The Effect of Microtexture Evaluated by EBSD (Electron Back-Scatter Diffraction) Method on Fatigue Crack Propagation Behavior in Rolled Copper Film

K. Shimizu[1] and T. Torii[2]

[1] Faculty of Engineering, Okayama University, 3-1-1 Tsushima-naka, Okayama 700-8530, JAPAN, kshimizu@mech.okayama-u.ac.jp
[2] Faculty of Engineering, Okayama University, 3-1-1 Tsushima-naka, Okayama 700-8530, JAPAN, torii@mech.okayama-u.ac.jp

ABSTRACT. *Using a fatigue testing method by which fatigue cracks can be initiated and propagated in a film adhered to cover a circular through-hole in a base plate subjected to push-pull cyclic loads, annealed rolled pure copper films of 100μm thickness were fatigued. The effects of microstructures such as crystal orientation due to rolling and annealing twin boundaries on fatigue crack propagation behavior are studied using two types of specimens that the rolling direction was parallel and perpendicular to the loading direction. The fatigue crack path showed larger zigzag pattern for the crack propagated toward the perpendicular direction to the rolling direction than toward the parallel direction to the rolling direction and the fatigue crack propagated slower toward the perpendicular direction to the rolling direction than toward the parallel direction. After the fatigue testing, the crystallographic characteristic of rolling textures around the fatigue crack in the annealed film is analyzed using EBSD (Electron Back-scatter Diffraction) system. As a result, the anisotropy of rolling texture remained after annealing and the annealing twin boundaries were inclined to orient to the rolling direction. The fatigue crack often propagated along the annealing twin boundaries. Since the annealing twin boundary was the same plane as the slip plane of the face-centered-cubic metal, the fatigue crack had a tendency to propagate along the slip line initiated along the annealing twin boundary.*

INTRODUCTION

In recent years, film materials are often used in electronic devices, such as the films deposited on rigid substrates [1] and on IC packages modeling a multi-layer construction [2, 3]. For reliability of these parts, it is necessary to estimate the fatigue properties of the film materials, of which mechanical properties will be different from those of bulk materials used as relatively large-sized components of machines. However, since fatigue testing presents a serious difficulty with regard to gripping small specimens, the fatigue properties of the film specimen have been hardly discussed as compared with those of the bulk specimen. As a result, the fatigue properties of bulk specimens are often used to design electronic parts. However since materials in the form of film have a small number of crystals against to its thickness compared with bulk materials, the properties of each crystals in the film are considered to have a great effect on fatigue fracture properties. Therefore the fatigue fracture property of a film is considered to be different from that of a bulk materials with the same structure as the film.

In this study, a film fatigue testing method was proposed by which fatigue crack initiation and propagation occurred on a film bonded to a circular through-hole in a base plate subjected to push-pull cyclic loads [4, 5]. If a film adhered to a through-hole in a base plate subjected to loading is regarded as the ellipsoidal inclusion in Eshelby's model [6], the strain and the stress will be uniform in the film. In this way, it is possible to conduct film fatigue testing by stress cycling on the base plate. Using this fatigue testing method of film, fatigue properties of the film with the thickness of 100μm are examined for rolled copper films annealed at 873 K and the effects of rolling direction on fatigue properties are examined for the two types of specimen that the loading direction is parallel and perpendicular to the rolling. Finally, the effects of crystal orientation on fatigue crack propagation behavior in the copper film is discussed with noticing the interaction between the crack and the annealing twin boundary observed by the crystal orientation analysis using EBSD (Electron Back-scatter Diffraction) method.

EXPERIMENTAL PROCEDURE

Specimens

The cold rolled pure copper films with a thickness of t_f=100μm were annealed at 873 K for one hour in a vacuum furnace. The base specimen of medium carbon steels (S45C) was machined to the dimension with a circular through-hole shown in Fig. 1, then polished with emery paper and finally annealed at 1123 K for one hour in a vacuum furnace. The thickness of the base plate is t_b=5.3mm. The chemical compositions of the film and the base plate are shown in Table 1. The film specimen specified by rolling direction was cut into a 30×40 mm^2 rectangle and was electro-polished by a few microns. Furthermore, a through-hole of 0.5 mm diameter was made at the center by using a drilling machine. The film and the base specimens were bonded with a cyanoacrylate cement so that the center of the film coincided with that of the hole in the base plate. These films were specified by the rolling direction as two types of specimen where the crack is propagated perpendicular or parallel to the rolling direction in relation to the cracking and the rolling directions as illustrated in Fig. 1. The former type is named the TC specimen, and the latter type the RC specimen.

