MEMOIRS OF THE SCHOOL OF ENGINEERING, OKAYAMA UNIVERSITY Vol. 5, No. 1, SEPTEMBER 1970

Further Considerations Concerning a Mechanism of Fatigue Crack Propagation

Kazuo HONDA and Tetsuro KONAGA

Department of Mechanical Engineering

(Received May 20, 1970)

Synopsis

X-ray microbeam diffraction technique is a useful one to investigate the features of the crystal deformation in a localized area. That is, this method have been adopted to examine the density and array of dislocation, microscopic lattice strain and macroscopic residual stress. And so, the informations obtained from the tip of the crack during the fatigue process have been correlated with the behaviours of the initiation and propagation of the crack.

The authors, in the present paper, investigated a relation between the distributions of the microscopic lattice strains which are calculated and measured by the technique, and suggested the sort of dislocation at the tip of the crack that relate to the fatigue crack propagation.

The crack initiated at the notch root of the specimen which was composed of the coarse grain and propagated along the grain-boundary in the early stage under fatigue process of the alternating stress 4.1 kg/mm^2. Thereafter, it changed the propagating direction toward the inside of the grain.

The distributions of the micro lattice strain in each reflecting plane which were measuerd at the plastically deformed zone in the vicinity of the grain-boundary and at the crack tip agreed well with modes of the strain distribution due to a screw and a edge dislocations by the calculation, respectively. From these results, the authors concluded that the fatigue crack propagation would relate closely to the changing in the sort of the dislocation from the screw to the edge.

§ 1. Introduction

The deformation and the fracture in metallic materials have been approached on lines of engineering, metallurgy and physics.

In fatigue fracture, especially, in order to make clear the mechanism of the crack propagation, many investigations[1)~8)] have pointed out recently a importance of" sub-structure" in the microscopic yielding region at the crack tip. While, many researchers[9)] who have put themselves elastic continuum theory give emphasis to "stress intensity factor" concerning to the crack propagation rate during fatigue process.

The authors, also, have investigated the relation between the mechanism of the fatigue crack propagation and the features of the plastically deformed zone at the tip of the crack by means of electron microscope and X-ray microbeam diffraction techniques in views of the physical metallurgy and the elastic continuum theory. The results obtained from those experiments were very usefull to know the outline of the fatigue crack propagation. However, it is not enough to explain more detailed mechanism of the fatigue crack propagation by those results alone. That is, we also must discuss a model of how the crack propagation.

After consideration on this respect, in the present paper, the authors submit data as a track in considering the model of the crack propagation. The data in which the authors investigated the relation between the distributions of the microscopic lattice strains which are calculated theoretically and measured by X-ray microbeam diffraction technique, and should show what sort of dislocation at the tip of the crack that relate to the fatigue crack propagation.

§ 2. Theoretical Analysis and Experimental Procedures

§§ 2.1. Theoretical Analysis of Distribution of the Microscopic Strain Due to a Dislocation

(1) The Microscopic Strain in Any Position and Direction Due to a Edge Dislocation

As shown in Fig. 1, let us lay the direction

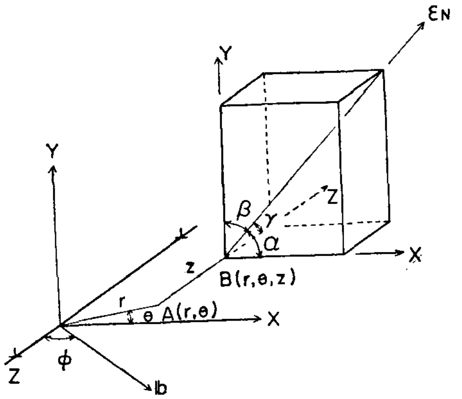

Fig. 1 Geometrical relationships in dislocation strain

of the dislocation line, the slip plane normal and Burger's vector along the Z-, Y- and X-axes, respectively. Position A lies on the plane XOY, and position B is on line and parallel to Z-axis, and far away z from position A.

