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Numerical investigation on residual stress distribution and evolution during multipass narrow gap welding of thick-walled stainless steel pipes

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ABSTRACT

The detailed pass-by-pass finite element (FE) simulation is presented to investigate the residual stresses in narrow gap multipass welding of pipes with a wall thickness of 70 mm and 73 weld passes. The simulated residual stress on the outer surface is validated with the experimental one. The distribution and evolution of the through-wall residual stresses are demonstrated. The investigated results show that the residual stresses on the outer and inner surfaces are tensile in the weld zone and its vicinity. The through-wall axial residual stresses at the weld center line and the HAZ line demonstrate a distribution of bending type. The through-wall hoop residual stress within the weld is mostly tensile. After the groove is filled to a certain height, the peak tensile stresses and the stress distribution patterns for both axial and hoop stresses remain almost unchanged.

1. Introduction

Pipe welding is widely used in a variety of engineering applications, e.g. nuclear and power plants, oil and gas industries. For large wall thickness in piping systems, the weld is often constructed of several weld passes. Due to the intense concentration of heat during welding, the weld line and its vicinity undergo severe thermal cycles, which cause non-uniform heating and cooling of the material, thus generating inhomogeneous plastic deformation and residual stress in the joint. The presence of welding residual stress can be detrimental to the performance of the welded product. For example, the tensile residual stress in the weld zone has been identified as a significant factor that contributes to the occurrence of intergranular stress corrosion cracking (IGSCC) in the girth weld of austenitic stainless pipes [1]. Therefore, it is extremely important to understand the distribution and the evolution of welding residual stress to facilitate the structure design and life evaluation of welded components.

The experimental measurement of residual stress has practical limitations. It is destructive as the hole-drilling technique. Even when non-destructive techniques are used (e.g. diffraction technique), residual stress can be measured only at discrete locations near the weld surface. In addition, the experimental measurement must be performed after the whole weld has been finished. For multi-pass welding in particular, the intermediate residual stress states can be difficult to determine by experiment.

The best solution to evaluate the welding residual stress is to integrate the experimental measurement with the numerical simulation. The finite element method (FEM) has been proved to be a useful and powerful numerical analysis tool to predict the welding temperature field, residual stress field and deformation during the entire welding process. Lindgren [2] gave a detailed review of the application of the finite element method to predict the thermal, material and mechanical effects of fusion welding from the 1970s to 2003.

Welding residual stress can be affected by several factors including material properties, structural dimensions, restraint conditions and welding parameters. Moreover, other variables are involved in multi-pass welding, e.g. the number of weld passes, welding sequences, preheating temperature and inter-pass temperature. Accordingly, the simulation of multi-pass welding could be very complex and difficult. Nevertheless, despite the complications, multipass welding simulation has received a lot of attention in recent years and significant progress has been achieved. A three-dimensional (3D) model can capture the temperature fields and residual stress distribution in detail during multipass welding. However, due to the long time cost, the 3D simulations of multipass welding are usually used for small size welded structures with thin wall thickness and only a few welding passes. For example, Fricke et al. [3] developed a 3D model to calculate the welding residual stresses in austenitic pipe welds with 6.3 mm thickness. Teng and Chang [4] presented a 3D finite element model to simulate the

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temperature and stresses in circumferential single-pass welded pipes. Sattari-Far and Javadi [5] proposed a 3D model to investigate the effect of welding sequence on welding deformations in pipe–pipe joints with single-pass welding and the pipes having a thickness of 6.2 mm.

To reduce the computing time with 3D models, a special 3D composite shell element model was developed by Dong [6] and a 3D model comprising only a segment of the welded structure was employed by Hossain et al. [7]. Much time can be saved if the 3D model can be replaced by a two-dimensional (2D) model or an axisymmetric model. The simulated welding residual stresses of full 3D and 2D (or axisymmetric) models were compared by Dong [6], Jiang et al. [8] and Deng and Murakawa [9]. Their investigations indicated that 2D, axisymmetric and 3D models could provide acceptable temperature and residual stress results. Therefore, more simulations were carried out with axisymmetric models for pipe welding afterwards. For example, Brickstad and Josefson [10] employed axisymmetric models to simulate a series of multi-pass circumferential butt-welds of stainless steel pipe with up to 40 mm wall thickness and 36 weld passes. Yaghi et al. [11] introduced an axisymmetric model to analyze the residual stress of butt welds in stainless steel pipes with different weld passes and wall thicknesses. Deng et al. [12] employed an axisymmetric model to simulate the welding residual stress of a 23 mm thick-walled austenitic stainless steel pipe.

