Study of Fatigue Crack Propagation Behavior of Film Materials*

(Fatigue Testing Method and Factors Controlling Fatigue Crack Propagation Rates)

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At present, materials with small dimensions such as thin films are often used in electronic packaging. This study concerns a film fatigue testing method, which makes it possible to observe the fatigue crack propagation behavior on a film bonded to a through-hole in a base plate subjected to push-pull cyclic loads. An analytical model for this testing method is presented using a boundary element method, so that the film fatigue fracture can be treated quantitatively in terms of fracture mechanics (K -values and J -integrals). The fatigue crack growth properties were examined for commercial-grade iron films with 100 μm thickness bonded to either a circular or an elliptical hole in the base plate. As a result, using the stress intensity factor based on the measured crack opening displacement, ΔK_{est} , the fatigue crack propagation behavior of the film could be understood in terms of the effective stress intensity factor widely used in the bulk specimen, ΔK_{eff} .

Key Words: Fatigue, Crack Propagation, Fracture Mechanics, Stress Intensity Factor, Crack Closure, Boundary Element Method, Film Material, Size Effect

1. Introduction

A current trend in electronic packaging is to increase packaging density, thus requiring materials with small dimensions such as thin films deposited on rigid substrates, lead wires and wire bonds with a small diameter of μm order⁽¹⁾⁻⁽⁴⁾. If these elements should be fatigue-fractured, the electronic parts could no longer function. Therefore, it is essential that the fatigue fracture properties of these parts are estimated accurately under various conditions as close as possible to those of practical use. However, since fatigue testing presents a serious difficulty with regard

to gripping small specimens, the mechanical properties of bulk specimens are often used to design electronic parts, providing they have the same chemical composition and microstructure as the small specimens^{(5),(6)}.

As to film fatigue testing, there have been many reports on the fatigue properties of a specimen coated with a thin film often having compressive residual stresses⁽⁷⁾⁻⁽⁹⁾. Although the fatigue properties are generally improved by the surface film coating, it has remained unclear how the surface of thin film contributes to the improvement in fatigue. In this regard, it seems difficult to evaluate the fatigue properties of the film material itself by a conventional fatigue testing method.

This study concerns a new film fatigue testing method, which makes it possible to observe the fatigue crack initiation and propagation on the film bonded to a hole in a base plate subjected to push-pull cyclic loads. An analytical model for this testing method is presented using a boundary element method (BEM), so that the film fatigue fracture can be treated quantitatively in terms of fracture mechanics. The fatigue crack growth properties were examined for

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commercial-grade iron films with 100 μm thickness and compared between film and bulk specimens, in order to obtain a common mechanical parameter controlling the fatigue crack propagation of the specimens.

2. Analysis

2.1 Analytical methods

If a film to be tested is adhered to one side of a through-hole in a base plate as shown in Fig. 1, then the film will be fatigued in accordance with the displacement along the hole circumference in the base plate subjected to push-pull cyclic loads. In this figure, the thickness is denoted by t_b and t_f for the base plate and the film, respectively. Although the crack analysis of the film for this method requires a

Fig. 1 Film fatigue testing method using a through-hole in a base plate

Fig. 2 BEM model for analysis

three-dimensional analysis, a two-dimensional model will be used for simplicity as shown in Fig. 2 where the stiffness against deformation is significantly lower in the film than the base plate, because t_f is very small compared with t_b . Namely, Young's modulus and Poisson's ratio of the part corresponding to the film are $E_2 = E_1(t_f/t_b)$ and $\nu_2 = \nu_1$, using E_1 and ν_1 for material constants of the base plate. Although the deformation may not be uniform microscopically, instead depending on each crystal grain in the film, it is assumed that the film has macroscopically the same elastic properties as the base plate. In reference to assumptions concerning the film's elastic behavior, a study has been reported in which the number of grains through the thickness of a thin plate considerably influenced the flow stress, but not the elastic behavior, as specified by the relationship between stress and crosshead distance in tensile testing⁽¹⁰⁾.

