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Finite element modeling of residual stress relaxation in steel butt welds under cyclic loading

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ABSTRACT

This study attempts to develop a numerical method to predict the real stress state in steel butt welds subjected to cyclic mechanical loading. 3-D FE thermal simulation of a butt welding is first performed to obtain the residual stresses. Then, 3-D elastic–plastic FE model which incorporates the cyclic plasticity constitutive equation based on the Chaboche nonlinear kinematic hardening and the isotropic hardening rule is developed to evaluate redistribution of the residual stresses under cyclic external loading. The analytical results have shown that the FE analysis method devised here can effectively predict the cyclic relaxation of the residual stresses.

1. Introduction

Steel structures in engineering practice are generally fabricated by welding. Welding is an efficient and reliable joining process whose advantage includes simple set up, low fabrication cost and high joint efficiency. However, during welding, residual stresses are unavoidably produced in the weld region and its vicinity due to the highly localized, non-uniform, transient heating and ensuing cooling of the welded material, and the non-linearity of the material properties. The existence of weld-induced residual stresses can be harmful to the structural integrity and the service behavior of the welded structure. Particularly, tensile residual stresses are detrimental, i.e. they increase the susceptibility of welds to fatigue damage and accelerate fatigue crack growth rate [1,2]. Therefore, accurate assessment of the residual stresses would be very helpful to ensure the sound design and safety of the structure. However, accurate prediction of welding residual stresses is very challenging task due to the complexity involved in welding process, which includes localized heating, metallurgical phase transformation, temperature dependent thermal and mechanical properties and moving heat source, etc. Accordingly, the simulation tool based on finite element (FE) technique has been popularly used to predict welding residual stresses. So far, a considerable number of FE models have been proposed and adopted to estimate welding residual stresses in steel welds [3–11]. Thus, welding residual stresses in welded components for structural applications have been thoroughly investigated.

Weld-induced residual stresses are included in the advanced design and fatigue failure analysis of components in the aerospace, nuclear and automotive industries. However, welding residual stresses can and do change in service. Under cycling loading, which generates cyclic plasticity, the residual stresses tend to relax to some extent after a certain number of cycles and become stabilized. It is well known that the residual stress relaxation is a complex phenomenon which depends on the interaction of several factors such as the cyclic stress amplitude applied, the loading mode and direction, the number of cycles and the cyclic characteristics of the material. Thus, the integration of the residual stresses in fatigue strength calculation without considering their relaxation during operation leads to inaccurate prediction of the fatigue life. Therefore, it is of critical importance to develop a model for evaluating the stabilized state of the residual stresses under cyclic mechanical loading. There have been many empirical models for assessing residual stress relaxation under cyclic loading [12–15]. However, these models are simple and can't take account of all the influence parameters with an acceptable accuracy. Therefore, numerical modeling based on the FE method has been used to analyze the cyclic mechanical relaxation of residual stresses. Smith et al. [16] investigated the interaction between residual stresses

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and cyclic mechanical loading in a forged and shot-blasted bar by elastic–plastic FE analyses using different material models, i.e. the linear kinematic hardening model and the multilinear kinematic hardening model were employed in the FE simulations. There were poor agreements between the numerical predictions and the experimental results. Zhuang and Halford [17] proposed an analytical relaxation model for estimation of residual stress relaxation under cyclic load by employing a nonlinear isotropic/kinematic hardening rule to consider the Bauschinger effect. The model was tested by rectangular steel bars treated by several surface processing, and it was able to predict the trends of the residual stress relaxation with a reasonable accuracy. The above studies demonstrated the significance of the cyclic plasticity constitutive equation in the FE modeling of the cyclic residual stress relaxation. Laamouri et al. [18] carried out numerical analyses of the cyclic residual stress relaxation of the ground and electro-polished stainless steel specimens, which featured cyclic hardening behavior, with the Armstrong and Frederick nonlinear kinematic hardening rule and the isotropic hardening model proposed by Chaboche. The FE analysis results yielded a close agreement with the experimental measurements. However, these works were confined to the cyclic relaxation of residual stresses produced by mechanical surface treatments such as shot peening, laser shot peening, hole expansion and low-plasticity burnishing. As for weld-induced residual stress relaxation under cyclic loading, very few works have been reported to date due to the truly complex analysis procedure involved in welding and subsequent cyclic mechanical loading problems and therefore deserves special attention. Actually, Dattoma et al. [19] conducted a series of numerical analyses to evaluate weld-induced residual stress relaxation in a butt-welded stainless steel plate submitted to sinusoidal external load. However, they only considered the longitudinal residual stress relaxation under the cyclic loading applied on the longitudinal direction. Moreover, they did not employ the cyclic plasticity in the constitutive modeling, i.e. they used a bilinear stress–strain equation with isotropic hardening, even though the cyclic plasticity model is essential in the FE simulation of the residual stress relaxation under cyclic load. Hence, the real stress state in a welded component submitted to cyclic mechanical loading remains not fully understood.

