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FEM prediction of welding residual stress and distortion in carbon steel considering phase transformation effects

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ABSTRACT

The objective of this study is to investigate the effects of solid-state phase transformation on welding residual stress and distortion in low carbon and medium carbon steels. In this study, based on ABAQUS code, a sequentially coupled thermal, metallurgical, mechanical 3-D finite element model is developed. In the numerical simulations, different continuous cooling transformation diagrams are used to predict the fractions of martensite for the fusion zone, the coarse-grained HAZ and the fine-grained HAZ, respectively. Effects of volume change due to austenite–martensite transformation on the final residual stress and the welding distortion are examined. The simulation results revealed that the final residual stress and the welding distortion in low carbon steel do not seem to be influenced by the solid-state phase transformation. However, for the medium carbon steel, the final residual stresses and the welding distortion seem to be significantly affected by the martensitic transformation.

1. Introduction

One of the major problems in welded structures is the welding residual stress and the welding distortion due to local heating. Residual stresses that develop in and around the welding zone are detrimental to the integrity and the service behavior of welded structures. The welding residual stress may promote brittle fracture, reduce the buckling strength and the fatigue life and promote stress corrosion cracking during service. Residual tensile stress also promotes cold cracking associated with hydrogen in certain steels before the welded part is put into service [1]. Welding distortion often results in problems such as dimensional inaccuracies during assembly and cost increase of the product.

Several factors may contribute to the formations of residual stress and deformation. The plastic deformation produced in the base metal and weld metal is a function of design (structure), material, and fabrication parameters. The design parameters include the joint type and the thickness of plates. The material parameters reflect the metallurgical condition of base metal and the weld metal. Fabrication parameters include the welding method, heat input, preheating, welding sequence and the restraint condition.

In certain steel welded parts, the solid-state austenite–martensite transformation during cooling has a significant influence on the residual stresses and distortion [2]. The martensitic transformation is a diffusionless solid-state shear deformation [3]. In steels, martensite is formed from austenite containing carbon atoms and, in view of the diffusionless nature of its formation, it ideally inherits the carbon atoms of the parent austenite. The carbon atoms are trapped in octahedral interstitial sites between iron atoms, producing a body centered tetragonal (bct) structure, and are in super-saturation relative to the body centered cubic (bcc) ferrite. In addition to the fact that the chemical composition of the austenite is directly inherited by the martensite, the martensitic shear deformation is accomplished by a plain-strain shape change parallel to a set of crystallographic planes of the parent austenite. Therefore, when the martensite is formed, the volume of metal is increased, and the transformation plasticity is also produced. During the welding process, the magnitude of the volumetric expansion in the heat-affected zone (HAZ) and the fusion zone (FZ) depends upon the volume fraction of martensite that formed.

Accurate prediction and reduction of welding residual stress and deformation are critical in improving the quality of welded structures. For certain steels, to evaluate the residual stress and deformation accurately, metallurgical phase transformation must be considered. In this study, a finite element computational procedure considering solid-state phase transformation is developed based on the existing researches [1–6], and the effectiveness of the proposed numerical method for analyzing the residual stress and the distortion in carbon steels specific to tungsten inert gas (TIG) arc welding is demonstrated. The finite element analysis package ABAQUS [7] is used in this study.

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2. Finite element modelling

The evolution of the residual stresses and distortion is investigated by means of thermal elastic plastic finite element method. In order to accurately capture the residual stress and distortion in the welded plate, a three-dimensional finite element model is developed. Because the dimensional changes in welding are negligible and mechanical work done is insignificant compared to the thermal energy from the welding arc, the thermo-mechanical behavior of the weldment during welding is simulated using sequentially coupled formulation. The heat conduction problem is solved independently from the stress problem and phase state to obtain temperature history. However, the formulation considered the contributions of the transient temperature field to the stress analysis through thermal expansion, as well as temperature-dependent thermo-physical and mechanical properties.

The solution procedure consists of two steps. First, the temperature distribution and its history in the welding model are computed by the heat conduction analysis. The temperature history is employed as a thermal load in the subsequent mechanical elastic–plastic calculation of the residual stress field. In this step, the volume fraction of martensite is also calculated, and volume change due to phase transformation is considered through modifying the thermal expansion coefficient over the temperature range in which austenite changes into martensite.

In this study, a plate model as shown in Fig. 1 is used. Because of the symmetry, one half of the model is selected as the analysis model. The FE model is shown in Fig. 2 with 4000 brick elements and 5355 nodes. It has a fine grid in the welding zone. The smallest element is 4 mm × 1 mm × 1.5 mm. The length, the width and the thickness of the model are 200 mm, 100 mm and 6 mm, respectively.

