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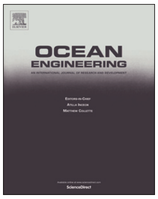

Behavior of a girth-welded duplex stainless steel pipe under external pressure

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ABSTRACT

This study attempts to investigate the effects that external pressure has on the residual stress behavior in a girth-welded duplex stainless steel pipe. At first, FE simulation of the pipe girth welding is performed to identify the weld-induced residual stresses and depressions using sequentially coupled three-dimensional (3-D) thermo-mechanical FE formulation. Then, 3-D elastic–plastic FE analysis is carried out to evaluate the residual stress redistributions in the girth-welded pipe under external pressure. The residual stresses and plastic strains obtained from the thermo-mechanical FE simulation are employed as the initial condition for the analysis. The FE analysis results show that the hoop compressive stresses induced by the external pressure significantly alter the hoop residual stresses in the course of the mechanical loading, i.e. the hoop residual stress distributions on both surfaces of the pipe weld shift downward considerably, whilst the axial residual stresses are little affected by the superimposed external pressure.

1. Introduction

Duplex stainless steels, with a microstructure comprised of nearly equal proportions of ferrite and austenite, are finding increased use in various engineering applications including oil and gas transmission lines, offshore and marine structures, nuclear power plants, and chemical process plant piping thanks to the remarkable mechanical properties: high tensile strength and fatigue strength, good toughness, adequate formability and weldability and excellent corrosion resistance (Del Coz Díaz et al., 2010). These outstanding properties enhance the use of duplex stainless steels in technological applications related to external pressure especially in a pipe form. Due to the long geometry relative to the diameter and the wall-thickness, girth welding of these duplex stainless steel pipes is often required. When two pipes are welded together, undesired residual stresses are produced in the vicinity of the weld region. This is attributed to the highly localized, non-uniform, transient heating and subsequent cooling of the welded material, and the non-linearity of the material properties. These stresses may lead to cracking just after welding and sometimes later, during the intended service life. Particularly, tensile residual stresses near the weld area generally have adverse effects by increasing the susceptibility of welds to fatigue damage and by accelerating the rate of fatigue crack growth (Withers, 2007). Furthermore, the combination of welding residual stresses with service loads causes premature yielding and loss of stiffness and may result in deterioration of the load carrying capacity in pipe systems. Accurate assessment of the weld-induced residual stresses and correct understanding of the service behavior of a girth-welded duplex stainless steel pipe under external pressure would be of big help to assure the sound design and safety of the structure. However, accurate prediction of welding residual stresses is very challenging task due to the complexity involved in welding process, which includes localized heating, metallurgical phase transformation, temperature dependent thermal and mechanical properties and moving heat source, etc. Accordingly, finite element (FE) simulation has become a popular tool for the prediction of welding residual stresses (Goldak et al., 1986; Goldak and Akhlagi, 2005; Hibbitt and Marcal, 1973; Karlsson and Josefson, 1990; Lindgren, 2001, 2006).

Until now, a significant amount of research activity on the FE simulation focusing on the girth weld-induced residual stresses has been performed employing the axisymmetric models (Brickstad and Josefson, 1998; Deng et al., 2008; Mochizuki et al., 2000; Rybicki et al., 1978; Ueda et al., 1986; Yaghi et al., 2006) or the three-dimensional (3-D) models (Deng and Murakawa, 2006; Deng and Kiyoshima, 2010; Duranton et al., 2004; Fricke et al., 2001; Karlsson and Josefson, 1990; Sattari-Far and Farahani, 2009).

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However, these works were generally confined to conventional stainless steel pipe welds. Thus, welding residual stresses in girth-welded austenitic stainless steel pipes have been thoroughly investigated. Meanwhile, recently, a number of investigations have been dedicated to reducing weld-induced residual stresses by optimizing welding technology. Jiang et al. (2012a) presented a study on the heat sink welding to decrease residual stresses in 316 L stainless steel welding joint and found that the heat sink technology could decrease the residual stress significantly. Jiang et al. (2012b) examined the effect of repair length on residual stresses in the repair weld of a stainless steel clad plate. They showed that the transverse residual stresses were greatly reduced by increasing the repair length, which had little influence on the longitudinal residual stresses. Guo et al. (2014) confirmed the feasibility of using the trailing heat sink technique to control residual stresses and distortions in pulsed laser welding process. Tan et al. (2014) investigated the effect of geometric construction on the distribution of residual stresses in a narrow-gap multipass butt-welded nuclear rotor and they revealed that the bottom protrusion at the weld seam could release the residual stresses and mitigate the stress evolution significantly on the inner surface. As for duplex stainless steel pipe welds, limited works have been conducted on the FE simulation of the residual stresses (Jin et al., 2004). Therefore, further investigation on the FE analysis is then needed to comprehensively understand the characteristics of welding residual stresses in a girth-welded duplex stainless steel pipe. Moreover, as for the behavior of residual stress under external pressure, very little attempts have been made to date because of the truly complex analysis procedure associated with welding and ensuing loading problems and thus deserves to be given special attention.

