

Buckling behavior of micro metal wire on polymer membrane under combined effect of electrical loading and mechanical loading

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Abstract: The buckling behavior of a typical structure consisting of a micro constantan wire and a polymer membrane under coupled electrical-mechanical loading was studied. The phenomenon that the constantan wire delaminates from the polymer membrane was observed after unloading. The interfacial toughness of the constantan wire and the polymer membrane was estimated. Moreover, several new instability modes of the constantan wire could be further triggered based on the buckle-driven delamination. After electrical loading and tensile loading, the constantan wire was likely to fracture based on buckling. After electrical loading and compressive loading, the constantan wire was easily folded at the top of the buckling region. On the occasion, the constantan wire buckled towards the inside of the polymer membrane under electrical-compressive loading. The mechanisms of these instability modes were analyzed.

Key words: delamination; instability modes; electrical loading; mechanical loading; interfacial toughness

1 Introduction

A structure composed of a micro/submicro metal wire and a flexible substrate has been extensively adopted in flexible electronic devices, semiconductor integrated circuits and micro-electro-mechanical systems [1,2]. The instability behavior of this kind of structure directly affects the reliability of micro-devices, and thus has attracted great attention of researchers in a variety of fields such as electronics, mechanics, physics and materials. Among various instability modes, the buckling of films is a ubiquitous mode affecting the reliability of film/flexible-substrate structures [3]. In the last decades, a large amount of work has been carried out to study the buckling behaviors of films on flexible substrates [4–8]. SUN et al [9] controlled the buckling morphologies of GaAs and Si nanobelts by exerting pre-tensile strain on polydimethylsiloxane substrates. The buckling as well as the fracture behaviors of Ni film [10] and Ta film [11,12] on polyimide substrates under uniaxial tensile loading

was studied. VELLA et al [13] systematically studied the buckling behaviors of rigid polypropylene films on flexible poly siloxane substrates under uniaxial compressive stress. Besides the above mentioned mechanical loading, thermal loading and electrical loading could also trigger the buckling of film wires on flexible substrates. BOWDEN et al [14] observed the buckling of metal films on a PDMS substrate by heating the PDMS substrate. WANG et al [15–18] investigated the buckling behaviors and the interfacial toughnesses of a constantan-wire/polymer structure under electrical loading.

Until now, most efforts focus on the buckling behaviors of films on flexible substrates under a single type of loading, such as mechanical loading, thermal loading or electrical loading. Due to the complicated loading condition the film wires bear in the processes of production and use, it is of vital importance to explore the buckling behavior of the film-wire/flexible-substrate structures under a coupled loading of at least two types of loadings [19]. In this study, the coupled electrical-

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mechanical loading was adopted. A typical structure consisting of a micro constantan wire and a polymer membrane, which is a basic component in strain gauges and thermocouples, was chosen as the object of study. The buckling and buckling-related behaviors under the coupled electrical-mechanical loading were investigated.

2 Experimental

2.1 Sample preparation

The sample is comprised of a polymer membrane and a constantan wire. The composition of the polymer membrane is polyvinyl formal-acetal with a small quantity of epoxy novolac. The constantan wire is composed of 55% copper and 45% nickel (mass fraction). Before the sample formation, the polymer is liquid and the constantan wire is sheet. The sample was fabricated by photolithography [18]. The liquid polymer was firstly coated onto the surface of the constantan foil and solidified for 3 h at 190 °C after spin coating. Then, the polymer membrane was used as the substrate and the constantan foil was coated by photoresist. Finally, the constantan wire was fabricated after exposure, development and fixation using a mask and the photoetching technique.

Figure 1(a) shows the SEM image of the constantan-wire/polymer structure. The constantan wire distributes in the shape of a narrow “S” and the parallel segments are in a series connection when they bear electrical current. The width and thickness of the constantan wire are $b_c=28\text{ }\mu\text{m}$ and $h_c=6\text{ }\mu\text{m}$ (Fig. 1(b)), respectively. The length of the parallel segments is $l_c=3100\text{ }\mu\text{m}$. The thickness of the polymer membrane is $h_p=60\text{ }\mu\text{m}$ with the length and width of $a_p=7\text{ mm}$ and $b_p=5\text{ mm}$. The above geometric dimensions were determined by a 3D super-depth digital microscope (KEYENCE FE500). The elastic modulus and the Poisson ratio of the constantan wire are $E_c=160\text{ GPa}$ and $\nu_c=0.33$, respectively. For the polymer substrate, the elastic modulus E_p and the Poisson ratio ν_p are 3.08 GPa and 0.31 [17], respectively.

