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纳米尺度金属薄膜在拉伸状态下的稳定性

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摘要:将薄膜和基底作为一个基本结构来研究薄膜的变形和损坏可预测纳米薄膜器件的使用寿命。本文讨论和研究了薄膜基底结构在拉伸载荷下薄膜出现的分叉和断裂的过程。用在相同厚度的 PET 基底上沉积不同厚度铝膜的薄膜基底结构作为试件,分别对薄膜厚度为 100,150 和 200 nm 的 3 种不同试件进行了拉伸加载实验,并在 OLYMPUS 显微镜下观察了薄膜表面的变化情况。分析和对比结果表明:随着薄膜厚度的增加,薄膜出现分叉现象的失效应变也随着增大;当薄膜表面出现裂纹时,裂纹密度的大小取决于薄膜的厚度和加载应变的大小。

关　键　词:纳米薄膜;金属薄膜;分叉;断裂;拉伸;微机电系统
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Stability of nano-scale thin metal films under tension

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Abstract: This paper presents a basic structure combined with a film and a substrate to investigate the damage and deformation of thin films and to predict the life time of MEMS. The bifurcation and fracture of thin films under a tensive load were determined by an experiment where the film/substrate structure was used as the specimen. The substrate was a deposited aluminium film with different thicknesses of 100,150 and 200 nm. Then the experiment was initiated using our designed loading device. An OLYMPUS microscope was used to observe the change of the topography of the film surface. The destruction of the film and the corresponding sizes of the load and displacement were recorded. Finally, the effects of film thickness on bifurcation and fracture were obtained by comparing experimental results. These show that the relevant rupture strain increases with the film thickness and the crack density along the loading direction depends on the thickness of the film and the failure stain when there are cracks appear on the film surface.

Key words: nano-scale thin film; metal film; bifurcation; fracture; tension; MEMS

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1 Introduction

The structures of the film/substrate and multilayer films/substrate play important roles in information science and engineering[1]. For example, there are many conductors, semi-conductors and insulating films in integrated circuits for data storage and processing systems, and magnetic films play a key role in disk storage systems. An important application is in MEMS, which has great prospects in the industrial, information, medical and other fields with the advantages of small size, light weight, and low power consumption[2]. In the application of these fields, one type of damage of the film is bifurcation and fracturing under tension; the second type is buckling and delamination under compression.

In recent years, many foreign researchers have focused on thin films mainly because of the wide use of them. Research in this area, not only numerical analysis, can be investigated by creating a reasonable mechanical model, but also by an experiment. Using numerical analysis, many valuable conclusions were obtained, such as Hill and Hutchinson[3], Dorris and Nemat-Nasser[4], Steif[5], Bigoni[6] on the depth study of bifurcation problems for the structure of nano-film substrates. They used a linear perturbation analysis, and introduced bifurcation perturbation methods to provide the relationship between bifurcation strain and wave number. However, the thickness of the film is usually nano-scale, so experiments are much more effective. For instance, Li T, Huang Z Y, Xi Z C, Lacour S P, Wagner S, Suo Z[7] did a preliminary study of the bifurcation problem for a thin film under a stretching load. They found that the film will produce fractures under a certain degree of tension, that is not caused by a brittle fracture but by strain localization, such as necking. Kang[8] researched an aluminum film deposited on a polyimide substrate, and the result of the experiment indicate that the film does not form cracks until the strain reaches 20%. Pashley[9] and Lee[10] performed experiments showing that metal films often rupture at relatively small strain. Further, Chiu[11], Macionczyk and Bruckner[12], Gage and Phanitsiri[13], Yu and Spaepen[14] studies a metal film on a polymer substrate, showing that the specimen can withstand a larger strain, ranging from several to tens of percent before fracture. In the present paper, based on these earlier studies, we investigate bifurcation and fracture for a structure consisting of a thin film bonded to a substrate. In this experiment, we use aluminum film deposited on a PET substrate as the test piece. We load the specimen with special loading equipment and use a OLYMPUS microscope to observe the bifurcation and fracture of the film surface.

2 Theory background

In Li Teng and Suo Z. [15], the mechanical analysis of the deformation for the specimen model is introduced. Fig. 1 describes the model; a metal film with initial thickness h, deposited on an elastomer substrate, with initial thickness H.

