Abstract of Invited Speech 7

Fatigue of Micro-sized Copper Single Crystal Specimen under Fully-reversed Axial Loading

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1. Introduction

In metals cyclically deformed, characteristic fatigue substructure is developed by self-organization of dislocations [1]. The substructure morphology changes while depending on plastic resolved shear strain amplitude, $\gamma_{pl.}$. Copper single crystal [2] cycled at a low plastic strain amplitude ($\gamma_{pl.}<10^{-4}$) has a substructure composed of veins, which are clusters of dislocation dipoles, and channels with low dislocation density. At a medium plastic strain amplitude ($10^{-4}<\gamma_{pl.}<10^{-2}$), a ladder-like structure consisting of dislocation walls and channels, which is known as "persistent slip band (PSB) [3]", is locally nucleated. The PSB has a thickness in the range of some microns [3], which is independent of material size. At a high plastic amplitude ($10^{-2}<\gamma_{pl.}$), multiple slip deformation induces dislocation labyrinth and cell structures. These dislocation structures are developed under reversed loading because the characteristic substructure formation requires dislocations with a different sign. The PSB brings about remarkable unevenness on material surface, which is called "extrusion/intrusion" [4].

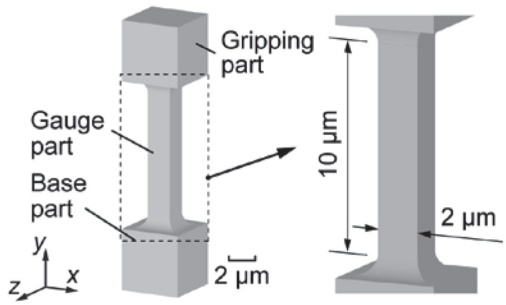

Fig.1 Schematic illustration of fatigue specimen of micro-sized single-crystal pure copper with a single slip.

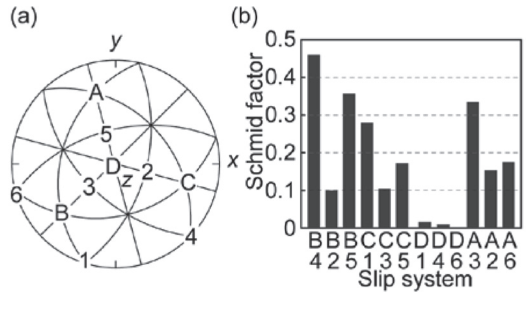

Fig.2 (a) Stereographic projection showing the crystallographic orientation of copper single-crystal specimen, and (b) Schmid factors of 12 slip systems. 12 slip planes and 6 slip directions are expressed as A-D and 1-6, respectively.

The fatigue limit generally corresponds to the lower end of the plastic strain amplitude where

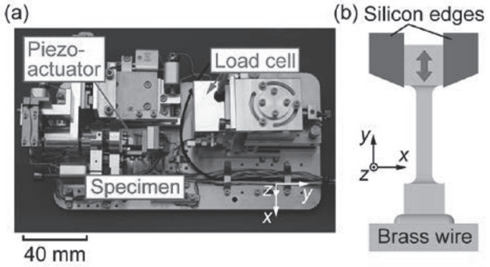

Fig.3 (a) Tension–compression cyclic loading device and (b) specimen gripper developed in this project.

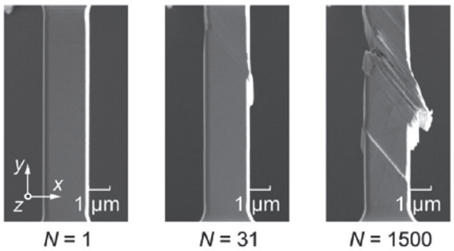

Fig.4 Morphological change of micro-sized single-crystal copper specimen under tension–compression cyclic loading

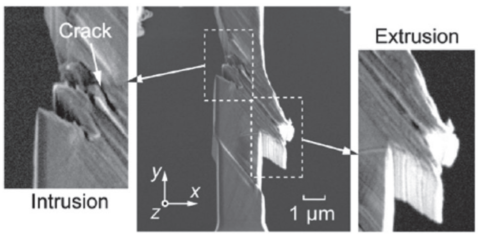

Fig.5 Morphological change of micro-sized single-crystal copper specimen under tension–compression cyclic loading

the ladder-like structure forms, because the PSB acts as preferential sites for the development of fatigue cracks due to highly localized and largely reversible slip.

