Applied Thermal Engineering 45-46 (2012) 33–41

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Temperature fields and residual stress distributions in dissimilar steel butt welds between carbon and stainless steels

Chin-Hyung Lee, Kyong-Ho Chang*

Department of Civil and Environmental Engineering, Chung-Ang University, 221 Heukseok-dong, Dongjak-ku, Seoul 156-756, Republic of Korea

ARTICLE INFO

Article history:
Received 24 October 2011
Accepted 3 April 2012
Available online 9 April 2012

Keywords:
Dissimilar steel welds
Temperature fields
Welding residual stresses
Finite element simulation
Thermal and mechanical properties

ABSTRACT

Dissimilar steel welds between carbon and stainless steels are necessary for the efficient utilization of stainless steels in construction. The structural integrity assessment of welded structures requires consideration of weld-induced residual stresses. Therefore, it is of critical importance to estimate the magnitude and distribution of residual stresses in the dissimilar steel welded joints. Simulation tools based on finite element (FE) method are very useful to predict welding residual stresses. However, the numerical reproduction of residual stresses in dissimilar steel welds is generally more challenging than that of residual stresses in similar steel welds because of the differences in thermo-physical and mechanical properties of the materials to be joined. In the present work, three-dimensional FE simulation of dissimilar steel welding process was carried out to identify temperature fields and residual stress states in dissimilar steel butt-welded joints between carbon and stainless steels. The thermo-mechanical FE model used as well as the simulation methodology is detailed, and the results are discussed. The simulated results demonstrated that welding residual stresses in the dissimilar steel butt welds are by no means of the same magnitude or distribution as those in corresponding similar steel butt welds.

1. Introduction

Traditionally, stainless steels have been regarded as an extravagant solution to structural engineering problems due to the high initial material cost. However, the emergence of structural stainless steel design codes and a better understanding of the additional benefits of stainless steels are bringing more interest into the use for conventional structural engineering applications including construction [1]. To achieve efficient utilization of stainless steels for civil structures, it is necessary to employ dissimilar steel welds between stainless and carbon steels. The steels employed are location dependent in the same structure for effective and economical utilization of the special properties of each steel. Dissimilar steel welded joints are also widely used in the construction of vessels and heat exchangers for several industrial applications [2–5].

Welding is a reliable and efficient metal joining process in the production of many engineering and structural components. The advantage of welding as joining process includes high joint efficiency, simple set up and low fabrication cost. Welding process consists of melting and solidification of weld metal and base metal in localized fusion zone by a transient thermal heat source. Due to the localized heating and subsequent cooling, highly non-uniform temperature distributions occur across the welded joints and base metal; thus they finally result in inevitable residual stresses there. 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 deleterious effects causing stress raising, fatigue failure and brittle fracture [6]. Therefore, accurate estimation of weld-induced residual stresses would be of big help to assure the sound design and safety of the structure. 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. Accordingly, finite element (FE) simulation has become a popular tool for the prediction of welding residual stresses [7–12].

The numerical reproduction of residual stresses in dissimilar steel welds is generally more challenging than that of residual stresses in similar steel welds because of the differences in the physical, mechanical and metallurgical properties of the materials to be joined. Over the last two decades or so, there have been significant research activities on the FE simulation focusing on welding residual stresses in dissimilar steel welded joints [13–17].

* Corresponding author. Tel.: +82 2 820 5337; fax: +82 2 823 5339.
E-mail address: ifinder11@freechal.com (K.-H. Chang).

1359-4311/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.applthermaleng.2012.04.007

Nomenclature

b_i	body force
c	specific heat
c_t	parameter to reflect stress increment due to the dependence of physical and mechanical material properties on temperature
E	Young's modulus
h	temperature-dependent heat transfer coefficient
h_c	convection coefficient
I	arc current
K_x, K_y, K_z	thermal conductivity
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
$r(t)$	radial coordinate with the origin at the arc center on the surface of work piece
r_0	arc beam radius
T	temperature
T_0	room temperature
U	arc voltage
V_p	considered weld pool volume
ε	emissivity
$d\varepsilon_{ij}$	total strain increment
$d\varepsilon_{ij}^{e}$	elastic strain increment
$d\varepsilon_{ij}^{p}$	plastic strain increment
$d\varepsilon_{ij}^{th}$	thermal strain increment
dT	temperature increment
$d\sigma$	stress increment
η	arc efficiency factor
σ	Stefan–Boltzmann constant
σij	stress tensor
ρ	density
ν	Poisson's ratio
$[D_d]$	elastic–plastic material matrix

Nevertheless, most of them are confined to circumferential welding with emphasis on pressurized pipe components, and few analyses have been made on traditional structural members. Therefore, investigation on the magnitude and distribution of welding residual stresses in dissimilar steel butt welds is needed. Actually, del Coz Diazet al. [18] performed thermal stress analyses in order to compare distortion modes and magnitudes of two different kinds of stainless steel butt welds. However, in their study, residual stress distributions in dissimilar steel butt welds were not reported. Sedek et al. [19] measured longitudinal residual stresses in butt-welded joints of dissimilar steels by trepanning and compared with the stresses in similar steel joints. But they only provided very limited information and detailed descriptions on the distribution of residual stresses in dissimilar steel butt welds could not be presented accordingly. Lee and Chang [20,21] evaluated residual stresses in similar and dissimilar steel butt welds by an FE method. However, they employed different kinds of carbon steels that shared similar thermal and mechanical properties except for the yield and tensile strengths, and thus residual stresses in dissimilar steel butt welds between carbon and stainless steels which in essence have different thermal and mechanical properties are still unknown.

In this study, an attempt was made to predict welding temperature fields and residual stresses, especially the longitudinal residual stresses which are in general most harmful to the integrity of the structure among the stress components, in dissimilar steel butt-welded joints between carbon and stainless steels using three-dimensional (3-D) thermo-mechanical FE analysis method. Moreover, residual stress states in similar steel butt welds were examined for comparison.

2. FE simulation of the welding process

Welding process simulation consists in principle of a thermal analysis, in which the temperature and phase evolution are determined as a function of time, followed by a mechanical analysis which employs the temperature history obtained from the thermal analysis. Since the thermal field has a strong influence on the stress field with little inverse influence, sequentially coupled analysis works very well. Therefore, in this study, the welding process was simulated using sequentially coupled 3-D thermo-mechanical FE formulation based on the in-house FE-code (FE-WELDSOL) written by Fortran language [22].

2.1. Thermal analysis

Thermal analysis solves for the transient temperature field and its history associated with the heat flow of welding. The spatial and temporal temperature distribution during welding satisfies the following governing partial differential equation for the three-dimensional transient heat conduction with internal heat generation and considering ρ, K and c as functions of temperature only.

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

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 with uniform density. At any time t, heat flux distribution at the surface of the work piece within the r_0 is defined by the following equation:

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

where

$$Q_A = \eta IU - Q_M \quad (3)$$

On the other hands, the heat from the melt droplets is applied as a volumetric heat source with the distributed heat flux (DFLUX) working on individual elements in the fusion zone.

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

where V_p 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 [23]. The arc efficiency factor is assumed as 0.85 for the FCA (flux cored arc) welding process and 0.7 for the GTA (gas tungsten arc) welding process, respectively, used in the present analyses. The heat flux was applied during the time variation that corresponded to the approach and passing of the welding torch.