Using the boundary element method under a plane stress condition, the numerical computation was carried out separately for the film and the base parts of 1/4 of a specimen with the total number of boundary elements given in Fig. 2, in such a way that both the continuity of displacement and the equilibrium of stress may be satisfied along the boundary between the film and the base parts. In addition, the BEM program uses a two-dimensional Kelvin solution as a fundamental solution, linear elements for discretizing and an analytical integration for the coefficient matrix of a system of linear equations⁽¹¹⁾. The material constants used in this computation were $E_1 = 206 \text{ GPa}$ and $\nu_1 = 0.3$ for the steel base plate.

2.2 Fracture mechanics parameters

Stress intensity factors (K -values), widely used as an important factor controlling the fatigue crack propagation in the bulk specimen, were calculated for various crack lengths up to the crack length $a = 4.0 \text{ mm}$ on the film bonded to the hole in the base plate subjected to a tensile stress of $(\sigma)_b = 50 \text{ MPa}$. The calculated results are shown in Fig. 3, using the symbols of $\triangle$ and $\blacktriangle$ for the circular and the elliptical holes in the base plate with the dimensions shown in Fig. 5 (described later). In this calculation, the K -value was evaluated by a displacement extrapolation method in the following manner⁽¹²⁾.

Using the BEM with the element divisions at an interval of 0.1 mm, each K -value calculated from the crack displacement at each distance from the crack tip, r , was plotted against the r value of eight points near the crack tip. It follows that the K -value was finally determined as a value at $r \rightarrow 0$ extrapolated from the straight line obtained by the least squares method for the data. The calculation error in this method did not exceed 1.7% of the theoretical value

Fig. 3 Analysis of stress intensity factors and J -integral on the film

for a center crack with 6 mm length in a strip plate with 35 mm width, under tension⁽¹³⁾.

It can be seen from Fig. 3 that the K -value first increases gradually, then remains almost constant during the greater part of crack propagation and finally decreases somewhat. This tendency is almost the same for the two types of holes in the base plate, except there is a small difference at their initial increasing stages. This result shows that the fatigue cracks on the film propagate with almost the same propagation rate, da/dN , in accordance with the nearly constant K values for a crack of any length. It should also be noted that this testing is substantially different from the conventional method in which the K -value increases with the crack length under a constant stress amplitude applied to a specimen.

Although J integrals are often used as a non-linear parameter in fracture mechanics, the K -value is uniquely related to the J -integral defined as the energy release rate in the elastic field. Therefore, the K -value is considered to be determined by the mechanical condition along a contour around the crack tip based on the path-independence concept of the J integral in an elastic calculation. Such path-independence of the J -integral is used to explain the constant K -value during crack propagation in this test. As an example, a calculation was conducted for the crack length of $a=2.5$ mm on the film bonded to the elliptical hole in the base plate subjected to a tensile stress of $(\sigma)_b=50$ MPa⁽¹⁴⁾. The calculated results of the J integrals along the two circular contours Γ_1 and Γ_2 (both divided into 60 elements) with the radii around the crack tip r_1 and r_2 , respectively, are shown in the table of Fig. 4. It can be seen that these values in this table are almost the same, corresponding to the path-independence of the J -integral.

Similarly, the J -integral along the contour Γ_0 (divided into 60 elements) defined by the hole circumference on the film was calculated. In this case, the

Fig. 4 Path independence calculation of J -integral on the film

gradient of the displacement necessary for the computation was determined numerically as the differential coefficient of a quadratic curve describing the displacement at each midpoint of three elements in series on the contour in the BEM analysis⁽¹⁵⁾. In this connection, very small elements were used near the corner points such as an intersection between Γ_0 and the y -axis so that the calculation result may be little influenced by omitting the small elements next to the corner points. In fact, it is found that the J -integral along Γ_0 , being equal to those along Γ_1 or Γ_2 , may be used as one of the parameters controlling the crack behavior on the film, as shown in the table of Fig. 4.