This paper aims to present a FE modeling procedure for characterizing the residual stress relaxation of steel butt welds subjected to cyclic loading, and focuses on the quantitative assessment of the influence factors on the cyclic residual stress relaxation. Three-dimensional (3-D) thermal–mechanical FE model is first presented in order to accurately predict the weld-induced residual stresses. Subsequently, 3-D elastic–plastic FE analysis model incorporated with the cyclic plasticity constitutive equation is developed to evaluate the real state of stresses in steel butt welds under cyclic mechanical loading. The effects of the cyclic stress amplitude level applied and the loading direction on the amount of the residual stress relaxation are investigated.

2. FE modeling of weld-induced residual stresses in steel butt welds

The thermal and thermal–mechanical process associated with welding residual stress evolution during welding can be extremely complex. Rapid arc heating during welding produces a molten weld pool. The weld pool shape can be largely influenced by the weld metal transfer mode and corresponding fluid-flow dynamics. On cooling, both rapid solidification within the weld pool and solid-state phase transformation in the weld and heat affected zones (HAZ) occur, depending on both peak temperature and cooling rate. Therefore, numerical simulation of residual stresses due to welding needs to accurately take account of the interactions between heat transfer, metallurgical transformations and mechanical fields. However, as far as welding residual stress modeling is concerned, numerical procedures can be significantly simplified, as discussed in the forthcoming [20].

The welding process is a coupled thermo-mechanical process. The thermal field strongly affects the residual stress field. On the other hand, the stress field has a weak influence on the thermal field. Therefore, sequentially coupled analysis works very well [21]. To conduct this type of FE analysis, in this work, sequentially coupled FE model is developed by using 3-D thermo-mechanical FE formulation based on the in-house FE code [22], which has been extensively verified against numerical results found in the literature and experiments [10,11]. The model consists of two parts: a thermal model followed by a mechanical model. The thermal model solves for the transient temperature history associated with the heat flow of welding, and the mechanical model takes the temperature fields and uses them as the thermal loading for the stress evolution at the end of the analysis which remains in the welded component as residual stresses.

2.1. Thermal model

The thermal model carries out a transient heat transfer analysis based on the heat conduction formulation with the moving heat source. The energy balance equation for the thermal model is given by:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right)+Q-\rho c\frac{\partial T}{\partial t}=0 \quad (1)$$

where T is the temperature, K is the thermal conductivity, c is the specific heat, ρ is the density and Q is the rate of moving heat generation per unit volume. The general solution is obtained by applying the following initial and boundary conditions:

$$T(x,y,z,0)=T_0(x,y,z) \quad (2)$$

$$\left(K_x\frac{\partial T}{\partial x}N_x+K_y\frac{\partial T}{\partial y}N_y+K_z\frac{\partial T}{\partial z}N_z\right)+q+h(T-T_0)+\sigma\varepsilon(T^4-T_0^4)=0 \quad (3)$$

where N_x, N_y, N_z are the direction cosines of the outward drawn normal to the boundary, q is the boundary heat flux, h is the convection heat transfer coefficient and is estimated using engineering formulae for natural convection to be 15 W/(m^2 K), $\sigma = 5.67\times10^{-8}$ J/(m^2 K^4 s) is defined as the Stefan–Boltzmann constant and emissivity ε is defined to be $\varepsilon = 0.2$ [23], finally T_0 = 20 °C is the room temperature.

In the present investigation, the heat from the moving welding arc is applied as a volumetric heat source with a distributed heat flux (DFLUX) working on individual elements in the fusion zone.

$$\mathrm{DFLUX}=\frac{Q}{V_p} \quad (4)$$

where Q is the power of the welding heat source, which is calculated by multiplying the welding current (I), the arc voltage (U) and the arc efficiency factor (η). The arc efficiency factor is assumed as 0.85 for the flux cored arc (FCA) welding process used in this work. V_p denotes the considered weld pool volume and can be obtained by calculating the volume fraction of the elements in currently being welded zone. In order to take the heat transfer due to fluid flow in the weld pool into consideration, the thermal conductivity for molten metal is assumed to increase linearly between the solidus temperature and 3000 K by a factor of three as suggested in [23]. The liquid-to-solid phase transformation effects of the weld pool are modeled by taking account of the latent heat of fusion.