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 a 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).
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 reactor 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 $\rho$, $K$ and $c$ as functions of temperature only.

$$\frac{\partial}{\partial x} \left( K \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( K \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( K \frac{\partial T}{\partial z} \right) + Q = \rho c \frac{\partial T}{\partial t}$$

(1)

where $T$ is the temperature, $K$ is the thermal conductivity, $c$ is the specific heat, $\rho$ 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:

$$Q(t) = \frac{3Q_0}{\sigma_0^2} \exp \left( -\left( \frac{r(t)}{r_0} \right)^2 \right)$$

(2)

where $r(t)$ is the radial coordinate with the origin at the arc center on the surface of the work piece and $Q_0$ is the heat input from the welding arc

$$Q_1 = \eta AV - Q_2$$

(3)

where $\eta$ 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.

$$\text{DFLUX} = \frac{Q_2}{V_p}$$

(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-
dependent heat transfer coefficient, \( h \), which is assumed to be the same as that for an austenitic stainless steel given by (Brickstad and Josefson, 1998)

\[
h = \begin{cases} 
0.06687 \, (W/m^2 \cdot ^\circ C) & 0 < T < 500 \\
0.2317 \, (W/m^2 \cdot ^\circ C) & T > 500 ^\circ C 
\end{cases}
\]

(5)

To account for the heat effects relevant to the molten metal of the weld pool, two methodologies are used: (1) the liquid-to-solid phase transformation effects of the weld pool are modeled by taking into account the latent heat of fusion, and (2) an artificially increased thermal conductivity, which is three times larger than the value at room temperature, is assumed for temperatures above the melting point, to allow for its convective stirring effect, as suggested in (Deng et al., 2008). The latent heat and melting temperature for duplex stainless steels are 500 J/Kg K and 1773 K, respectively (Del Coz Díaz et al., 2010).

2.2. Mechanical (stress) analysis

The subsequent thermal-mechanical analysis entails the use of the temperature histories calculated by the previous heat transfer analysis for each time increment as an input (thermal loading) for the computation of transient and residual thermal stress distributions. In the present investigation, the effect of solid-state phase transformation on the residual stresses is assumed to be insignificant, i.e. the volumetric change associated with the metallurgical phase transformation is considered to be very small since the austenitic phase which forms approximately 50% of duplex stainless steel microstructure does not undergo solid-state phase transformation during welding, even though it is needed to clarify the influence that the metallurgical transformation has on the residual stresses in the girth-welded duplex stainless steel pipe used in this analysis. This assumption is supported by Del Coz Díaz et al. (2010) and Jin et al. (2004), who conducted FE analyses of residual stresses and distortions in duplex stainless steel weldments without taking solid-state phase transformation into account. The modeling procedure for the FE simulation of pipe girth welding incorporating solid-state phase transformation can be found in (Lee and Chang, 2011). Therefore, additive strain decomposition can be used to decompose the differential form of the total strain into three components as follows:

\[
d_{eq} = d_{eq}^p + d_{eq}^P + d_{eq}^h
\]

(6)

where \( d_{eq}^p \) is the elastic strain increment, \( d_{eq}^P \) is the plastic strain increment and \( d_{eq}^h \) is the thermal strain increment. The elastic strain increment is calculated using the isotropic Hooke's law with temperature-dependent Young's modulus and Poisson's ratio. The thermal strain increment is computed using the coefficient of thermal expansion. For the plastic strain increment, rate-independent elastic–plastic constitutive equation is considered with the Von Mises yield criterion, temperature-dependent mechanical properties and linear isotropic hardening rule. A large strain formulation is employed in the continuum mechanics.

In general, when the temperature of a material point exceeds a certain value, the material point loses its hardening memory (so-called annealing). Therefore, plastic strains accumulated prior to the annealing temperature in a material point that undergoes reheating should be excluded. In the mechanical analysis, the equivalent plastic strain is set to zero when the temperature is higher than the annealing temperature to account for the annealing effect. The annealing temperature was assumed to be 950 °C for both the base metal and the weld metal.

In the thermal and mechanical analyses, element birth and death technique with respect to a group of elements representing weld metal deposition is used to simulate the weld filler variation with time. The thermal aspect of the technique is to change the thermal conductivity of the relevant part of the FE mesh corresponding to the weld metal that has not been laid down yet. Although the FE mesh is generated prior to the performance of the FE analysis, the parameters governing the behavior of the FE model in both the thermal and mechanical analyses are altered so that the FE elements simulate the welding procedure. In the thermal analysis, the FE elements which correspond to the weld metal before being laid down are given a value for thermal conductivity equivalent to that of air. At the time of application of weld metal deposition, the thermal conductivity is made to change from air value to that of the material used. The mechanical aspect of the technique is to change the stiffness of the FE elements in welded zone. The FE elements which the welding torch has not yet approached, a severely reduced material stiffness is assigned (Lindgren, 2001).

