Fatigue fracture behavior of *MEMS* Cu thin films

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ABSTRACT

Various *MEMS* devices have been developed based on the advances on micro-electro-mechanical systems technologies. It has become important to ensure their performance and reliability. The fatigue behavior of Cu thin films widely used in *MEMS* devices are essential to evaluate performance and reliability of these devices, and it has been well known that fatigue behavior of thin films are different from those of bulk materials. As model specimens to investigate the fatigue behavior of Cu thin films, pure copper films with thickness of 100 μm were bonded with epoxy resin and directly diffused to steel base plates. The fatigue crack initiation and propagation from the notch root of the specimen were faster for the epoxy–bounded film than for diffused bounding specimen. Moreover, the fatigue crack initiation life on film surface is found to be higher in case of diffusion-bounding. On the other hand, crack initiation and propagation also increased as the stress amplitude increase while decreased as mean stress increase. Roughness of surface films has been measured by laser microscope. These results showed the effect of different stress amplitudes and mean stresses on the fatigue behavior of Cu thin film.

KEYWORDS

MEMS devices, Cu thin film, Fatigue behavior, crack initiation

INTRODUCTION

Laminated copper thin films bounded to metal substrate are successfully used as interconnects and small functional or structural components in micro-electro-mechanical systems; MEMS [1, 2]. In MEMS devices, thermal, mechanical and multi-physics issues are playing a dominant role as they are influencing more and more their reliability [3]. It is well known that fatigue damage is caused in MEMS devices by thermal cyclic and mechanical vibrations during operation [4]. Furthermore, MEMS device such as RF (radio frequency devices switches) are subjected to cyclic loading under frequency conditions of kHZ~GHZ [4-7]. Only a few studies on fatigue behavior of thin films under tension-tension loading can be found because of some limitations of a testing machine [8]. The mechanical properties; specially fatigue behavior, of thin films widely used in MEMS devices are essential to evaluate their performance and reliability; it has well known that mechanical properties of thin films are quite different from those of bulk materials [8-15]. Several investigations have been devoted to obtain mechanical properties of thin films such as elastic modulus, yield stress and tensile strength by applying bending test [9, 10], bulge [11, 12] and tensile test [13-15], respectively.

Works on fatigue behavior of thin films are not enough to reveal its dominant role in film performance. Most fatigue tests have been performed under bending, though fatigue test under tension-tension loading is more relevant as is the case wit obtaining mechanical properties of thin films [16, 17]. The fatigue strength of any material can be significantly reduced by the presence of a crack or any other sharp discontinuities. More commonly fatigue cracks propagate from the initial to the critical crack size before final failure occurs [18]. Moreover, fatigue crack growth in metallic materials is controlled by intrinsic factors, such as material property and microstructure, and extrinsic properties, such as loading condition [19]. In the case of variable amplitudes, crack growth depends also on the preceding cyclic loading history.

In this study, model specimens of pure copper films bonded with epoxy resin adhesive or diffused directly to the surface of steel base plate were prepared. Using these specimens, the fatigue fracture behavior of copper thin films was studied. The fatigue crack initiation and propagation were examined mainly through observing the cracks on the surface film. In addition, some differences between the two bonding methods in the fatigue crack initiations lives are reported and discussed from the point of view of the microstructure. Moreover, the effect of stress amplitude and mean stress as extrinsic properties on the film fatigue behavior is studied.

SPECIMEN, MATERIAL AND TESTING

Material

Pure copper films with thickness of 100 μm were bonded to steel (S45C) base plates by means of epoxy resin or directly diffused. The chemical compositions are listed in Table 1 while material properties including epoxy resin employed as adhesive are in Table 2. The base plate was annealed at 1173 K for 1 hr, machined to the dimensions shown in Fig.1 and consequently annealed at 873 k for 1 hr to avoid residual stress. The copper films with thickness of 100 μm were shaped into rectangular with dimensions 40 X 30 mm as shown in Fig. 1, and annealed at 837 for 1 hr. Then, these films were bonded with the epoxy resin at 373 K for 40 min. to both sides of the base plate. Finally, a small through hole with a 0.5 mm diameter was drilled at the centre of the specimen as a notch, so that the fatigue crack would initiate from the notch root.

