Corrosion Science 110 (2016) 242–252

Contents lists available at ScienceDirect

Corrosion Science

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

Sulphide stress cracking behaviour of the dissimilar metal welded joint of X60 pipeline steel and Inconel 625 alloy

Chengshuang Zhou [a], Qiuyan Huang [a], Qiang Guo [b], Jinyang Zheng [c,*], Xingyang Chen [d], Jun Zhu [d], Lin Zhang [a,*]

[a] College of Materials Science and Engineering, Zhejiang University of Technology, Hangzhou 310014, China
[b] Department of materials science and Engineering, China University of Petroleum, Beijing 102249, China
[c] Institute of Process Equipment, Zhejiang University, Hangzhou 310027, China
[d] College of Mechanical Engineering, Zhejiang University of Technology, Hangzhou 310014, China

ARTICLE INFO

Article history:
Received 30 January 2016
Received in revised form 23 April 2016
Accepted 26 April 2016
Available online 27 April 2016

Keywords:
A. Low alloy steel
C. Sulphide cracking
C. Welding
C. Stress corrosion
C. Hydrogen embrittlement

ABSTRACT

The sulphide stress cracking (SSC) behaviour of the dissimilar metal welded joint of X60 pipeline steel and Inconel 625 alloy in H_2S environment was investigated using constant load testing, weight loss testing and finite element analysis. The dissimilar welded joint shows high SSC susceptibility, and the asymmetric stress concentration after corrosion is the prerequisite for crack initiation. Anodic dissolution prevents crack blunting, whereas hydrogen embrittlement increases the crack propagation rate and affects SSC to propagate along the fusion boundary.

1. Introduction

Dissimilar welds between Ni-based alloys and ferritic steels have been used in a wide range of engineering applications, including pressure vessels and oil exploration. In general, Ni-based alloys are corrosion-resistant alloys that have been are widely used in high-temperature and high-pressure H_2S environments [1]. Low-alloy pipeline steels are used in mild environments owing to their favourable mechanical properties and low cost. Transition joints between Ni-based alloys and low-alloy steels have thus become necessary because they provide a compromise between the corrosion resistance of low-alloy steels and the high cost of Ni-based alloys. In addition, transition joints appear in Ni-based alloys lined with a composite steel pipe consisting of Ni-based alloy lining coated by carbon steel.

Process and metallurgical challenges have been associated with this dissimilar joint. On the process side, large differences in melting temperatures and fluidity may lead to fusion defects. Regarding metallurgical weldability, solidification cracking, hard interfacial regions, material intermixing and carbon diffusion issues may compromise the joint performance [2,3]. In the transition region (or weld bond), chemical compositions, microstructures, and physical and mechanical properties all change sharply. The transition region can be separated by a weld interface into two zones, namely, an unmixed zone and a partially melted zone. The formation of the zones is related to the difference in melting temperatures and chemical compositions between the filler material and the base metal [4]. A martensite-like layer may exist in the unmixed zone [5]. The morphology of this layer is controlled by weld current, weld metal nickel content, and base metal carbon content [6]. In particular, a large weld current, high Ni content, and high carbon content can minimise the width of the martensite-like layer.

The mechanical and corrosion properties of the dissimilar weld can be compromised because of the as-cast structure [7], and several problems arise in the use of such dissimilar metal welds. Patterson and Milewski [8] observed cracking at the fusion zone of dissimilar joints of Inconel 625 and AISI 304L while employing both autogenous gas tungsten arc and continuous current gas tungsten arc welding processes. They attributed such cracking susceptibility to the segregation of sulphur, phosphorus, and niobium to the interdendritic phase. Furthermore, recent studies have reported on the stress corrosion cracking (SCC) of Ni-based alloy weld metals in high-temperature water [3,9–11]. Interdendritic cracks rapidly propagate in the transition region, namely, in the fusion boundary

* Corresponding authors.
E-mail addresses: jyzh@zju.edu.cn (J. Zheng), zhlin@zjut.edu.cn (L. Zhang).

http://dx.doi.org/10.1016/j.corsci.2016.04.044
0010-938X/

Table 1
Composition of experimental alloys (wt%): Inconel 625 (weld metal) and X60 pipeline steel (base metal).

	C	Si	Mn	Cr	Ni	Fe	Ti	Mo	Nb	P	S
625	0.022	0.11	0.17	22.80	Rem.	3.24	0.24	9.23	3.68	<0.1	<0.02
X60	0.12	0.31	1.42	0.02	0.02	Rem.	0.01	–	0.03	<0.1	<0.02

region of Ni-based alloy–low-alloy steel dissimilar welded joints [12–15]. The microchemistry of grain boundary plays an important role in the intergranular SCC behaviour of Ni-based alloys. The precipitation of chromium carbides causes chromium depletion at the gain boundary, which weakens the intergranular cracking resistance of Ni-based alloys in high-temperature oxygenated water [16,17].

H_2S is an important corrosive agent to aggress the steels used in sour oil and gas fields. H_2S corrosion not only causes steel thinning or perforation [18] but also results in hydrogen embrittlement [19], which may induce sulphide stress cracking (SSC). However, the SSC mechanism of dissimilar metal welds of Ni-based alloys and low-alloy steels in the wet H_2S environment remains unclear.

The present study investigated the SSC behaviour of dissimilar welded joints of Inconel 625-X60 pipeline steel in wet H_2S media by using constant load test, weight loss test, scanning electron microscopy (SEM), electrochemical hydrogen charging and finite element analysis. The cracking process is analysed, and the SSC mechanism is discussed.

