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Quantitative Evaluation of Microstructural Influence on the Brittle Fracture Toughness of Ferrite-Pearlite Steels

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The influence of the microstructure on the brittle fracture toughness was evaluated quantitatively. It was assumed that the microscopic process of brittle fracture initiation in ferrite-pearlite steel is composed of three stages. The three stages were formulated in consideration of the scatter of the brittle fracture toughness. A ferrite grain was modeled as a sphere, and a pearlite particle was modeled as a spheroid. On the basis of the above quantitative evaluation, a numerical model for predicting the brittle fracture toughness of ferrite-pearlite steel was developed. The proposed model was validated by a comparison of the predicted results of the fracture toughness with the experimental results of the fracture toughness.

NOMENCLATURE

- a Major axis length of elliptical crack
- b Minor axis length of elliptical crack
- d Notch depth of the specimen (= 7 mm)
- E Young's modulus
- K Stress intensity factor
- K_{ab} Stress intensity factor for elliptical crack
- K_C Fracture toughness
- K_L Stress intensity factor for penny-shaped crack
- L Diameter of penny-shaped crack
- P_P Probability of nucleation of a crack
- R^P Ratio of the number of pearlite particles
- r_p Rotation factor (= 0.4) in the Crack Tip Opening Displacement (CTOD) estimation formula
- V_p Plastic component of the notch mouth opening displacement
- $\bar{V}^F$ Average volume of a ferrite grain
- $\bar{V}^P$ Average volume of a pearlite particle
- V_f^P Volume fraction of pearlite
- W Specimen width (= 20 mm)
- $\gamma_{\alpha\alpha}$ Effective surface energy for a crack to propagate across ferrite grain boundary
- $\gamma_{P\alpha}$ Effective surface energy for a crack at a pearlite particle to propagate into ferrite matrix
- δ_c Critical quasi-CTOD
- ε_p^P Equivalent plastic strain in a pearlite particle
- ν Poisson's ratio
- σ Stress tensor
- σ_{FF} Local fracture stress in Stage III
- σ_{FP} Local fracture stress in Stage II
- σ_{FPab} Fracture stress for elliptical crack
- σ_{FPL} Local fracture stress for a penny-shaped crack
- σ_{max} Macroscopic maximum principal stress
- σ_{min} Macroscopic minimum principal stress
- σ_n Normal stress working on the plane where crack initiates
- σ_Y Yield stress
- τ_{max}^P Maximum shear stress at a pearlite particle

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KEY WORDS: Brittle fracture, fracture toughness, quantitative evaluation, microstructure, ferrite-pearlite steel, experiment.

INTRODUCTION

As is widely known, steel materials are fundamental materials that constitute almost all structures. Recently, the strength of steel materials has gotten higher, and the fracture toughness and resistance to brittle fracture need to be secured simultaneously. However, even the model of low-strength steel, which is based on the microfracture mechanism and has a more simple mechanism than that of high-strength steel, has hardly existed.

The brittle fracture is the phenomenon depending on the weakest part. The fracture toughness has scatter and is difficult to evaluate quantitatively. There is much research attempting to predict the brittle fracture initiation. For example, Gumbsch (1995) used atomistic techniques (the Finite Element Atomistic model) to study brittle fracture. Hua et al. (1997) employed molecular dynamics to model the fracture of a two-dimensional triangular atomic lattice and estimated brittle fracture propagation. However, these models are based on an atomistic mechanism and cannot be directly connected with conventional fracture mechanics theory that comes from continuum mechanics. Rafii-Tabar et al. (1998) developed a multi-scale model of brittle crack propagation that combined molecular dynamics with finite element analysis. Nevertheless, the model did not characterize a fracture property on the basis of the microstructure of materials. Although there is a strong correlation between the fracture toughness and microstructure in steels, the quantitative relationship between the fracture toughness and microstructure has not been sufficiently clarified yet.

Crystal plasticity finite element analysis has been used to investigate material properties or the fracture mechanism, including brittle fracture, in steel materials on the basis of their microstructure (Kadkhodapour et al., 2011; Eyckens et al., 2015). Modeling of the ferrite-pearlite structure using the crystal plasticity finite element method has been tried (Watanabe et al., 2012; Debehets et al., 2014; Berisha et al., 2015). However, ferrite-pearlite has a complicated structure, such as lamellae, so it is necessary to set various variables to model the ferrite-pearlite structure. Many experiments and measurements are needed to set these variables. Moreover, the crystal plasticity finite element method takes much time to calculate. Since it requires so much time and labor, it is not easy to use the crystal plasticity finite element analysis to predict the fracture toughness in practice.