Using the J -integral along Γ_0 , the change of K -value during crack propagation can be explained. As shown in Fig. 3, the change of K -values is found to be very similar to that of J -integrals calculated for each crack length on the film. When examined in detail, the K -value and the J -integral are found to satisfy the equation $K=\sqrt{EJ}$ derived under plane stress conditions in linear fracture mechanics. As an example, for crack length $a=2.0$ mm on the film, $J=468.77$ and $J=730.35$ N/m result in $\sqrt{EJ}=9.83$ and $\sqrt{EJ}=12.27$ MPa√m using $E=206$ GPa, which almost equal $K=10.01$ and $K=12.45$ MPa√m for the circular and the elliptical holes, respectively, in Fig. 3. It is concluded that K -values, like J -integrals, are determined by the stress and displacement along the hole circumference on the film, which do not change appreciably during the crack propagation in this testing method.

3. Experimental Procedure

3.1 Specimens

Using S45C steel with the chemical composition shown in Table 1, the base specimen was machined with a circular or an elliptical through-hole to the

Table 1 Chemical composition

	C	Si	Mn	P	S
Base	0.45	0.18	0.78	0.012	0.006
Film	0.035	0.023	0.149	0.004	0.008

Fig. 5 Dimensions of the film and the base specimens

Fig. 6 Photo-microstructure through the thickness of the film

dimensions shown in Fig. 5, then polished with emery paper and finally annealed at 1123 K for one hour in a vacuum furnace. The film was commercial-grade iron with the chemical composition shown in Table 1, the thickness of which was of 100 μm . Each film specimen was cut into a 30 $\times$ 40 mm² rectangle, then annealed at 1173 K for one hour in a vacuum furnace and finally polished with alumina powder so that the fatigue crack propagation behavior could be observed and the crack opening displacement measured more easily. Furthermore, after drilling to form a hole of 0.5 mm diameter at the center, the film specimens were annealed at 873 K for one hour in a vacuum furnace in order to eliminate the residual stress due to machining. As shown in Fig. 6, since the films have about five grains through the thickness of 100 μm , the grain size is found to be approximately 20 μm in diameter. After being roughened with emery paper and then washed with acetone, the surfaces of the film and base specimens were bonded by a cyanoacrylate cement so that the center of the film coincided with that of the hole in the base plate.

3.2 Fatigue testing

The base plate with the bonded test film was subjected to push-pull cyclic loads at a speed of 20 Hz

under a stress ratio $R=0$ and a constant stress amplitude of sinusoidal wave loads $(\sigma_a)_b$, using a servo-hydraulic fatigue testing machine. The fatigue crack initiation and propagation behaviors on the film were observed using a photomicroscope attached to a testing machine.

3.3 Measurement of crack opening displacement distribution

A pair of micro-Vickers impressions marked longitudinally at a gage length of about 60 μm containing a crack line were spaced at 0.1 mm intervals along a crack. The difference between the distances measured under loading and unloading was defined as the COD at the position indicated by micro-Vickers impressions along a crack. The distance for a pair of impressions was measured by image processing. Using a video camera connected to a photomicroscope, an image of the region near the crack containing a pair of impressions was inputted to a personal computer, and then the distance was determined on an image screen⁽¹⁶⁾.

4. Experimental Results and Discussion

4.1 Stress intensity factors on the film

The stress intensity factor on the film was obtained theoretically by the two-dimensional BEM model described in Fig. 2. It is possible to check the validity of this model by a comparison between the measured and the theoretical values of the crack opening displacement and the resulting stress intensity factors in the following manner.

A fatigue crack on the film was formed under the stress amplitude imposed on the base plate with a circular hole of $(\sigma_a)_b = 50$ MPa, and finally annealed at 873 K in order to eliminate the residual stress due to the crack propagation. The film peeled off after annealing even at this low temperature, and was again bonded to the base plate in such a way that the center of the film coincided with that of the hole. Using these annealed cracks, the crack opening displacements measured under a tensile stress, $(\sigma)_b = 50$ MPa, are shown against the distance from the crack tip, r , for three values of crack length, a , in Fig. 7. In this figure, the experimental results are in good agreement with the BEM analytical results, as shown by each line corresponding to each crack length.