Giving such definitions, the distributions of the stress and the strain around a edge dislocation in position A are equal to them in position B, and they are independent on z. Thus the stresses and the strains in position A are

$$\left.\begin{aligned}\sigma_x &= -\mu b\sin\theta(2+\cos 2\theta)/2\pi r(1-\nu)\\ \sigma_y &= \mu b\sin\theta\cdot\cos 2\theta/2\pi r(1-\nu)\\ \sigma_z &= \nu(\sigma_x+\sigma_y)\\ \tau_{xy} &= \mu b\cos\theta\cdot\cos 2\theta/2\pi r(1-\nu)\end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned}\varepsilon_x &= -b\sin\theta(2-2\nu+\cos 2\theta)/4\pi r(1-\nu)\\ \varepsilon_y &= b\sin\theta(2\nu+\cos 2\theta)/4\pi r(1-\nu)\\ \gamma_{xy} &= b\cos\theta\cdot\cos 2\theta/2\pi r(1-\nu)\end{aligned}\right\} \quad (2)$$

where b and ν are Burger's vector and Poisson's ratio, respectively. All other components being zero.

Now, ε_N which is a strain along any direction in position A,

$$\varepsilon_N = l^2\varepsilon_x + m^2\varepsilon_y + n^2\varepsilon_z + lm\gamma_{xy} + mn\gamma_{yz} + nl\gamma_{zx} \quad (3)$$

where l, m and n are the direction cosines to X-, Y- and Z- axes.

Substituting Eq. (2) into Eq. (3), ε_N becomes :

$$\varepsilon_N = \frac{b\{-l^2\sin\theta(2-2\nu+\cos 2\theta)+m^2\sin\theta(2\nu+\cos 2\theta)+2lm\cos\theta\cdot\cos 2\theta\}}{4\pi r(1-\nu)} \quad (4)$$

It is easily understood that the root mean square strain ε_{NR} of Eq. (4) is given in the form of the following integral :

$$\varepsilon_{NR} = \sqrt{\frac{\int_0^{2\pi}\varepsilon_N^2 d\theta}{2\pi}} \quad (5)$$

Substituting Eq. (4) into Eq. (5) yields

$$\varepsilon_{NR} = \frac{b\sqrt{(2\nu^2-3\nu+5/4)l^4+(2\nu^2-\nu+1/4)m^2+(4\nu^2-4\nu+3/2)}}{4\pi r(1-\nu)} \quad (6)$$

(2) The Microscopic Strain in Any Position and Direction Due to a Screw Dislocation

For a screw dislocation lying in a slip plane with the Burger's vector along the Z-axis, the distributions of the stresses and strains in the position A are

$$\left.\begin{aligned}\tau_{xz} &= -\mu b\sin\theta/2\pi r\\ \tau_{yz} &= \mu b\cos\theta/2\pi r\end{aligned}\right\} \quad (7)$$

$$\left.\begin{aligned}\gamma_{xz} &= -b\sin\theta/2\pi r\\ \gamma_{yz} &= b\cos\theta/2\pi r\end{aligned}\right\} \quad (8)$$

All other components being zero. ε_N along any direction in position A is then :

$$\varepsilon_N = \frac{b(-nl\sin\theta+mn\cos\theta)}{2\pi r} \quad (9)$$

Calculating ε_{NR} in the same way as the case of the edge dislocation

$$\varepsilon_{NR} = \frac{\sqrt{2}\sin\gamma\cos\gamma}{4\pi r} \quad (10)$$

(3) The Strain in Any Position and Direction Due to a Mixed Dislocation

Defining ϕ as the angle between the Burger's vector and Z-axis as shown in Fig. 1. Then, the components of the stress and strain around a mixed dislocation are the sum of the strengths of the edge component of bsinϕ and of the screw component of bcosϕ.

Accordingly, ε_N along any direction in the position A is then :

$$\varepsilon_N = \frac{b\sin\phi\{-l^2\sin\theta(2-2\nu+\cos 2\theta)+m^2\sin\theta}{4\pi r(1-\nu)} \overline{(2\nu+\cos 2\theta)+2lm\cos\theta\cdot\cos 2\theta\}} + \frac{b\cos\phi(-n'l'\sin\theta+m'n'\cos\theta)}{2\pi r} \quad (11)$$

where l. m and n and l', m' and n' are the direction cosines which are provide for X-, Y- and Z-axes in the case of the edge and the screw dislocations, respectively.