Film Fatigue Testing

The film to be tested was adhered to one side of a through-hole in a base plate as shown in Fig. 1 and the film was fatigued in accordance with the displacement along the hole circumference in the base plate subjected to push-pull sinusoidal cyclic loads with a constant stress amplitude, $(\sigma_a)_b$=30MPa, at a speed of 20 Hz and a stress ratio R = 0, using a servo-hydraulic fatigue testing machine. In this fatigue testing, the cyclic strains and stresses are uniform in the film adhered to a through-hole in a base plate subjected to cyclic loading, as described in the ellipsoidal inclusion in Eshelby's model [6]. The stress distribution calculated using a two-dimensional BEM (Boundary Element Method) analysis was almost uniform on the film, the value of which was almost 1.6 times of applied stress $(\sigma_a)_b$. The fatigue crack behavior on the film was observed using an optical microscope attached to the testing machine.

Table 1. Chemical compositions.

(mass %)

	Al	Ni	Sn	Pb	Fe	Zn	Mn
Pure copper (Film of 100μm thickness)	5×10^{-5}>	5×10^{-5}>	5×10^{-5}>	5×10^{-5}>	5×10^{-5}>	5×10^{-5}>	4×10^{-5}
	C	Si	Mn	P	S		
Medium carbon steel (S45C) (Base plate)	0.45	0.18	0.78	0.012	0.006		

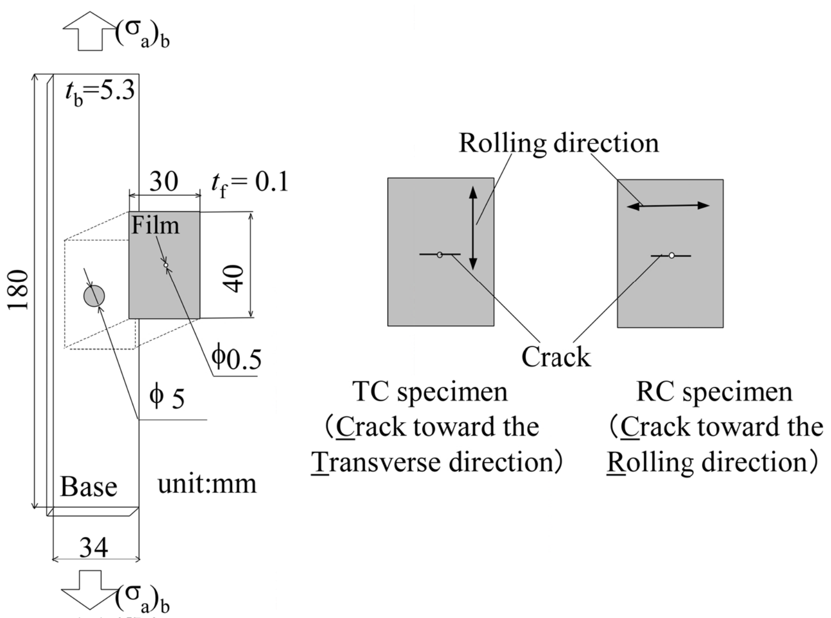


Figure 1. Dimensions of the film and the base specimen.

Crystal Orientation Analysis

The crystallographic information of rolling textures in annealed copper films was analyzed using a EBSD system (Link OPAL, Oxford Instruments) [7]. The results of crystal orientation analysis are represented using a COM (Crystal Orientation Map).

EXPERIMENTAL RESULTS

Fatigue Crack Propagation

Figure 2 shows the crack propagation curves of the copper film. The fatigue cracks propagated with temporally crack arrests in both the TC and the RC specimen. It is shown that the periods of the crack arrest in the TC specimen is longer than in the RC specimen. As a result, the number of cycles to the crack length of a≅1.0mm is larger in the TC specimen than in the RC specimen. The periods indicated using 'A' and 'B' show the temporally crack arrests more than 2×10^5 cycles.

