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Failure pressure of a pressurized girth-welded super duplex stainless steel pipe in reverse osmosis desalination plants

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ABSTRACT

Pressurized super duplex stainless steel grade S32750 pipe is the most important element in SWRO (Sea Water Reverse Osmosis) plants. This paper presents FE (finite element) analyses to investigate the residual stress distributions produced by the girth welding of the thin-walled super duplex stainless steel pipe and the failure pressure of the girth-welded super duplex steel pipe under internal pressure. FE simulation of the girth welding process was first performed to predict the weld-induced residual stresses employing a sequentially coupled three-dimensional (3-D) thermo-mechanical FE formulation. The residual stresses were then incorporated into the 3-D elastic-plastic FE analyses to explore the failure behavior of the girth-welded super duplex steel pipe subjected to superimposed internal pressure. GPD (Global Plastic Deformation) was used as an indicator of the failure pressure. The FE results have shown that the failure of the girth-welded thin-walled super duplex stainless steel pipe under internal pressure occurs when the effective stress approaches at a certain level which is much lower than the ultimate tensile strength and the burst pressure is weakly influenced by the weld-induced residual stresses.

1. Introduction

Water shortage is one of the most serious global challenges of our time. Currently, a large proportion of the world's population lives in water-stressed countries, and climate change and population growth will probably add to these numbers. One way to circumvent the limited supply of fresh water dictated by hydrologic factors is to remove the salt from seawater, i.e. seawater desalination. Seawater desalination offers a seemingly limitless, steady supply of high-quality water, without impairing natural fresh water ecosystems. Indeed, seawater desalination plants have already been in operation as a means to augment water supply around the world. Early desalination plants were based on thermal desalination, where the seawater is heated and the evaporated water is condensed to produce fresh water [1]. Such plants consume substantial amounts of thermal and electric energy, which result in a large emission of greenhouse gases [2]. Recently, the vast majority of seawater desalination plants have been constructed based on reverse osmosis technology, where seawater is pressurized against a semipermeable membrane that lets water pass through but retains salt. The development of high rejection, low energy membrane products and high efficiency energy recovery devices has made SWRO (Sea Water Reverse Osmosis) technology very competitive [3]. At present, reverse osmosis is the most energy-efficient technology for seawater desalination [2,4].

Desalination plants are known to be very severe environments due to the high chloride, high pressure conditions [5]. In the past, austenitic stainless steels in the ASTM (American Society for Testing and Materials) 300 series tended to be the material of choice in desalination plants. However, experience from a lot of SWRO plants already in service has revealed that there is a high risk of corrosion if the wrong stainless steel is used in the high-pressure piping needed for the environment. The 316L (EN 1.4404) and 317L (EN 1.4438) grades do not possess sufficient corrosion resistance properties to withstand the environment. Consequently, highly alloyed austenitic steel grades of 6Mo such as 254 SMO (EN 1.4547) were deemed more or less mandatory for large SWRO plants [6]. However, the high cost of alloying elements, such as molybdenum and nickel, has presented a need to look for more effective options. One solution is a super duplex grade S32750, i.e. SAF 2507 (EN 1.4410). It has almost the same resistance to pitting and crevice corrosion as 254 SMO and thus has a similar shelf life. Moreover, it has twice the strength, and the cost is far lower. S32750 is used for the high-pressure piping that feeds the incoming seawater through the initial SWRO pass for the plant [7].

In practical situations, girth welding of the super duplex stainless steel pipe is frequently required owing to the long geometry

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Nomenclature

b_i	body force
c	specific heat
E_0	initial Young's modulus
$E_{0.2}$	tangent stiffness at the 0.2% proof stress
h	temperature-dependent heat transfer coefficient
I	arc current
K_x, K_y, K_z	thermal conductivity
m	additional strain hardening exponent
n	strain hardening exponent
P	magnitude of internal pressure
P_b	burst pressure
Q	rate of moving heat generation per unit volume
$Q(t)$	heat flux distribution
Q_A	heat input from the welding arc
Q_M	energy induced by high temperature melt droplets
R_i	inner radius
R_o	outer radius
$r(t)$	radial coordinate with the origin at the arc center on the surface of work piece
r_0	arc beam radius
T	temperature
U	arc voltage
V_p	considered weld pool volume
ε	engineering strain
$\varepsilon_{t,0.2}$	total strain at the 0.2% proof stress
ε_u	plastic strain at the ultimate strength
$d\varepsilon_{ij}$	total strain increment
$d\varepsilon_{ij}^{e}$	elastic strain increment
$d\varepsilon_{ij}^{p}$	plastic strain increment
$d\varepsilon_{ij}^{th}$	thermal strain increment
η	arc efficiency factor
σ	engineering stress
$\sigma_{0.2}$	0.2% proof stress
σ_y	yield stress
σ_u	ultimate strength
σij	stress tensor
ρ	density