The root mean square strain ε_{NR} of ε_N in the mixed dislocation is given in the form of the following integral.

$$\varepsilon_{NR} = \frac{\sqrt{\int_0^{2\pi}\int_0^{\pi}\varepsilon_N^2\, d\phi d\theta}}{2\pi^2} \quad (12)$$

Therefore, the conbination of Eqs. (11) and (12) results in

$$\varepsilon_{NR} = b\sqrt{\frac{(2\nu^2-3\nu+5/4)l^4+(2\nu^2-\nu+1/4)m^4}{2(1-\nu)^2} \frac{+(4\nu^2-4\nu+3/2)l^2m^2}{+n'^2(1-n'^2)}} \quad (13)$$

Finally, considering the relations between the direction cosines of l, m and n, and l', m' and n', we are able to find out the relation of $l'=n$, $m'=m$ and $n'=l$.

Therefore, Eq. (13) may be simplified, then

$$\varepsilon_{NR} = b\sqrt{\frac{(2\nu^2-3\nu+5/4)l^4+(2\nu^2-\nu+1/4)m^4}{2(1-\nu)^2} \frac{+(4\nu^2-4\nu+3/2)l^2m^2}{+l^2(1-l^2)}} \quad (14)$$

§§ 2.2. Experimental Procedures

(1) Specimen and Fatigue Test

The specimen used in this experiment was annealed pure copper (99.9%). Before testing, the specimen was annealed for 10 hrs. at 960 °C under vacuum, furnace cooled, and so it was composed of the grain size of about 3 mm in diameter.

The specimen whose stress concentration factor α determinated from the theory of H. Neuber[10] was 4.0 was prepared.

The specimen was applied fully reversed bending monent in the plane normal to the surface of specimen by using the Shimadzu fatigue testing machine (UF-500 type) after it was recomposed to fit the present experiment.

(2) X-ray Microbeam Diffration Technique

X-ray microbeam used in this experiment was collimated by double pin holes (100μ ϕ-50$\mu\phi$) because of the large spot on the target of the X-ray tube. The resolving power was 0.4μ, and size of area on the specimen surface irradiated by X-ray was about 170μ in diameter. CuKα radiations were used. The conditions for X-ray observation were given in Table I in the lump.

Table I Conditions of X-ray microbeam diffraction

Target	Cu
Tube voltage (kV)	40
Tube current (mA)	20
Slit diameter, double pin holes ($\mu\phi$)	50
Distance from specimen to film (mm)	55
Divergence (rad)	3.6×10^{-4}
Illuminated area ($\mu\phi$)	170

X-ray microbeam camera shown in Fig. 2 was used. The camera is composed of the camera cassette (1), specimen holder (2) which is able to rotate centering around a point on the specimen surface, in vertical and horizontal planes to the X-ray incident beam, and optical microscope (3). Then the X-ray microbeam can be irradiated with high accuracy on any specimen surface by this camera.

As micro lattice strain $\Delta d/d$ in each reflecting plane was measured in the same way as the technique in the case of the polycrystalline, the detailed explanations will be given elsewhere. Therefore, in this paper, the authors indicate the final formura which give one.

$$\Delta d/d = \frac{\cos^2 2\theta}{2\tan\theta} \cdot \frac{\Delta S_R}{R_0}$$

where θ is Bragg's angle, $\Delta S_R = S_R - S_{R0}$, and S_{R0} is the value of S_R for the radial width of the spot in the virgin grain, and R_0 is the distance between film and specimen.

