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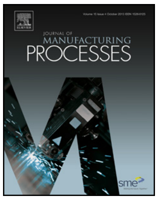

Technical Paper

Effects of filler metals on the segregation, mechanical properties and hot corrosion behaviour of pulsed current gas tungsten arc welded super-austenitic stainless steel

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ABSTRACT

Segregation of Mo is one of the most detrimental problems associated with the welding of super-austenitic stainless steels. The present study articulates the effects of fillers on the microstructure and mechanical properties of pulsed current gas tungsten arc (PCGTA) welded joints of AISI 904L. Four different fillers namely ERNiCrMo-4, ERNiCrMo-10, ERNiCrMo-14 and ERNiCu-7 were employed for joining 5 mm thick plates of AISI 904L. Efforts had been taken to investigate the effect of filler wires on the segregation of Mo in the fusion zone. Studies attested to the retention of Mo in the dendritic regions while employing Ni-Mo rich fillers. Evidently, Mo in the fusion zones was comparatively greater than that in the parent metal. Microstructure studies revealed the formation of unmixed zones at the weld interface while employing these fillers. Migrated grain boundaries were prominent in the fusion zone of ERNiCu-7 weldments. Tensile studies demonstrated that failures occurred at the parent metal of AISI 904L irrespective of fillers employed. Charpy V-notch studies showed that the impact toughness at the cap zones of the weldments was superior to the root regions for all the cases of the weldments. Also, the welded coupons were subjected to cyclic hot corrosion studies at 650 °C in a synthetic molten salt mixture containing K_2SO_4 + 60% NaCl for 50 cycles. The corrosion studies attested that the fusion zone employing ERNiCrMo-14 exhibited better corrosion resistance than the other fillers and also the parent metal employed in the study. Surface analytical techniques were employed to investigate the hot corroded species.

1. Introduction

Super-austenitic stainless steel (SASS) grade AISI 904L has been widely used in devising components for chemical and petrochemical, marine and offshore, paper and pulp industries, structural applications for heat exchangers, piping and desalination equipment [1–4]. AISI 904L is highly resistant towards pitting, crevice and chloride stress corrosion cracking due to the presence of higher amounts of Cr, Ni and Mo [5] compared to conventional austenitic stainless steels. In addition to better corrosion resistance, this alloy offers an excellent combination of strength, ductility and toughness. The presence of higher amounts of Ni ensures that this alloy remains a ferrite free austenitic stainless steel having a face centred cubic (FCC) crystal structure even at sub-zero temperatures so that the impact properties are retained and hence suitable for use in cryogenic applications [6–8].

Although AISI 904L is easily weldable and formable, one of the major problems reported during welding of AISI 904L is the segregation of Mo rich phases. It was reported that during solidification of the weld, Mo segregates preferentially to the liquid, due to lower solubility of Mo in the austenitic (γ) phase. This micro-segregation of Mo solute results in the formation of Mo-depleted dendrite cores that could reduce the mechanical properties as well as develop a greater susceptibility to localized corrosion [9]. In general, over alloyed filler metals are preferred which could compensate for the loss of alloying elements, occurring due to the high heat inputs during welding, in turn protecting the local area which has a lesser composition due to the segregation in the welds.

Studies have been conducted to investigate the selection of fillers in the welding of super-austenitic stainless steels. Lippold and Kotecki [10] recommended the use of Mo rich-Ni based filler metals to improve the pitting corrosion resistance of AISI 904L. The authors claimed that a filler wire with at least 9% Mo was essential

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to match the pitting resistance of 6% Mo base metals. Similarly, Banovic et al. [11] reported the use of Mo rich-Ni based filler metals namely IN 625 (~9 wt.% Mo) and IN 622 (~14 wt.% Mo) fillers to circumvent the problem of segregation during gas tungsten arc welding of super-austenitic stainless steel. However, it was noticed that micro-segregation of Mo was not completely eliminated with the use of these fillers. Anderson et al. [12] reported that a ferritic solidification mode and subsequent solid state transformation from ferrite to austenite would minimize micro-segregation during solidification due to elevated diffusion rates. Further, the welds that solidified as primary ferrite were extremely resistant to cracking. In a research work carried out by du Toit [13], the author investigated 10 mm thick joints of super-austenitic stainless steel obtained from gas metal arc-welding (GMAW) and flux cored arc welding (FCAW) processes employing ER2209, ER307 and 15CrMn fillers. The authors observed formation of delta ferrite as the leading phase in the fusion zones of ER2209 and ER307 welds, which in turn contributed to better hot cracking resistance. There are several advantages reported regarding the presence of delta ferrite in the fusion zone. However, exposure to high temperature results in the transformation of δ-ferrite into brittle intermetallic phases, such as σ (sigma), carbide and χ (chi), at temperatures ranging from 500 to 850 °C for σ and 650 to 950 °C for χ. The precipitation rate for σ and χ phases increases with the chromium and molybdenum contents [14]. Raffi Mohammed et al. [15] observed lower pitting corrosion resistance in the weld metal interface of a high nitrogen stainless steel which was due to the presence of 3.7% delta ferrite. The authors inferred that the potential difference between ferrite and austenite and the distribution of ferrite as continuous network caused the galvanic interaction between austenite and delta ferrite interface.

