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A Uniform-Gaussian distributed heat source model for analysis of residual stress field of S355 steel T welding

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ABSTRACT

A novel combined heat source model is derived for the simulation of the residual stress field of a T welding. The model is derived combining Gaussian surface and uniform volume heat source, and is applicable to simulate welding process as the electric arc is moving across an angled structure. By both physical characteristics of T and arc welding process, one part of heat input is from the welding arc acting in the workpiece surface, the other is from the molten metal droplets. The two portions are accurately calculated by Gaussian surface heat source distribution and uniform volume source. The numerical simulation of the welding process for a S355 steel T welding based on this novel model has been done and obtain the transient temperature field, stress evolution and residual stress field of the structure. The comparison between measured results by the hole drilling and X-ray diffraction (XRD) and simulation indicates that the combined heat source is sufficient to allow for an overall prediction of the entire welding process of T joints.

1. Introduction

Fusion welding process is to get the substrates melted and then solidified afresh to form the metallurgical boundary between different parts. However, it involves the usage of a concentrate heat source which will introduce localized heat then result in the generation of precipitous temperature gradients in both fusion zone and its vicinity. The uneven temperature distribution is the main source of large discrepancies in micro-structure [1]. The mechanical performances are inhomogeneous due to the effects of a considerable level of residual stress. To achieve an accurate simulation of welding process by finite element method, it is necessary to define an effective heat source model for the reason that conservation of energy is the essential issue in thermal-mechanical analysis [2]. For MIG fusion welding, the heat source model is the mathematical expression of the thermal characteristics for actual welding process. How accurate are the numerical predictions for transient temperature fields, stress evolution and residual stress fields will in turn depend on a precise description of the welding heat input [3]. To balance the simulation accuracy and calculation cost, a chance for the prediction of transient thermal field is to ignore mass transport in the weld pool and in other circumstances, then to solve heat equations by adopting a characteristic model of the welding heat source. With the development of simulation technique, three-dimensional heat sources have been proved to potentially produce the most accurate predictions in such phenomenon [4]. However, given that material model adopted in mechanical process will have a significant influence on residual stress, a multi-pass elastic-plastic finite element calculation method was developed based on Quik Welder Software. The results of the study on stainless steel plate indicated that the welding sequence has a great influence on the peak value and distribution shape of welding residual stress [5]. Then in determining the parameters of the heat source model, a segmented moving double-ellipsoidal heat source model was developed. The heat source can effectively express the heat distribution of MIG welding in aluminum alloy welding process, however it is not sufficient to simulate the high energy beam welding process like laser welding etc. [6]. Then two heat source models, Gaussian and double ellipsoidal, were applied to prophesy the distortion and residual stress [7]. Double ellipsoidal model achieved remarkably better temperature distributions in the fusion and heat-affected zones than those calculated with the Gaussian model for MIG welding process. By improving the existing double-ellipsoidal heat source, a Sabapathy model that was applicable to describe the welding process of oil and gas pipelines was established [8]. To describe the swing process of manual welding and automatic welding, a swing heat source model was proposed [9]. A simplified variable length heat source was introduced to study the weld residual stress relaxation induced by cutting. It indicated that to ensure that the stress relaxation is no less than 3% of the initial stresses in a high-

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strength steel weld, the minimum cutting length for measurement is about 300 mm [10].Then in order to get a better know of the arc shape changes during the welding process, composite heat source characteristics was taken as the research object, Y4-S2 high-speed camera was used to record different arc shapes in a certain time interval. However, the interaction between the arc and the workpiece was neglected.

Although numerical simulation that is based on finite element (FE) method has been proved a useful tool for computer-aided welding process design, a superabundance of dedicated software have been developed to give an overall simulation of entire welding process both from micro-structure and macro mechanics points of view. As a rule of thumb, experiments are the most realistic methods to verify the simulation results and test physical phenomenon, even though measurements might bring about detections or errors themselves or they depends on multitudinous factors during the tests [11]. From the perspective of measurement technology, X-ray and synchrotron and neutron diffraction measurement techniques were adopted to measure the residual stress field of both the work piece surface and the entire structure. Effects of low-temperature transformation (LTT) and plasticity on welding residual stresses were studied by adopting a developed FE model, which coupled thermal field and phase transformation to analyze the residual stress in ferritic marine steel plate. The good agreement of results produced by developed prediction model and neutron diffraction measurement reported that the LTT alloy can reduce and even decrease to compressive residual stress in the weld zone due to the interrupted cooling shrinkage caused by LTT [12].The residual stress and warping of single-sided and double-sided joints were studied using both numerical and experimental methods, but the influence of heat source topography on the numerical simulation was ignored [13]. When samples are subjected to distortion, whether resulting of heat treatment or machining, surface situations are significant factor of residual stress measurements, hole drilling can be efficiently indicative of interior stresses, especially on larger or thicker (>0.25 in., 6.3 mm) parts.

