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Investigation on welding sequence of I-beam by hybrid inversion

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ABSTRACT

A thermal-mechanical model based on welding experiment and finite element (FE) method was developed for welding deformation analysis and welding sequence optimization of arc welding process used in hull steel structure forming process. By means of digital image correlation (DIC) and electrical measurement method, the deformation of T-beam was measured, and the equivalent heat source parameter (EHSP) was inversed by an optimization algorithm. The purpose of the inversion is to match the numerical results with the experiment results, so the EHSP has taken account into the influence of various factors on the welding deformation and residual stress. Thus, the developed method can avoid using the highly physical nonlinearity algorithm when considering the complex material constitutive and phase transformation process, which greatly improves the efficiency of calculation. Finally, the EHSP obtained from the hybrid inversion is applied to investigate the influence of welding sequence on welding deformation and residual stress in I-beam. This method can be applied to other metal materials and weld form.

1. Introduction

Arc welding is the main joining technology in the welding forming process. The high concentration of heat and steep temperature gradient in the weld zone and heat affected zone will result in uneven plastic deformation and residual stress in the welded structure [1]. Rectification of welding deformation not only increases the manufacturing cost but also spends enormous amount of time. Besides, the existence of residual stress will reduce the life of welded structures [2]. Welding deformation and residual stress are affected by the factors such as heat input, constraint condition and welding sequence [3–6]. Among them, selecting a reasonable welding sequence is an effective method to reduce the welding deformation and residual stress [7,8].

A rational welding sequence can provide a powerful guidance for the actual process. The optimal welding sequence of simple welded structures can be determined by the engineering experience, but for the complex welded structures, a comprehensive numerical analysis should be carried out to explore the complex deformation mechanism so as to get a reasonable welding sequence. Guirao et al. [9,10] studied the deformation mechanism of different welding sequences in the welding process and an optimal welding sequence was obtained. Yupiter et al. [11] investigated the effect of welding sequence on the angular deformation of multi-angle welding by combing the FE method and the welding experiment, and the analysis results showed that “from outside to inside”

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produced a smaller angular deformation than " from inside to outside". Jiang et al. [12] investigated the effect of three welding sequences on the residual stress distribution in multi-pass welding of pipe joints with 3D thermo-mechanical model. It was found that the residual stress did not change much in the three sequences. The stiffened plate under four different welding sequences was analyzed by Gannon [13], and the results showed that the symmetrical cross welding method produced the smallest welding deformation and residual stress. Teng et al. [14] evaluated the residual stress in a variety of welding sequences for single pass butt welding, multi-pass butt welding and ring welding, and then the preferred welding sequence was given, respectively. Based on ABAQUS, the influence of segment welding and progressive welding on the welding deformation and residual stress of T-beam was studied [15].

Although the FE analysis and welding sequence optimization of the welding process have been developed rapidly, the following difficulties still exist:

(a) Heat source parameter. It is necessary for suitable heat source parameters to accurately predict the mechanical field of complex structures [16], but the heat source parameters (pool morphology) are difficult to be measured directly. For example, the double-ellipsoid heat source model [17] is widely used in the temperature field simulation of fusion welding [18–20]. The heat source model is based on the molten pool in the welding process, but it is difficult to determine the morphology of the molten pool with a high temperature. Dual cameras were employed to observe the complete topside weld pool from the lateral side and to capture the keyhole entrance from the rear view in plasma arc welding and the images were fused into a cohesive whole in the same physical coordinate system by image registration [21]. Colegrove et al. [3] used the weld pool size as heat source parameters in the double-ellipsoid heat source model. The numerical results of residual stress agree well with the experimental results. However, the welding process is usually accompanied by intense light and high temperature, which brings many inconveniences and difficulties to the image capture and post-processing. Moreover, the research in this field is still relatively rare.

(b) Material model. As described in reference [22], how to develop advanced material model to roundly consider the influence of microstructure change on welding deformation and residual stress in certain steels is still a difficult problem. In low carbon steel, microstructure changes have little effect on residual stress and welding deformation [23], so accurate results can be obtained using straight-forward constitutive relationships. In medium and high carbon steel, the material properties near the welds drastically change, so the material nonlinearity near the welds due to microstructure changes requires careful consideration. However, it is mainly characterized by straight-forward constitutive relationships at present [24,25], which certainly results in some error. Thus, thermal-metallurgical-mechanical analysis should be carried out to consider the material nonlinearity due to the microstructure while using the straight-forward constitutive relationships. For a large-scale complex welded structure, the low computational efficiency resulted from the nonlinear calculation is usually unacceptable, and even a convergence solution cannot be obtained. So it is theoretically feasible to establish an effective and efficient equivalent algorithm which can predict the welding deformation roughly to give the qualitative analysis for the numerical simulation of welding process whose purpose is to seek the optimal welding sequence.

(c) Phase transformation. Based on the thermal-mechanical analysis, Velaga et al. [26] verified the accuracy of the heat source parameters through the temperature field and weld pool size, and the residual stress is in agreement. However, Deng et al. [23] found that the thermal-mechanical analysis (ignore the influence of phase transformation) will cause a large error of welding deformation and residual stress in medium and high carbon steel. Through the above analysis, the heat source parameters obtained by the temperature agreement can predict the welding deformation and residual stress well in the materials whose phase transformation has little influence, while it does not work for other materials. At present, the thermal-metallurgical-mechanical analysis is usually employed in medium and high carbon steel. However, this method is less efficient than thermal-mechanical analysis, and its application is not widespread. It has not been well implemented in general finite element software. Many studies are based on the in-house procedures [22,27].

(d) Experiment expense and efficiency. Compared to simple structures (T-beam in this study), complex structures (I-beam) welding experiment performed to obtain the heat source parameters need more experiment expense and time. And during the inversion of heat source parameters, the more elements, nodes and welding time due to larger size and more welds of complex structures will reduce the inversion efficiency [24].

In this paper, in order to solve the above problems, a method is proposed that the EHSP of the typical welded joint contained in the complex structures is obtained based on the welding deformation and/or residual stress of a simple structure containing the typical welded joint and then is applied to the simulation of the complex structures, and the outline of the proposed method is shown in Fig. 1. This method ignores the complicated phase transformation and material properties change during the welding process and the accuracy loss is corrected through the EHSP. The EHSP is obtained by the agreement of numerical results and experimental results of the welding deformation and/or residual stress, thus it also includes the influence of the phase transformation and material nonlinearity on the mechanical field near the welds. Using the proposed method, the EHSP of the T-welded joint was inversed under the present welding conditions and environment. Finally, based on the inversed EHSP, the influence of welding sequence on the welding deformation and residual stress of I-beam was studied.

This method has the following advantages. First of all, it requires less experiment expense and time because the simple structure welding experiment is carried out to obtain the heat source parameters. Then, the heat input in the welding process, phase transformation and the complex material properties change near the weld are equivalent to the EHSP, which can avoid the complex inefficient immature thermal-metallurgical-mechanical analysis (compared with thermal-mechanical analysis), simplify the numerical model and improve the computation efficiency. What is more, the thermal-mechanical analysis is still valid thanks for the EHSP