The above mechanism cannot be applied to the fatigue failure of metals with a size of several microns or less, because there is not enough space for PSB formation. A few cyclic bending experiments of small components were reported [5-6]. However, the specimens which receives bending have stress gradient inside. It is known that the stress gradient creates a size effect on the fatigue strength. In order to clarify the size effect on fatigue strength in micro- or nano-scale components, which depends on only material size, an axial tension-compression experiment is required.

In this project, we conducted cyclic loading experiment for a copper single crystal micro-sized specimen under fully reversed axial loading and investigate the fatigue behavior with in-situ observation.

2. Experimental

A polycrystalline copper (Cu) plate (purity 99.999%) was mechanically polished and annealed at 1072K for 24 hours. A single crystal specimen with a single slip orientation was fabricated from a grain with the desired crystal orientation using a focused ion beam (FIB) processing system. Figure 1 (a) shows the schematic illustration of the specimen. The specimen has a dog bone shape consisting of a base, a gauge and a grip parts. The gauge part dimensions are 10 μm (height) × 2 μm (width) × 2 μm (depth). Figures 2(a) and (b) show a stereographic projection of the specimen and the Schmidt factors of 12 slip systems, respectively. We developed a tension-compression cyclic loading device (See Fig.3) that can be inserted into a field emission scanning electron microscope (FE-SEM), and carried out fully-reversed tension-compression cyclic loading experiment. The applied displacement amplitude was controlled so that the average stress amplitude became about 40 MPa.

3. Results and Discussion

Figure 4 shows the in-situ observation image of the specimen at N = 1, N = 31 and N = 1500. At the upper side of the gauge part, the right and left side surfaces were damaged and extrusion and intrusion along the primary slip system B4 were generated, respectively. It was observed that the damage propagates downward while repeating forward and reverse slippage with the increase of the number of cycles. In this deformation, the specimen did not show cyclic work hardening. Detailed observation at N = 3400 (Fig.5) indicated that extrusions/intrusions composed of nano- thickness plate-like structures (thickness: 10 nm-15 nm) penetrating the gauge part was formed. The height and depth of the extrusions/intrusions corresponded to about 40% of the width of the gauge part. The fact that the specimen did not show cyclic work hardening suggested that the formation of stable dislocation structures (aggregated dipoles), which is observed in bulk materials, was not formed in the early stages of fatigue. It was revealed that the micron-sized specimen possesses a characteristic fatigue behavior much different from bulk counterparts on the basis of the extrusions/intrusions composed of nano-thickness plate-like structures and an internal observation using a transmission electron microscope (TEM).

4. Summary

In the present work, we developed a device that can realize tension-compression cyclic loading and conducted a fatigue experiment for a copper single crystal micro-sized specimen with in-situ observation. Extrusions/intrusions consisting of numerous fine plates were generated along the primary slip system B4. The fact that the specimen did not show cyclic hardening indicates that stable dislocation structures did not form.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Numbers JP18H03753, JP18K18807, JP18H05241, JP15H02210, JP18H01344.

References

[1] C. Laird, P. Charsley, and H. Mughrabi, Low energy dislocation structures produced by cyclic deformation, *Materials Science and Engineering*, 81 (1986) 433-450.

[2] H. Mughrabi, The cyclic hardening and saturation behaviour of copper single crystals, *Materials Science and Engineering*, 33(2) (1978) 207-223.

[3] P. J. Woods, Low-amplitude fatigue of copper and copper-5 at. % aluminium single crystals, *Philosophical Magazine*, 28(1) (1973) 155-191.

[4] E. E. Laufer and W. N. Roberts, Dislocations and persistent slip bands in fatigued copper, *Philosophical Magazine*, 14(127) (1966) 65-78.

[5] D. Kiener, C. Motz, W. Grosinger, D. Weygand, and R. Pippan, Cyclic response of copper single crystal micro-beams, *Scripta Materialia*. 63 (2010) 500-503.

[6] T. Sumigawa, R. Shiohara, K. Matsumoto, T. Kitamura, Characteristic features of slip bands in submicron single-crystal gold component produced by fatigue, *Acta Materialia*, 61 (2013) 2692-2700.