent weldability, excellent corrosion resistance, and high-temperature strength while on the other hand AISI 4340 finds its application in the design of aerospace components such as landing gear. Due to their high impact strength and superior fatigue properties, these steels are also preferred to manufacture components pertaining to aerospace, nuclear
and defense applications. Due to design constraints and industrial applications yielding to design flexibility, dissimilar welding processes are employed which make the joining of two dissimilar weldments possible. Several industrial applications need welding of dissimilar joints because of its economic benefits [1-2]. Joining materials with different elemental compositions pose a challenging task, since they have a huge variation in the co-efficient of thermal expansion and thermal conductivity. Even if successful joint is made between them, the metallurgical, mechanical and corrosion properties will be inferior and a detailed study of each dissimilar joint in its environmental condition is of paramount importance to analyse the service life of the joints. One of the important ways to improve these properties is the selection of proper joining processes and welding filler rod. However, dissimilar weldments tend to fail at high temperatures because of the aggressive corrosive nature of the industrial environments. The hot corrosion of these dissimilar joints exposed to chlorine is unfavorable for the service life of power plant components, where the fuel comprises of coal which contains chlorides [3-4].

Various researchers have reported the failure of components in these service conditions [5]. Failure is generally observed in the weld zone since most of the times it is inferior to the base material. The morphology of the weldment undergoes a transformation on exposure to high-temperature conditions. Recent advances in research on high-temperature corrosion primarily focus on the correlation of the service life failure of operational welded joints to the degradation of microstructural properties during welding [5-6]. It has been stated that the highest operational temperature of welded joints of the existing materials employed in the power plants are below 600°C [7]. The hot corrosion effects are more aggressive at 600°C because of the high sulphidation tendency which is caused due to generation of low-melting alkali sulphate of eutectic mixtures [8-9]. By studying the past research works, it can be said that the dissimilar joints of AISI 304L and AISI 4340 are used in wide ranging corrosive environments. Therefore, it is of utmost importance to study the hot corrosion properties of these joints at elevated temperatures. Also, various researchers have reported that the Pulsed Current Gas Tungsten Arc Welding (PCGTA) methods deliver higher cooling rates and shorter solidification times which support enhanced weld mechanical properties than the continuous current gas tungsten (CCGTA) welding [10-11]. However, reports related to the systematic investigation of dissimilar weldment corrosion resistance employing these welding techniques using different filler wire materials are not available at present.

In this research work, CCGTA and PCGTA welding processes were employed using ERNiCr-3 as the filler material. The hot corrosion studies were carried out in a molten salt environment of K$_2$SO$_4$ + 60% NaCl at 600°C to simulate a power plant environment as pointed out by Neilsen. The objective of this work is to identify and compare the two welding processes (CCGTA and PCGTA) and conclude which one of them is better suitable for the filler material being used (ERNiCr-3) for the welding processes. The corrosive behaviour on the weldments was analysed extensively using SEM/EDS and XRD to provide a brief report about the extent of the corrosive reaction on the weldment.

2. Experimental procedure

2.1 Specimen preparation

For proceeding with the experiment, two dissimilar base metal plates of AISI 304L stainless steel and AISI 4340 aeronautical steel were taken. The two dissimilar plates were then joined by GTA welding process using continuous and pulsed current mode by using ERNiCr-3 as the filler material. The elemental composition of the parent materials used for this experiment is listed in Table 1. The macrographs of the weldments were taken, and the root dimensions were measured which is shown in Figure 1. Successful dissimilar joints of these materials were obtained by continuous current gas tungsten arc welding (CCGTA) process and pulsed current gas tungsten arc welding (PCGTA) process.
Table 1 Elemental composition of the parent material

| Base metal | C   | Si  | Mn  | Cr  | Ni  | Mo  | Fe  |
|------------|-----|-----|-----|-----|-----|-----|-----|
| AISI 4340  | 0.31| 0.23| 0.64| 0.98| 1.34| 0.23| Bal.|
| AISI 304L  | 0.037| 0.46| 0.95| 19.14| 8.35| 0.17| Bal.|

Figure 1. Macrographs of dissimilar weldments of AISI 304L and AISI 4340 welded using (a) CCGTA-ERNiCr-3; (b) PCGTA-ERNiCr-3