The lumped pass technology was employed to further save the computational time for multipass welding simulation [13]. The weld passes are grouped and each group (lump of passes) is treated as a single pass in the lumped pass technology. The lumping technique is effective only when the passes are grouped following the right strategy, which is largely based on the pass sequence. However, finding the optimum grouping strategy is always a matter of numerical tests and time cost. In addition, the lumping techniques involve some loss in accuracy because they limit the way in which the stress field from one pass may contribute to the stress history of subsequent passes [14]. In addition, stress evolution during the multipass welding process cannot be fully demonstrated with the lump model.

Due to the cost of carrying out welding experiment and computation, there is little information available about detailed residual stress distribution and its evolution in welds involving thicknesses greater than 50 mm and the number of weld pass greater than 70. In the present paper, the residual stress of multipass welding of 304L stainless steel pipes is simulated. The wall thickness of the pipes is 70 mm and the weld pass number is 73. The axisymmetric FE model is used and a detailed pass-by-pass simulation of the welding process is performed to investigate the presence of stress at each pass. Moreover, the residual stress is measured on the outer surface to validate the simulation model.

2. Experimental procedure

Two welding experiments were carried out on the thick-walled pipes in two kinds of assembly location, horizontal and vertical one. The stresses and the transient distortions were measured and calculated for the two experiments. The detailed information about the transient distortions of the two experiments can be found in the literature [15]. The distribution and the evolution of the welding stresses in the two welds are almost the same; therefore, one of the experiments is selected to be introduced in detail in the present paper. The two 304L austenitic steel pipes with an outer diameter of 680 mm, a thickness of 70 mm and a length of 320 mm are narrow-gap multipass butt welded with an automatic girth-welding machine. Before welding, the pipes are tack welded together without an initial gap between the pipes. The two pipes are horizontally assembled in a special fixture. One end of the assembled pipes is fixed and the other is simply supported. The inter-pass temperature is kept below 100 °C. The dimensions of the groove are schematically shown in Fig. 1. The welded pipe is shown in Fig. 2.

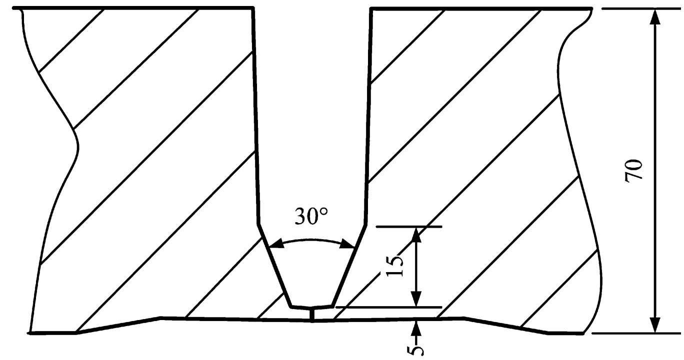

Fig. 1. Dimensions of the groove.

Fig. 2. Welded pipe.

The filler metal is LNM316LSi with a diameter of 0.8 mm and argon gas is used as the shielding gas. All the 73 weld passes are performed counterclockwise from their start position. Welding specifications for each pass are given in Table 1.

After completion of welding, the blind-hole drilling method is used to determine the surface residual stresses. A strain gauge rosette of type BE120-2CA-K is attached on the carefully polished surface and a hole with a diameter of 2.0 mm is drilled using a

Table 1
Welding specifications for each pass.

Pass number	Current (A)	voltage (V)	Speed (cm/min)
1–3	130–140	8.6–9	10–11
4–8	160–180	9–9.8	9–10
9–12	205–220	9.6–12	9
13–41	230–240	9–10	9–10
42–61	250–260	9.5–10	10–10.5
62–71	230–240	9–9.8	9–10
72–73	200	10.2	9