Applied Thermal Engineering 63 (2014) 140–150

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Comparative study on girth weld-induced residual stresses between austenitic and duplex stainless steel pipe welds

Chin-Hyung Lee, Kyong-Ho Chang*

Department of Civil and Environmental & Plant Engineering, Chung-Ang University, 84, Huksuk-ro, Dongjak-ku, Seoul 156-756, Republic of Korea

HIGHLIGHTS

- Residual stresses in austenitic and duplex stainless steel pipes were investigated.
- Comparative study on the girth weld-induced residual stresses was performed.
- Sequentially coupled 3-D thermo-mechanical FE analysis was conducted.
- Considerably different welding residual stress distributions could be demonstrated.

ARTICLE INFO

Article history:
Received 3 June 2013
Accepted 1 November 2013
Available online 13 November 2013

Keywords:
Austenitic stainless steel pipe welds
Duplex stainless steel pipe welds
Welding residual stresses
Three-dimensional finite element simulation
Thermal and mechanical properties

ABSTRACT

Duplex stainless steel pipes find increasing use as an alternative to austenitic stainless steel pipes, particularly where chloride or sulphide stress corrosion cracking is of primary concern, due to the excellent combination of strength and corrosion resistance. During welding, duplex stainless steel pipes do not create the same magnitude or distribution of weld-induced residual stresses as those in girth-welded austenitic stainless steel pipes due to the different physical and mechanical properties between them. In this work, a comparison of the residual stresses between girth-welded austenitic and duplex stainless steel pipes was performed utilizing sequentially coupled three-dimensional thermo-mechanical finite element analysis method to accurately predict temperature fields and residual stress states in pipe girth welds. The results have shown that girth-welded austenitic stainless steel pipes produce much higher axial and hoop residual stresses normalized by the yield stress at the weld and its vicinity in which the welding start/stop effects are more significant and they have wider regions subjected to tensile or compressive stresses adjacent to the weld area.

1. Introduction

Duplex stainless steels, with a microstructure comprised of nearly equal proportions of ferrite and austenite, combine the attractive properties of austenitic and ferritic steels: high tensile strength and fatigue strength, good toughness even at low temperatures, adequate formability and weldability and excellent resistance to stress corrosion cracking, pitting and general corrosion [1–3]. They, especially in the pipe form, find increasing use as an alternative to austenitic stainless steels, particularly where chloride or sulphide stress corrosion cracking is of primary concern, e.g., in the chemical, oil and gas, paper and pulp, marine and petrochemical industries and pollution control equipment. In practical situations, girth welding of duplex stainless steel pipes is often needed owing to the long geometry relative to the diameter and the wall-thickness.

Welding is a crucial manufacturing process and widely used in industries to assemble various engineering and structural components. The advantage of welding as joining process includes high joint efficiency, simple set up and low fabrication cost. In welded structures, the inevitable existence of welding residual stresses is well known, which are produced as a result of plastic deformation caused by non-uniform thermal expansion and contraction imposed during welding process. The residual stresses are always self-equilibrated and the magnitude of tensile residual stresses within and near the weld area is great enough to have deleterious effects on the structural integrity of the welded joints, increasing the susceptibility to fatigue damage, stress corrosion cracking and brittle fracture [4]. These stresses when combined with the applied stresses can reduce the fatigue life, accelerate growth rates of pre-

* Corresponding author. Tel.: +82 2 820 5337; fax: +82 2 823 5339.
E-mail address: ifinder@hanmail.net (K.-H. Chang).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.11.001

Nomenclature

A	arc current
c	specific heat
h	temperature-dependent heat transfer coefficient
k	thermal conductivity
$\dot{q}$	rate of moving heat generation per unit volume
$q(r)$	heat flux distribution
Q_1	heat input from the welding arc
Q_2	energy induced by high temperature melt droplets
r	radial coordinate with the origin at the arc center
r_0	arc beam radius
T	temperature
$\dot{T}$	rate of temperature change
V	arc voltage
V_p	considered weld pool volume
dT	temperature increment
η	arc efficiency factor
ρ	density
$[B]$	displacement-strain matrix
$\{c\}$	parameter to reflect stress increment due to the dependence of physical and mechanical properties of a material on the temperature
$[D_d]$	constitutive matrix
$\{dF\}$	increment of equivalent nodal force due to the external force
$\{dR\}$	increment of equivalent nodal force due to the temperature change
$\{dw\}$	increment of nodal displacement
$[K]$	element stiffness matrix
$\{L\}$	load correction term
$\{d\varepsilon\}$	incremental form of strain
$\{\varepsilon\}$	strain
$\{\varepsilon_O\}$	small strain
$\{\varepsilon_L\}$	large strain
$\{d\sigma\}$	incremental form of stress
∇	spatial gradient operator

