Numerical Study on Cyclic Crystalline Slip Deformation of Polycrystalline Metallic Material by Homogenization Method

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ABSTRACT

Cyclic crystalline slip deformations of a bulk body and a center-cracked plate consist of polycrystalline metallic media subject to cyclic loadings are investigated by using newly developed homogenized crystalline elastic-plastic FE theory which can take into account cyclic crystalline slip. Both coupling and Terada-and-Kikuchi's decoupling schemes are adopted. Localization and homogenization analyses are performed in the user subroutine of a commercial nonlinear FE code. Hill's anisotropic elastic-plastic constitutive relation, which cannot simulate cyclic hardening or softening, is adopted in the decoupling scheme. As results, it is found that the decoupling scheme can simulate the macroscopic stress-strain relation during the preloading of models with and without stress gradient, but the stress-strain relation and the shear slip deformation after the reloading show significant difference. It is not appropriate to apply the decoupling scheme that uses a constitutive equation which cannot simulate cyclic hardening or softening to the microscopic slip deformation analyses in fatigue crack problems.

KEY WORDS: Crystalline slip, Homogenization method, Fatigue crack, Finite element method

INTRODUCTION

Experimental data has conclusively demonstrated that crystalline slip is a basic mechanism of fatigue process. There is interaction between macroscopic deformation behavior and slip system activity. This interaction should be investigated in order to clarify microscopic aspects of fatigue process. Crystalline elastic-plastic FE (CEPFE) analysis can be adopted in such studies. Multi-scale analysis can be carried out by using homogenization method.

Homogenized CEPFE (HCEPFE) theories were studied by many researchers (Uetsuji et al. (2003), Nakamachi et al. (2004), Watanabe et al. (2005), Terada et al. (2006), Watanabe and Terada (2010)). The target of these studies was plastic processing, and to the best knowledge of the authors, there is no report on the application of HCEPFE analyses to fatigue problems. HCEPFE theories developed in these earlier studies cannot be applied to fatigue problems because cyclic crystalline slip deformation was not taken into account in those formulations. It is needed to develop a new HCEPFE theory which can simulate cyclic crystalline slip deformations.

When the cyclic deformation behavior near a fatigue crack tip is analyzed by HCEPFE theory, it is needed to prepare microscopic FE models at each macroscopic integration point. This requires huge computing man-hours. Terada and Kikuchi (1995) proposed to use an equivalent macroscopic elastic-plastic constitutive equation determined by 'numerical material tests'. They showed the effectiveness of their proposal for monotonic loading cases, but its applicability for cyclic deformation analysis has not been examined.

In this paper, a new HCEPFE theory which can take into account cyclic crystalline slip deformation is developed. Cyclic crystalline slip deformations of a bulk body and a rectangular center-cracked plate consist of polycrystalline metallic media are investigated by using the developed HCEPFE theory. Both coupling and Terada-and-Kikuchi's decoupling schemes are adopted by using commercial nonlinear FE code MSC.Marc. In the decoupling scheme, Hill’s anisotropic elastic-plastic constitutive relation is adopted. In the coupling scheme, the macroscopic elastic-plastic tangent modulus is calculated by MSC.Marc's user subroutine in which localized and homogenized analyses are performed. The effectiveness of the decoupling scheme is examined by comparing macroscopic and microscopic deformation behaviors calculated by two schemes.

THEORY

Homogenization theory

Let \( \Omega \) be a macroscopic region. In order to carry out multi-scale analysis, the microstructure of polycrystalline metal is modeled by a microscopic periodic structure \( \omega \) consisting of unit cells. \( \omega \) is assumed to distribute over \( \Omega \), and the size of \( \omega \) is very small compared with that of \( \Omega \). We can consider that \( \omega \) corresponds to a material point in the \( \Omega \). Let \( Y \) be a macroscopic region with comparable size to \( \Omega \), and \( Y \) is created by magnifying \( \omega \) so that \( \omega = \eta Y \). This enlarged region \( Y \) is called a unit cell.