The metal film obeys the J_2 deformation theory. Under a tension load, the metal deforms under the rule $\sigma = K\varepsilon^N$, where. K is the pre-factor, and N is the hardening exponent. The sub-

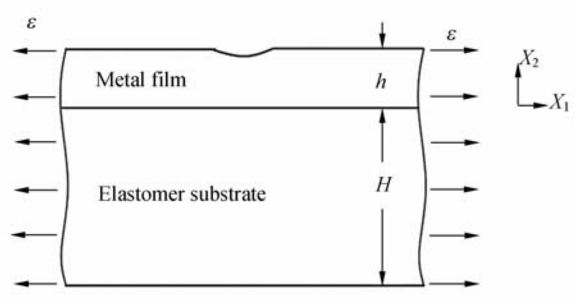


Fig. 1　A metal film under tension showing local necking

strate deforms according to

$$\sigma=(E/3)(\exp(2\varepsilon)-\exp(-\varepsilon)) ,$$

where E is Young's Modulus. Because of the plane strain condition, for x_1 direction in the metal thin film $\sigma_{\mathrm{film}}=K(2/\sqrt{3})^{N+1}\varepsilon^N$ and in the elastomer substrate $\sigma_{\mathrm{sub}}=(2E/3)\sinh(2\varepsilon)$. However, by volume conservation, the film and substrate will be thinner in x_2 direction. Consequently, the homologous force in the x_1 direction is

$$\frac{F}{Kh}=[(\frac{2}{\sqrt{3}})^{N+1}\varepsilon^N+\frac{2}{3}\sinh(2\varepsilon)\ \frac{EH}{Kh}]\exp(-\varepsilon) .$$

We define a parameter EH/Kh, which measures the reaction of the substrate. In addition, different values of parameters determine different bifurcation phenomena. In this article, we use the specimen in which the films with different thicknesses are deposited on the substrates with the same thickness to change the value EH/Kh.

3　Experiments

The thickness of the PET substrate of the specimen used in this experiment is 0.12 mm, and the viewed area width is 3 mm. Fig. 2 shows the shape of specimens that are prepared by magnetic sputtering in a vacuum. Before sputtering the film, substrates are cleaned by sonicleaning using absolute ethyl alcohol, and then are sputtered to deposit the aluminum layer on the substrate. Controlling the sputtering time, changes the thickness of the specimen film. In this experiment, there are three thicknesses 100 nm, 150 nm, and 200 nm.

Fig. 2　Specimen with aluminum layer on a PET substrate. The position of circle hole fixes the specimen and the middle of specimen is the observation area.

We designed an in-situ stretching device. There is a force sensor in the loading device to measure the corresponding force. We used a micro-cantilever sensor to record the change in displacement. The topography of the film surface was observed using an OLYMPUS microscope. Loading the specimen slowly, we recorded the changes of the film surface under different tensile loads applied on the specimen using a CCD camera.

4　Results and discussion

4.1　Results of the experiment

In Li T and Suo Z[15], Li T, Huang Z Y *et al*[7], Xiang Y, Li T *et al*[16], under stretching, the local strain concentration of the film leads to local elongation. The local elongation requires additional space for its accommodation. By volume conservation, this space cannot be created on the film bonded to the substrate. Hence, the film will be thinner at these spots and necking appears beyond a certain strain. Studies show that a metal film on an elastomer substrate may develop an array of necks before rupture. Once the film forms a neck at a local spot, further deformation is localized in the neck, and leads to rupture. In the experiment, limitations of the microscope, make it difficult to capture the critical bifurcation point, but we observe micro-cracks on film surface result from the neck. We can use these cracks to observe the bifurcation arising from stretching. Fig. 3 shows micro-cracks captured during the test. From micro-photos, we find that there are more micro-cracks for a film with a thickness of 100 nm. However, for a film with a thickness of 200 nm, a smaller number of cracks were observed. Although there are no micro-cracks captured with a film thickness of 150 nm by counting the number cracks, we find that the number of micro-cracks for this film is below that of the 200 nm film, but more than of the 150 nm film.

After micro-cracks appear on the surface of the metal film with increasing of tension strain, the cracks start to propagate. Fig. 4 shows the distribution of cracks in films with different thicknesses. When the films are stretched by 3%, we find a great number of spallation cracks in the image but only a few cracks run through the viewing area. However, for the 150 nm film, we can see more traversal cracks and a smaller of spallation cracks. There are no cracks on the film surface for a 200 nm film. If the film is stretched by 12%, there are more cracks for all three thicknesses of films and the cracks are more uniform. The number of cracks decreases as the film thickness increases. For a 100 nm film, the shape of the cracks is not constant. Based on continuity of the original cracks, a great number of additional discrete cracks appeared on the 150 nm film. In the photos of the 200 nm film, we find that the shape of the cracks appear mainly discontinuous, and are accompanied by small traversal cracks.

