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Residual stress simulation in thin and thick-walled stainless steel pipe welds including pipe diameter effects

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Abstract

In this paper, residual stresses in welded components are discussed and a brief review of weld simulation is presented. The general methodology of the FE analysis methods used for welded sections of steel pipes is explained. FE analyses are performed for two axisymmetric butt welds in stainless steel pipes having a 4-pass or a 36-pass weld in a pipe with a wall thickness of 7.1 or 40.0 mm, respectively. In addition, more FE models with inside radius to wall thickness ratio ranging from 1 to 100 have been analysed to investigate the effect of pipe diameter on residual stresses. Residual axial and hoop stresses are plotted for the considered range of pipe diameters for the two simulated pipe wall thicknesses and the differences are discussed.

Keywords: Finite element analysis; Residual stresses; Welds; Stainless steel pipes

1. Introduction

The process of welding is an integral manufacturing procedure in the production of many engineering and structural components, having a direct influence on the integrity of the components and their thermal and mechanical behaviour during service. Due to the high temperatures introduced during welding and the subsequent cooling of the welded metal, welding can produce undesirable residual stresses and deformations. Such stresses can be simulated for the process of welding to delineate the ensuing residual stresses and deformations and for use in the prediction of the behaviour of welded structures.

Welded structures are an essential part of many buildings, bridges, ships, pipes, pressure vessels, nuclear reactors and other engineering structures [1,2]. Circumferentially welded pipes are often used in oil transport systems and steam piping for conventional and nuclear systems. Residual stresses are important in the consideration of cracking and fracture problems in welded structures. Their evaluation can help resolve problems, for example, related to intergranular stress corrosion cracking, hydrogen-induced cracking and, to some extent, fatigue strength.

The numerical simulation of the process of welding can take place in two alternative ways [3]. Firstly, the complex fluid and thermo-dynamics local to the weld pool are modelled by looking at the weld pool and the heat-affected zone (HAZ). The conservation of mass, momentum and heat together with the latent heat and surface tension boundary conditions are equated to represent the physical phenomena of the molten weld pool and thermal behaviour of the HAZ. Secondly, the solid mechanics approach is adopted by modelling the global thermo-mechanical behaviour of the weld structure, paying special attention to the heat source. A variety of simplified heat source models can be used in the simulation of welding, the accuracy of which relying on the theoretical and empirical parameters describing the weld pool size and shape.

In their brief review of weld simulation, Teng and Chang [1] state that a thermomechanical model was developed by Friedman [4] using the FE method to calculate temperatures, stresses and distortions during welding; that elasto-plastic FE computer programs were developed by Muraki

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Nomenclature

C	specific heat capacity (kJ/kg K)
DFLUX	distributed heat flux (W/m^3)
E	elastic modulus (Pa)
h	heat transfer coefficient (W/m^2 K)
HAZ	heat-affected zone
I	current (A)
ID	inside
OD	outside
PM	parent metal
Q	net line energy (J/m)
R_i	pipe inside radius (mm)
T	pipe wall thickness (mm) or temperature (°C)
TSOFT	softening temperature (°C)
U	voltage (V)
v	weld electrode speed (m/s)
V	weld pass volume (m^3)
WCL	weld centre line
WM	weld metal
α	coefficient of linear thermal expansion (1/K)
Δt	duration of the triangular time function (s)
η	arc efficiency
λ	thermal conductivity (W/mK)
ν	Poisson's ratio
σ_y	yield stress (Pa)

et al. [5] to monitor welding thermal stresses and metal movement; that residual stresses were estimated by Josefson [6] in a multi-pass weld and in a spot-welded box beam with SOLVIA and ABAQUS, which are commercially available FE codes for non-linear analyses; and that temperatures and stresses were analysed by Karlsson [7] and Karlsson and Josefson [8] in single-pass girth butt welding of carbon-manganese pipe using the FE codes ADINAT and ADINA.

Brickstad and Josefson [9] simulate residual stresses due to welding using ABAQUS to perform an FE analysis, consisting of two main parts, thermal and structural. They use a technique called 'element birth' to represent the laying of weld beads to avoid any displacement or strain mismatch at the nodes connecting the weld elements to those of the base material. Fanous et al. [10] have introduced another technique for metal deposition using element movement. Temperature dependency of material properties is taken into account in the latter two papers.

In one published paper out of many on weld simulation by Dong [11], FE analyses have been performed on stainless steel and carbon steel welded pipes with different geometries, obtaining a range of through-thickness residual stresses. He has conducted a careful parametric investigation using his research results and other data published in literature to find characteristic trends for through-thickness residual stresses due to welding.

This current paper describes the numerical methodology for obtaining residual stresses in a multi-pass butt-welded stainless steel pipe. The model geometry and material properties for this study are described in detail, followed by an account of the discrete parts of the numerical methodology, starting with an FE thermal analysis and ending with an FE structural analysis, sequentially coupled and modified by a user's subroutine to manipulate the temperature field in the material. The results are then presented in the form of temperature contours, temperature graphs and residual axial and hoop stresses for two pipe thicknesses and a wide range of pipe diameters. The effect of pipe geometry on residual stresses is discussed, pointing out the main features of the residual stress fields.

2. Finite element analysis

FE weld simulation in principle consists of a thermal analysis, which represents the thermal process during welding culminating in revealing the temperature contours associated with welding, followed by a structural analysis which is based on the thermal findings. The structural analysis takes the temperature contours, made available by the thermal simulation, and uses them as input data to calculate a range of stress contours at the end of the analysis which remain in the modelled component as residual stresses. To conduct this type of FE analysis, a sequentially coupled thermal-stress analysis is adopted. For accurate simulation of the temperature history it is important to use a user subroutine, an ABAQUS FORTRAN program, to adjust the temperature values at certain times and locations before being utilised in the structural analysis. Since the stress or displacement solution is dependent on a temperature field with no inverse dependency, a sequentially coupled thermal-stress analysis is performed [12].

2.1. Model geometry and material properties

The simulation of the process of welding has been performed on steel pipes with two wall thicknesses of 7.1 mm and 40 mm, containing 4 weld passes and 36 weld passes, respectively. Each of the modelled weldments consists of two stainless steel pipes circumferentially welded with stainless steel weld metal with significantly higher yield stress values, which is not an unusual occurrence in practice. The types of welding which have been modelled using the same FE technique are the tungsten inert gas welding, the shielded metal arc welding and the submerged arc welding. The pipes are Swedish stainless steel BWR-pipes which are significantly overmatched in yield stress, i.e. the weld metal yield stress being