relative to the diameter and the wall-thickness. When two steel pipes are welded together, a non-uniform temperature field induced during the welding process produces undesired residual stresses and deformations. The presence of weld-induced residual stresses originated from the elastic-plastic response of the material during the thermal cycles can be a major concern in structural integrity assessment of the pressurized girth-welded steel pipe [8]. These stresses, especially tensile stresses within and near the weld area generally have adverse effects, increasing the susceptibility to fatigue damage, stress corrosion cracking and brittle fracture [9]. When combined with service loads, welding residual stresses can reduce the fatigue life, accelerate growth rates of pre-existing or service-induced defects in pipe systems [10]. Accurate estimation of the weld-induced residual stresses, and understanding the service behavior of the girth-welded super duplex stainless steel pipe under internal pressure are therefore very crucial for the effective operation of the high-pressure piping system, production of an efficient and economic design and safety of the structure. Validated methods for predicting welding residual stresses are desirable because of the complexity of welding process which includes localized heating, temperature dependence of material properties and moving heat source, etc. Accordingly, FE simulation has become a popular tool for the prediction of welding residual stresses [11–16].

Over the last three decades or so, there have been a significant volume of research activities on the FE simulation focusing on welding residual stresses in welded shells including girth-welded steel pipes [9,17–22]. However, limited works have addressed the 3-D features of the residual stresses induced by the traveling arc and welding start/stop effects during the girth welding process [23]. For example, Karlsson and Josefson [24] calculated the residual stresses in a single-pass girth-welded pipe using the FE code ADINA, Dong and Brust [25,26] employed the special shell element and moving welding arc to simulate the residual stresses in stainless steel pipe weld, and Fricke et al. [27], Duranton et al. [28] and Deng and Murakawa [29] developed 3-D FE models based on the SYSWELD software and the ABAQUS code to predict the residual stress distributions in multi-pass girth-welded stainless steel pipes. Recently, Lee and Chang [30] predicted the axial and hoop residual stresses produced in high strength carbon steel pipe weld incorporating solid-state phase transformation during the girth welding by employing a sequentially coupled 3-D thermal, metallurgical and mechanical FE model, and Lee et al. [31] estimated the magnitude and distribution of the residual stresses in dissimilar steel girth-welded pipe joints using 3-D thermo-mechanical FE analysis method. Further investigation on the 3-D FE analysis is then needed to comprehensively understand the characteristics of welding residual stresses in girth-welded steel pipes. Moreover, to the knowledge of the authors, very few works have been published on the analysis of welding residual stresses in girth-welded super duplex stainless steel pipes. As a matter of fact, Jin et al. [32] evaluated the axial and hoop residual stresses in circumferentially butt-welded 2205 (EN 1.4462) duplex stainless steel pipe through the numerical simulation based on the nonlinear thermo-mechanical FE analysis. Nevertheless, their work was confined to axisymmetric model which was not capable of predicting the 3-D effects induced by the girth welding process.

Much work has been devoted to investigating the failure response or pressure of internally pressurized steel pipes with or without flaws. Ozaki et al. [33] examined the mechanical strength of steel pipes suspended vertically from a ship-type floating base for CO_2 sequestration in the ocean considering the static tension due to the weight of the pipe itself and buoyancy of additional floaters as well as the dynamic tension due to wave-induced motion of the floating base. Christoper et al. [34] analyzed existing test data on the failure pressure of different steel pipes subjected to internal pressure in the context of various theories and procedures in order to estimate the maximum pressure in end-capped unflawed cylindrical pressure vessels. Brabin et al. [35] evaluated the failure pressure of thin and thick-walled steel cylindrical pressure vessels by employing the axisymmetric FE models based on the GPD (Global Plastic Deformation). In another study, Jayadevan et al. [36,37] numerically investigated the fracture response of an offshore pipeline segment with an external, circumferential part-through surface crack under axial tension or bending combined with internal pressure using the evolution of CTOD. Kamaya et al. [38] assessed the failure pressure of steel pipes containing wall thinning under internal pressure by using 3-D elastic-plastic FE analyses. Three kinds of steel pipes, i.e. line pipe steel, carbon steel pipe and stainless steel pipe were considered and the