	Al	Ni	Sn	Pb	Fe	Zn	Mn
Film (Cu)	0.00005>	0.00005>	0.00005>	0.00005>	0.00005>	0.00005>	0.00004>

	C	Si	Mn	P	S
Base (S45C)	045	0.18	0.78	0.012	0.006

Table 1: Chemical compositions; mass%

	Young's modulus, *E* GPa	Linear thermal expansion

		coefficient, α/K
Film (Cu)	123	1.68×10^{-5}
Epoxy	5.4	4.0×10^{-5}
Base (S45C)	206	1.10×10^{-5}

Table 2: Material properties

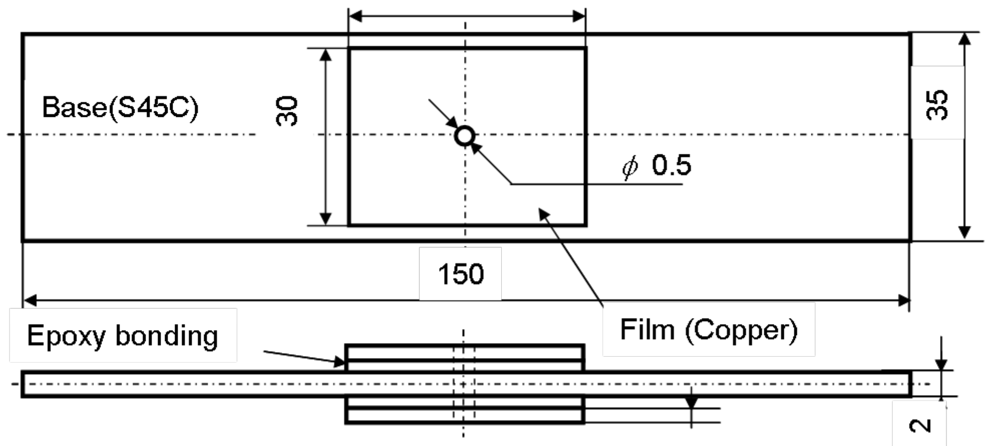


Fig. 1: Model specimen with epoxy-bonded film

Fatigue testing

Specimens were subjected to push-pull cyclic loading under a constant sin wave, with stress amplitudes of σ_a = 140 and 180 MPa, a frequency of 20 Hz and a stress ratio of R= -1. On the other hand, loading regime with different mean stresses values was applied on specimens to reveal mean stress effect on fatigue behavior. Using the specimens without notch hole [20], the longitudinal axial strains were measured on both the epoxy-bonded film and base plate by the strain gauge method. Axial strain values were measured for epoxy resin bonded as well as for directly diffused specimen. As shown in Fig. 2, the maximum longitudinal strain; ε_{yymax}, measured during fatigue were almost constant. As well there were no significant differences between the film and base plate, irrespective of the film thickness.

In a fatigue crack initiation test, the length of the fatigue crack on the surface film was measured by a photomicroscope attached to the fatigue test machine. Moreover, surface profile near the fatigue crack was measured by laser microscope.

EXPERIMENTAL RESULTS AND DISCUSION

Stress amplitude effect

Many MEMS's devices experience variable loading pattern, containing periodic overload and/or under-load cycles. These loading regimes have different stress amplitudes. Therefore, it is necessary to study the effect of different stress levels, as extrinsic factor, on fatigue behavior, and consequently on crack initiation and propagation, as intrinsic property. Model specimens with Cu films, which were bonded at left (Side I) and at right (Side II), were subjected to two stress amplitudes; σ_a = 140 and 180 MPa. The mean stress is kept to be zero in order to study stress amplitude effect only. At these stress amplitudes, the fatigue crack initiation lives at the notch root and on the film surface are reported in Fig. 3.a and 3.b, respectively. The crack initiation lives at the notch root are lower than those on film surface. Moreover, the lowest initiation lives were found at the notch root at stress amplitude of 180 MPa showing the severe effect of rising loading stress.