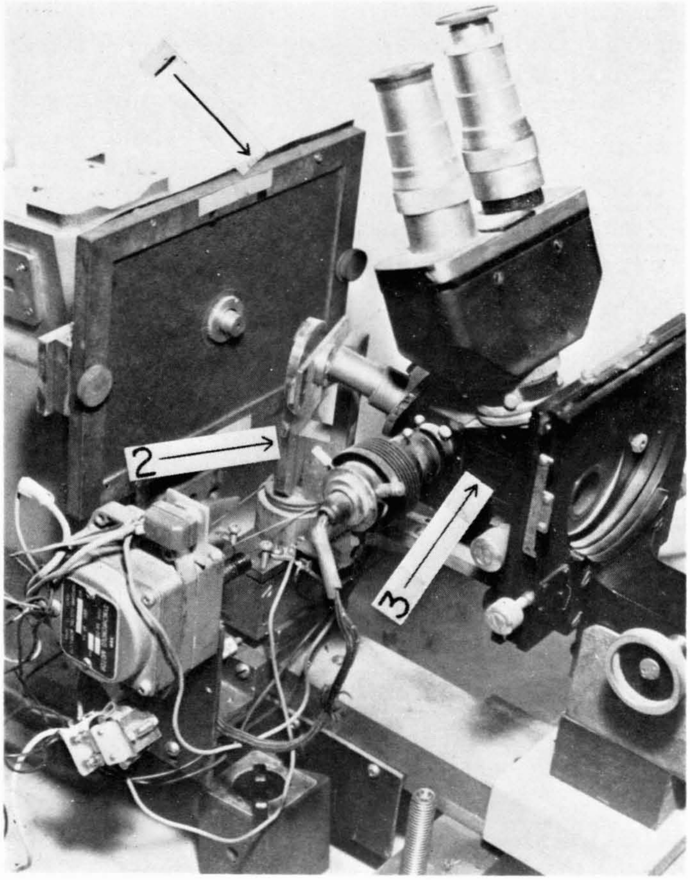

Fig. 2 X-ray microbeam camera

In this specimen subjected alternating stress of 4.1 kg/mm^2, the fatigue crack propagated along the grain-boundary in early stage under fatigue process. In the next stage the crack changed its direction of the propagation toward the inside of the grain along the slip band, and propagated with increase of the cyclic number. A relation between the crack length l_c and the cyclic number N is shown in Fig. 4, the circles in Fig. 5 are positions of irradiation of X-ray microbeam during the fatigue process.

X-ray microbeam diffraction technique used in the present paper gives some informations, micro lattice strain, misorientation, substructure and macroscopic residual stress. The authors, however, dwell upon the

§ 3. Experimental Results and Discussions

Fig. 3 shows the orientation of the crystal which was situated at the notch root of the V shaped notch specimen.