2.2 Hot corrosion

Cyclic hot corrosion studies were carried out on samples (30 × 15 × 5 mm) which were cut out from the dissimilar weldments of AISI 304L and AISI 4340 using a wire cut electrical discharge machine (EDM). The samples were polished using emery paper of 400, 600 and 1000 grit size. A eutectic solution of K$_2$SO$_4$ and 60% NaCl salt was applied over the entire surface of the hot corrosion study sample to simulate a corrosive environment. The surface density of the salt layer was measured to be around 3-5 mg cm$^{-2}$. The samples were preheated to 200°C to remove any residual moisture before subjecting them to the cyclic hot corrosion tests. For each cycle, the sample was put in a hot tubular furnace and subjected at 600°C for 1 hour continuously. It was immediately followed by cooling the sample at room temperature for 20 mins. The change in weight of the sample was then recorded using an electronic analytical weighing balance to carry out the thermo-gravimetric analysis further and find out the corrosion rate. This whole process was repeated for 50 cycles (Figure 5 (a) and 5 (b)) to get an extensive data set for investigation of the hot corrosion behavior. Metallurgical characterization of the hot corroded samples after the 50 cycles was executed using a scanning electron microscope (SEM), energy dispersive spectroscopy (EDS) and analyzing the spalled off corrosion products using X-Ray Diffraction (XRD) as well.
3. Results and discussions

3.1 Microstructure

In the CCGTA welding process, the microstructures were observed to exhibit d-ferrite clusters with a well-defined weld interface at the heat affected zone in the AISI 304L region (Figure 2-a). The weld-zone can be perceived to be austenitic. Cellular structures can be observed in the weld-zone along-with the presence of martensitic grain boundaries adjacent to the weld interface. While on the other hand, the AISI 4340 region (Figure 2-c) exhibited a prominent martensitic phase along-with dispersed carbides. In the PCGTA welding process, the microstructures showed similar d-ferrite clusters as that in the CCGTA welding process around the AISI 304L region. However, the weld zone in the PCGTA welding process showed the presence of very fine equiaxed grain growth (Figure 3-b) which can be cited as a reason for the improvement of corrosion resistance properties [2, 10]. The AISI 4340 region showed similar martensitic phase as that in the CCGTA welding process along-with dark dispersed carbides [2].

![Figure 2. Microstructure of CCGTAW AISI 4340 and AISI 304L welded with ERNiCr-3 filler wire a) Interface between AISI 304L and weld b) CCGTAW ERNiCr-3 weld zone c) Interface between weld and AISI 4340](image1)

![Figure 3. Microstructure of PCGTAW AISI 4340 and AISI 304L welded with ERNiCr-3 filler wire a) Interface between AISI 304L and weld b) PCGTAW ERNiCr-3 weld zone c) Interface between weld and AISI 4340](image2)

3.2 Hot corrosion

It can be visibly noticed to some extent that the weld-zone with the ERNiCr-3 filler material by the PCGTA welding process (Figure 4) has relatively minor corrosion aggravation than the weld zone by the CCGTA welding process (Figure 4) around the 30th cycle. In the 50th cycle, it can be distinctly noticed that the weld-zone in the PGGTA welding process has better corrosion resistance than CCGTA welding process.
Figure 4. Hot corroded dissimilar joints welded with CCGTA and PCGTA ERNiCr-3 filler (a) after polishing (b) after salt coating and at the end of (c) 10th cycle (d) 30th cycle (e) 50th cycle.

3.3 Thermo-gravimetric analysis

The corrosion kinetics for ERNiCr-3 filler wire is shown in Figure 5 (a) and (b). It is evident from the plot that it follows the parabolic rate law. A plot calculated the $K_p$ (parabolic rate constant) for weight gain square vs. time linear least-square algorithm to a function in the form of $(\Delta W/A)^2 = K_p \times t$. The corrosion rate ($K_p$) for the corresponding bimetallic joints employing CCGTA and PCGTA welding process was calculated to be $63.73 \times 10^{-2} \text{ mg}^2 \text{ cm}^{-4} \text{ s}^{-1}$ and $17.14 \times 10^{-2} \text{ mg}^2 \text{ cm}^{-4} \text{ s}^{-1}$. 
Figure 5. Plot of (a) cumulative weight gain as a function of time and (b) weight gain square Vs time for dissimilar joint between AISI 304L and AISI 4340 using ERNiCr-3