2.2 Experiments

In order to investigate the instability modes under the action of a combined electrical and mechanical loading, the experimental setup was composed of a simple closed circuit, an optical microscope and a mechanical loading device, as shown in Fig. 2. The circuit was formed with a power supply (stabilized voltage supply), an ammeter (ampere-volt-ohm meter), a resistor and a switch. The power supply could provide alternating current (AC) source with frequency of 50 Hz. The optical microscope was used to observe the surface topography of the sample. The mechanical loading

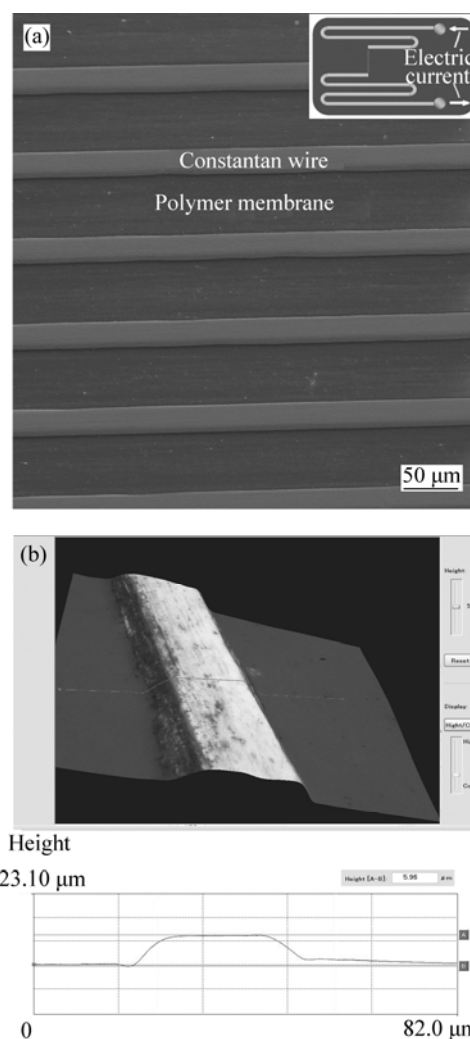


Fig. 1 SEM image of constantan-wire/polymer structure (a), and 3D super-depth digital microscope image for determining height of constantan wire (b)

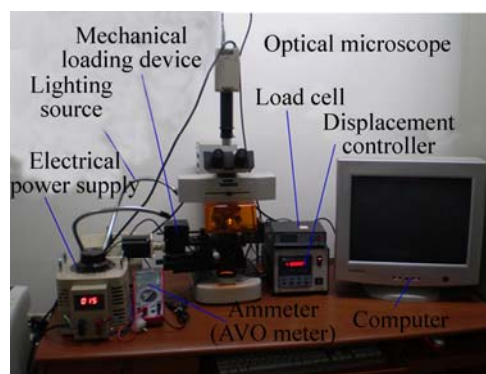


Fig. 2 Experimental setup for combined electrical and mechanical loading, where electrical loading was applied to constantan wire and mechanical loading was imposed on sample supporter

device developed by our laboratory was utilized to cooperate with the closed circuit to realize the combined electrical and mechanical loading onto the sample.

To perform mechanical loading, the constant-wire/polymer sample was pasted using glue on a supporter such as an aluminum tensile specimen, an aluminum bending specimen or a rubber compressive specimen. The sample experienced tensile strain when the aluminum tensile specimen or the aluminum bending specimen was used, and compressive strain was imposed on the sample when the rubber compressive specimen was utilized. The direction of mechanical loading was parallel to the axial direction of the constantan wire. During the loading process, mechanical loading was first applied to the sample and then electrical loading was applied. Before mechanical unloading, electrical loading was first stopped. The experiments were conducted at room temperature. The applied current density of electrical loading was set as $2.8 \times 10^8 \text{ A/m}^2$. The corresponding surface temperature in the central region of the sample was around 38°C recorded by a thermal infrared imager (ThermaCAM P60), lower than the glass-transition temperature of the polymer (120.09°C) measured using a differential scanning calorimeter (DSC-60).