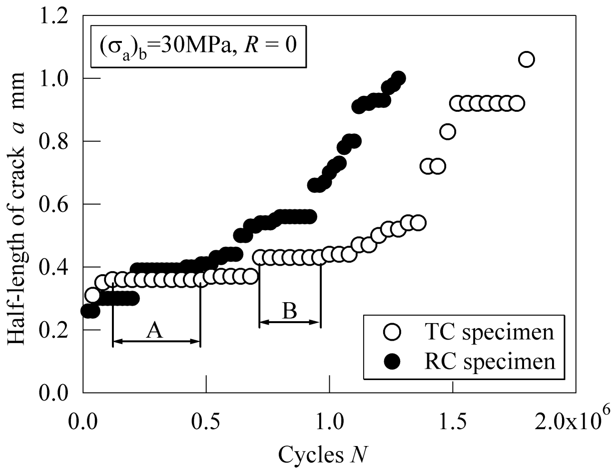
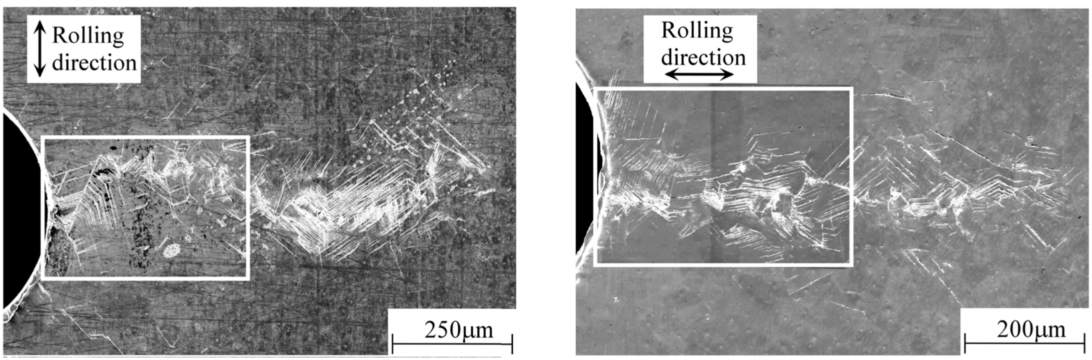


Figure 2. Crack propagation curves.

Figure 3(a) and (b) shows the surface crack observed through the use of a SEM (Scanning Electron Microscope) in the TC and the RC specimen, respectively. From Fig. 3, it can be seen that the wandering of the fatigue crack in the TC specimen is larger than that in the RC specimen and the crack propagated in a large zigzag pattern in the TC specimen, while the crack propagation path in the RC specimen is nearly straight.



(a) TC specimen (a=1.06mm, N=1.06×10^6 cycles). (b) RC specimen (a=1.00mm, N=1.28×10^6 cycles).

Figure 3. SEM micrographs of fatigue cracks in the film.

Crack Orientation Analysis

The rolling textures near the notch root expressed by a rectangle in Fig. 3(a) were examined using EBSD technique, as shown in Fig. 4, in terms of the COM that shows the crystal orientation toward the transverse direction to the rolling direction. As the point expressed by the same contrast has the same crystal orientation, it is likely to indicate a grain. From these figures, the grain size ranges from 40μm to 100μm and some large grains of 200μm or larger can be seen and the crack propagates along the grain boundary and across the grain boundary in some cases. The points 'A' and 'B' show the temporally crack arrests indicated in Fig. 2. The crack propagation rate is plotted against the crack length in Fig. 5. The data with the downward arrow indicate the temporally crack arrests and the data expressed by 'A' and 'B' are the crack arrests more than 2×10^5 cycles.

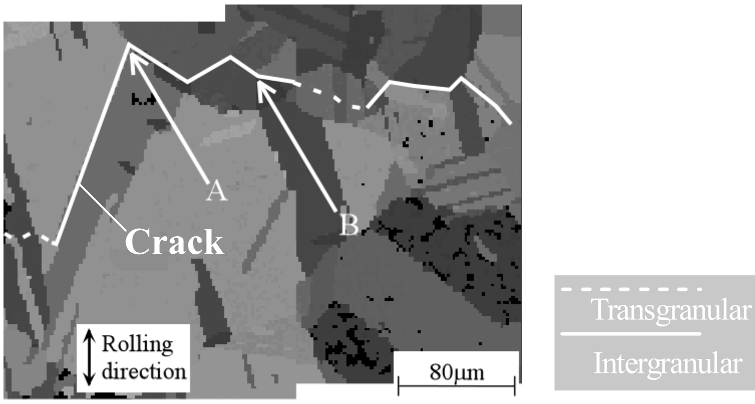


Figure 4. Crystal orientation map (TC specimen).