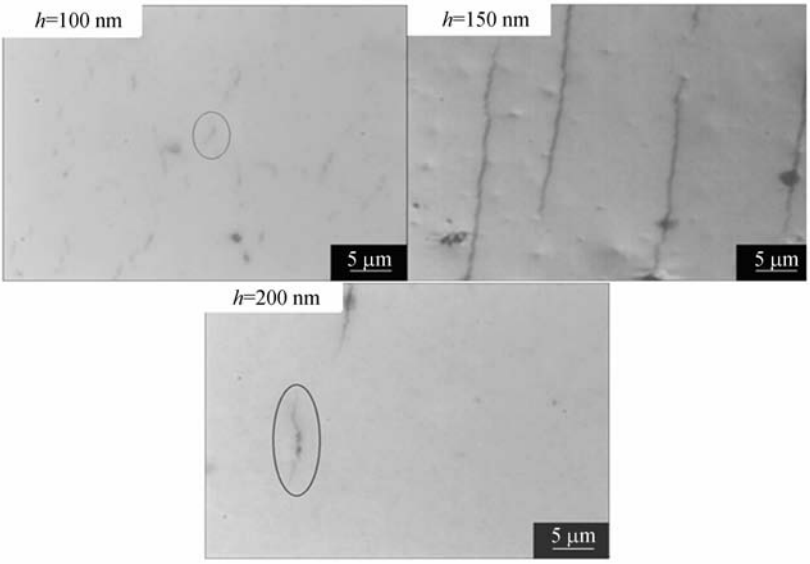
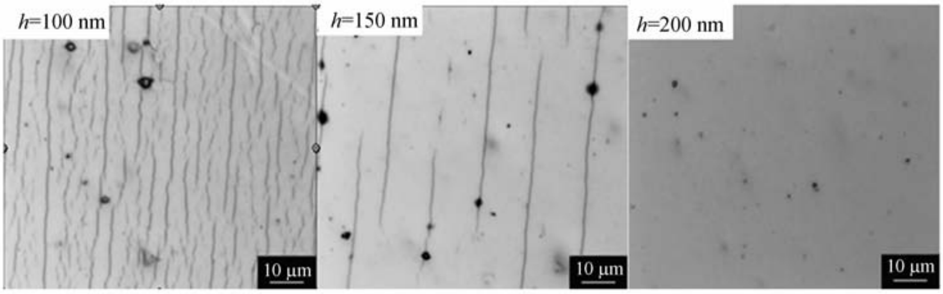
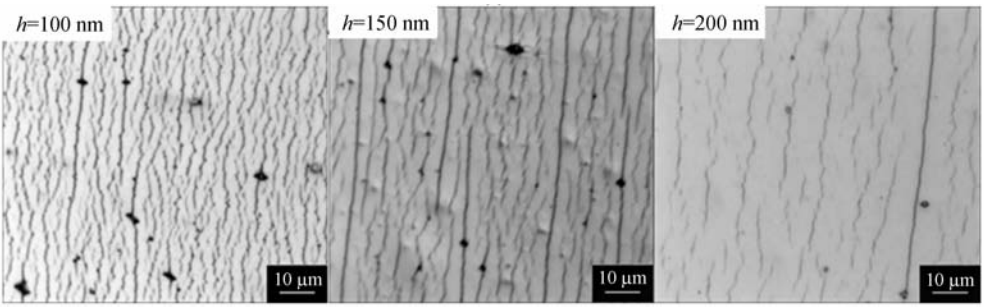


Fig. 3 Micrograph of films when micro-cracks appear on the surface, and the direction of load is horizontal



(a) Film stretched by 3 %



(b) Film stretched by 12 %

Fig. 4　Micrograph of films under different strains horizontally

4.2　Discussion

Using the experimental information we plot a trend line of the failure strain as a function of film thickness in Fig. 5. It is evident from Fig. 3 that the 200 nm film has the highest failure strain, and the 100 nm film has the lowest failure strain. From the trend line, we see that the failure strain for the 150 nm film is intermediate. In addition, the failure strain rises rapidly with increasing film thickness.

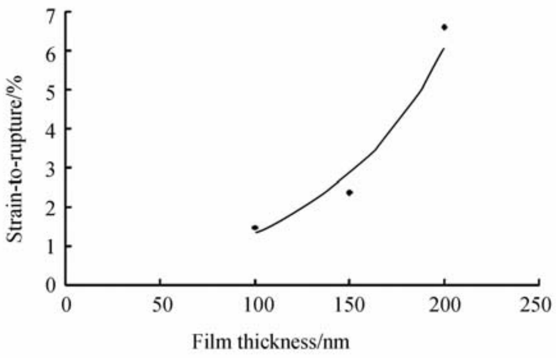


Fig. 5　Plot of the failure strain as a function of film thickness for a metal film on a PET substrate

As the applied tensile strain increases, more cracks appear. We can count the number of cracks on a certain length along the loading direction. Fig. 6 shows that rupture strains affect on the number of cracks per 100 μm, we call this density of cracks along the loading direction. We can use this Fig to study the role of film thickness on the rupture strain. From Fig. 4(b), the density of cracks in the 150 nm film is between that for films of 100 nm and 200 nm thicknes.