3 Results and discussion

3.1 Buckling-driven delamination

After the coupled electrical-mechanical loading, the parallel segments of the constantan wire were observed to buckle from the polymer membrane. Figures 3(a), (b) and (c) display three typical buckling morphologies of three constantan wires under electrical-tensile and electrical-compressive loadings. The arrows indicate the directions of the applied mechanical loading. The buckling morphologies are similar to the reported buckling-driven delamination only under electrical loading [15,17].

The buckling of the constantan wire was triggered by the relative thermal mismatch between the constantan wire and the polymer substrate, due to the different thermal expansion coefficients (TECs) of the constantan wire ($\alpha_c = 14.9 \times 10^{-6} \text{ K}^{-1}$) and the polymer membrane ($\alpha_p = 70 \times 10^{-6} \text{ K}^{-1}$). The applied mechanical loading gives the same strain to the polymer membrane and the constantan wire, whereas the electrical loading induces different stresses in the constantan wire and the polymer membrane. During the electrification process, the temperature of the sample increases quickly and then almost remains unchanged. When the electrical loading is ceased, the temperature gradually decreases and the polymer membrane shrinks faster due to the greater TEC, which results in biaxial compressive stress on the constantan wire. When the compressive stress exceeds the bonding strength between the constantan wire and the polymer membrane, the constantan wire will delaminate

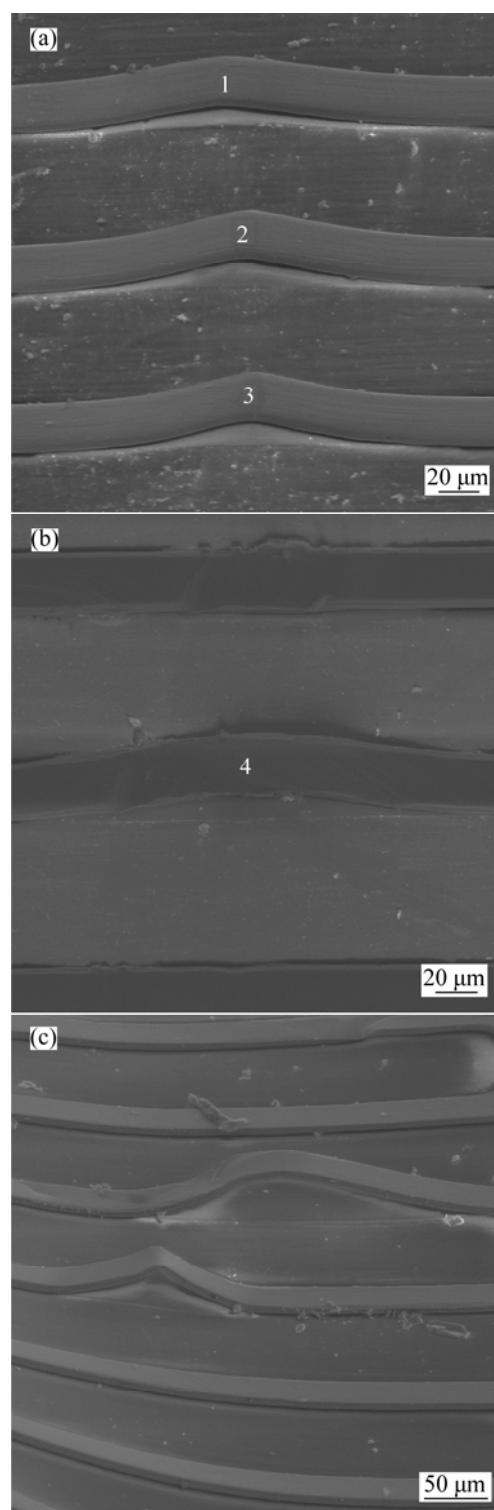


Fig. 3 Buckling morphologies of constantan wire on polymer membrane after combined action of $2.8 \times 10^8 \text{ A/m}^2$ AC and 0.012 tensile strain (a), 0.076 compressive strain (b) and 0.168 compressive strain (c)

from the polymer membrane. The constantan wire tends to buckle in a curve shape like a compressed beam to minimize the potential energy. The mechanical loading may affect the buckling deflection and the buckling

wavelength. However, it has little influence on the buckling morphologies of the constantan wire on the occasions of Figs. 3(a) and (b) compared with the reported buckling morphologies only under electrical loading [15, 17]. If the applied strain is large enough as the big compressive strain in Fig. 3(c), the polymer membrane will be distorted or even broken and the buckling shape of the constantan wire will not be sinusoid.

