X-RAY FRACTOGRAPHY ON THE FATIGUE FRACTURED SURFACE

疲労破面におけるX線フラクトグラフィ

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X-ray fractography is a technique to analyze the cause of the fracture from the X-ray information obtained from the irradiation on the fractured surface. The qualitative relations between the X-ray parameters and the fracture mechanics parameters has been known but quantitative relation is still under development. Through various kinds of load controlling fatigue tests, including constant effective stress intensity factor range tests, a new model for the residual stress distribution was proposed. The quntitative relation between the X-ray and fracture mechanics parameters can be obtained from this model.

Key words:X-ray fractography, Fracture analysis, Fatigue fractured surface

1.INTRODUCTION

The name of X-ray fractography was introduced by Kitagawa and Matumoto¹ in 1975, and has been developed as a powerfull tool for analyzing the cause of fractures. The electron microscope fractography also has been used successfully in industries. However the X-ray fractography is useufel when the fractured surface was contaminated or oxidized, where the electron microscope fractography is impossible.

The correlation of residual streess on the fractured suface to the fracture mechanics parameters has been known for the high strength brittle materials,² or for ductile materials.³ These two types of stress distributions are quite different,but the mechanism to introduce these residual stress distributions must be the same. In our laboratory experimental results under various load control conditions have been accumulated on a structural steel, and an attempt has been made to establish a quntitative evaluation method to predict the residual stress distributions from fatigue loading conditions for ductile materials, for the brittle materials the experiments are now under way.

specimens were CT with 15mm-thick and 76mm-ligament.

Fatigue tests were performed at room temperature in laboratory air by a electrohydraulic testing machine with a sine wave loading. The test frequencies were 5-40Hz. The fatigue crack opening ratio was measured by the unloading elastic compliance method.⁴ Five loading patterns were used, namely the ordinary constant-load-amplitude (ΔP) test, the constant- ΔP on arrested crack test, the decreasing- ΔP test, the constant- ΔK test, and the constant- ΔK_{eff} test. In the constant- ΔP on arrested crack test, the load amplitude was decreased until the crack propagation was stopped, then a constant amplitude load was applied to achive a different crack closure condition from the ordinary constant- ΔP test of the same load ratio. The relations between the stress intensity factor and the crack length are shown schematically in Figure 1(a)-(d) for each test.

Table 1. Chemical compositions (wt%)

C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Al
0.39	0.28	0.75	0.013	0.003	0.06	1.93	0.92	0.23	0.039

2.EXPERIMENTAL PROCEDURE

The material used was a structural steel (JIS SNCM 439 equivalent to AISI 4340), which was oil quenched after being held at 850°C for 30minutes and tempered at 600°C. The chemical composition and the mechanical properties after the heat treatment are given in Table 1 and 2. The

Table 2. Mechanical properties

Yield point (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)	Vickers hardness
880	1020	16.7	60.1	324

Figure 1. Schematic illustration of stress intensity factor(K) vs. crack length(a).

Table 3. Conditions of X-ray stress measurement

Characteristic X-Ray	Cr-Kα
Diffraction plane	α-Fe(211)
Slit divergence angle	0.35
Filter	V foil
Counter	Scintillation counter
Tube voltage	30kV
Tube current	10mA
Irradiated area	0.8×6.0mm ²

The residual stress distributions on the fatigue fractured surface were measured by X-Ray diffraction method by the conditions shown in Table 3.

3.RESULTS AND DISCUSSION

3.1 Crack Propagation Rate (da/dN)

Figure 2 shows the relation between the da/dN and the ΔK . The results of the ordinary constant- ΔP tests are fallen into a band in spite of different load ratios. On the other hand the results of the constant- ΔP on arrested crack test, the decreasing- ΔP test and the constant- ΔK test are not contained in the band because of crack-closure was occurred by the effect of the load history.

Figure 3 shows the relation between the da/dN and the ΔK_{eff} . The data points of five fatigue loading patterns are contained in a band, except the data points of less than $5MPa\sqrt{m}$. This result indicates that the da/dN is closely related to the ΔK_{eff} than the ΔK .

3.2 Residual stress distribution

Figure 4 shows the relation between the residual stress and the K_{max} . The data points of solid circle are results of the constant- ΔP on arrested crack test. The residual stress are high in the low K_{max} range and decrease with increasing K_{max} . Therefore in cases of different crack closure behaviors, the residual stress distribution is different even if the load ratios are equal. By indicating the values of the ΔK_{eff} on data points in the figure, it was found that the residual stress is higher for the lower ΔK_{eff} at each K_{max} .

Figure 2. Relation between da/dN and ΔK .

Figure 3. Relation between da/dN and ΔK_{eff} .

Figure 5 shows the relation between the residual stress and the ΔK_{eff} . The data points fall in a band shown in this figure, except those points with the K_{max} lower than $35MPa\sqrt{m}$ or higher than $90MPa\sqrt{m}$. This is interpreted as the residual stress is controlled by ΔK_{eff} alone in the range of $35 \leq K_{max} \leq 90MPa\sqrt{m}$.