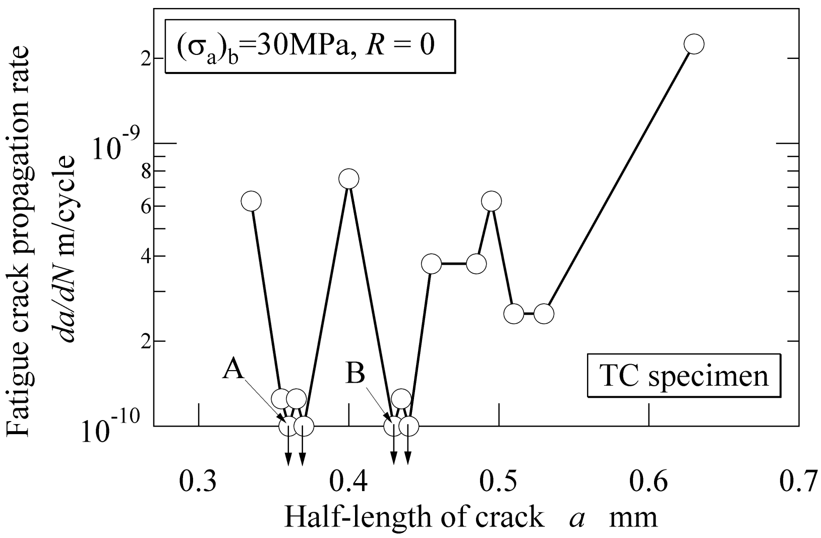


Figure 5. Change of crack propagation rate with crack growth (TC specimen).

Figure 6 shows the COM obtained from the area expressed by a rectangle in Fig. 3(b) and Fig. 7 shows the variation of crack propagation rate with the fatigue crack growth. The crack propagates along the grain boundary and across the grain boundary with temporally crack arrests like the TC specimen as shown in Fig. 4. Since the crack propagation rate observed in Fig. 7 is almost the same with that in Fig. 5, the difference in the number of cycles to the crack length of 1.0mm between the TC and RC specimen seems to be affected by the length of temporally crack arrests period.

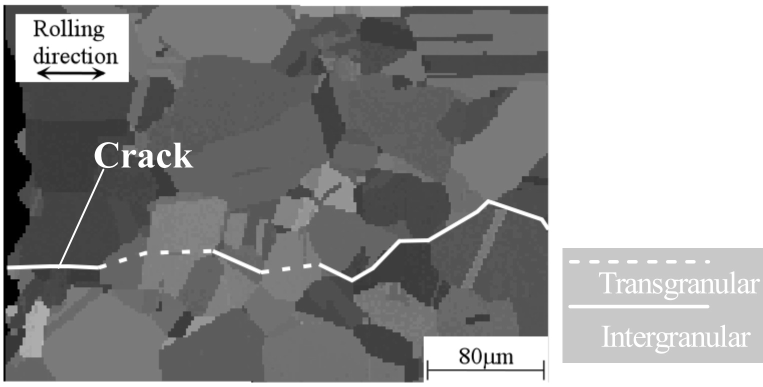


Figure 6. Crystal orientation map (RC specimen).

