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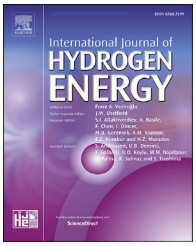

Optimization of girth welded joint in a high-pressure hydrogen storage tank based on residual stress considerations

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ABSTRACT

The cylinder sections in a high-pressure hydrogen storage tank are usually connected by girth welded joints. However, due to the ultra-thick wall of the cylinder, the weld geometry has a significant influence on the residual stress distributions, which are very difficult to be fully determined by experimental methods. Therefore, in this paper, four sequential coupling two-dimensional (2D) axisymmetric finite element (FE) models with different weld geometries have been developed to study the effects of weld groove shape on the residual stresses. In addition, the effects of working pressure (75 MPa) on the welding residual stress distributions have been investigated. The results demonstrate that different weld groove shapes bring different residual stress distributions, leading to different influences on structural integrity. Among the four types of welded joints, V and U types have similar residual stress distributions, and X and d-U types have similar distributions, but the latter two types have large tensile residual stresses at their inner surfaces, which have a greater risk of generating hydrogen induced cracking (HIC). After introducing a working pressure of 75 MPa, the welding residual stresses are redistributed, and the weld regions of the four types of welded joints are all fully yielded and plasticized. Based on the residual stress considerations, using V-shape groove can obtain the best residual stress distributions in an ultra-thick girth welded joint, which provides a reference for the welding and fabrication of a high-pressure hydrogen storage tank.

Introduction

The rapid and extensive development of world economy has driven a correspondingly rapid demand of fossil fuels for fulfilling the practical requirements of industrial applications. However, these conventional energy sources are not infinitely available and if they were, their combustion products contribute significantly to the increase of greenhouse gases along with pollution levels [1–3]. To address these problems, an efficient strategy is to use hydrogen as energy source in place of non-renewable fossil fuels [4–6]. As one of the most important renewable and sustainable energy sources, hydrogen has exhibited numerous advantages, such as high efficiency, zero-emission of greenhouse gases, and extensive sources for producing [7–9]. In general, hydrogen can be

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Nomenclature

U	voltage, V
I	current, A
η	arc efficiency
V	volume of welding pass, m^3
Q	net line energy, J
v	welding speed, m/s
ε	total strain
ε^e	elastic strain
ε^p	plastic strain
ε^{th}	thermal strain
h	heat transfer coefficient, °C
T	temperature, °C
p_i	inner pressure, Pa
R_i	inner radius, m
R_o	outer radius, m
r	radius, m

stored in the form of high-pressure gas [10], cryogenic liquid [11], or physically or chemically bonded to a suitable solid-state material [12,13]. Among these approaches, high-pressure gaseous hydrogen storage is one of the main hydrogen storage methods owing to its simple equipment, low energy consumption, as well as high filling and releasing speed [7,14]. In this procedure, a high-pressure tank made up of metallic material is commonly employed as the container. The cylinder of a stationary-type tank is manufactured more than 10 m high with a spherical head at each end. Due to the size limitation, the cylinder is divided into several sections, and the adjacent two sections are welded together with a circular welding seam.

During welding process, residual stresses are inevitably introduced due to the non-uniform temperature distribution, which have a great effect on strength [15], fatigue [16], and failure [17] of the welded structures. In particular, in a hydrogen environment, residual stresses can accelerate the hydrogen diffusion and play a detrimental effect on hydrogen embrittlement (HE) and hydrogen induced cracking (HIC), which may lead to severe and unexpected catastrophic events [18]. High-pressure hydrogen storage tank has an ultra-thick wall of up to 200 mm which is 1-2 orders of magnitude larger than common pressure vessels, and thus its welded joint has a large number of welding passes. Consequently, the weld geometry will have pronounced effects on the residual stress distributions. Therefore, it is very important to investigate the effects of the weld geometry on the welding residual stresses of a hydrogen storage tank for improving its reliability and hence the service life.

In a high-pressure hydrogen storage tank, usually there are three types of welds according to their locations: (i) welds of nozzle-to-head; (ii) welds of head-to-cylinder and (iii) welds between cylinder sections. In the past few years, only few researches have been published regarding welding residual stresses in a high-pressure hydrogen storage tank, and the former two types have been studied [19,20]. Xu et al. [19] numerically investigated the residual stress distributions in a girth welded joint between nozzle and head of a layered high-pressure hydrogen storage tank, and the influences of preheating temperature and welding heat input were analysed. They [20] also performed a numerical simulation to discuss the effects of autofrettage on a girth welded joint between head and cylinder of a high-pressure hydrogen storage tank, and found that autofrettage process can largely reduce the stress non-uniformity. However, the welding residual stress state between cylinder sections has still not been reported.

In addition to high-pressure hydrogen storage tank, scholars have also carried out many analyses of welding residual stresses in pipes, plates, and other types of pressure vessels. Sattari-Far et al. [21] studied the effects of weld pass number and weld groove shape on welding residual stresses in two butt welded pipes with different thicknesses (6 mm and 10 mm respectively) by numerical and experimental methods. Farahani et al. [22] presented a finite element analysis to investigate the influence of the groove shape on the residual stresses of a 6 mm thick weld plate, and also provided the corresponding experimental verification. However, because the thicknesses of the pipe and plate in the above researches [21,22] are relatively small, the groove shape does not obviously affect the residual stress distributions. Woo et al. [23] determined the through-thickness residual stress distributions in an 80 mm thick ferritic steel weld plate using neutron diffraction and contour methods. Jiang et al. [24] built a finite element model to study the effects of applied load on welding residual stress and deformation of an ultra-thick tube-sheet (390 mm thickness). Mitra et al. [25] carried out a calculation of estimating residual stresses in an 800 mm thick weld plate using a pass-by-pass model along with two different lumped models (a simplification scheme in which multi beads are assumed as one pass). In this study, the effects of phase transformation were taken into consideration, and the results were verified by X-ray diffraction method. Although these researches [23–25] were focused on the residuals tress distributions in ultra-thick plates, the welding residual stress state in plates differs significantly from that in revolved structures (e.g., pipes and cylinders). Liu et al. [26] presented a simulation to investigate the residual stresses in a 70 mm thick pipe with a narrow gap multi-pass welded joint. Tan et al. [27] studied the influences of lumped passes on the welding residual stresses in a 150 mm thick nuclear rotor steel pipe, and found that lumped-pass model can improve the computational efficiency without reducing the accuracy. Tan et al. [28] subsequently proposed three different finite element models (model-1 has a conventional weld shape, model-2 includes a bottom protrusion at the weld region, and model-3 is butt-welded by two rotor discs with a bottom protrusion at the weld region) to discuss the effects of geometric construction on the residual stress distributions before and after heat treatment in a nuclear welded rotor. Generally, these researches [26–28] were focused on the welding stress distributions of ultra-thick pipes or cylinders. Unfortunately, no related work has been carried out to study the influences of weld geometry on residual stress distributions although weld geometry, to a large extent, may determine the residual stress state in an ultra-thick welded joint.

In recent years, neutron diffraction [29], hole drilling [30], and x-ray diffraction [31] techniques have been widely used to measure the residual stresses. However, these methods are

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