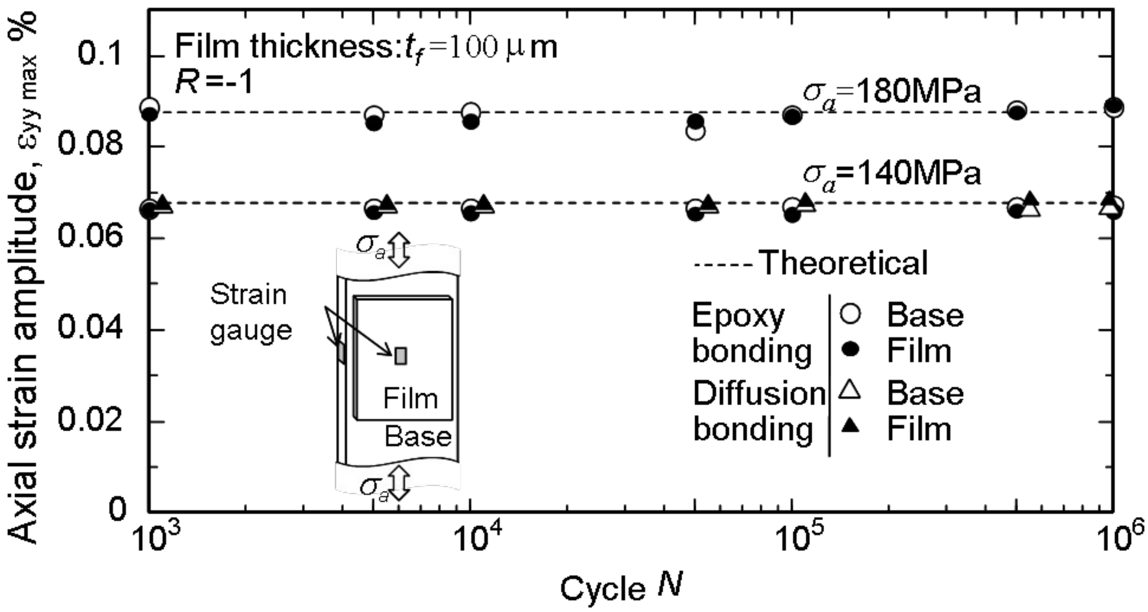


Fig. 2: Maximum longitudinal strain during fatigue. (t_f = 100 μm)

Mean stress effect

Mean stress can significantly increase or decrease the life for crack initiation in fatigue loading of engineering materials. At stress raiser, the local mean stress strangely influences the life crack initiation [21]. Different models have been developed for including mean stress effects in fatigue life calculations, such as those of Goodman, of Morrow and of Smith-Watson-Topper (SWT) [22].These models were for metals and alloys of considerable big size while there are few studies on MEMS devices which have small size.

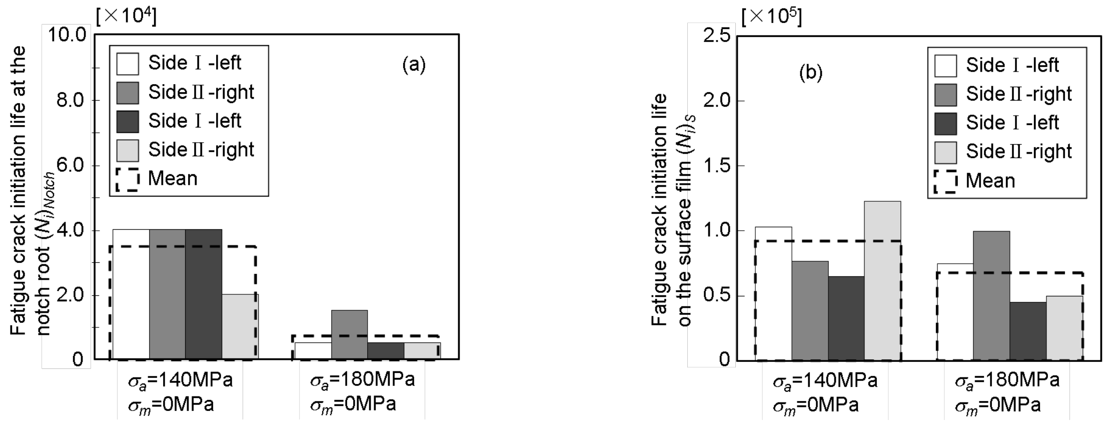


Fig. 3: Fatigue crack initiation lives (a) at notch and (b) on film surface. (σ_a = 140 and 180 MPa and σ_m = 0)