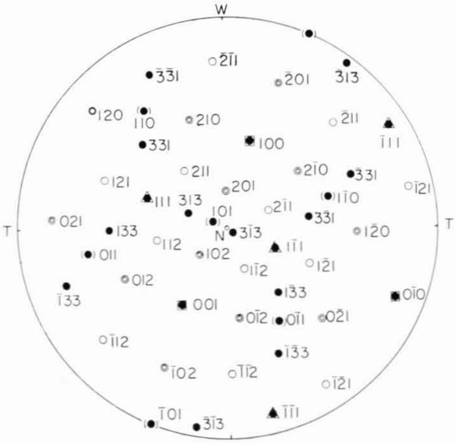

Fig. 3 Orientation of crystal

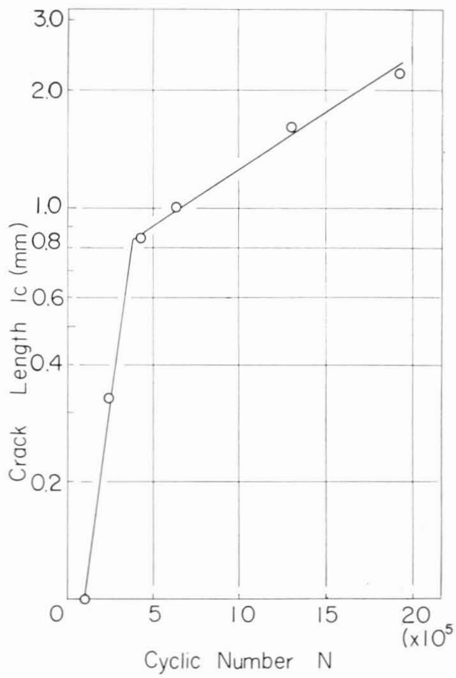

Fig. 4 Relation between crack length l_c and cyclic number N

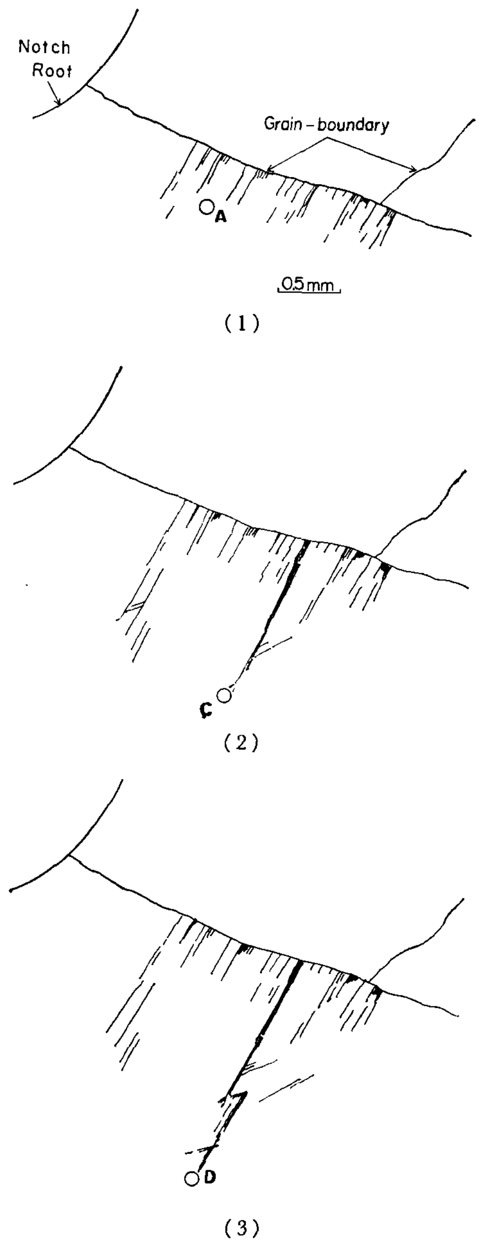

Fig. 5 Schematic expression of fatigue crack propagation and areas of X-ray microbeam irradiation

(1) $N=1.0\times10^5$ cycles, $l_c=0$ mm
(2) $N=6.5\times10^5$ cycles, $l_c=1.0$ mm
(3) $N=1.3\times10^6$ cycles, $l_c=1.6$ mm
(4) $N=1.95\times10^6$ cycles, $l_c=2.2$ mm

Table II Micro lattice strains obtained from reflecting planes during fatigue process ($\times10^{-3}$)

Plane	A	B	C	D	E	F
102	0.95	1.43	0.84	0.89	0.89	0.45
313	0.85	1.21	0.34	0.41	0.44	0.48
$3\bar{3}1$	0.55	0.61	0.39	0.44	0.46	0.20
$1\bar{3}3$	1.24	1.62	0.31	0.34	0.31	0.52
112	0.87	1.24	0.38	0.41	0.41	0.45
$2\bar{1}1$	0.62	0.75	0.54	0.69	0.83	0.21
$\bar{1}21$	0.81	1.04	0.12	0.25	0.15	0.40
211	0.75	0.95	0.10	0.10	0.13	0.35

microscopic lattice strain in connection with the mechanism of the fatigue crack propagation, only, others will be given elsewhere.

The micro lattice strain for some diffraction planes measured in each position of irradiation of X-ray microbeam are arranged in Table II. It is found in the table that the strain for each diffraction plane is difference. Accordingly, it is very important to make a cause of the difference clear in order to reveal the mechanism of the fatigue crack propagation, too.

Figs. 6 show the relation in the micro lattice strains between the calculated and the measured. That is, Figs. 6 (a), (b) and (c) are ones in the case of the edge, the screw and the mixed dislocations, respectively, and (d) shows a measured value in each position during the fatigue process.

It is seen in Fig. 6 (d) that the micro lattice strain which were obtained from the diffraction planes are devided roughly into two groups, A, B and F and C, D and E. That is, the distributions of the strains in the positions of A, B and F agree well with ones due to the edge dislocation, and while the micro lattice strains in the positions C, D and E resemble closely to the mode of the calculated ones on the screw dislocation. It would be supposed from these difference that the fatigue crack propagation is related to the changing of the edge dislocation to the screw dislocation.

