Development of ΔK -decreasing test method of the metal film by displacement constraint along the elliptical through hole-edge

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Abstract

A new ΔK -decreasing test method of the metal film was developed. The film was adhered to a through elliptical hole in a base plate and was fatigued in accordance with the displacement constraint along the hole-circumference in the base plate subjected to a cyclic stress. Commonly, a stress intensity factor range was increased with a crack propagation under a constant stress amplitude but was decreased toward the hole-edge because of the difference in thickness between the film and the base plate in this ΔK -decreasing test method. The decrease in a stress intensity factor with a crack propagation was calculated by FEM analysis and the optimum aspect ratio of an elliptical hole was determined. Using the ΔK -decreasing test method, the crack propagation test was conducted for metal films. As a result, the fatigue crack propagation rate was decreased and was arrested near the hole-edge under the constant stress amplitude to the base plate. The threshold stress intensity factor ranges were obtained for some kinds of metal film and the accuracy of the testing method was discussed.

Key words : Metal film, ΔK -decreasing test, Threshold stress intensity factor range, Crack opening displacement, Finite element method

1. Introduction

In recent years, film materials are often used in electronic devices, such as the films deposited on rigid substrates and on IC packages modeling a multi-layer construction (Nix, 1989, Oda, et al., 1991 and Hoffman, et al., 1992). 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 crack propagation behavior of the freestanding film specimen have been hardly discussed (Singh, et al., 2011 and Kondo, et al., 2012). Especially, the threshold stress intensity factor range, ΔK_{th} , is difficult to estimate because more accurate load control in the load shedding process is necessary in comparison with the bulk materials (Bartosiewicz, et al., 1992, Zhao, et al., 1999, Hadrboletz, et al., 2001 and Kondo, et al., 2014).

In this study, a new ΔK -decreasing test method of the metal film was developed. In our previous study, we found that 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 and discussed about the effect of the thickness on the fatigue crack propagation behavior with the rate of 10^{-9} m/cycle and over. (Torii, et al., 1996, Torii, et al., 1999, Shimizu et al., 2002, Shimizu et al., 2005 and Shimizu et al., 2008) In this experimental method, the stress within the hole is uniform because the film can be regarded as the ellipsoidal inclusion in the Eshelby's elastic inhomogeneity model (Eshelby, 1957 and Mura, 1982). Then, the film was fatigued in accordance with the displacement constraint along the hole-circumference in

the base plate. Commonly, a stress intensity factor range, ΔK , was increased with a crack propagation under a constant stress amplitude but was decreased toward the hole-edge because of the difference in thickness between the film and the base plate. Namely, ΔK -decreasing test method is possible to conduct under the constant stress amplitude without a load decreasing process described in ASTM E647 (Hudak, et al., 1981). First, the optimum dimension of the test specimen was discussed by using FEM analysis and fatigue crack propagation test was conducted so as to obtain the fatigue crack propagation threshold intensity factor, ΔK_{th} , for some kinds of metal film.

2. Analysis

If the thin film is adhered to one side of a through elliptical hole in a thick base plate, the film will be fatigued in accordance with the displacement along the hole-circumference in the base plate subjected to unidirectional cyclic stress, σ_b . The crack analysis of film is conducted using a two-dimensional finite element method (FEM) under the stress, σ_b , in the y direction as shown in Fig. 1, where the stiffness against deformation is significantly lower in the film than in the base plate, because the film thickness, t_f , is very small compared to the plate thickness, t_b . Namely, Young's modulus of the film are reduced to $(t_f/t_b)E_f$ in the two-dimensional FEM analysis, where E_f is the Young's modulus of the film material. The Young's modulus, E_f , used in the analysis was experimental value obtained from the film tensile test as indicated in Table 1 of Chapter three. The Poisson's ratios are $\nu_f=0.33$ for the aluminum film and the copper film and $\nu_f=0.34$ for the titanium film, respectively. For the base plate, the Young's modulus is $E_b=69\text{GPa}$ and the Poisson's ratio is $\nu_b=0.33$.

Fig. 1 The film fatigue specimen adhered to a through elliptical hole in a base plate.