From these experimental results, when K_{max} is less than $35MPa\sqrt{m}$ or more than $90MPa\sqrt{m}$, the residual stress is affected by both K_{max} and ΔK_{eff} . To separate the effects of K_{max} and ΔK_{eff} in this range the constant- ΔK_{eff} tests were carried out.

Figure 6 shows the residual stress versus the K_{max} in the constant- ΔK_{eff} tests. When ΔK_{eff} is kept at $5MPa\sqrt{m}$ the residual stress increases

Figure 4. Relation between residual stress and K_{max} .

(a) Effect of K_{max}

Figure 5. Relation between residual stress and ΔK_{eff} .

(b) Effect of ΔK_{eff}

Figure 7. Effect of K_{max} or ΔK_{eff} on residual stress.

Figure 6. Relation between residual stress and K_{max} for constant- ΔK_{eff} tests.

sharply up to $K_{max} = 35 \text{ MPa}\sqrt{\text{m}}$, and then becomes nearly constant up to $K_{max} = 90 \text{ MPa}\sqrt{\text{m}}$ and after that it decreases gradually. When ΔK_{eff} is kept at $40 \text{ MPa}\sqrt{\text{m}}$ the residual stress is nearly constant up to $K_{max} = 90 \text{ MPa}\sqrt{\text{m}}$ and then decrease gradually.

From the above, the residual stress is higher with higher K_{max} in the range of $K_{max} \leq 35 \text{ MPa}\sqrt{\text{m}}$

and always lower with higher ΔK_{eff} . That is to say, K_{max} and ΔK_{eff} correspond to tensile and compressive residual stress respectively and then the residual stresses are the sum of the both factors. This is shown as follows.

$$\sigma_r = \sigma_r(K_{max}) + \sigma_r(\Delta K_{eff}) \quad (1)$$

where σ_r : the residual stress on the fractured surface, $\sigma_r(K_{max})$: the tensile residual stress controlled by K_{max} , $\sigma_r(\Delta K_{eff})$: the compressive residual stress controlled by ΔK_{eff}

The correlation of the residual stress and the K_{max} is expressed by three linear functions from Fig. 6. When semi logarithmic scales are used the band in Fig. 5 is a straight line. These correlation can be shown by eq. (2) and (3) respectively.

$$\left. \begin{aligned} \sigma_r(K_{max}) &= c_1 \cdot K_{max} & (0 < K_{max} < 35 \text{ MPa}\sqrt{\text{m}}) \\ \sigma_r(K_{max}) &= c_2 & (35 \leq K_{max} \leq 90 \text{ MPa}\sqrt{\text{m}}) \\ \sigma_r(K_{max}) &= c_3 \cdot K_{max} + c_4 & (90 < K_{max}) \end{aligned} \right\} \quad (2)$$

$$\sigma_r(\Delta K_{eff}) = c_5 \cdot \log \Delta K_{eff} \quad (3)$$

where, $K_{max} : (MPa\sqrt{m})$, $\Delta K_{eff} : (MPa\sqrt{m})$, $c_1 \sim c_5$: the experimental constants ($c_1=28.6$, $c_2=1000$, $c_3=-2.5$, $c_4=1225$, $c_5=-376$)

Figure 7 (a) and (b) show these equations (2) and (3). Comparing the calculated values and the experimental results, they agree well as can be seen in Fig.8, for example. Equations (1),(2),and (3) are consistent in spite of various conditions of crack-closure. The contact effect of two fractured surfaces can be ignored within this experimental conditions.

Figure 8. Results of estimation of residual stress.

4. CONCLUSIONS

The quantitative analysis technique of the correlation of the residual stress on the fatigue fractured surface and the K_{max} or ΔK_{eff} was

proposed. The main conclusions obtained are as follows.

1. In spite of different load controlling method and load history, the correlation of the residual stress on the fractured surface and the K_{max} or ΔK_{eff} is expressed by the following equations.

$$\sigma_r = \sigma_r(K_{max}) + \sigma_r(\Delta K_{eff}) \quad (1)$$

$$\begin{aligned} \sigma_r(K_{max}) &= c_1 \cdot K_{max} & (0 < K_{max} < 35 MPa\sqrt{m}) \\ \sigma_r(K_{max}) &= c_2 & (35 \leq K_{max} \leq 90 MPa\sqrt{m}) \end{aligned} \quad (2)$$

$$\begin{aligned} \sigma_r(K_{max}) &= c_3 \cdot K_{max} + c_4 & (90 < K_{max}) \\ \sigma_r(\Delta K_{eff}) &= c_5 \cdot \log \Delta K_{eff} \end{aligned} \quad (3)$$

$c_1 \sim c_5$: the experimental constants ($c_1=28.6$, $c_2=1000$, $c_3=-2.5$, $c_4=1225$, $c_5=-376$)

2. The ΔK_{eff} , so the crack propagation rate, can be estimated from conclusion 1.
3. The constant- ΔK_{eff} test is effective for the quantitative analysis of the correlation of the residual stress on the fatigue fractured surface and the fracture mechanics parameters.

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