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A model to predict the relaxation of weld residual stress by cyclic load: Experimental and finite element modeling

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ABSTRACT

In this paper, the relaxation of weld residual stress in a 316L stainless steel weld joint under cyclic loading was researched by experimental and finite element method (FEM). Initially, the as-weld residual stresses were calculated by a sequential coupling thermo-mechanical FEM. Subsequently, a cyclic plasticity constitutive model was proposed to study the redistribution of the residual stress by the cyclic load. Significant residual stresses are released during the first few cycles. Especially, about 45–60% of the maximum residual stresses are released during the first cycle because of the plastic deformation caused by the superposition between the as-weld residual stress and the applied load. More residual stresses are released with the increase of the stress amplitude and cyclic number. An analytical model, which considers the effects of the initial residual stress, yield stress, stress amplitude, and number of cycles, was proposed to predict the relaxation of the weld residual stress by the cyclic load. In addition, experimental measurements were also performed to validate this model. Experimental results prove that the proposed model can be used as a valid tool to predict the relaxation of residual stress by the fatigue load.

1. Introduction

Welding is widely used to fabricate engineering structures because of its low cost of fabrication, high efficiency and convenience. However, the production of residual stresses is unavoidable in the welded region and its vicinity. The existence of residual stresses greatly affects the structural integrity and the service behavior of the component, particularly, in the presence of cyclic loading [1–4]. Actually, compressive residual stresses can improve fatigue strength, while tensile residual stresses deteriorate the fatigue crack initiation and growth resistance with superimposed cyclic loads [5,6]. Considering the residual stress in the prediction of fatigue life for welding joint has been realized essential [7]. However, the difficulty is that weld residual stresses can be relaxed by fatigue loads [8–17]. Therefore, an accurate calculation of residual stress and its relaxation becomes more essential for fatigue life prediction.

The prediction of weld residual stress relaxation under cyclic loading is a very difficult problem because it is influenced by several key factors, such as the initial value of residual stresses, loading amplitude, number of cycles, and characteristics of material. Several empirical models have been proposed to evaluate the residual stress relaxation under cyclic loading [18–21], but they cannot take account of all the influencing factors with acceptable accuracy. In the recent years, finite element method (FEM) has been a popular method to assess the relaxation of residual stress. Toribio et al. [22] used isotropic strain hardening model to study the residual stress distribution induced by fatigue in cold-drawn prestressing steel wires, but it cannot describe the cyclic behavior of the material and cannot reveal the relationship between the stress relaxation and number of fatigue. Smith et al. [23] used the simple linear kinematic hardening and multilinear hardening model to investigate the interaction between residual stress and mechanical loading, but the prediction results showed poor agreement with the experimental results for cyclic loading. Laamouri et al. [24] proposed the isotropic and nonlinear kinematic model [25,26] to evaluate the residual stress relaxation of AISI 316L stainless steel, and the prediction results matched well with the experimental. In addition, Zhuang and Halford [27] presented an analytical physics-based model to evaluate the residual stress relaxation produced by cold work under cyclic loading, which also proved the validity of nonlinear isotropic/kinematic hardening model. They concluded that the isotropic and nonlinear kinematic model proposed by Chaboche [25,26] can describe the cyclic behavior of the material accurately. The aforementioned works

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focused on the cyclic relaxation of residual stress induced by mechanical surface treatment. However, few studies have been conducted on the relaxation of weld residual stress under cyclic loading. In fact, Dattoma et al. [28] evaluated the stress state of a welded component subjected to a sinusoidal external load by the bilinear isotropic hardening model, but the results still cannot clarify the relationship between the residual stress relaxation and the number of cycles. Recently, Lee et al. [29] and Cho et al. [30] developed 3D elastic-plastic FEM to evaluate the reconstruction of weld residual stresses under cyclic loading, and found that their FEM was effective in predicting the cyclic relaxation of the weld residual stresses. This study attempts to explore the weld residual stress relaxation under cyclic loading by experimental and analytical methods. At first, a sequential coupling 3D thermo-mechanical FEM was developed to study the weld residual stress distribution in a 316L stainless steel weld joint. Subsequently, a cyclic plasticity constitutive model capable of describing the cyclic response was proposed to study the residual stress relaxation under cyclic loading. Experiments were also carried out to verify the accuracy of the present FEM.