Fig. 2 FEM model of the film fatigue specimen. (a) Whole model and (b) Detail of the film on the elliptical through hole.

Using the FEM model under a plane stress condition, a computation was carried out for the quarter part of the specimen as shown in Fig. 2. The film is a pure aluminum, pure copper and pure titanium with the thickness of $t_f=30\mu\text{m}$. The base plate is an aluminum alloy, A2017, with the thickness of $t_b=2\text{mm}$. The FEM solver used in the analysis is MARC and a 4-node quadratic isoparametric element is used. The element size around the crack is $10\times 10\mu\text{m}^2$. A stress intensity factor, K , is calculated by the modified crack closure integral technique (Rybicki, et al., 1997).

A variation of stress intensity factor with the crack propagation in the copper film was calculated for various aspect ratios, $\lambda=a/c$, of the elliptical hole as shown in Fig. 3. The long axis, $2a$, of the elliptical hole is fixed on 6mm to the width of the base plate, $2W=30\text{mm}$. The applied stress to the base plate is $\sigma_b=1\text{MPa}$. As the crack tip reaches near the hole-edge, the stress intensity factor decreases for all aspect ratios. But the decreasing rate of stress intensity factor is relatively small for the aspect ratio of 1. Therefore, the aspect ratio of the hole is desirable to be 1.5 and over.

Figure 4 shows the crack opening displacement for each aspect ratios. The crack lengths are 1.5mm and 2.9mm. Each line indicates the theoretical value obtained from the single plate under the same stress intensity factor using Eq. (1).

$$V(x) = \frac{2K}{E} \sqrt{\frac{a^2 - x^2}{\pi a}} \quad (1)$$

For all aspect ratios, the crack opening displacement near the crack tip is almost the same between the film specimen and the single plate specimen. On the other hand, the crack opening displacement obtained from the film specimen is depressed at the crack center for the aspect ratios 2 and 4.

Figure 5 shows the FEM analyzed crack opening displacement normalized by the theoretical value. The normalized crack opening displacements of $\lambda=2$ and 4 is less than 1 with the crack length of $a=1.5$ mm. As a result, the crack propagation rate may be smaller for the film on the elliptical through hole than for the simple plate because of the crack contact at the crack center in the specimens of $\lambda=2$ and 4. Therefore the aspect ratio of the through-hole is decided to be 1.5 in this study.

Figure 6 shows the variation of stress intensity factor with the crack propagation for the aluminum film, the copper film and the titanium film. The applied stress to the base plate is $\sigma_b=1$ MPa and each line indicates the polynomial approximation. Using the approximate equation obtained from each film, the stress intensity factor was evaluated by the function of the crack length, a .

Fig. 3 Variation of stress intensity factor with the crack propagation in the copper film for various aspect ratios of the elliptical hole in the base plate.

Fig. 4 Crack opening displacement calculated by FEM and elastic theory in the copper film for the aspect ratios, (a) $\lambda=1$, (b) $\lambda=1.5$, (c) $\lambda=2$ and (d) $\lambda=4$.

Fig. 5 Normalized crack opening displacement calculated by FEM and elastic theory in the copper film for the aspect ratios, (a) $\lambda=1$, (b) $\lambda=1.5$, (c) $\lambda=2$ and (d) $\lambda=4$.

Fig. 6 Variation of stress intensity factor with the crack propagation calculated by FEM in the aluminum, the copper and the titanium films and polynomial fitting curves for each materials.

3. Experimental procedure

3.1 Materials

Pure aluminum films, pure copper films and pure titanium films with a thickness of $t_f=50\mu\text{m}$ were electro-polished to $t_f=30\mu\text{m}$, respectively. Then aluminum films were annealed at 623K for one hour in a vacuum furnace. Similarly, copper films were annealed at 673K for one hour and titanium films were annealed at 1073K for three hours. The grain sizes are 19 μm , 34 μm and 39 μm for aluminum films, copper films and titanium films, respectively. The base plate is aluminum alloy, A2017, with the thickness of $t_b=2.0\text{mm}$.