2.3. Verification

In order to verify the validity of the FE analysis method employed in the present investigation, the experimental work by Deng and Murakawa (2006) in which the residual stresses in a girth-welded austenitic stainless steel pipe constructed with two-pass GTA welding were measured by the strain gauge method was simulated. In addition, the experimental investigation by Um and Yoo (1997) where the axial and hoop residual stresses in a ferritic carbon steel pipe weld were evaluated by the hole-drilling method was reproduced due to the scarcity of the experimental data on the residual stress distributions in the girth-welded duplex (austenitic-ferritic) stainless steel pipe. The specific details on the experiments can be found elsewhere (Deng and Murakawa, 2006; Um and Yoo, 1997). The analytical results were compared with the corresponding experimental measurements. The modeling procedure for the respective experiment is the same as that given in the forthcoming section except for the temperature-dependent thermal and mechanical properties. Fig. 1(a) and (b) portrays the axial and hoop residual stresses, respectively, computed by the FE simulation of the stainless steel pipe weld at those locations where the circumferential angle from the welding start/stop position is 180° on the inside surface with respect to axial distance from the weld centerline. On the other hand, the axial and hoop residual stress distributions calculated by the numerical reproduction of the girth-welded ferritic carbon steel pipe at those locations where the circumferential angle is 120° on the inside surface are shown in Fig. 2(a) and (b), respectively. Superimposed, in the figures, are the experimental measurements performed on the respective weld specimen. The comparisons reveal that the predicted trends are in good agreement with the measured results. Therefore, the FE analysis method used here can be considered appropriate for analyzing the residual stresses in the girth-welded duplex stainless steel pipe.

2.4. 3-D FE analysis

Duplex stainless steel pipe girth welding was simulated using the sequentially coupled thermo-mechanical FE analysis method. A schematic of the pipe joint configuration with outer diameter
Practical welding conditions were adopted and the welding shown in Fig. 3. A single pass girth-welded joint geometry with a (stainless steel pipe weld): (a) axial residual stresses, and (b) hoop residual stresses.

Fig. 1. Comparisons of the FE analysis results with the experiment (austenitic stainless steel pipe weld): (a) axial residual stresses, and (b) hoop residual stresses.

(D) of 180 mm, length (L) of 360 mm, and thickness (t) of 6 mm is shown in Fig. 3. A single pass girth-welded joint geometry with a single V-groove was constructed. The welding arc travel direction is also illustrated in the figure by the arrow. Welding started at the circumferential angle \( \theta = 0^\circ \), and ended at the same position. Practical welding conditions were adopted and the welding parameters chosen for this analysis are listed in Table 1 (Sattari-Far and Javadi, 2008).

The 3-D FE mesh model is displayed in Fig. 4 with eight-noded isoparametric solid elements. Four layers are used to discretize the computational domain. Note that the FE model only represents one half of the weld piece due to the symmetry conditions with respect to the weld centerline. A finer discretization close to the weld region was performed in order to apply heat flux more accurately when the moving heat source passes the area at specific time steps and to capture the anticipated high temperature and stress gradients there. Element size increases progressively with distance from the weld centerline. A mesh sensitivity analysis was carried out to examine the dependence of FE mesh size on the accuracy of the analysis results. A minimum element size of 0.9 mm (axial) \( \times 1.5 \) mm (thickness) \( \times 26.3 \) mm (circumference) was found as the best compromise between the model accuracy and the computational time. In order to facilitate nodal data mapping between heat transfer and stress models, the same FE mesh refinement scheme was employed except for the element type and applied boundary conditions. The element type in heat transfer model is the other with three translational degrees of freedom at each node. As the pipes were assumed not to be clamped during welding, no mechanical boundary conditions except those to prevent rigid body motion of the weld piece were applied. The detailed boundary conditions used in the FE model are shown in Fig. 4 by the arrows.