In order to clarify the effect of phase transformation on welding residual stress and deformation, two kinds of steel, namely low carbon steel (S15C) and medium carbon steel (S45C), are selected in this study. The chemical compositions and thermal properties as functions of temperature are shown in Table 1 and Fig. 3 [8], respectively. In this study, it is assumed that the thermal properties of S15C steel are the same as those of S45C steel.

In the mechanical analyses, because of the lack of material data, the variation of yield strength due to martensite transformation is neglected.

2.1. Heat source and thermal analysis

Tungsten inert gas arc welding is the most frequently modelled arc welding process in which the heat source is a non-consumable electrode. In the direct current electrode negative TIG process, the weldments are joined together by the following four primary mechanisms: (1) kinetic energy of the electrons that constitute the arc current, (2) heat of condensation of the electrons penetrating the solid work surface, (3) radiation from the arc, and (4) thermal conduction from the arc plasma to work-piece. The first two mechanisms constitute the major source of energy for the weldment [9].

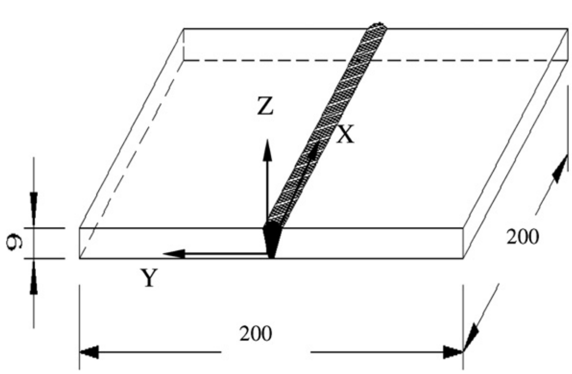

Fig. 1. Geometry of plate and coordinate system.

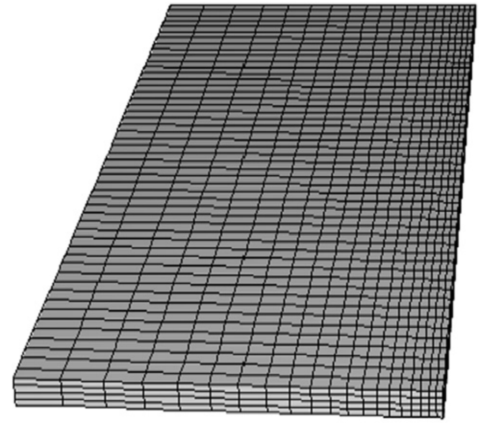

Fig. 2. Plate model used for finite element analysis.

Table 1
Chemical composition of S15C and S45C steels, wt%

Steel	C	Si	Mn	P	S	Cr
S15C	0.15	0.22	0.41	0.021	0.024	0.06
S45C	0.44	0.22	0.66	0.022	0.029	0.15

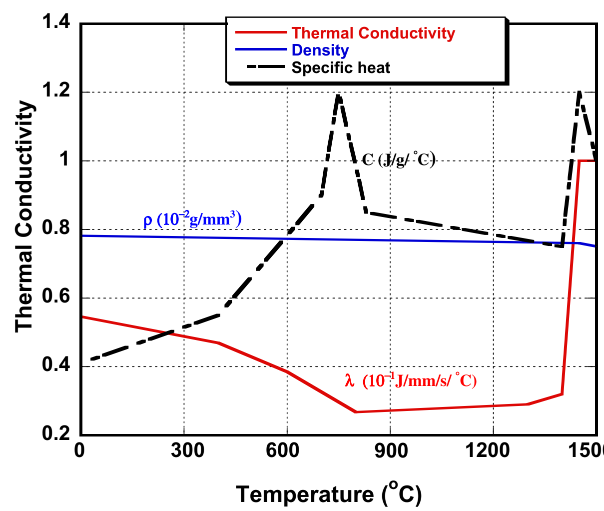

Fig. 3. Temperature-dependent thermal–physical properties.

According to the nature in which energy is transferred from the arc, the heat input of the TIG arc welding process to the weldment can be modelled by a point source or a line source. A more realistic approach is to consider the heat flux on the surface or the heat generation distribution in the metal, or a combination of the two.

In this work, the heat from the moving welding arc is applied as a volumetric heat source with a double ellipsoidal distribution proposed by Goladk et al. [10]. This is represented by the following equations:

For the front heat source

$$q(x,y,z,t) = \frac{6\sqrt{3}f_f Q}{a_1 bc\pi\sqrt{\pi}} e^{-3(x-vt-x_0)^2/a_1^2} e^{-3y^2/b^2} e^{-3z^2/c^2} \quad (1)$$