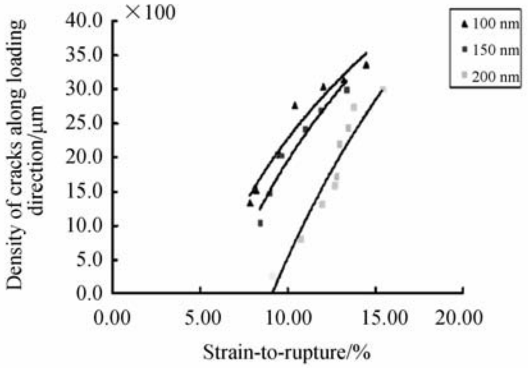


Fig. 6　Effect of rupture strains on the number of cracks per 100 μm

Furthermore, as the failure strain increased, the density along the loading direction also increases, when the rupture strain is below 20%.

5 Conclusions

In this paper, we investigated the crack distribution in aluminum films with different thicknesses deposited on PET substrate under tensile loading. Above the bifurcation point, the cracks evolved from micro-cracks to spallation cracks. As the film thickness decreased, the relevant rupture strain also decreased. In addition, comparing the images between the films with different thicknesses stretched by 3% and 12%, we find that when the specimen is stretched by a large strain to a certain degree, the crack density along the loading direction depends on the thickness of film and the failure stain. At the same applied strain, as the film thickness increased, the cracks density decreased and at the same cracks density, when film thickness increased, the required rupture strain increased.

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References:

[1] GIOLA G, ORTIZ M. Delamination of compressed thin films [J]. *Adv. Appl. Mech.*, 1997, 33: 120-192.

[2] ZHOU Z Y, YE X Y, CUI T H, *et al.*. Micro-technology/nanotechnology and MEMS [J]. *Opt. Precision Eng.*, 1998, 6(2): 1-7.

[3] HILL R, HUTCHINSON J W. Bifurcation phenomena in the plane tension test [J]. *Mech. Phys. Solid*, 1975, 23: 239-264.

[4] DORRIS J F, NEMAT-NASSER. Instability of a layer on a half space [J]. *Appl. Mech.*, 1980, 47: 304-312.

[5] STEIF P P. Periodic necking instabilities in layered plastic solids [J]. *Solids Struct*, 1986, 22: 195-207.

[6] BIGONI D, ORTIZ, M. Needleman. Effect of interfacial compliance on bifurcation of a layer bonded to a substrate [J]. *Solids Struct.*, 1997, 34: 4305-4326.

[7] LI T, HUANG Z Y, LACOUR S P, *et al.*. Stretch ability of thin metal films on elastomer substrates [J]. *Appl. Phys. Lett.* 2004, 85: 3435-3437.

[8] KANG Y S. *Microstructure and strengthening mechanisms in aluminum thin films on polyimide film* [D]. Austin: The University of Texas, 1996.

[9] PASHLEY D W. A study of the deformation and fracture of single-crystal gold films of high strength inside an electron microscope [J]. *Proc. Roy. Soc. Lond. A*, 1960, 255: 218-231.

[10] LEE ZHANG H J, BRAVMAN J C. Tensile failure by grain thinning in micro-machined aluminum thin film [J]. *Appl. Phys*, 2003, 93: 1443-1451.

[11] CHIU S L, LEU J, HO P S. Fracture of metal-polymer line structures [J]. *Appl. Phys*, 1994, 76: 5136-5142.

[12] MACIONCZYK F, BRUCKNER W. Tensile testing of Al/Cu thin films no polyimide foils [J]. *Appl. Phys*, 1999, 86: 4922-4929.

[13] GAGE D M, PHANITSIRI M. Experimental and mathematical analysis of tensile fracture mechanics in thin-film metal deposits [D]. *Princeton: Princeton University*, 2001.

[14] YU D Y W, SPAEPEN F. The yield strength of thin copper films on Kapton [J]. *Applied Physics*, 2004, 95: 2991-2997.

[15] LI TENG, SUO Z. Deformability of thin metal films on elastomer substrates [J]. *Solids and Structures*, 2006, 43: 2351-2363.

[16] XIANG Y, LI T, SUO Z, *et al.*. High ductility of a metal film adherent on a polymer substrate [J]. *Appl. Phys*, 2005, 87: 161910.

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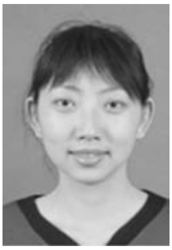

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