The present work focuses on characterizing the residual stress evolution in a girth-welded duplex stainless steel pipe (S32750) subjected to external pressure. A sequentially coupled 3-D thermo-mechanical FE analysis which simulates the girth welding process to identify the weld-induced residual stresses is first performed. 3-D elastic–plastic FE analysis in which the residual stress redistributions in the girth-welded duplex stainless steel pipe under superimposed external pressure are explored taking the residual stresses and plastic strains as the initial condition is next carried out. Finally, the paper concludes from the discussion of the analysis results, and outlines future works.

2. FE simulation of the residual stresses

Numerical simulation of weld-induced residual stresses needs to accurately take account of: (1) conductive and convective heat transfer in the weld pool; (2) convective and radiative heat losses at the weld pool surface; (3) heat conduction into the surrounding solid materials as well as the conductive and convective heat transfer to ambient temperature (Lindgren, 2006). Moreover, one needs to account for temperature-dependent material properties and the effects of liquid-to-solid and solid-state phase transformation in the material (Lee and Chang, 2011).

The welding process is essentially a coupled thermo-mechanical process. The thermal field is strongly dependent on the mechanical field. On the other hand, the structural field has a negligible influence on the thermal field. Therefore, sequentially coupled analysis works very well. In this study, the girth welding process was simulated using a sequentially coupled 3-D thermo-mechanical FE formulation based on the in-house FE code written by Fortran language (Lee, 2005), which has been extensively verified against numerical results found in the literature and experiments (Lee and Chang, 2012), in order to accurately capture the residual stress distributions in the girth-welded duplex stainless steel pipe. The solution procedure for welding residual stresses can be split into two steps: a transient thermal analysis, which solves for the transient temperature history associated with the heat flow of welding, followed by a transient mechanical (stress) analysis which is based on the thermal solutions. The mechanical analysis takes the temperature fields, and uses them as the thermal loading for the stress evolution at the end of the analysis which remains in the modeled component as residual stresses. The FE meshes and time steps for both the heat flow analysis and the structural analysis are identical.

2.1. Thermal analysis

The spatial and temporal temperature distribution during welding satisfies the following governing partial differential equation for the 3-D transient heat conduction with internal heat generation and considering ρ, K and c as functions of temperature only.

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right)+Q=\rho c\frac{\partial T}{\partial t} \quad (1)$$

where T is the temperature, K is the thermal conductivity, c is the specific heat, ρ is the density and Q is the rate of moving heat generation per unit volume.

According to the nature of arc welding, the heat input to the work piece can be divided into two portions. One is the heat of the welding arc, and the other is that of the melt droplets. The heat of the welding arc is modeled by a surface heat source with a Gaussian distribution, and that of the melt droplets is modeled by a volumetric heat source. At any time t, points lying on the surface of the work piece within the arc beam radius r_0 receive the distributed heat fluxes $Q(t)$ according to the following equation:

$$Q(t)=\frac{3Q_1}{\pi r_0^2}\exp\left[-\left(\frac{r(t)}{r_0}\right)^2\right] \quad (2)$$

where $r(t)$ is the radial coordinate with the origin at the arc center on the surface of the work piece and Q_1 is the heat input from the welding arc

$$Q_1=\eta AV-Q_2 \quad (3)$$

where η represents the arc efficiency factor which accounts for radiative and other losses from the arc to the ambient environment, A is the arc current, V the arc voltage and Q_2 is the energy induced by high temperature melt droplets. On the other hand, the heat from the melt droplets is applied as a volumetric heat source with a distributed heat flux (DFLUX) working on individual elements in the fusion zone.

$$DFLUX=\frac{Q_2}{V_p} \quad (4)$$

where V_p denotes the considered weld pool volume and can be obtained by calculating the volume fraction of the elements in currently being welded zone. The heat of the welding arc is assumed to be 40% of the total heat input, and the heat of the melt droplets 60% of the total heat input (Pardo and Weckman, 1989). The arc efficiency factor is assumed to be 0.7 for the gas tungsten arc (GTA) welding process used in the present analysis. The heat flux is applied during the time variation that corresponds to the approach and passing of the welding torch.

As for the boundary conditions during the thermal analysis, both radiation and convection are taken into account. During the thermal cycle, radiation heat losses are dominant in and around the weld pool; whereas, away from the weld pool convection heat losses are dominant. This is modeled by defining the temperature-