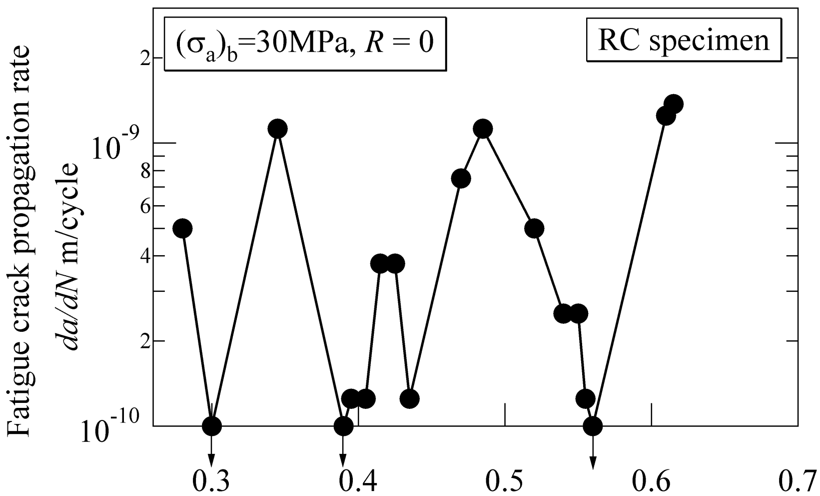
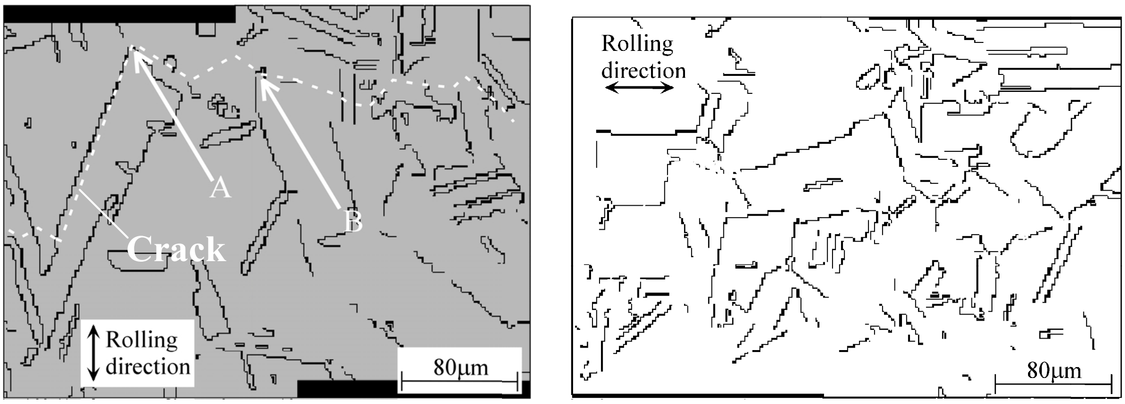


Figure 7. Change of crack propagation rate with crack growth (RC specimen).

DISCUSSIONS ABOUT THE EFFECTS OF TWIN BOUNDARY

Figure 8 shows the annealing twin boundaries existed in the area of Figs. 4 and 6. As shown in the figures, most of the grain boundaries are the twin boundaries and the long twin boundaries seem to grow toward the rolling direction. It is found that the fatigue crack often propagates along the twin boundary. For the face-centered-cubic material, the twin boundary is (111) planes in accord with the slip plane of the face-centered-cubic metal. The misorientation of a twin boundary is 60 degree about the [111] direction. Since the angle of misorientation in the twin boundary is much larger than that in any other grain boundary, the deformation between the twin boundaries seems to become larger. As a result, the slip plane in accord with the twin boundary appears to slip easier than any other slip plane and the fatigue crack is prone to propagate along the twin boundary. As the long twin boundary has a tendency to grow toward the rolling direction, the fatigue crack path shows larger zigzag pattern in the TC specimen than in the RC specimen.

When the angle between the twin boundary and the loading direction is small, the Schmid factor of the slip system on the twin boundary is small. As a result, the twin boundary with near direction toward the loading direction seems to arrest the crack propagation. Namely, the crack in the TC specimen tends to be arrested by the twin boundary that is nearly perpendicular to the crack propagation direction, as indicated by the points ‘A’ and ‘B’, while the twin boundary that is nearly parallel to the crack propagation direction in the RC specimen is liable to accelerate the crack propagation.



(a) TC specimen. (b) RC specimen.

Figure 8. Annealing twin boundary obsereved by EBSD method.

CONCLUSIONS

The microtexture such as annealing twin boundary in the copper films was analyzed using the EBSD method and the copper films were fatigued using a method of film fatigue testing. The main results obtained are as follows:

(1) The fatigue crack path showed larger zigzag pattern for the crack propagated toward the perpendicular direction to the rolling direction (TC specimen) than toward the parallel direction to the rolling direction (RC specimen) and the fatigue crack propagated slower toward the perpendicular direction to the rolling direction (TC specimen) than toward the parallel direction (RC specimen).

(2) From the result obtained using EBSD (Electron Back-scatter Diffraction) system, the anisotropy of rolling texture remained after annealing and the annealing twin boundaries were inclined to orient to the rolling direction.

(3) The fatigue crack often propagated along the annealing twin boundaries. Since the annealing twin boundary was the same plane as the slip plane of the face-centered-cubic metal, the fatigue crack had a tendency to propagate along the slip line initiated on the annealing twin boundary.

(4) The twin boundary with the direction near the loading direction seems to arrest the crack propagation, while that with the perpendicular direction is liable to accelerate the crack propagation.

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