The tensile test was conducted by using electromagnetic force micro material tester (Shimadzu, Micro-Servo MMT-250N-50) and the displacement between the length of 10mm was measured by using laser displacement gage (Keyence, LS-7030MT). Table 1 shows the Young's modulus and 0.2% proof stress obtained from the pure aluminum films, pure copper films and pure titanium films.

Table 1 Mechanical properties of metal films and base plate.

Material		Young's modulus E GPa	0.2% proof stress $\sigma_{0.2}$ MPa
Film	Pure aluminum	63	35
	Pure copper	104	63
	Pure titanium	109	305
Base	Aluminum alloy (A2017)	69	275

3.2 Fatigue test

Figure 7 shows a fatigue test specimen. The film was cut into a $20 \times 20 \text{mm}^2$ rectangle and a slit hole with the length of 1.4mm was made at the film center by a wire cut electrical discharge machining. The base plate was machined with an elliptical through hole of the aspect ratio, $\lambda=1.5$, as shown in Fig. 7. Finally, the film was bonded to the base plate with a cyanoacrylate cement so that the center of the film coincided with that of the hole in the base plate. Then the base plate was subjected to a cyclic load with a constant stress amplitude at a speed of 20Hz and a stress ratio of $R=0$, using a servo-hydraulic fatigue testing machine. The fatigue crack propagation was observed by digital microscope attached to the fatigue testing machine.

Fig. 7 Dimensions of the film fatigue specimen and the base plate with an elliptical through hole. The film was bonded to the base plate with a cyanoacrylate cement so that the center of the film coincided with that of the hole in the base plate and the base plate was subjected to a cyclic load.

4. Experimental results and discussions

4.1 Crack propagation

Crack propagation curves obtained from the aluminum, copper and titanium films are indicated in Fig. 8. The crack length is expressed by the half-length of the whole crack including the slit. For the aluminum film, the fatigue crack stopped at the crack length of $a=1.6\text{ mm}$ under $(\sigma_b)_{\max}=15\text{ MPa}$ as shown in Fig. 8(a). The rightward arrows indicated the crack arrest more than 10^6 stress cycles. Then the cyclic stress was increased to $(\sigma_b)_{\max}=20\text{ MPa}$, the fatigue crack propagated again and reached to the edge hole of $a=3.0\text{ mm}$ without the crack arrest. For the copper films, the crack fatigued under $(\sigma_b)_{\max}=15\text{ MPa}$ stopped at the crack length of $a=2.4\text{ mm}$ as shown in Fig. 8(b). The crack fatigued under $(\sigma_b)_{\max}=20\text{ MPa}$ propagated faster than that fatigued under $(\sigma_b)_{\max}=15\text{ MPa}$ and reached to the hole edge. For the titanium films, the both cracks fatigued under $(\sigma_b)_{\max}=17$ and 19 MPa were stopped. In comparison with the aluminum and copper films, the fatigue cracks were decelerated drastically as the crack tip approached the hole edge. The fatigue crack propagated faster in the film fatigued under $(\sigma_b)_{\max}=19\text{ MPa}$ than that fatigued under $(\sigma_b)_{\max}=17\text{ MPa}$.

Fig. 8 Crack propagation curves obtained from (a) aluminum, (b) copper and (c) titanium films. The crack length is expressed by the half-length of the whole crack including the slit. The rightward arrows indicated the crack arrest more than 10^6 stress cycles.

Figure 9 shows fatigue cracks observed in the aluminum, copper and titanium films under the $(\sigma_b)_{\max}=15$, 15 and 19 MPa, respectively. The black regions around the fatigue crack in the aluminum and the copper film are slip lines. On the other hand, the fatigue crack propagated without slip lines in the titanium film owing to the higher proof stress. From the microscopic observation, zigzag of the crack path is larger for the titanium film than for the aluminum and copper films because the number of slip systems in the titanium with hexagonal close-packed (hcp) structure is smaller than that in the aluminum and the copper with face-centered cubic (fcc) structure.

(a)

(b)

Fig. 9 Fatigue cracks observed in (a) aluminum, (b) copper and (c) titanium films under the $(\sigma_b)_{\max}=15$, 15 and 19 MPa, respectively by using digital microscope.