In a T welding process, a certain angle between welding wire and work piece is employed to obtain good welding quantity. The heat distribution on the surface of the weld is different from that in the root region. Gaussian heat source model is suitable for the numerical calculation of the temperature field with a small arc heat impact force, so the effect of droplets on heat distribution is ignored, therefore it is less appropriate for T joint where the heat flow at the root of the weld is complex. T joint is one of the most common joints adopted in high speed train design, both in the bogies and the middle car sand removal device mounting. These structures are all key components that have a vital effect on safety operation. Meanwhile, in spite of the fact that MIG welding is affected by some major shortcomings, such as residual stresses and distortions on welded joints, it is one of the most widely employed joining technologies in high speed train industry due to its high productivity and efficiency. In this background, how to accurately define and control the distribution of welding residual stress of MIG process in T joint is a problem that cannot be ignored in ensuring the safe bearing of the structure.

In this paper, based on the standard Gaussian heat source, a uniform-volume Gaussian-surface moving heat source model for T joint is proposed. The new model is sufficient for the simulation of high-speed train S355 steel T multi-pass welding process. It is performed by the secondary development of the APDL language in the ANSYS software, the transient temperature field, stress evolution and residual stress field in the welding process are well predicted. The X-ray diffraction method and hole drilling method are adopted to test the welding residual stress of the sample. The experimental results coincide well with the numerical simulation results, which proved the validity of the model. The effective expression of heat input provides a reference for the understanding the complex physicochemical and metallurgical changes in the welding process. The deeper understanding helps to develop welding parameters that contribute to higher quality. It is expected that this research of modeling method for T joints can provide a fundamental knowledge for additional research.

2. Model based on combined Uniform volume and Gaussian moving surface heat source

2.1. Basic assumptions and descriptions of heat sources

Due to limited space, the arc and bottom plate have a certain angle when the T joint is welded. According to whether or not the joint needs to be penetrated, the angle between the wire and the center of the groove facing the web is controlled in a range from 38 to 45° [5]. Therefore, the heat source profile of the traditional butt welding arc cannot be directly applicable to describe the heat source profile when it is not vertical to the surface of the work piece. When the T-joint structure is welded, the conditions of the molten force around the deep-melting pores are significantly changed. Under the action of gravity, the lower end of the molten droplets is uniformly distributed in the deep-melting pores, and the relationship between the heat released from the arc portion and surface of the work piece can be expressed by Gaussian distribution.

Based on the existing researches that the net energy imported into the workpieces through a combination of two mechanisms. A fraction of the energy is transferred from the electric arc to the weld pool surface and the rest of the net energy is carried into the workpiece in the form of the superheated metal droplets [14–18]. In the simulation process, for any time t during the welding process, the total heat input is divided into two parts reasonably due to the heat distribution in workpiece, as shown in Fig. 1. The first part is the arc heat that acts on the work piece surface and the other is droplet heat in the penetration direction. The heat that acts on the surface is modeled by a surface heat source that distributed as Gaussian formula. The heat in the molten droplets is expressed by a uniform volumetric heat source. Then a uniform volume-Gaussian surface moving heat source model is shown in Fig. 2.

Description of the heat source function:

(1) The heat source moves along the welding direction at the welding speed, the arc heat obeys a Gaussian distribution in the space, and the point within the radius of the arc beam on the work piece surface receives heat according to formula (1);
(2) The total heat of the welding process consists of the arc heat and the droplet heat, and the heat in molten droplet is described by a 3D heat source that the heat flow distributed with a uniform density.

$$q(t) = \frac{3Q_A}{\pi r_a^2} \exp\left[-\left(\frac{r(t)}{r_a}\right)^2\right] \tag{1}$$

$$Q_A = \eta IU - Q_W \tag{2}$$

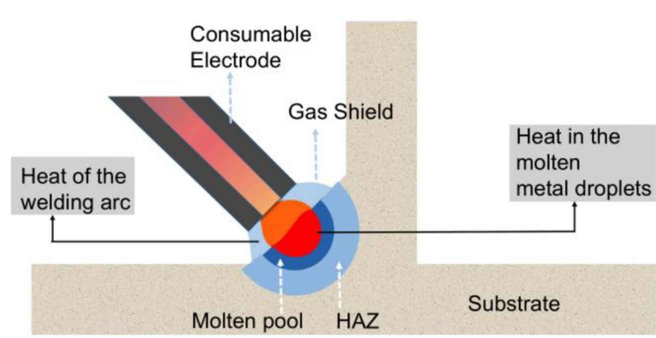

Fig. 1.. MIG Welding and heat distribution.