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Investigations on welding residual stresses in penetration nozzles by means of 3D thermal elastic plastic FEM and experiment

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ABSTRACT

Recent discoveries of stress corrosion cracking (SCC) in weldments including penetration nozzles at pressurized water reactors (PWRs) and boiling water reactors (BWRs) have raised concerns about safety and integrity of plant components. It is well known that welding residual stress is an important factor resulting in SCC in weldments. In the present work, both experimental method and numerical simulation technology are used to investigate the characteristics of welding residual stress distribution in penetration nozzles welded by multi-pass J-groove joint. An experimental mock-up is fabricated to measure welding residual stress at first. In the experiment, each weld pass is performed using a semi-circle balanced welding procedure. Then, a corresponding finite element models with considering moving heat source, deposition sequence, inter-pass temperature, temperature-dependent thermal and mechanical properties, strain hardening and annealing effect is developed to simulate welding temperature and residual stress fields. The simulation results predicted by the 3D model are generally in good agreement with the measurements. Meanwhile, to clarify the influence of deposition sequence on the welding residual stress, the welding residual stress field in the same geometrical model induced by a continuous welding procedure is also calculated. Finally, the influence of a joint oblique angle on welding residual stress is investigated numerically. The numerical results suggest that both deposition sequence and oblique angles have effect on welding residual stress distribution.

1. Introduction

Recent discoveries of stress corrosion cracking (SCC) in weldments including penetration nozzles at pressurized water reactors (PWRs) and boiling water reactors (BWRs) have raised concerns about safety and integrity of plant components. [1–5]. It is well known that three major factors, namely materials properties, caustic media and stress status including residual stress and applied stress, have large contributions to SCC. It is recognized that tensile residual surface stress largely increases the risk of initiating SCC. Moreover, through-wall residual stress profile influences the stress intensity factor, which has a direct relationship with cracking growth rate. Therefore, sound design and structural integrity assessment require an accurate estimation of residual stress introduced during fabrication.

During the course of manufacturing a nuclear power plant, many different origins such as cold work, machining and thermal processing often introduce residual stress into the components. In these origins, welding process is a main factor, which usually gives rise to large residual stress especially near the weld zone. Generally, it may not be possible or feasible to directly measure the residual stress in thick components using non-destructive methods. Finite element (FE) method is a powerful numerical simulation tool, and it is a good alternative to estimate welding residual stress. In the past decades, many FE models have been developed to compute welding residual stress for welded structure in nuclear power plants. However, most researchers used 2D plane-strain model or 2D axis-symmetric model or 3D shell model to predict welding temperature and residual stress fields [6–10]. Recently, some researchers have developed 3D models [11–13] to simulate welding residual stress with considering detailed welding conditions, but the number of weld passes in their models was no more than a few passes. Meanwhile, the measured data of welding residual stress in thick components welded by a multi-pass welding process is also very limited in the opening literature.

To obtain sound numerical results, in addition to developing a sophisticated computational procedure, there also is the need to

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carry out an elaborate experiment to verify it. In the present work, both experimental method and numerical simulation technology are used to study the characteristics of welding residual stress distribution in a multi-pass J-groove joint. At first, a mock-up is fabricated to measure welding residual stress in a dissimilar metal J-groove joint. In the experiment, each weld pass is performed using a semi-circle balanced welding procedure. Then, a corresponding 3D finite element model with considering a moving heat source, deposition sequence, inter-pass temperature, temperature-dependent thermal and mechanical properties, strain hardening and annealing effect is developed to simulate welding temperature and residual stress fields. The simulation results predicted by the 3D model are compared with the measurements. Meanwhile, to clarify the influence of deposition sequence on the welding residual stress, the welding residual stress field in the same geometrical model induced by a continuous welding procedure is also calculated. Finally, the influence of a joint oblique angle on welding residual stress is investigated numerically by using another J-groove joint with a 45° oblique angle.

Quick Welder software [14] developed by the Research Center of Computational Mechanics Inc. is used to conduct the thermo-mechanical finite element analyses.

