Applied Surface Science 389 (2016) 609–622

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Recommend design of filler metal to minimize carbon steel weld metal preferential corrosion in CO_2-saturated oilfield produced water

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ARTICLE INFO

Article history:
Received 13 June 2016
Received in revised form 23 July 2016
Accepted 25 July 2016
Available online 27 July 2016

Keywords:
Mild steel
Weight loss
XPS
Welding
Acid corrosion

ABSTRACT

The paper proposes a recommend design for the alloying elements in the filler metal to minimize preferential weld corrosion of carbon steel. The tensile and corrosion resistance properties of the weld metal are considerably improved by using a filler metal containing alloying elements according to the recommended design. Analysis of the morphology and composition of corrosion products on weld metals showed that the common weld metal suffered severe localized corrosion, whereas the weld metal with the alloying elements exhibited uniform corrosion. Based on these results, a tentative mechanism of CO_2 corrosion resistance for both weld metals has been proposed.

1. Introduction

Pipeline failures usually occur from pitting or galvanic corrosion of welds [1,2]. Corrosion failures are caused by the local differences in composition and microstructure of the weld metal and base metal [1,3,4]. Over 90% of corrosion failures for the transmission pipeline sector in the USA between 1970 and 1984 were due to localized pitting corrosion [5], and 36% of corrosion failures in petroleum-related industries are due to pitting and galvanic corrosion of weld metal [6]. Although many scholars have focused on the issue [7–12], they have not found a way to reduce pitting or galvanic corrosion of weld metals that causes pipeline failure [13–17]. Therefore, it is crucial to improve the corrosion resistance of weld metals.

Preferential weld corrosion (PWC) occurs mainly from galvanic effects due to local compositional and microstructural differences between the weld metal (WM), heat affected zone (HAZ), and base metal (BM) [7,8,18–20], and PWC has been a serious issue in the oil and gas industry for many years [8–12,21,22]. PWC is usually controlled by using filler materials with the addition of more noble elements such as nickel, chromium, molybdenum, copper, aluminium, and vanadium [8,12,23]. In 1941, Copson [24] found that Cu and Ni additions increased pore-plugging of the corrosion product for the structural steels. Meanwhile, Cu and Ni also helped these steels limit the formation of soluble ferric chloride. During the 1980s, the research was focused on the corrosion of carbon steel welds in weakly sour seawater pipelines, and it was found that the addition of up to 1% of nickel weld consumables can minimize PWC [8,10,25]. Although the practice is helpful in most cases, PWC has resulted in numerous incidents in various working environments [8,26]. Thus, much work has been conducted to investigate the relationship between chemical composition and PWC. In 1988, M.W. Joosten et al. [27] proposed the guidelines for the element content in the weld metal to prevent preferential weld corrosion, namely Cu (*wt.%*) > 0.05, Ni (*wt.%*) > 0.03, either Ni (*wt.%*) – 5.85 P (*wt.%*)> – 0.005 or Ni (*wt.%*) – 5.85 P (*wt.%*)> – 0.021 and Ni (*wt.%*) + Cu (*wt.%*) > 0.10. Further PWC work was done in association with CAPCIS, UK, on several North Sea projects [28]. Some significant findings on the elimination of PWC are as follows:

a $\Delta = 3.8\,(Cu_{base}\,(wt.\%) - Cu_{weld}\,(wt.\%)) + 1.1\,(Ni_{base}\,(wt.\%) - Ni_{weld}\,(wt.\%)) + 0.3$, where positive Δ values indicated that the base metal is the cathode, and negative Δ values indicated that the weld metal is the cathode.
b Mn >1.1%, Si >0.35% lead to heat affected zone corrosion.
c $(Si_{weld}\,(wt.\%) - Si_{base}\,(wt.\%)) \leq 10–20\%\,(Si_{base}\,(wt.\%))$.

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http://dx.doi.org/10.1016/j.apsusc.2016.07.151
0169-4332/

Table 1
The chemical compositions of base material (BM) and both filler metals.

Composition (wt.%)	C	Mn	Si	S	P	Ni	Cr	Cu	Mo	Fe
BM	0.21	0.42	0.28	0.01	0.02	0.012	0.023	0.008	<0.01	Balance
FM	0.08	1.52	0.91	0.012	0.013	0.004	0.017	0.10	0.005	Balance
FM1	0.08	1.00	0.3	0.012	0.013	0.5	0.45	0.3	0.3	Balance