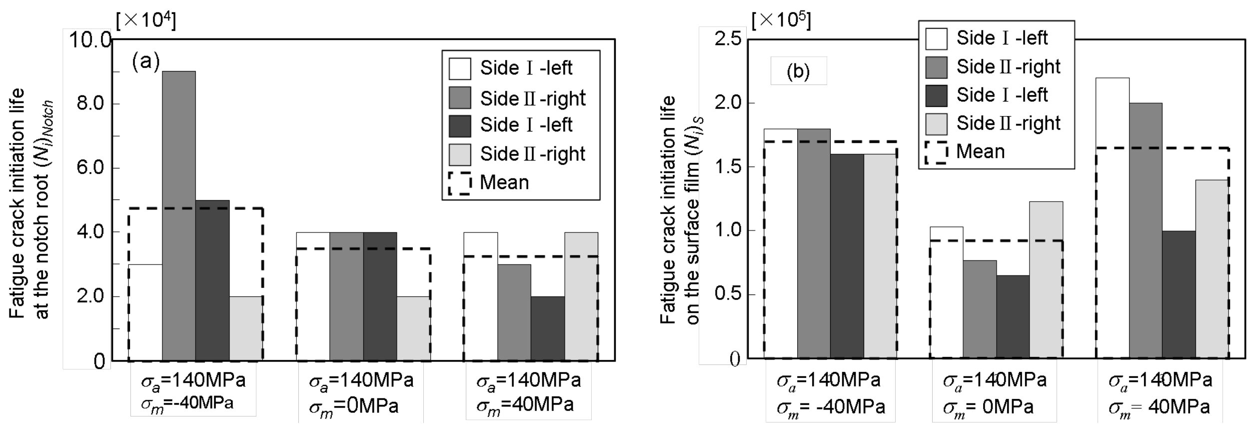


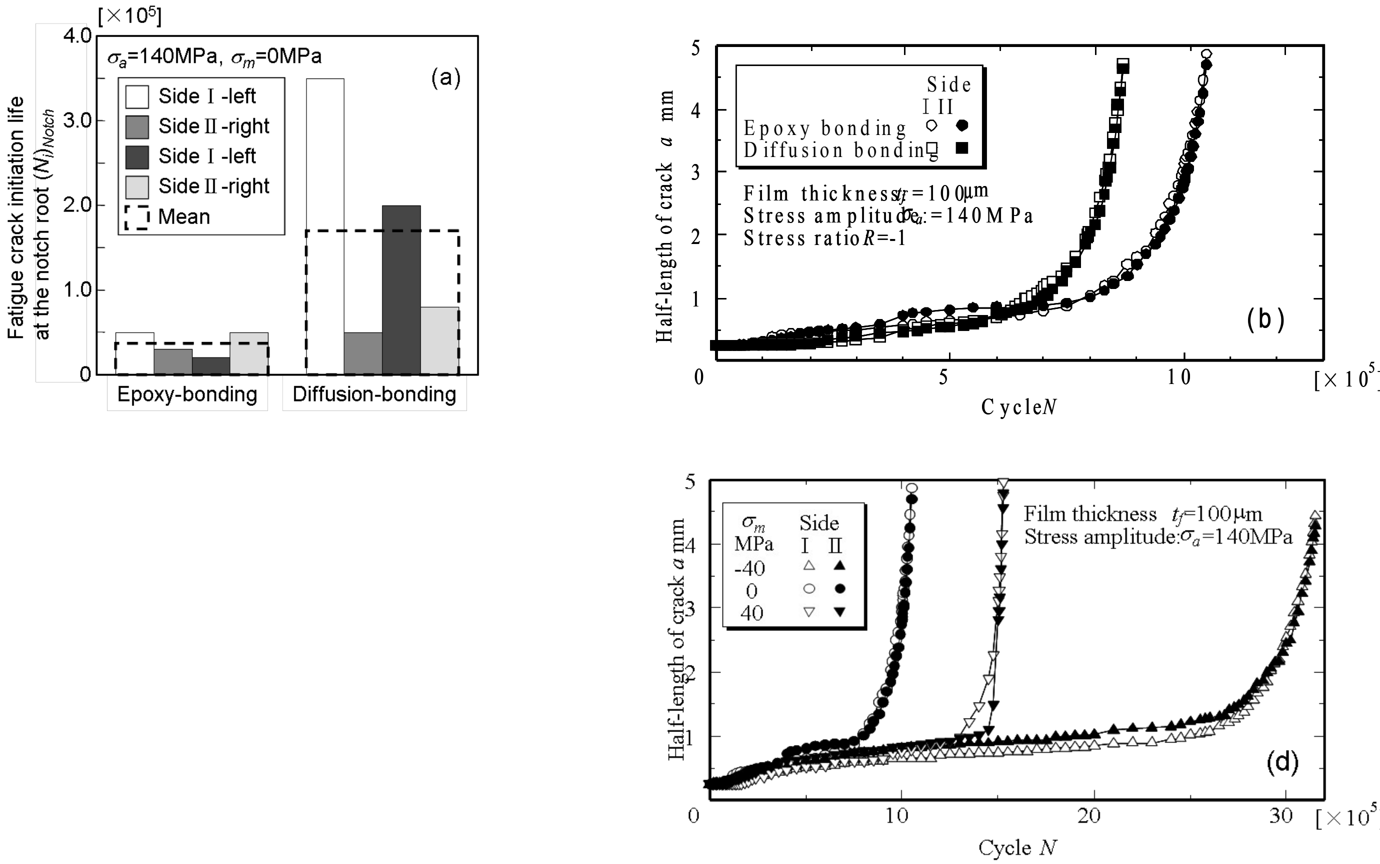
Fig. 4: Fatigue crack initiation lives (a) at notch and (b) on film surface. (σ_a =140 MPa and σ_m = 0, -40, and 40 MPa, respectively)