As described earlier and in Table 1, the base material used here is S32750 super duplex stainless steel pipe. Detailed information on the base metal is given in (Iris, 2008). Its physical properties such as thermal conductivity, specific heat and density, and mechanical properties such as Young's modulus, thermal expansion coefficient, Poisson's ratio and yield stress are dependent on temperature. In the FE analysis, the temperature-dependent thermal and mechanical properties were incorporated. Fig. 5 shows the physical constants at high temperatures (Del Coz Díaz et al., 2010; Haz Metal, 2013) in which the units are organized so that they can be shown on one graph for clarity. It is worth noting that only the temperature-dependent thermal conductivity is different from that of austenitic stainless steels and the other properties are the same (Del Coz Díaz et al., 2010; Haz Metal, 2013). For obtaining the temperature-dependent thermo-mechanical properties, the elevated temperature tensile coupon tests were conducted in accordance with Korean standards (KS D 0026, 2002) to determine the mechanical properties at high temperatures. An universal testing machine equipped with a specially made electrical furnace heated by thermal rays was used for the elevated temperature tensile test. Test specimens were machined as per the specifications (KS D 0026, 2002) and tests were carried out in the elevated temperature range from room temperature (20 °C) to 900 °C at intervals of 100 °C with a strain rate of 1 mm/min, and the temperature was controlled to be within \( \pm 2 ^\circ \)C. In the experiment, thermal expansion was allowed by maintaining zero tension load during the heating process. Each specimen was held for approximately 20 min at the testing
temperature before testing began to make sure the temperatures evenly distributed throughout the specimens. Fig. 6 depicts the dependence of the mechanical properties on temperatures based on the elevated temperature tensile test results. Both the yield and tensile stresses and the elastic modulus are reduced to 5.0 MPa and 5.0 GPa, respectively at the melting temperature to simulate low strength at high temperatures (Barsoum, 2008). For the weld metal, autogenous weldment was assumed. This means that the weld metal, the heat affected zone and the base metal share the same thermal and mechanical properties (Teng et al., 2003).

During welding process, because the weld metal and the base metal adjacent to the weld region are subject to cyclic thermal loads, the materials in these zones undergo plastic deformation to some extent; hence the weld area and its vicinity work harden during welding. The work hardening has a significant influence on the yield stress within and near the weld region. Higher yield stress due to the strain hardening induces high residual stresses there. As such, the work hardening behavior should be carefully taken into account when a numerical method is utilized to accurately predict welding residual stresses. In this work, temperature-dependent strain hardening rule was used. A linear strain hardening was assumed with the rate of 500 MPa for the temperature range $20^\circ\text{C} – 700^\circ\text{C}$ and 20 MPa for the temperatures above $1000^\circ\text{C}$ (Haz Metal, 2013; Taljat et al., 1998). A linear transition between the hardening rate at $700^\circ\text{C}$ and that at $1000^\circ\text{C}$ was assumed.

### Table 1

<table>
<thead>
<tr>
<th>Base metal</th>
<th>Welding process</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
<th>Speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S32750 duplex stainless steel pipe</td>
<td>GTA</td>
<td>230</td>
<td>22</td>
<td>1.3</td>
</tr>
</tbody>
</table>

2.5. Results and discussion

Results are first presented for the assessment of the weld-induced residual stresses in the girth-welded duplex stainless steel pipe. Four different positions which have different circumferential angles from the welding start/stop position, i.e. $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$, respectively are selected to portray the residual stress
distributions in order to investigate the 3-D effects, i.e. the circumferential variation of the residual stress profile. The axial residual stresses at the locations with different circumferential angle on the inside and outside surfaces are given in Fig. 7(a) and (b), respectively with respect to axial distance from the weld centerline. From the simulated results, it can be observed that bending axial stress distribution through the wall-thickness occurs within and near the weld region. Fig. 8 shows a representative plot of the radial displacement distributions of the pipe weld after the welding. The weld distortions are presented at the locations where the circumferential angles are 0° and 180°, respectively, on the outside surface. This figure unveils that the diameter of the girth-welded pipe in the weld region and its neighborhood becomes smaller due to the circumferential shrinkage after welding; hence a bending moment is generated there. This explains why axial tensile residual stresses are produced on the inside surface balanced by compressive stresses on the outside surface. A stress reversal from tensile to compressive on the inside surface away from the weld centerline is seen and vise versa on the outside surface. It must also be recognized that the axial residual stresses are not axisymmetric, i.e. the residual stress distributions show deviations along the circumference. This is because the internal restraint during the welding process changes spatially due to the sequential deposition of the weld filler material as welding arc moves around the circumference. The welding start/stop effects at the overlapping region (θ = 0°) render the variation severe.