3.4 SEM/EDS

The SEM morphology of CCGTA sample has been shown in Figure 6. While observing the heat affected zone of the AISI 304L region, it was seen that the region had undergone significant corrosion and the corrosion products were discernible in the region. By analyzing Figure 6 (a) and (b), it can be said that the corrosion was uniform in both the Z1 and Z2 regions. However, it can be distinctively seen that the corrosion was more severe in the AISI 304L weld interface as compared to the weld interface of AISI 4340. From the EDS elemental composition, it was seen that AISI 4340 region had comparatively very less Cr content while it had the presence of a more significant amount of iron oxides as compared to that of the AISI 304L region.

The SEM morphology of PCGTA sample has been shown in Figure 7. Evidently, the corrosion products have reduced as compared to that of the CCGTA process. It is observed that the oxide grains over the weld-zone are fine-grained which was also observed in the microstructure image (Figure 3). High concentrations of Fe₂O₃ was found in the scales over the weld zone while the scales over the HAZ of the AISI 304L region chiefly consisted Cr₂O₃ [2].
Figure 6. SEM/EDS results of CCGTA ERNiCr-3 at interface between a) AISI 304L and weld zone; b) Weld zone and AISI 4340.

Figure 7. SEM/EDS results of PCGTAW ENiCr-3 at interface between a) AISI 304L and weld zone; b) Weld zone and AISI 4340.
3.5 XRD

The XRD pattern of the spalled off surface products from the weldments produced by both CCGTA and PCGTA welding processes on exposure to the molten salt environment have been shown in Figure 8. On analysis of the corrosion products that spall off after the hot corrosion studies, the following metal oxides were found to exist: Fe$_2$O$_3$, Cr$_2$O$_3$, FeCr$_2$O$_4$, NiFe$_2$O$_4$, and Cr$_2$NiO$_4$. The oxides of Si and Mn were also found to co-exist in the corrosion products, which are known to degrade the corrosion resistance properties. XRD revealed the presence of metallic chlorides such as FeCl$_2$, CrCl$_2$ and NiCl$_2$ on all the weldments [10].

![XRD analysis of peaks for the dissimilar AISI 4340 and AISI 304L hot corroded joint welded with ERNiCr-3 filler.](image)

Figure 8. XRD analysis of peaks for the dissimilar AISI 4340 and AISI 304L hot corroded joint welded with ERNiCr-3 filler.

4. Conclusions

After the comparative hot corrosion behavioral studies of the dissimilar weldments of AISI 304L and AISI 4340 welded by PCGTA and CCGTA processes while making use of ERNiCr-3 as the filler material, the following conclusions can be derived:

- A sound weld joint between AISI 4340 and AISI 304L by employing ERNiCr-3 filler was fabricated.
- The $K_p$ (corrosion rate) for the PGTA welding process ($17.14 \times 10^{-2} \text{ mg}^2 \text{ cm}^{-2} \text{ s}^{-1}$) was found to be less than the conventional current process ($63.73 \times 10^{-2} \text{ mg}^2 \text{ cm}^{-2} \text{ s}^{-1}$). This shows that corrosion resistance of the joints fabricated by pulsed current has better hot corrosion behavior.
- Oxides formed on the AISI-4340 was permeable and were spalling leading to severe corrosion and loss of material.
- A strong protective oxide layers of Cr$_2$O$_3$ and NiO were observed on the base material AISI-304L and the fusion zone.
- In a molten salt high-temperature environment, the corrosion resistance of pulsed current ERNiCr-3 weldment is more prominent than continuous current ERNiCr-3 weldment. The occurrence of fine equiaxed grains in the PCGTA ERNiCr-3 can be cited as a reason for superior corrosion resistance.
- The corrosion resistance and aggregate mechanical properties can be attributed to the use of ERNiCr-3 filler wire which is suitable for industrial applications making use of AISI 4340 and 304L in pulsed current mode.
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