Although such a phenomenon during the process of plastic deformation have been also revealed in BCC metals[11], it seems that it is necessary further experiments and detailed considerations to explain why the edge dislocation is required to make the fatigue crack propagation or the fatigue damage accelerate.

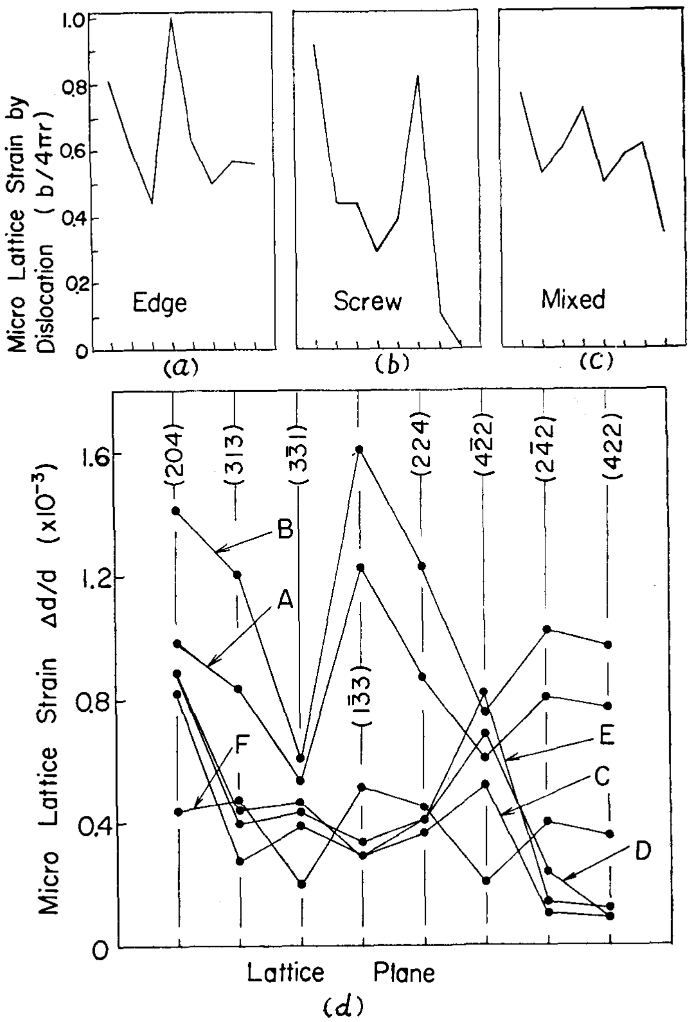

Fig. 6 Micro lattice strain in each reflecting plane
(a), (b) and (c) ; theoretical calculation
(d) ; experimental result

The authors reported in the present paper the relation between the fatigue crack propagation and the distribution of the micro lattice strain due to a dislocation. However, it is a remaining problem whether only the strains due to the dislocations would control the crack propagation, for it is considered that the fatigue crack propagation would be influenced by the stress distribution and the substructure at the crack tip. Accordingly, although it is necessary a synthetic study which is taken the factors into consideration, the study are presented in other paper.

References

1) J. C. GROSSKREUTZ : J. Appl. Phys., **34**, (1963) 372
2) J. C. GROSSKREUTZ and G. G. SHAW : Phil. Mag., **10**, (1964) 961
3) S. TAIRA and K. HAYASHI : JIME, **33**, (1967) 1
4) S. TAIRA and K. HAYASHI : JSME Semi-Inter. Sympo., (1967) 251
5) S. KARASHIMA, H. OIKAWA and T. OGURA : JIM, **31**, (1967) 669
6) S. KARASHIMA, H. OIKAWA and T. OGURA : JIM, **31**, (1967) 674
7) T. KONAGA and K. HONDA : JSME, **18**, (1969) 1118
8) T. KONAGA and K. HONDA : Proc. 11th Japan Cong. Mat. Res., (1968) 13
9) T. KONAGA and N. TOI : JIME, in press
10) H. NEUBER : Kerbspannungenslehre, Berlin, Julius Springer (1937)
11) H. SUZUKI : Lattice Defects and Mechanical properties of Metals, Supplement, Soc. JIM (1966)