Engineering Failure Analysis 62 (2016) 287–299

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

Mechanical and electrochemical behaviors of butt-welded high temperature steel pipes

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ARTICLE INFO

Article history:
Received 29 August 2015
Received in revised form 10 December 2015
Accepted 20 January 2016
Available online 22 January 2016

Keywords:
Cyclic loading
Fatigue
Corrosion fatigue
Residual stresses
A106-B steel pipe

ABSTRACT

In this study, fatigue, corrosion fatigue and electrochemical behaviors of butt-welded A106-B steel pipes were investigated. These pipes were subjected to mechanical and thermal cyclic stresses due to the internal pressure fluctuations and cooling–heating cycles. Residual stress measurements were carried out for three different depths through the thickness and were correlated to the microstructural observations and microhardness measurements. Results showed that the maximum tensile residual stresses existed at the boundary of weld metal and base metal because of the contraction–expansion effects resulting from phase transformations and cooling rate differences. Fatigue fractures occurred at regions experiencing the maximum tensile residual stress under fatigue and corrosion fatigue tests. The change in frequency had no significant effect on the atmospheric fatigue. However, lower frequencies were associated with shorter corrosion fatigue lives in the corrosive environment containing Cl^{-} ions. The corrosion potentials for different regions of weld zone were close to each other while corrosion current density and corrosion rate varied significantly.

1. Introduction

It is a well-known fact that almost all fabrications of structures involve welding. Therefore, the effect of welding on the life of structures subjected to cyclic loading must be considered to have economical and safe designs [1].

Fatigue is defined as cumulative, localized and permanent damage caused by repeated fluctuations of stresses usually below the static design stresses of the structures. It is noteworthy that welded components are less tolerant to the fluctuating loads than their non-welded counter parts due to the following reasons [2]:

(i) Welds contain internal flaws which could act as crack initiation sites.
(ii) Welds create stress concentrators which are susceptible to crack initiation.
(iii) The welding process introduces residual stresses in the weld zone which may exacerbate the applied fluctuating stresses.

Weld flaws, such as cracks and discontinuities, have a major role in the fatigue process [3]. Discontinuities may exist because of the fabrication process and cracks initiate in the structures even before they are put into service as a result of the transportation. Every time that a load is applied to a structure containing a crack, the crack may grow. Pre-existing crack-like defects or discontinuities typically exist in welded structures due to the presence of undercut, porosity, lack of fusion and partial penetration. These flaws are formed during the fabrication and welding of steel structures and significantly reduce the fatigue life compared to

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http://dx.doi.org/10.1016/j.engfailanal.2016.01.010
1350-6307/

the non-welded structures [4]. The fatigue fracture of structural details subjected to cyclic loads mostly occurs at a critical cross-section with stress concentration. In a welded joint, fatigue crack initiates at the weld toe and propagates through the main plate until the final fracture occurs [5].

Residual stresses are self-balanced internal stresses existing in a free body with no external loads or constraints on its boundaries [6]. Residual stresses are created in most manufacturing processes such as casting, machining, welding and all processes in which force and/or heat are operative. Local residual stresses are a combination of the following three types of stress fields: (i) residual stress fields whose size are in the macro range. They are homogenous and distributed in an area larger than the grain size, (ii) residual stress fields in the micron size which are created by microstructural differences of materials and their maximum loading area is in the order of grain size, and (iii) residual stress fields whose size are in the submicron range. Residual stress fields in the sub-micron range are created by lattice defects and influence an area in the order of atomic dimensions [7–9].

The joint type, applied stress range, number of cycles, and residual stresses can play important roles in determining the fatigue performance of a structural component [10]. When steel structures are fabricated and welded, residual stresses are introduced due to the welding which have significant effects on the initiation and propagation of fatigue cracks. As the weld cools down, it tries to contract. However, the plate and the weld still need to maintain their length compatibility. For this reason, the plate restrains the weld material during cooling and contraction period, which puts the welded area and parts of the plate in tension while the rest of the plate in compression [4].

The distribution and pattern of the residual stresses resulting from the welding process usually depend on factors such as steel strength, geometry of contracted components, weld size and welding procedure. The magnitude of the tensile residual stress can be as high as the yield strength of the material [4].

Weldments can experience all of the classical forms of corrosion, but they are particularly susceptible to those affected by variations in microstructure and composition, specifically galvanic corrosion, pitting, stress corrosion and inter-granular corrosion. Stress corrosion originates from welding residual stresses discussed previously [11]. In addition to the residual stresses, the fusion welding processes result in metallurgical changes which increase the crack driving force and reduce the resistance to the brittle fracture as well as the environmental fracture [12].

In particular, the weld metal and its periphery are more sensitive against corrosive environment than the base metal. The presence of corrosive environment in association with the cyclic loading is an effective parameter on the fatigue behavior of welded components. The corrosive environment affects the fatigue behavior by the following mechanisms: (i) the formation of pits which may act as the crack nucleation regions, and (ii) increasing the growth rate of cracks [13]. Accordingly, application of most welded metals and alloys such as A106-B steel in the present study is challenging in these environments. A106-B steel is widely used as pipe steel in oil, gas and petrochemical industries. Due to the presence of chlorides, sulfides and other acids in such industries, A106-B steel is confronted with detrimental effects of different mechanisms of corrosion in these environments during the service condition. Therefore, investigation of the mechanical and electrochemical properties of this steel is of a crucial importance since it provides the prediction of lifetime as well as the required period for its inspection.

Altogether, in the present research work, the atmospheric fatigue behavior, the refinery fatigue behavior in corrosive environment (with and without the Cl^- ion in two different frequencies) and the electrochemical behavior of A106-B steel pipes were investigated.

2. Materials and methods

The material used in the present work was A106-B carbon steel which is commonly used in pressure vessel applications and gas transportation pipes. The detailed chemical composition of the investigated steel is presented in Table 1.

The A106-B steel pipe with inner diameter of 127 mm (5 in.) is used in LPG production unit in Sarkhoon and Qeshm gas refinery. Eight pipes with inner diameter and thickness of 127 and 6.5 mm, respectively, were welded in V-groove (60° included angle) and three passes in butt-welded joint configuration according to ASME Sec. 9 standard [15] by shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) processes. The welding parameters are presented in Table 2. The types of electrodes together with their specifications are listed in Table 2 according to AWS A5.1 standard [16].

In order to study the effect of welding heat input on the microstructural variations of welded specimens, metallographic observations were done for different areas of welded cross-sections according to ASTM E3 standard [17]. Microhardness measurements were carried out for different zones of welded cross-sections each for three different depths through the thickness according to ASTM E384 standard [18]. Fig. 1 shows the investigated regions of the welded joint cross-section for metallographic observations, hardness measurements and electrochemical evaluations.

Non-destructive residual stress measurements were carried out by ultrasonic method. The measurement setup included an ultrasonic box with integrated sender and receiver, computer and two normal transducers assembled on a united wedge. A two-probe arrangement was used with one sender and one receiver. Six transducers in three different frequencies with nominal frequencies of 2, 4, and 5 MHz were used. Application of different frequencies helped to evaluate residual stresses through the

Table 1
Chemical composition of A106-B steel [14].

Element	C (max)	Mn	P (max)	S (max)	Si (min)	Cr (max)	Cu (max)	Mo (max)	Ni (max)	V (max)	Fe
wt.%	0.30	0.29–1.06	0.035	0.035	0.10	0.40	0.40	0.15	0.40	0.08	Bal.