From the buckling morphologies of the constantan wires in Figs. 3(a) and (b), the interfacial toughness of the sample was estimated to evaluate the interfacial bonding capacity between the constantan wire and the polymer membrane. The interfacial toughness between the rigid constantan film wire and the flexible polymer membrane can be obtained from the following expression [13, 17]:

$$\Delta\gamma = 2\pi^4 \frac{Bw_0^2}{\lambda^4} \quad (1)$$

where $\Delta\gamma$ is the interfacial toughness, $B=E_c h_c^3/12$ means the bending rigidity of the constantan wire, λ represents the buckling wavelength, which is also called the delamination length, and w_0 is the maximum buckling deflection of the constantan wire. This equation can be applied only under the situation that the film is incompressible compared with the substrate. In this study, $E_c h_c$ of the constantan wire is more than 5 times greater than $E_p h_p$ of the polymer substrate. As a consequence, this equation can be approximately used to estimate the interfacial toughness of the constantan-wire/polymer structure.

Figure 4 shows the calculated interfacial toughnesses of the buckled constantan segments labeled in Figs. 3(a) and (b). The interfacial toughnesses between the constantan wire and the polymer membrane are

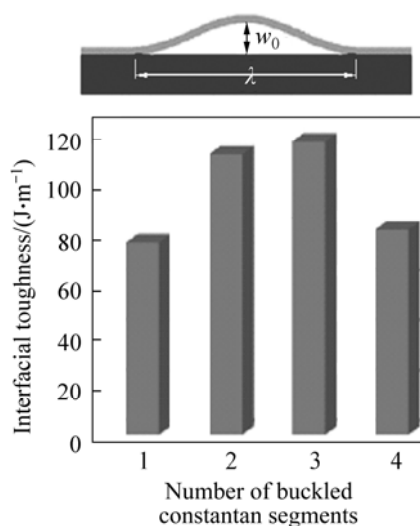


Fig. 4 Interfacial toughness of buckled constantan segments labeled in Fig. 3(a) and (b)

greater than the reported values in Ref. [17]. The possible reason lies in the great diversity of the constantan-wire/polymer samples. It should be noted that the interfacial toughness cannot be calculated from Fig. 3(c), because the shape of the buckled constantan segments are not sinusoid owing to the big compressive strain exerted on the sample.

3.2 Fracture and folding based on buckling

Besides buckling-driven delamination, several other instability modes along with buckling were also observed under the coupled electrical-mechanical loading. Figure 5 illustrates the instability modes based on buckling of the constantan wire on the polymer membrane after the coupled electrical-tensile loading. In Fig. 5(a), the buckled constantan wire suffers a fracture around the top of the buckling under AC 2.8×10^8 A/m² and tensile strain 0.009. The fracture is caused by the combined effect of the applied mechanical tensile stress and the buckling bending stress of the constantan wire. On the other hand, when the applied mechanical tensile