4.2 Crack propagation rate

Variation of crack propagation rate with the crack growth is shown in Fig. 10. The crack propagation rates are decreased drastically as the crack tip approach the hole-edge for the arrested cracks in the aluminum film of $(\sigma_b)_{\max}=15$ MPa, the copper film of $(\sigma_b)_{\max}=15$ MPa and titanium films of $(\sigma_b)_{\max}=17$, 19 MPa. On the other hand, the crack propagation rates are approximately constant for the propagating cracks in the aluminum film of $(\sigma_b)_{\max}=20$ MPa and copper film of $(\sigma_b)_{\max}=20$ MPa. Fluctuations of the crack propagation rate is larger for the lower applied stress in each film. The effect of microstructures, such as grain boundaries and crystal orientations, on the fatigue crack propagation behavior may be larger for the lower applied stress than for the higher applied stress.

Figure 11(a) shows the relationship between the crack propagation rate, da/dN , and the stress intensity factor range, ΔK . Continuous relationships between da/dN - ΔK for the different $(\sigma_b)_{\max}$ in each materials. Though the high crack propagation rates were not obtained, the Paris' law seems to be satisfied over $da/dN=1 \times 10^{-10}$ m/cycle. The threshold stress intensity factor ranges, ΔK_{th} , are obtained 2.3 MPa $\sqrt{m}$, 3.3 MPa $\sqrt{m}$ and 3.5 MPa $\sqrt{m}$ for the aluminum, the copper and the titanium films, respectively. The value of ΔK_{th} is smaller for the copper film than for the bulk one with the comparable proof stress (Liaw, et al., 1982 and Marchand, et al., 1988). On the other hand, the ΔK_{th} for the titanium film has about the same value with the bulk one (Ogawa et al., 1988). It is probable that a trend of increasing ΔK_{th} -value with increasing film thickness can be observed for metal films with the lower proof stress like the copper (Hadrboletz, et al., 2001).

(c)

Fig. 10 Variation of crack propagation rate with the crack growth obtained from (a) aluminum, (b) copper and (c) titanium films. The downward arrows indicated the crack arrest more than 10^6 stress cycles.

Figure 11(b) shows the relationship between the crack propagation rate, da/dN , and the stress intensity factor range divided by Young's modulus, $\Delta K/E$. All data tend to merge into a unique relationship regardless of the materials. Because it is well known that the relationships between $da/dN - \Delta K/E$ are almost identical for different bulk metal materials, the proposed ΔK -decreasing test method is utilized for the fatigue crack propagation test of the metal films with various Young's modulus and proof stress.

Fig. 11 (a) Relationship between the crack propagation rate, da/dN , and the stress intensity factor range, ΔK , and (b) relationship between the crack propagation rate, da/dN , and the stress intensity factor range divided by the Young's modulus, $\Delta K/E$, for aluminum, copper and titanium films. All data tend to merge into a unique relationship regardless of the materials by using the parameter, $\Delta K/E$.

5. Conclusions

A new ΔK -decreasing test method was developed by using metal film adhered to a through elliptical hole in a base plate and was fatigued in accordance with the displacement constraint along the hole-circumference in the base plate subjected to a cyclic stress. The optimum aspect ratio of an elliptical hole was determined using FEM analysis and the crack propagation test was conducted for aluminum, copper and titanium films. The following conclusions were obtained.

- (1) The stress intensity factor, K , was calculated by FEM. The stress intensity factor decreased continuously with increasing the crack length. From the K -decreasing rate and the crack opening displacement calculated by FEM, the optimum aspect ratio of the elliptical hole was determined.
- (2) Using the ΔK -decreasing test method, the crack propagation test was conducted. As a result, the fatigue crack propagation rate was decreased and was arrested near the hole-edge under the constant stress amplitude to the base plate.
- (3) The threshold stress intensity factor ranges, ΔK_{th} , were obtained for various metal films. The relationship between the crack propagation rate and the stress intensity factor range divided by the Young's modulus, $\Delta K/E$ for various metal films tend to merge into a unique relationship.

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