In this study, mean stress effect on crack initiation life and crack propagation is investigated. Figure 4 represents the fatigue crack initiation lives at notch root and on film surface at stress amplitude of 140 MPa and different mean stress values. At notch root Fig. 4.a, the fatigue crack initiation lives are lower than those on the film surface; Fig 4.b, at all mean stress values. Moreover, the fatigue crack initiation life at the notch root decrease as mean stress increase. While, these crack initiation lives are almost the same on film surface regardless the type of mean stress is tensile (40 MPa) or compressive (-40 MPa) as shown in Fig. 4. b.

Crack initiation and propagation

Figure 5.a shows the fatigue crack initiation life at the notch root for Cu films which were adhered by epoxy and direct diffusion method, respectively. Mean crack initiation lives are lower in samples which were bonded by epoxy-resin on both sides Ⅰ and Ⅱ. On the other hand, the fatigue crack propagation curves from the notch root on the epoxy-bonded film are shown in Fig

5.b, c, and d, where the half-length of cracks including notch, a, is plotted against the stress cycle, N. The fatigue crack initiates and propagates rapidly near the notch at the initial stage but subsequently propagates slowly, and finally propagates rapidly during fatigue. This crack propagation behavior is similar to those seen when using different bonding method, (Fig 5.b), amplitudes (Fig 5.c), and mean stress values (Fig. 5.d).



<u>Fig. 5:</u> Fatigue crack initiation lives (a) at notch for both types of bonding and fatigue crack propagation curves from the notch root (b) for both types of bonding, different stress amplitudes (c) and various mean stress values (d).

Film surface profile

Films profiles near the fatigue crack were measured by laser scanning microscope. Roughnesses of film surface are plotted in Fig. 6 for laminated Cu films bonded by epoxy-resin at different stress amplitudes and mean stress values. These results showed the same fatigue crack initiation and propagation behaviors which are in previous sections. These results show the elevation profile on the film surface with the fatigue crack initiation and propagation, irrespective of the stress amplitude and mean stress.