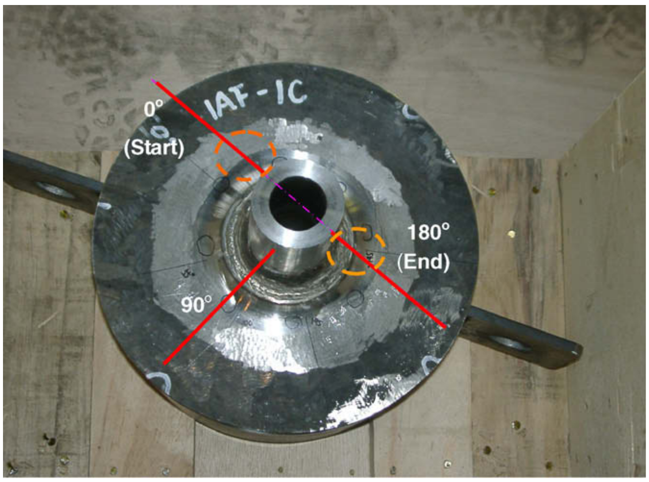

Fig. 1. Picture of mock-up used in experiment.

2. Experimental procedure

In this work, an axis-symmetric penetration nozzle mock-up as shown in Fig. 1 is fabricated to measure welding residual stress after multi-pass welding. This mock-up consists of a tube with small diameter and a thick block. The geometric features and materials surrounding the nozzle penetration are depicted in Fig. 2, while the groove of a J-weld and weld passes can be seen in Fig. 3. The groove is prepared by machining. The cladding layer and overlay (Alloy 82) are deposited to the low alloy steel (SQV2A)

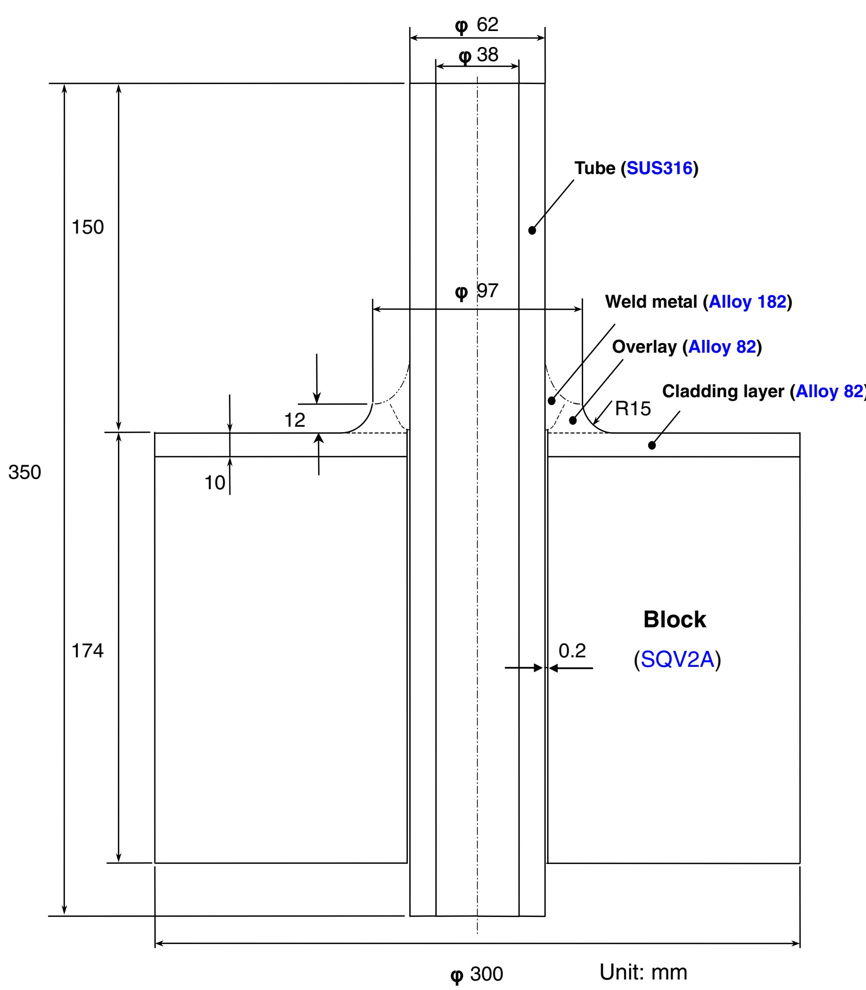

Fig. 2. Dimensions of mock-up.