Pulsed current gas tungsten arc welding (PCGTAW) is a variant of the gas tungsten arc welding (GTAW) process, which attracted researchers owing to its several advantages attained in terms of improved mechanical properties and corrosion resistance due to controlled heat input. Researchers observed an improvement in tensile strength [16–18] and minimized segregation levels while employing PCGTA welding for joining nickel based super-alloys [19–21], stainless steels [22,23], titanium alloys [24], etc. Shinoda et al. [25] carried out comparative studies on austenitic stainless steel welds obtained from continuous current GTA (CCGTA) and PCGTA welding processes. Due to moderate cooling rates experienced in PCGTAW, the authors experienced grain refinement, lower segregation and also improved solidification cracking in the PCGTA welds. Yousefieh et al. [26] concluded in their studies that optimized heat inputs during PCGTA welding resulted in better corrosion resistance of duplex stainless steel and also reduced the formation of deleterious phases in the fusion zone.

Hot corrosion is the degradation of metals and alloys owing to an oxidation process, which is affected by a liquid salt deposit. Low-grade fuels with high concentrations of sulfur, potassium and sodium are widely used in oil and coal fired power generation. During combustion, alkali metal sulphate vapours combine with other ash constituents that deposit onto the component surfaces. Similarly, boilers and other components exposed in off-shore industrial rigs undergo hot corrosion when the sodium chloride from the ocean breeze mixes with K_2SO_4 from the fuel. This forms molten deposits on the hot-sections of the metal surfaces through condensation of volatile compounds present in the gas stream. These deposits produce aggressive conditions leading to rapid corrosion of weldments due to oxidation, sulfidation, and chloridation.

Tsaur [27] investigated the hot corrosion of 310 stainless steel in Na_2SO_4/NaCl mixture at 750 °C. The authors reported that addition of 10% NaCl in Na_2SO_4 coatings can easily cause cracking of the protective Cr_2O_3 layers and increase the amount of sulfur incorporated into the substrate, accelerating the corrosion of alloys. Ahila et al. [28] studied the hot corrosion behaviour of welded and unwelded 2.25 Cr-1 Mo steel exposed to K_2SO_4 + 60% NaCl at 650 °C. The authors observed formation of oxides in the uncoated coupons whereas oxides and sulphides were formed on the salt coated samples. The welds were prone to a higher degree of corrosion attack in this molten salt environment. Devendranath Ramkumar et al. [29] investigated the hot corrosion behaviour of dissimilar joints involving Monel 400 and AISI 304 subjected to cyclic air oxidation and to a K_2SO_4 + 60% NaCl molten salt environment at 600 °C. The authors recommended the use of Ni rich filler such as ERNiCu-7 which showed better resistance towards molten salt high temperature corrosion compared to the austenitic filler metal, ER309L used in the study.

It is evident from the earlier studies that AISI 904L exhibited better pitting and crevice corrosion resistance. However, the high temperature corrosion behaviour of AISI 904L welds has not been reported adequately. This paper addresses the investigations carried out to assess the performance of 5 mm thick PCGTA welded AISI 904L joints by using ERNiCrMo-4, ERNiCrMo-10, ERNiCrMo-14 and ERNiCu-7 fillers. The welded joints have been characterized for their metallurgical and mechanical properties. Further emphasis has also been laid on the high temperature corrosion behaviour of the weldments exposed to a synthetic molten salt environment containing K_2SO_4 + 60% NaCl at 650 °C for 50 cycles. The hot corrosion products have been systematically analyzed using X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy dispersive X-ray (EDAX) analysis. The outcomes of this specific study will be highly helpful to the end user operations involving AISI 904L welds.

2. Experimental procedure

2.1. Base metal and welding procedure

The base metal employed in the study was hot rolled AISI 904L of 5 mm thickness. The chemical composition analysis on the base metal was carried out by dry spectroscopic methods. The filler wires employed in the study were ERNiCrMo-4, ERNiCrMo-10, ERNiCrMo-14 and ERNiCu-7 of 1.6 mm diameter. The nominal chemical compositions of both the candidate and filler metals are shown in Table 1. The base metal has been investigated for its microstructure and mechanical properties that include tensile, impact and bend tests. The average tensile strength and impact toughness of AISI 904L in the unwelded, as-received condition was reported to be 685 MPa and 62 J respectively (Table 2). The selection of filler metals was done with the emphasis to minimize the

Table 1
Chemical composition of parent metal AISI 904L.

Base or filler metal	C	Si	Mn	Cr	Mo	Ni	Cu	Fe	Others
AISI 904L	0.019	0.365	1.39	20.3	4.1	23.11	1.26	Rem.	P – 0.017; S – 0.004
ERNiCrMo-4	0.02	0.03	0.41	15.90	16.25	Rem.	0.05	5.45	P – 0.007; S – 0.003; Al – 0.31; Ti – 0.10; Co – 0.18; V – 0.18; W – 3.4
ERNiCrMo-10	0.015	0.05	0.55	22.4	14.0	Rem.	0.2	2.5	P – 0.00001; S – 0.001; Co – 0.22; V – 0.01; W – 3.34
ERNiCrMo-14	0.01	0.02	0.8	21.3	15.4	Rem.	0.002	3.0	P – 0.0002; S – 0.001; Al – 0.30; Ti – 0.05; W – 4.0
ERNiCu-7	0.026	0.13	3.61	Nil	Nil	62.85	Rem.	0.53	P – 0.005; S – 0.004; Al – 0.10; Ti – 2.55