2. Experimental

2.1. Sample preparation

In this paper, the fatigue test was carried out in the standard specimen with the dimensions shown in Fig. 1. The residual stress will be relaxed during the cutting if the small sample is cut from a weld joint [31]. A single overlay welding was performed on the middle surface of the standard specimen to avoid this problem, as shown in Fig. 2. At first, the specimen was prepared according to the dimensions shown in Fig. 1, and then the overlay welding was performed by manual argon arc welding. The base and welding material were also 316L stainless steel and the chemical compositions are listed in Table 1. The welding current, voltage, and speed are 75 A, 22 V, and 1.3 mm/s, respectively.

2.2. Fatigue test

The welded specimens were subjected to cyclic loading using a fatigue testing machine at room temperature, and the experimental setup is shown in Fig. 3. The stress amplitude was 80 MPa with a stress ratio R = 0.1. The frequency was 0.1 Hz. The number of applied cycles were 1, 9, and 40 in turn, and then the residual stresses were measured by X-ray diffraction method after corresponding cycles, which aimed to explore the relationship between the residual stresses relaxation and the number of cycles.

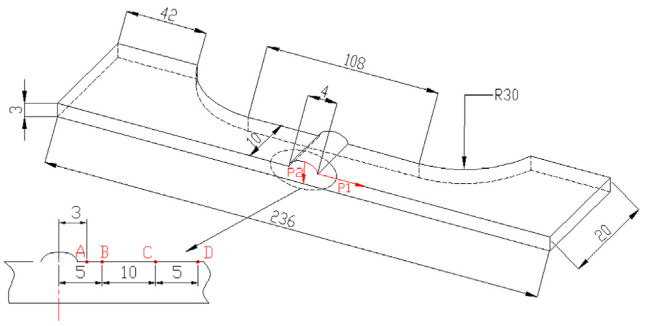

Fig. 1. The sketching of the half of specimen and the distribution of the measurement position.

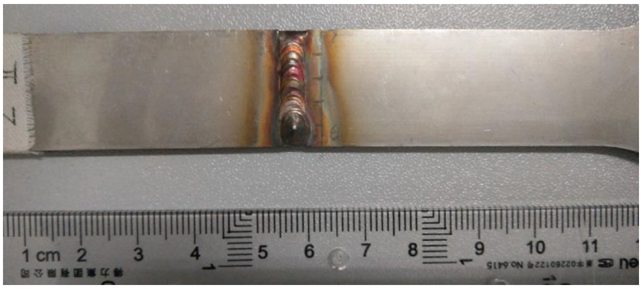

Fig. 2. The welded specimen.

2.3. Residual stress measurement by X-ray diffraction

X-ray diffraction was used to determine the magnitude of the residual stress by Bragg's law [32,33]:

$$\lambda = 2d\sin\theta \tag{1}$$

where λ is the wave length, d is the interatomic lattice spacing, and θ is the diffraction angle.

The test method is 2θ-$\sin^2\psi$ [34], and the residual stress is calculated by:

$$\sigma_x = K \cdot M \tag{2}$$

$$K = -\frac{E}{2(1+\nu)} g \frac{\pi}{180} ctg\theta_0 \tag{3}$$

$$M = \frac{\partial(2\theta_{\psi x})}{\partial(\sin^2\psi)} \tag{4}$$

where θ_0 is the diffraction angle under a stress-free state, Ψ is the angle between the normal crystal surface and the material surface, and K is the stress constant. A linear relationship exists between 2θ and $\sin^2\psi$, and M is the slope between the diffraction angle 2θ and $\sin^2\psi$. M is calculated if more than three points (2θ, $\sin^2\psi$) are determined.

The four measurement positions A, B, C, and D are presented in Fig. 1. The measurement was performed by the X-350A type stress gauge at the Shandong Special Equipment Inspection Institute. The voltage and current are 25 kV and 7 mA, respectively. For the 316L stainless steel, (2 2 0) is used as the crystal face, and 2θ varies from 123° to 132° at a scanning step of 0.1°. The experimental setup is shown in Fig. 4.

3. Finite element simulation

The weld residual stress was first simulated by a sequential coupling 3D thermo-mechanical FEM. Then, residual stress relaxation under cyclic loading was simulated by a cyclic plasticity constitutive model based on the in-house FE-code ABAQUS. A 3D finite element model was built according to the model in Section 2.1. The 3-D eight-node reduced integral solid elements with three translational degrees of freedom at each node were used in both two analytical models. And the finite element meshing is shown in Fig. 5. A fine meshing in the weld joint and its vicinity exists. The sensitivity of the meshing to the calculation result was carried out. In total, 18,564 elements and 24,068 nodes were meshed and the average length of element was 0.657 mm. Due to the fact that the plate and welding material have almost same chemical compositions shown in Table 1, the same mechanical properties were used for both materials in our analytical simulation.