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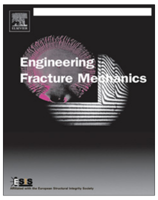

Development of integrated framework for fatigue life prediction in welded structures

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ABSTRACT

A new fatigue prediction method for wide range of welded structures has been developed by integrating several advanced computational techniques such as thermo-mechanical finite element method, crystal plasticity model and extended finite element method. The method consists of the following procedures: (i) computation of materials properties; (ii) analysis of temperature field, microstructure and residual stress generated during a welding process; (iii) stress distribution analysis under cyclic loading; (iv) fatigue crack initiation analysis by the Tanaka-Mura model; (v) fatigue crack propagation analysis. Using the proposed methodology, the fatigue life of butt joint was evaluated and compared with the experimental data.

1. Introduction

Development of new materials and structure often takes considerable time and cost to evaluate its performances. In the case of fatigue performances of welded structures, a huge amount of fatigue tests need to be conducted to validate statistical behavior of fatigue failure. Accordingly the evaluation of fatigue properties with shorter time becomes quite essential. In the conventional fatigue evaluation, fatigue design curves based on S-N curves (the inverse power law for the relationship between stress range and number of cycles to failure) are used. In this approach, mainly the geometries of the joint are considered, and the effect of the residual stress and microstructure are ignored under almost situations. On the other hand, several new materials are under developing to improve the fatigue performance. For example, low transformation temperature (LTT) welding materials reduce the residual stress [1–3], and dual phase steels improve the fatigue property by controlling the microstructure [4–6]. Therefore, the evaluation of the effect of residual stress and microstructure is becoming more important.

Under such background, various numerical simulation techniques related to fatigue in the welded joints have been proposed. The phase field method is one of the promising methods to predict the complicated microstructure [7,8], and the crystal plasticity model which accounts for the physical deformation mechanisms such as crystallographic slip and twinning have been received considerable attention in recent years [9,10]. The prediction of the fatigue crack initiation life based on the microstructure and crystal plasticity have been conducted actively. [11–14]. The extended finite element method (X-FEM) is a powerful and widely used tool to predict the fatigue crack propagation and the further improvement is still continuing [15,16].

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Nomenclature

A	coefficient of Armstrong–Frederick hardening law
a	crack length
B	coefficient of Armstrong–Frederick hardening law
C	constant of Paris law
C_d	constant of grain growth equation
D	austenitic grain size
d	length of slip band
G	shear modulus
HV_{bainite}	Vickers hardness of bainite
HV_{ferrite}	Vickers hardness of ferrite
$HV_{\mathrm{martensite}}$	Vickers hardness of martensite
h_0	hardening coefficient
$h^{\alpha\beta}$	hardening matrix of slip system α and β
K	stress intensity factor
ΔK	stress intensity factor range
L_{ij}	latent heat of the phase transformation from phase i to j
m	exponent of Paris law
N	number of cycles
N_f	number of cycles to failure
N_i	number of cycles for crack initiation
N_p	number of cycles for crack propagation
N_s	number of active slip system
p	exponent of grain growth equation
Q	activation energy
$q^{\alpha\beta}$	coefficient of hardening matrix
R	stress ratio
R_g	gas constant ($8.314\ \mathrm{J{\cdot}K^{-1}{\cdot}mol^{-1}}$)
T	temperature
V_r	cooling rate at 700 °C
w	hardening exponent
W_s	fracture surface energy pre unit area
$\dot{\gamma}^{\alpha}$	plastic shear strain rate
λ	austenite proportion
$\dot{\lambda}$	austenite proportion variation rate
ν	Poisson's ratio
$\dot{\xi}_{ij}$	proportion of phase i which is transformed into phase j in unit time
τ^{α}	resolved shear stress of slip system α
τ_c^{α}	critical resolved shear stress of slip system α
τ_{cs}	saturated critical resolved shear stress
χ^{α}	backstress of the slip system α

The objective of this study is to develop an extensible framework by integrating the advanced computational techniques as explained above in order to predict the fatigue performance of the welded joint. The framework consists of the following procedures: (i) computation of mechanical and thermal properties of base metal and welding material; (ii) analysis of temperature field, microstructure and residual stress generated during a welding process; (iii) macroscopic stress distribution analysis with continuum approximations under cyclic loading; (iv) mesoscopic stress distribution analysis with a microstructural model and fatigue crack initiation analysis; (v) fatigue crack propagation analysis. The computing system that automatically executes a series of these calculations has been constructed. As an example, a fatigue problem in widely used butt joint with low carbon steel (0.15% C) was assessed by the proposed method.

2. Analytical methods

2.1. Material properties

Overview of proposed method for predicting fatigue life of welded joints is shown in Fig. 1. The method consists of the following procedures: (i) materials properties including CCT curves, and mechanical and thermal properties of steels are estimated by using commercially available software and database; (ii) temperature field, residual stress and distortion gener-

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