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Research paper

Optimized segmented heat source for the numerical simulation of welding-induced deformation in large structures

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ABSTRACT

A segmented heat source is typically used in welding processes with high energy density and high welding speed, such as laser beam welding. In such welding processes, the intense heat source runs through one segment so quickly that the heating processes in each segment could be considered as a segmented heat source with the largest heat flux heating in a short time. It is then possible to use a segmented heat source model to reduce the computation time. In the present work, a feasible and highly efficient optimized segmented heat source, in which cooling time is considered, was proposed to extend its application area. The optimized segmented heat source could be applied to simulate welding processes with various welding speeds and to simulate large structures with high efficiency. The axial strain in welding a pipe with external diameter of 510 mm and wall thickness of 13.5 mm by shielded metal arc welding was measured to verify the accuracy of the proposed heat source. The temperature filed characteristics and the prediction of welding deformation and its distribution were discussed to measure the accuracy and efficiency of the model with the proposed heat source. The model with the optimized segmented heat source predicts the welding deformation with higher accuracy compared to the model with the traditional segmented heat source; however, the efficiency was compromised. Its accuracy is in the range of 10% compared to the model with a double-ellipsoidal heat source, but it is more effective.

1. Introduction

Welding is an important joining method for the fabrication of large constructions, such as ships, hoisting equipment, and platforms in offshore engineering. Localized heating and fast cooling during the welding process induce a complex residual stress distribution in the weld and its adjacent region, and often result in deformation of the whole structure [1,2]. Welding deformation affects installation accuracy during fabrication, degrades load-bearing capacity especially in large structures, and even degrades the operational performance. Correction of the welding-induced deformation often requires additional equipment and post-weld reworks, which are time consuming and costly [3].

Accurate prediction of the welding-induced deformation and residual stress in large structures helps to control the geometry of the welded structure, improve its load-bearing capacity, and prolong its fatigue life. The finite element (FE) simulation is an effective tool to predict the welding-induced deformation and residual stress [4,5]. However, its practical application to large structures is limited owing to the huge computational time and large memory holding required, and to the performance of FE models in such cases.

Developing a high-accuracy and time-effective numerical model with a complex material model to simulate the welding process is an urgent requirement. Researchers proposed some effective FE models to save time and to increase the numerical accuracy [6]. Guirao et al. [7] implemented a substructure technique, and Bhatti et al. [8] used a method available in commercial FE software to reduce the analysis time. Deng [9] conducted a 2D axisymmetric model to simulate both the temperature and residual stress field in a dissimilar metal welded pipe. The results showed that the 2D model could give a reasonable prediction of the residual stress distribution, except that at the welding start and stop location.

In FE models, one of the most important factors affecting their accuracy and efficiency is the heat source imposed on the workpiece. According to the weldment size and the properties of the heat source, welding heat conduction can be classified into tri-dimensional, bi-

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dimensional and uni-dimensional. In thick plate welding, the heat source could be considered as a point, and heat is conducted in a tri-dimensional manner. In practice, heat sources have volume and distribution; thus, they are imposed on the workpiece as surface heat source (for example, Gaussian heat source [10]) and body heat source. The body heat source provides a closer simulation to the welding heat input, especially in a welding process with impacts on the weld pool. Hemi-spherical [11], hemi-ellipsoidal [11], and double-ellipsoidal heat sources [11,12] are typical of body heat sources. The double-ellipsoidal heat source is currently considered as one of the most accurate heat sources for welding simulation, but it is not efficient especially in large structures. A time effective model based on a segmented heat source, which kept the heat source distribution perpendicular to the welding direction but imposed an equivalent segmented heat source, one by one, in the traveling direction, was employed by Deng [5] and Kiyoshima et al. [13] to save computational time. In numerical models with a segmented heat source, the welding processes have been simulated with a rapid heating and shortened welding time but without considering the cooling time (t_c) for every segment, which is similar to that in high-speed welding process. Thus, the segmented heat source is inapplicable to simulate welding deformation in welding processes with a low welding speed. Owing to the complexity of large structures (for example, there are many KTY joints in offshore structures) and high quality requirements, these are usually welded by shielded metal arc welding (especially the root pass, which requires full penetration but low heat input). That method has a low welding speed, although much effort has been made to automate or to mechanize the welding processes for the fabrication of large structures. Therefore, the traditional segmented heat source with high efficiency cannot be used in large-structure computation, although the root pass welding for large structures has a good cooling condition, which is similar to that in fast speed welding.