Next, based on linear fracture mechanics, the K -value can be evaluated from the crack opening displacement $v = \{(1/2)\text{COD}\}$ near the crack tip at $\theta = \pi$, using Eq. (1)⁽¹⁷⁾.

$$v = \frac{K}{2G} \sqrt{\frac{r}{2\pi}} \sin \frac{\theta}{2} \left(\alpha + 1 - 2 \cos^2 \frac{\theta}{2} \right) \quad (1)$$

In this equation, G is shear modulus and α a material constant related to Poisson's ratio ν . The computation

Fig. 7 Crack opening displacements measured along the annealed cracks on the film

Fig. 8 Fatigue crack propagation curves for the film bonded to a circular hole in the base plate

Fig. 9 Fatigue crack propagation curves for the film bonded to an elliptical hole in the base plate

was carried out using $G=79.2$ GPa and $\chi=2.08$ with $\nu=0.3$ under the plane stress condition for steel. The evaluated K -value was defined as a mean of the values calculated for five different distances near the crack tip. As shown in the table of Fig. 7, the evaluated K -values are almost constant in a range of the crack length $a=2\sim 4$ mm, in good agreement with the theoretical values of $K=9\sim 10$ MPa $\sqrt{\text{m}}$ for the film bonded to the circular hole presented in Fig. 3.

It is concluded that the stress intensity factor on the film can be calculated by the proposed two-dimen-

sional analysis, and experimentally evaluated from the crack opening displacement along a crack on the film.

4.2 Fatigue crack propagation curves on the film

Fatigue cracks were formed after slip initiation near the notch and subsequently propagated on the films bonded to the circular and elliptical holes in the base plate subjected to various stress amplitudes (σ_a)_b, as shown in Figs. 8 and 9, respectively. From a comparison between these figures, it is found that both the fatigue crack initiation and propagation lives are smaller for the elliptical hole than the circular one under the same stress amplitude. There is also a common tendency in which the crack propagation rate, da/dN , defined as the slope of the curves is nearly constant in the greater part of the propagation and finally tends to decrease somewhat. Such differences and similarities between the two holes in the fatigue crack behavior correspond well to those between the two holes in the fracture mechanics parameters (K -values and J -integrals) presented in Fig. 3.

As to the experimental result of fatigue limit, under the stress amplitude (σ_a)_b=28.0 MPa for the elliptical hole shown in Fig. 9, it was difficult to find nonpropagating small cracks although a few occurrences of slip were seen near the notch on the film. On the other hand, nonpropagating cracks have often been observed for bulk specimens of low-carbon steels⁽¹⁸⁾. Whether or not such a difference occurs between the film and the bulk specimens is very important for discussing the fatigue limit microscopically in terms of grain deformation.

4.3 Fatigue crack propagation rates on the film

As is well known, the stress intensity factor range ΔK is equal to the K_{max} calculated for the maximum stress $\sigma_{\text{max}}=2(\sigma_a)_b$ under stress ratio $R=0$. The fatigue crack propagation rates, da/dN , defined as the slope of each curve shown in Figs. 8 and 9, are plotted against ΔK for the circular and elliptical holes in log-log scale in Fig. 10. These data obtained under the various stress amplitudes lie in a narrow band around a straight line for both holes, thus demonstrating Paris' law in fracture mechanics. However, it should also be noted that most of the data lie below the dotted line of the da/dN - ΔK relation for the bulk specimen (thickness of $t=6$ mm) of the same low-carbon steel as the film. This bulk relation was reported by Tanaka et al. elsewhere⁽¹⁹⁾.

Next, in order to discuss the crack closure level for the fatigue crack on the film, the crack opening displacement was measured for the fatigue and the annealed cracks with the same length on the film bonded to the circular hole of the base plate subjected to a tensile stress (σ)_b=50 MPa, as shown in Fig. 11.

