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Development of Micro-Shear Fatigue Test and Its Application to Single Crystal of Pure Iron

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Abstract

In this study, a new fatigue testing method under shear and axial loading was developed for small specimens (3 mm long and 0.3 mm thick). The method was applied to a single crystal of pure iron and extra-low carbon steel in order to investigate the effect of shear and normal stress on cyclic slip activity. The specimen was sufficiently small to be prepared from a single crystal, aiming at a specific slip system in the shear loading direction. Moreover, the specimen had a single edge notch, which was designed to generate both pure shear stress and normal stress. Using this testing method, shear fatigue strength with a static normal stress on the slip system $(\bar{1}10)[111]$ was evaluated, and the fatigue strength was compared with that of polycrystalline ferrite steel with static axial loading.

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Keywords: Multiaxial fatigue, Shear fatigue strength, Slip plane, Single-crystal iron, Small specimen

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1. Introduction

Fatigue crack initiation in metals is induced by cyclic slip deformation. Slip activity is affected by multiaxial stress state in both the shear and normal directions on a slip plane. However, it is difficult to evaluate the effect of multiaxial stress on the slip activity in a certain slip system using the conventional multiaxial fatigue testing method for polycrystals because constraints of deformation by grain boundaries cause a complicated stress distribution and then multi-slip easily occurs. To solve this difficulty, it is necessary to conduct a single-crystal fatigue test suitable for evaluating the slip activity in the single slip system.

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Many researchers have performed the single-crystal test to investigate the slip system. The single-crystal fatigue test was carried out by Leidermark et al. with a notched specimen for superalloys [1]. Franciosi et al. evaluated the slip system activity in iron single crystals [2]. Landa et al. evaluated fatigue crack growth with an Fe-2.7wt%Si single crystal by experiment and molecular dynamics (MD) [3]. They claimed that the Paris exponents evaluated by the experiment and MD were similar. These researches evaluated the slip activities, however, there have been fewer applications to BCC than to FCC, due to the complication of the multi-slip systems activity. Iron, a BCC metal, is widely used in construction and other applications. If the effects of multiaxial fatigue on the slip activity in the iron were quantitatively evaluated, the mechanism of fatigue crack initiation could be clarified.

There are three difficulties in conducting the single-crystal iron fatigue test in the single slip system. The first problem is to obtain a large single-crystal iron aiming at the crystal direction. It is not easy to grow a large single crystal of metal, and a large single crystal is less than 10 mm, which is quite small for conducting the fatigue test. Moreover, the growth of the crystal is random direction. Thus, it is difficult to make a specimen for the purpose of the single-crystal iron fatigue test because it needs large single crystal and high accuracy of the crystal orientation. The second problem is to activate a single slip plane. A slip is activated by shear loading. Single-crystal torsion tests have been carried out [4,5], but in these tests the maximum shear stress was applied on the surface of the cylindrical area, and the shear stress on the slip plan is different at each point on the surface of the cylindrical area. Therefore, the conventional torsion test could not be applied for the activation of the single slip plane. The third problem is multiaxial loading fatigue. There has been a limited number of multiaxial fatigue testers. For the purpose of evaluating the multiaxial fatigue on slip activity, the fatigue tester needs a loading device applying the shear and normal stresses to the single slip system.

In this study, a new fatigue testing method under shear and axial loadings was developed for a small specimen (3 mm long and 0.3 mm thick), and was applied to a single crystal of pure iron and extra-low carbon steel in order to investigate the effect of shear and normal stresses on cyclic slip activity. The specimen was sufficiently small to be prepared as a single crystal aiming at a specific slip system in the shear loading direction. Moreover, the specimen had a single edge notch, which was designed to generate both pure shear stress and normal stress. Using this testing method, shear fatigue strength with static normal stress on the slip system $(\bar{1}10)[111]$ was evaluated, and the fatigue strength of a single-crystal iron was compared with that of polycrystalline ferrite steel subject to static axial loading.

2. Experiments

2.1. Material

A polycrystal of hot rolled extra-low carbon steel and a commercial single crystal of pure iron were evaluated. The chemical composition of the steel is given in Table 1 and the properties of the single-crystal iron are summarized in Table 2. The material process and mechanical properties of these materials are shown in Table 3. These materials were categorized as pure iron, thus solute strengthening and precipitation hardening effects were eliminated. The hot rolled extra-low carbon steel was rolled to 7 mm thick, and had polycrystalline ferrite phase. The single-crystal iron was coin-shaped (9 mm diameter and 2 mm thickness) with an orientation $(\bar{1}10)[111]$. The single-crystal iron was produced by Metal Crystals & Oxides Ltd. using thermal annealing processes. The single-crystal iron also has a ferrite phase.

Table 1 Chemical composition of polycrystal of extra-low carbon steel (mass%).

C	Si	Mn	P	S
0.0016	0.01	0.1	0.021	0.006

Table 2 Property of single crystal of iron.

Process	Thermal annealing process
Purity	3N8
Size	ϕ9×t2[mm]
Orientation	Polished surface: {111} orientation flat:<110>