The present work aims at improving the traditional segmented heat source (Section 2), making this heat source applicable to simulate the root pass welding process, which has a low welding speed, in large structures. The axial strain when welding a pipe with a large diameter by the shielded metal arc welding method will be measured to verify the accuracy of the proposed heat source (Section 3). The temperature field, and the welding deformation and its distribution, will be discussed (Section 4) to measure the accuracy and efficiency of the model with the proposed heat source. This will be obtained by comparing the proposed model with those of models with double-ellipsoidal heat source and with traditional segmented heat source

2. Optimized segmented heat source

The volumetric heat source with double ellipsoidal distribution proposed by Goldak et al. [12] was used as moving heat source, which could be described by:

$$q_f(x, y, z) = \frac{6\sqrt{3}f_f Q}{a_1 bc\pi\sqrt{\pi}} e^{-3x^2/a_1^2} e^{-3y^2/b^2} e^{-3z^2/c^2} \quad (1)$$

$$q_r(x, y, z) = \frac{6\sqrt{3}f_r Q}{abc\pi\sqrt{\pi}} e^{-3x^2/a^2} e^{-3y^2/b^2} e^{-3z^2/c^2} \quad (2)$$

where q_f and q_r are the head and rear of the heat source respectively, f_f and f_r are ratio coefficients determined by the moving speed of the weld pool, and $f_f + f_r = 2$. a_1, a, b, and c are the parameters of the weld pool.

The optimized and traditional segmented heat sources had the same heat input and the model of heat source was as follows:

$$q(x, y, z) = \frac{6\sqrt{3}Q}{abc\pi\sqrt{\pi}} e^{-3y^2/b^2} e^{-3z^2/c^2} \quad (3)$$

The largest heat flux in the double-ellipsoidal heat source is regards as the heat flux in each cross section of the segment, as shown in Fig. 1. The length of the segmented heat source depends on the actual welding speed and the computer's configuration. Both the optimized and traditional segmented heat sources ignore the heat flux distinction in the head and rear of the weld pool along the welding direction, which makes them more applicable to high-speed welding processes. The prediction accuracy should be subjected to verification before using the segmented heat source, especially in a low speed welding process.

A significant improvement in the optimized segmented heat source is that the cooling process was considered by adding t_c using a Dflux subroutine and pre-sets in the software after heating time (t_h) was finished. Adjusting the segment length and t_c could make the optimized segmented heat source applicable to different speed welding processes. In each segment, a longer length and shorter t_c are used for high-speed welding, while a shorter length and longer t_c are appropriate for low-speed welding. It also makes the transient temperature field of the optimized segmented heat source closer to the actual one.

Before the computation, the ratio of t_c to t_h should be determined for each segment in the models with the optimized segment heat source. A feasible and easy-to-operate method was proposed, as shown in Fig. 1. When the temperature of point B' reaches its peak, the temperature of point A' (the midpoint of the previous segment) was recorded as the reference. t_c should be determined by setting the cooling parameters, which could result in the temperature of point A (the midpoint of the previous segment) attaining the reference when the temperature in point B reaches its peak. The ratio of t_c to t_h was set as 3:1 in the present work, with $t_c = 4.5$ s and $t_h = 1.5$ s.

3. Accuracy verification of optimized segment heat source

3.1. Axial strain measurement experiment

Two DH36 pipes, as shown in Fig. 2a, were prepared with a groove of 60° and a root face of 1.5 mm. The dimensions of the DH36 pipes are shown in Fig. 2b. The external diameter of the pipe is 510 mm, wall thickness is 13.5 mm, the pipe length is 420 mm.

In the experiment, only the root pass in the butt joint was welded and a strain gauge equipment was employed to measure the strains at the same time. Five strain gauges, whose operating temperature range is under 150 °C, were glued to their positions on external surface of the bottom pipe, which were at a 120 mm distance from the center of weld to eliminate the influence of welding temperature on the strain gauge (Fig. 2). The distribution of strain gauges is shown in Fig. 2b. The obtained axial strain data will be compared with the simulation result. Tack welds were made at four quadrants points of the weld seam before welding.

Horizontal position welding, as shown in Fig. 2, was conducted in the experiment. Shielded metal arc welding (SMAW) was employed to weld the root pass. The welding electrodes were E7016 with a diameter of 3.2 mm. The root pass in multi-pass joint usually requires low heat input in order to guarantee welding quality, and thus, the welding parameters listed in Table 1 were used in the experiment and FEM model.

3.2. Finite element modeling

Taking both time cost and prediction accuracy into account, a half pipe model with root pass was established by the commercial FE software ABAQUS. The parameters for the half pipe model were set as identical with those for the workpiece used in the experiment above. Three models with double-ellipsoidal heat source (Model a), traditional segmented heat source (Model b), and optimized segmented heat source (Model c) were established to simulate the welding deformation.

3.2.1. Meshing

The meshes of the three models were identical, as shown in Fig. 3. Fine and coarse meshes were used in the model to decrease the number of elements, and there were transitional meshes between the fine and