Fig. 9(a) and (b) depicts the hoop residual stress distributions at the four locations. Regarding the hoop residual stresses, their magnitude is influenced by the axial residual stresses. This explains why on the outside surface, which is undergoing axial compression, the hoop residual stresses are less tensile at the weld area and its vicinity compared to those on the inside surface. Similar trends of stress reversal to the axial residual stress distributions are observed. In addition, it can also be noticed that like the axial residual stresses, spatial variations of the stress profiles are present along the circumference due to the moving arc and welding start/stop effects. A rapid change of the residual stresses is also seen at the weld start/stop position. The aforementioned FE analysis results indicate that 3-D FE simulation of the girth welding process is necessary to accurately identify the residual stress distributions.

It is worth while to say that the isotropic hardening model employed in this analysis may lead to overestimation of the residual stresses (Muránsky et al., 2012; Jiang et al., 2015). Nevertheless, the overall trends of the predicted residual stresses are considered to match reasonably well with the real residual stress states, as demonstrated in the comparisons between the analytical and experimental results in Figs. 1 and 2. Furthermore, the
isotropic hardening rule might be a more appealing choice to engineers requiring a conservative design regarding welding residual stresses (Muránsky et al., 2012).

3. Behavior of residual stresses in the girth-welded duplex steel pipe subjected to external pressure

3.1. FE model for analysis

3-D elastic–plastic FE analysis was performed to explore the residual stress evolution in the girth-welded duplex stainless steel pipe submitted to superimposed external pressure incorporating both geometrical and material nonlinearity based on the in-house FE code (Lee, 2005), i.e. an elastic–plastic constitutive material model with the Von Mises yield criterion and the large strain formulation were considered in the analysis. Similar geometry and material to the residual stress analysis were used, except for the applied loading and boundary conditions. The same FE mesh model was employed due to the symmetry in both the geometry and the residual stresses with respect to the weld centerline, using 3-D eight-noded isoparametric solid elements with three translational degrees of freedom at each node. The residual stresses and plastic strains of magnitude and distribution as given by FE simulation of the welding process were introduced as initial conditions into the FE model. Then, pressure load was applied on the outside surface as a distributed load. The external pressure loading on the model was carried out in increments up to the maximum load given by \( \sigma_0/\varepsilon_0 = 0.75 \), where \( \sigma_0 \) is the external pressure-induced hoop stress \( (\sigma_0 = PD/2t) \), \( P \) is the magnitude of external pressure) and \( \varepsilon_0 \) is the material yield stress. It should be noted that the maximum external pressure applied to the pipe model was calculated to be 32.9 MPa, which did not exceed the critical external pressure for the buckling (51.5 MPa). The girth-welded pipe was assumed to be open at the ends, i.e. the axial force at the ends due to external pressure load was zero. Like the preceding residual stress analysis, the structural boundary conditions during loading were prescribed for preventing rigid body motion of the girth-welded pipe.

As mentioned earlier, autogenous weldment was employed during the girth welding. As such, representative constitutive equations for the girth-welded duplex stainless steel pipe can be used to identify the material response. In the present study, the modified Ramberg–Osgood stress–strain relations (Rasmussen, 2003) given by Eqs. (7) and (8) were incorporated into the FE model to duplicate the nonlinear behavior of the duplex stainless steel pipe.

\[
\varepsilon = \frac{\sigma}{E_0} + 0.002 \left( \frac{\sigma}{\sigma_{0.2}} \right)^n \quad \text{for } \sigma \leq \sigma_{0.2}
\]

\[
\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_0 \left( \frac{\sigma - \sigma_{0.2}}{\varepsilon_0 - \sigma_{0.2}} \right)^m + \varepsilon_{0.2} \quad \text{for } \sigma \leq \sigma_{0.2}
\]

where \( \sigma \) and \( \varepsilon \) are the engineering stress and strain, respectively, \( E_0 \) is the initial Young’s modulus, \( \sigma_{0.2} \) is the 0.2% proof stress and \( n \) is the strain hardening exponent. \( E_0 \) is the tangent stiffness at \( \sigma_{0.2} \), \( \varepsilon_0 \) is the ultimate strength, \( \varepsilon_0 \) is the plastic strain at \( \sigma_0 \) and \( \varepsilon_{0.2} \) is the total strain at \( \sigma_{0.2} \), which are all expressed in terms of \( \sigma_{0.2}, E_0 \) and \( n \) (Rasmussen, 2003). \( m \) is an additional strain hardening exponent expressed as

**Fig. 10.** Evolution of the residual stresses under superimposed external pressure given by \( \sigma_0 = 0.25\varepsilon_0 \) at the four locations: (a) axial residual stresses on the inside surface, (b) axial residual stresses on the outside surface, (c) hoop residual stresses on the inside surface, and (d) hoop residual stresses on the outside surface.
The resulting material model is able to describe the full stress–strain curve for the duplex stainless steel pipe by using the three basic parameters $\sigma_{0.2}$, $E_0$ and $n$, among which the two former material properties were measured from the tensile coupon test at ambient temperature and the last one was obtainable from elsewhere (EN 1993-1-4, 2004).