Meanwhile, P.V. Mahajanam [12] recommended that the filler metal for use in PWC susceptible pipelines should contain 1% Ni, 0.35% Si, and 0.5% Cr (only if the base metal has 0.5%–1% Cr). In addition, the Cu-Ni equivalent should be preferably negative ($\Delta < 0.3\%$ is acceptable) for optimal PWC resistance. Therefore, a review of the literature [12,27,28] indicates that Si is a detrimental element and that Ni, Cu, and Cr are beneficial elements to prevent PWC. It is well known that Cu and Ni locate in the upside of the galvanic series and exhibit more positive corrosion potential [29]. Hence, Cu and Ni are not prone to corrosion and can improve the corrosion resistance of carbon steels. Mo is an effective alloying element to enhance the corrosion resistance of carbon steels. However, it is still unclear as to the mechanism of Mo in enhancing corrosion resistance of carbon steels [30]. Cr locates at the bottom of the galvanic series and shows a lower free corrosion potential [29]. However, Cr can strengthen the protective ability of the scale to steel substrate and improve the resistance to localized corrosion in a CO_2 environment [31]. Carvalho et al. [32] found that the addition of 1%–5% Cr to the iron matrix was useful to diminish the corrosion rate only for low pH medium. Kermani et al. [33] investigated that the in-field corrosion performance of 3Cr steel in sweet downhole production, and found that the improved corrosion performance was attributed to the formation of a Cr enriched corrosion scale. Meanwhile, Cr, Ni, and Mo were demonstrated for improving the corrosion resistance in Fe-based alloys such as stainless steels [34,35]. However, no research dealing with corrosion behavior of weld metals produced by filler metals containing Ni, Cu, Cr, and Mo appears in literature.

It is well known that the alloying elements of Ni, Cu, Cr, and Mo contribute to the corrosion resistance of Fe-based alloys, but this is not a good way to join the alloying elements in the filler metal regardless of the cost in the industrial manufacture. Therefore, this work proposes a recommend filler metal design to minimize PWC. The corrosion resistance of a novel filler metal is identified through weight loss and electrochemical tests, and the possible CO_2 corrosion mechanism of weld metals containing Ni, Cu, Cr, and Mo is proposed for the first time. It is expected that this study would propel the application of filler metals with alloying elements in the oilfield produced water.

2. Experiments

2.1. Fabrication of the experimental filler metal

The effect of alloying elements on corrosion resistance of weld metals has been widely reported [8,9,12]. However, no recommend filler metal design has been reported for minimizing PWC. Combining the cost, weldability, and mechanical properties, a summary of the recommend design on the alloying elements in the filler metal to minimize PWC is proposed as follows:

a Cr: 0.5% (only if the base metal has 0.5%–1% Cr), otherwise <0.5%.
b Cu and Ni: $\Delta = 3.8\ (Cu_{base}\ (wt.\%) - \rho \cdot Cu_{filler}\ (wt.\%)) + 1.1\ (Ni_{base}\ (wt.\%) - \rho \cdot Ni_{filler}\ (wt.\%)) + 0.3$. where ρ is the filler metal deposition rate; positive Δ values indicate that the base metal is the cathode, and negative Δ values indicate that the weld metal is the cathode.
c Si: $(\rho \cdot Si_{filler}\ (wt.\%) - Si_{base}\ (wt.\%)) \leq 10–20\%\ (Si_{base}\ (wt.\%))$.
d P: $\rho \cdot (Ni\ (wt.\%) - 5.85 \times P\ (wt.\%))_{filler} > -0.005$.
e Mn <1.1%, Mo: 0.3%.
f The content of carbon in the filler metal is slightly lower than that in the base metal. The content of the other elements in the filler metal is generally close to that in the base metal.

To evaluate the corrosion resistance of the filler metal (FM1) containing Ni, Cu, Cr, and Mo, a common carbon steel filler metal (FM) was used for comparison purposed in the experiment. The chemical compositions of the base metal (BM) and both filler metals are listed in Table 1.

2.2. Production of the weld metals

To evaluate the corrosion performance of the weld metals, low carbon steel pipes (ϕ219.1 mm × 10.3 mm) were used with a groove angle of 60°, thickness of root face of 1.2 mm, and root gap of 2.4 mm. With each of the experimental filler metals, all-weld-metal coupons were welded with gas tungsten arc welding (GTAW). Two kinds of weld metals were obtained: (1) weld metals without alloying elements (designated as W), and (2) weld metals with alloying elements (designated as W1). The chemical compositions of both weld metals are listed in Table 2. Welding was performed at 155 A, 12 V, and a heat input of 1.53 KJ mm^{-1}. The interpass temperature was 61 °C, controlled by a thermal chalk. The inner surface of the steel pipes was exposed to a corrosive medium, so the following research focused on the root pass.

2.3. Material and solution

The dimension of the weld metals used in the weight loss tests was 4 × 8 × 10 mm. The inner surfaces of the samples were subsequently ground with 300, 600, 800, and 1200 grit silicon carbide paper, degreased with acetone, rinsed with absolute alcohol, and weighed with an electronic balance (precision of 0.1 mg). The test solution, which simulated the produced water in an oil field, was made from analytical grade reagents and deionized water (18 MΩ cm in resistivity), and the chemical composition of this solution was as follows: 0.337 g/L $NaHCO_3$, 28.234 g/L NaCl, 1.047 g/L KCl, 1.487 g/L $MgCl_2 \cdot 6H_2O$, 1.080 g/L $CaSO_4 \cdot 2H_2O$, 2.755 g/L $CaCl_2 \cdot 2H_2O$ and 0.125 g/L $FeCl_2 \cdot 4H_2O$.

Table 2
The chemical compositions of both weld metals.

Composition (wt.%)	C	Mn	Si	S	P	Ni	Cr	Cu	Mo	Fe
W	0.13	1.05	0.63	0.015	0.015	0.013	0.018	0.075	<0.01	Balance
W1	0.1	0.68	0.21	0.009	0.007	0.37	0.31	0.26	0.23	Balance