Fig. 10 Relationship between stress intensity factor range and fatigue crack propagation rate

Fig. 11 Comparison between annealed and fatigue cracks of the same length in crack opening displacement

From the results, it can be seen that the fatigue crack exhibits remarkable crack closure. The residual stress is eliminated in the annealed crack, but it is possible that a compressive residual stress occurs near the fatigue crack. In addition, using the cracks fatigued under the various stress amplitudes with lengths of up to $a=4.0$ mm, it can be seen that the crack opening displacement decreases with increasing stress amplitude, $(\sigma_a)_b$, as shown in Fig. 12. This result was obtained for films bonded to both the circular hole and the elliptical hole in the base plate. As a result, it is considered that plastic deformation near the crack tip occurs easily for the film with plane stress condition as compared with the bulk specimen with plane strain condition in its interior⁽²⁰⁾. This consideration agrees with other experimental results in which the yield stress markedly decreases with

Fig. 12 Crack opening displacement measured for cracks fatigued under various stress amplitudes

Fig. 13 Relationship between effective stress intensity factor range and fatigue crack propagation rate

decreasing specimen thickness for polycrystalline iron⁽¹⁰⁾.

It is well known that effective stress intensity factors ΔK_{eff} are very useful for understanding the fatigue crack propagation behavior in relation to the residual plastic layer near the crack. In this connection, the stress intensity factor for the real fatigue crack under tension, K_{est} , can be evaluated from the crack opening displacement measured near the crack tip ($r \leq 0.5$ mm), using Eq. (1). The K_{est} values thus estimated for the crack opening displacement of Fig. 12 are found to be lower than the theoretical stress intensity factors K_{max} and the difference ($K_{max} - K_{est}$) is shown in the table of this figure. Because these values are the stress intensity factors corresponding to the crack closing under tension, they may have the same mechanical meaning as stress intensity factors at the crack opening, K_{op} , which are widely used in the

bulk specimen⁽²¹⁾. In other words, the stress intensity factor range estimated based on the measured crack opening displacement, ΔK_{est} , may be regarded as the effective stress intensity factor range, ΔK_{eff} , for the fatigue crack on the film.

When ΔK_{est} is used for some data taken from Fig. 10, the experimental data change from ΔK (■) to ΔK_{est} (□) so as to lie on the line representing the $da/dN - \Delta K_{\text{eff}}$ relation (●, ○) for the bulk specimen reported by Tanaka et al.⁽¹⁹⁾, as shown in Fig. 13. The bulk data for the plate thickness $t=4$ and 6 mm were for the same iron as the film. It is concluded that the effective stress intensity factor is a common mechanical parameter controlling the fatigue crack propagation for the film ($t_f=100\ \mu\text{m}$) and the bulk specimens.

5. Conclusions

Fatigue crack propagation behavior was examined for films of commercial-grade iron with 100 μm thickness, using a new fatigue testing method in which the film was bonded across circular and elliptical holes in a separate base plate subjected to push-pull cyclic loads. A mechanical aspect for this testing method was defined using a boundary element method (BEM), and the experimental results were quantitatively related to the fracture mechanics parameter for both hole shapes in the base plate. The following conclusions are obtained.

(1) The stress intensity factor on the film calculated by a two-dimensional BEM analysis showed an almost constant value for the greater part of the crack propagation, in agreement with the experimental results obtained from the crack opening displacement in the annealed crack.

(2) The fatigue crack propagation rate on the film, in this testing method, was almost constant during the greater part of the crack propagation, as expected from the fracture mechanics parameters (K -value and J -integral) obtained by the BEM analysis.

(3) The fatigue crack on the film tended to cause a considerable residual plastic layer to form in the wake of the propagation, which made the fatigue crack propagation rate, da/dN , lower than that of the bulk specimen in Paris' law ($da/dN - \Delta K$ relation). However, using the stress intensity factor based on the measured crack opening displacement, the fatigue crack propagation behavior of the film could be understood in terms of the effective stress intensity factor widely used in the bulk specimen. Namely, the effective stress intensity factor range was considered to be a common parameter controlling the fatigue crack propagation in both the film (100 μm thickness) and the bulk specimens.

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