2. Experimental procedures

The dissimilar welded joint of Inconel 625-X60 pipeline steel was fabricated by welding two X60 pipeline steels with Inconel 625 as the dissimilar filler metal and then performing post-welding heat treatment at 625 ± 5 °C for 3 h to relieve residual stress. The chemical compositions of both materials are shown in Table 1. Transverse sections including weld metal, heat-affected zone (HAZ), fusion area and base metal regions of the weldment were observed under an optical microscope. SEM coupled with energy dispersive spectroscopy (EDS) was also applied to observe the fusion area. The base metal (X60 pipeline steel), weld metal (Inconel 625), and welded joint (transverse section of the weld) specimens were subjected to tensile tests at a nominal loading rate of 1 mm/min to determine the mechanical properties of the welded joint. The hardness and elastic modulus of the fusion area were measured using the keysight G200 nano indenter at a load of 50 mN [20]. Each experiment was repeated three times.

2.1. Weight loss test

Standard weight loss tests were performed using the ASTM G31 procedure [21]. Base and weld metal specimens with a size of 50 mm × 10 mm × 3 mm and dissimilar welding specimens with a size of 60 mm × 10 mm × 3 mm were cut from the welded joint. The testing specimens were progressively ground with SiC paper up to 800 grit, degreased with acetone, rinsed with absolute alcohol, and then weighted in a precision of 0.1 mg. Then, the working areas of the X60 pipeline steel and Inconel 625 were measured. The specimens for the weight loss tests were weighed, and then immersed into the test medium containing NACE TM-0177 test solution A (hereafter referred to as NACE A solution) [22]. NACE A solution consisted of 5.0 wt.% NaCl and 0.5 wt.% CH_3COOH (HAc). The weight loss test was carried out under 0.1 MPa H_2S. After 168 h of immersion, the specimens were removed from the medium. The corrosion scales were cleaned using 10 wt.% HCl added with 10 g/L hexamine stabiliser. The specimens were washed with deionised water and then with acetone before weighing again. On the basis of the weight

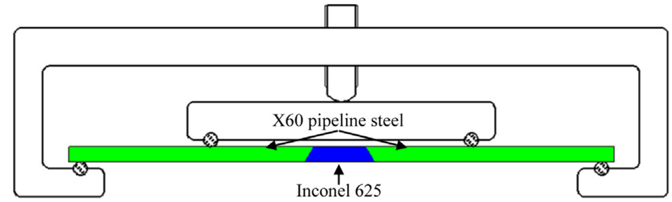

Fig. 1. Schematic with the geometry and position of the dissimilar metal welded joint of X60 pipeline steel (base metal) and Inconel 625 alloy (weld metal) with respect to loading in four-point bending.

loss of the specimens, general corrosion rates were calculated using the following equation:

$$R = \frac{8.76 \times 10^4 \times (M_1 - M_2)}{tSD} \quad (1)$$

where R is the corrosion rate, mm/year; M_1 is the weight of the test specimens before immersion test, g; M_2 is the weight of the test specimens after the corrosion products were removed, g; S is the area of the test specimens, cm^2; t is the immersion time, h; and D is the density of the metal (X60 pipeline steel, 7.86 g/cm^3, Inconel 625, 8.4 g/cm^3).

Ni-based alloys demonstrate a high corrosion resistance in H_2S–Cl^- environments [23]; the corrosion rate is hardly affected by galvanic corrosion in a dissimilar welded specimen. Thus, the corrosion rate of Inconel 625 in the dissimilar welded specimen is consistent with that of the Inconel 625 weld metal. Thus, the corrosion rate of X60 pipeline steel in the dissimilar welding specimen was calculated using the following equation,

$$R_d = \frac{8.76 \times 10^4 \times (M_1 - M_2 - R_n \times S_n)}{ts_d D} \quad (2)$$

where R_d is the corrosion rate of X60 pipeline steel in the dissimilar welded joint, mm/year; R_n is the corrosion rate of Inconel 625; S_n is the area of Inconel 625 in the dissimilar welding specimen; and S_d is the area of X60 pipeline steel in the dissimilar welding specimen.

2.2. Four-point bending test

The SSC behaviour of the dissimilar metal welded joint of X60 pipeline steel and Inconel 625 alloy was investigated by using a four-point bending test rather than a slow strain rate tensile test. The former is suitable to study the cracking behaviour, whereas the latter is suitable to evaluate the susceptibility to hydrogen embrittlement. The specimens were subjected to a four-point bending test (Fig. 1) for 30 days in three environments in accordance with the ISO 7439-2 standard [24]. The schematic with the geometry and position of welding with respect to loading in four-point bending is presented in Fig. 1. In this test, the tension imposed was adjusted by specimen deflection controlled by a screw. The outer surfaces of the specimens were loaded with 80% of the actual yield stress of the X60 pipeline steel [25].

Three environments were supplied to investigate cracking susceptibility, as shown in Table 2. The first environment is NACE A solution with 0.1 MPa H_2S (hereafter referred to as H_2S solution), which is similar to the environment of weight lost test. The X60 pipeline steel, Inconel 625 welding metal, and welded joint specimens were immersed in this solution for the SSC test. The second environment is NACE A solution with 0.1 MPa CO_2 (hereafter referred to as CO_2 solution). The welded joint specimens were subjected to this solution. The third environment is a hydrogen-charging solution. The four-point bending welded joints were charged hydrogen by an electrochemical technique in a 0.5 mol/L H_2SO_4 + 2 g/L thiourea solution for 30 days. The constant current density for hydrogen charging was determined by using a