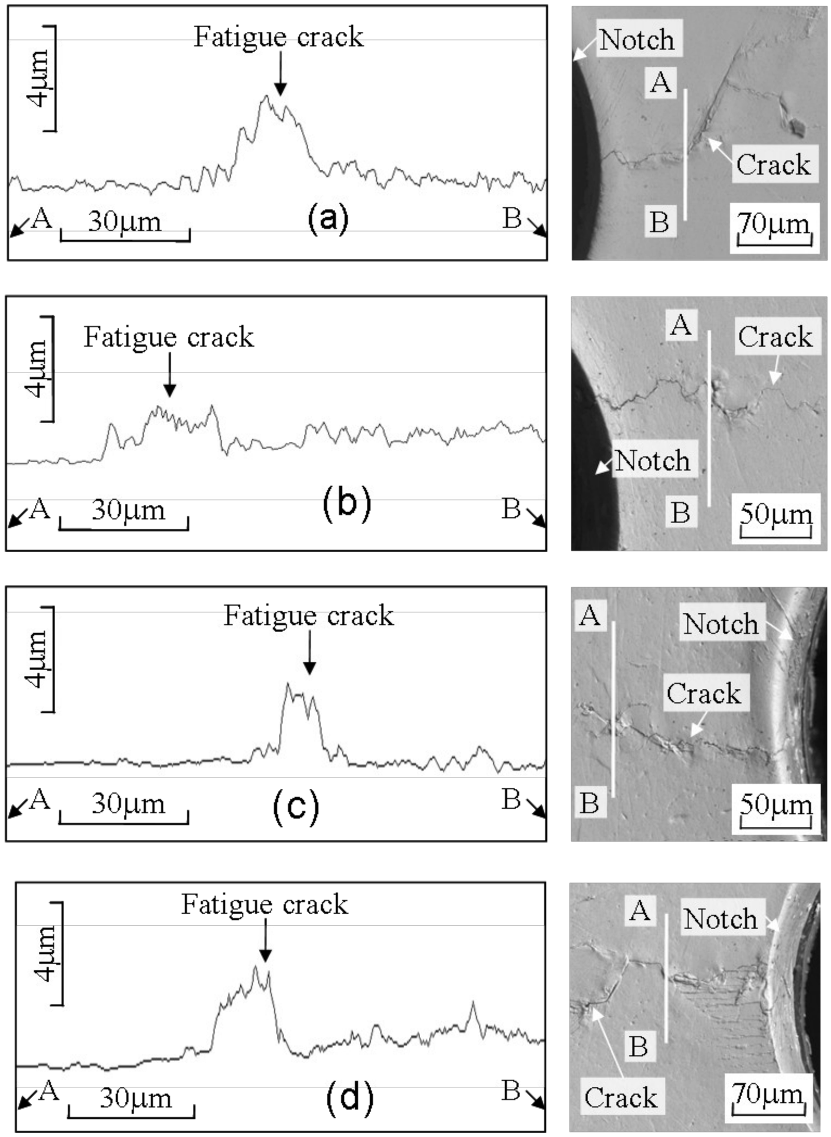


Fig. 6: Roughness of film surface near the fatigue crack measured by laser microscope. (a) σ_a = 140 MPa, σ_m = 0 MPa and N = 32.0 X 10^4, (b) σ_a = 140 MPa, σ_m = 40 MPa and N = 32.0 X 10^4, (c) σ_a = 140 MPa, σ_m = -40 MPa and N = 20.0 X 10^4, (d) σ_a = 180 MPa, σ_m = 0 MPa and N = 8.0 X 10^4,

CONCLUSIONS

The fatigue fracture behavior of thin cu films which are widely used as MEMS's devices were examined. Laminated cu thin films were successfully bonded by epoxy-resin and/or directly diffusion methods. These specimens were subjected to fatigue loads with different stress amplitude and means stress values. As a result, fatigue crack initiation lives decreased near the notch root as well as on film surface with increasing stress amplitudes. Moreover, mean stress had a considerable effect on crack initiation lives on the film surface. On the other hand, fatigue crack propagation lives from the notch root were increased and decreased with the compressive and tensile mean stress, respectively. The fatigue crack initiation and propagation from the notch root of the specimen were faster for the epoxy–bounded film than for diffused bounding ones. Film surface profiles near the fatigue crack which, were measured by laser microscope showed the elevation on the film surface with the fatigue crack initiation and propagation.

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