existing or service-induced defects in structural systems. Knowledge of the distribution and magnitude of the residual stresses, therefore, would be of big help for the production of an efficient and economic design and safety of the structures. However, accurate prediction of welding residual stresses is very difficult because of the complexity of welding process which includes localized heating, temperature dependence of material properties and moving heat source, etc.

Nowadays, numerical modeling based on finite element (FE) method is used to predict welding residual stresses due to the expense and impracticalities of generating comprehensive structural performance data through experiments [5–13]. Numerical techniques have become an important part of most structural research communities, since they can be employed as a useful tool for analyzing the behavior of structures provided that suitable care is taken to ensure that the modeling is appropriate for the analysis [14].

Until now, a large number of FE simulations focusing on the circumferential welding of austenitic stainless steel pipes have been performed to predict the girth weld-induced residual stresses through the axisymmetric models [15–20] or the three-dimensional (3-D) models [7,21–27] by using commercially available FE-codes such as ABAQUS, ANSYS and SYSWELD, etc. Thus, welding residual stresses in girth-welded stainless steel pipe components have been thoroughly investigated. As for the duplex stainless steel pipe welds, to the knowledge of the authors, very few works have been published on the FE analysis of welding residual stresses. Jin et al. [28] evaluated the axial and hoop residual stresses in a 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 the axisymmetric model which was not capable of predicting the 3-D effects induced by the girth welding process. Díaz et al. [2] conducted thermo-mechanical FE analyses in order to compare weld-induced distortion modes and magnitudes between austenitic and duplex stainless steel butt welds. However, in their study, comparison of welding residual stress distributions between the dissimilar steel butt welds was not reported, i.e. they only provided limited information on the weld deformations, and thus the residual stress distributions in duplex stainless steel butt welds could not be presented. Therefore, 3-D FE analysis of the residual stresses in girth-welded duplex stainless steel pipes is needed to clearly identify the magnitude and distribution of the weld-induced residual stresses. Moreover, studies on the comparison of welding residual stresses in austenitic and duplex stainless steel pipe welds seem to be very scarce in the open literature. It cannot simply be assumed that welding residual stresses in duplex stainless steel welds are of the same magnitude or distribution as those in austenitic stainless steel welds, due to the different physical and mechanical properties. Differences include lower thermal expansion rate, higher thermal conductivity and higher strength with duplex stainless steels, and a rounded stress-strain curve with significant strain hardening (work hardening) with austenitic stainless steels.

In this paper, at first, 3-D thermo-mechanical FE analysis method was developed in order to establish exact numerical model which can accurately capture the 3-D features of welding residual stress distributions in austenitic and duplex stainless steel pipe welds. In the FE analysis method, temperature-dependent material properties, work hardening behavior of the material welded, and weld filler variation with time are taken into account. Verification of the FE method was also implemented through the previously published experimental works. Then, based on the FE analysis method, the residual stresses in girth-welded austenitic stainless steel pipes were investigated and compared with those in duplex stainless steel pipe welds.

2. FE simulation of the girth welding process

It is generally understood that welding involves highly complex phenomena, arising from the interactions between heat transfer, metallurgical transformation and mechanical fields. Complex numerical approaches are then needed to accurately model the welding process. However, as far as welding residual stress modeling is concerned, numerical procedures can be significantly simplified, as discussed in Ref. [29].

The welding process is essentially a coupled thermo-mechanical process. Because the thermal field has a strong influence on the stress field with little inverse influence, 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 [30] in order to accurately capture the residual stress distributions in girth-welded stainless steel pipes. The