3.2. Results and discussion

Figs. 10 and 11 show the stress development in the girth-welded duplex stainless steel pipe under different levels of external pressure. Like the residual stress analysis, the axial and hoop stress distributions are reported at the four locations along the circumference on both the inside and the outside surface with respect to axial distance from the weld centerline. Fig. 10(a) and (b) shows the axial stress evolution under the external pressure given by $\sigma_h/\sigma_0 = 0.25$ on the inside and the outside surface, respectively. It can be found that in and around the girth weld, the magnitudes of tensile residual stresses on the inside surface and those of compressive residual stresses on the outside surface are reduced, whereas the residual stresses on both the surfaces away from the weld region remain unchanged as the external loads are applied. It is apparent that the weld shrinkage induced by the welding process causes the secondary axial bending moment to be generated when the external pressure is applied, by which additional axial tensile stresses are produced on the outside surface balanced by compressive stresses on the inside surface. Note that even though the axial bending effect alters the residual stress distributions within and near the weld region, the effect is not significant and fades away as the distance from the weld centerline increases. Hence, the axial residual stresses far from the weld region seem to be little affected by the superimposed external pressure load. It implies that the axial residual stress distributions are little affected by the external pressure. The hoop stress distributions on the inside and the outside surface are presented in Fig. 10(c) and (d), respectively. As can be seen in the figures, hoop tensile residual stresses on both the surfaces in the weld region and its neighborhood are decreased considerably and the residual stresses on both the surfaces far from the welded zone shift downward due to the hoop compressive stresses induced by the external pressure. The axial residual stress redistribution of the girth-welded duplex stainless steel pipe subjected to the superimposed external pressure given by $\sigma_h/\sigma_0 = 0.75$ on the inside and the outside surface are shown in Fig. 11(a) and (b), respectively. Similar results to the case for the lower external pressure are seen except for slight increase of the bending effect. Fig. 11(c) and (d) depicts the hoop stress evolution under the superimposed external pressure ($\sigma_h/\sigma_0 = 0.75$) on the inside and the outside surface, respectively. It is unveiled that the magnitudes of hoop tensile stresses in the welded zone and its neighborhood are lessened and the hoop compressive stresses remote from the weld region increase to higher values due to the addition of the hoop compressive stresses, as compared with the stress distributions of the pipe weld subjected to the external pressure given by $\sigma_h/\sigma_0 = 0.25$. 
4. Conclusions

This paper focused on the residual stress evolution in a girth-welded duplex stainless steel pipe subjected to external pressure by FE analysis method. Sequentially coupled 3-D thermo-mechanical FE analysis for predicting residual stresses and depressions induced by the girth welding was first carried out. 3-D elastic–plastic FE analysis in which the residual stress evolution in the girth-welded pipe under superimposed external pressure was scrutinized taking the weld-induced residual stresses and geometric imperfections into account to elucidate the effects of applied external pressure on the residual stress behavior was next performed. Based on the results in this work, the following conclusions can be drawn:

(a) 3-D FE model is essentially needed to accurately simulate the girth welding of a duplex stainless steel pipe because the weld-induced residual stresses and depressions are by no means axisymmetric, which is induced by the traveling arc and welding start/stop effects.

(b) When external pressure is applied to a girth-welded duplex stainless steel pipe, the weld contraction due to the welding process leads to the secondary axial bending moment by which supplementary axial tensile stresses are generated on the outside surface balanced by axial compressive stresses on the inside surface. However, the axial bending effect is not remarkable and fades away as the distance from the weld centerline increases. It can therefore be concluded that the axial residual stress distributions are weakly influenced by superimposed external pressure.

(c) For the hoop residual stresses, their distributions are significantly affected by the hoop compressive stresses induced by external pressure, i.e. the residual stress distributions on both surfaces of the pipe weld shift downward considerably. The effect of superimposed external pressure on the residual stress evolution becomes pronounced with increase in applied external pressure.

(d) External pressure can cause buckling in a girth-welded duplex stainless steel pipe and hence the residual stresses should be taken into account in assessing the buckling behavior. Therefore, a more extensive parametric study is needed to clarify the effect of residual stresses on the buckling behavior of girth-welded duplex stainless steel pipes with varying slenderness ratios under external pressure, at which the future works are aimed.

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