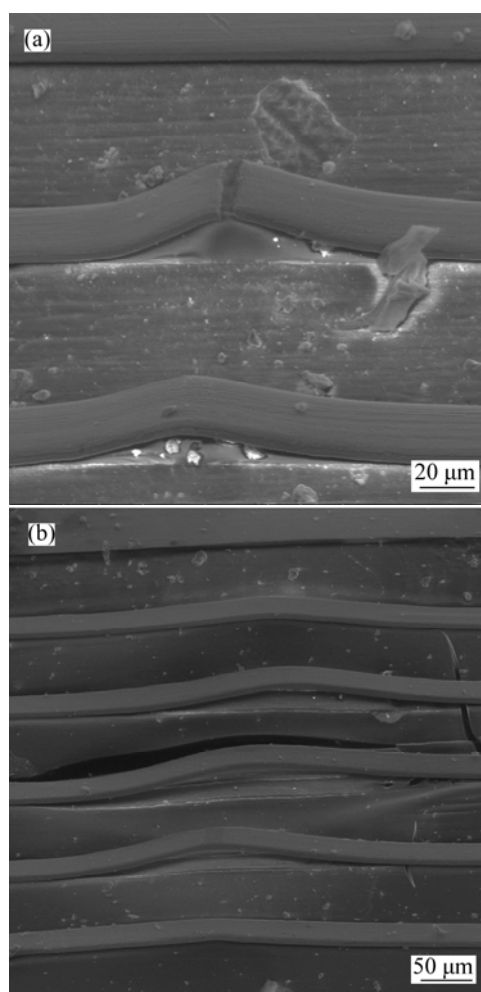


Fig. 5 Instability modes based on buckling of constantan wire on polymer membrane after combined effect of AC 2.8×10^8 A/m² and tensile strain of 0.009 (a) and 0.021 (b)

strain is large, such as under AC 2.8×10^8 A/m² and tensile strain 0.021 in Fig. 4(b), the polymer membrane tends to fracture besides the buckling of the constantan wire as a result of the mechanical compressive stress and the compressive stress generated from the TEC difference during the electrical loading process.

Figure 6 displays the instability modes of the

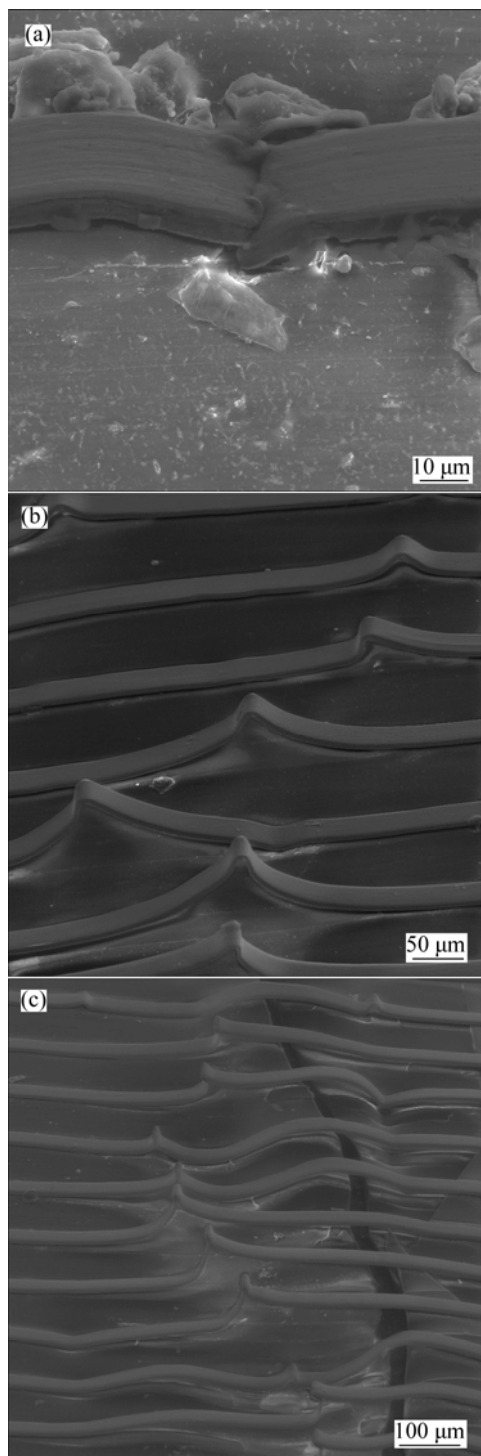


Fig. 6 Instability modes based on buckling of constantan wire on polymer membrane after combined effect of AC 2.8×10^8 A/m² and compressive strain of 0.066 (a), 0.083 (b) and 0.102 (c)

sample under the coupled electric-compressive loading. The buckling direction of the constantan wire, depending on the disturbance acted on the sample, may point to the inside of the polymer membrane as shown in Fig. 6(a) with compressive strain 0.066. The fracture of the constantan wire results from the bending tensile stress of the buckling. More generally, the buckled constantan wire is likely to be folded at the top of the buckling region, i.e., the folding of the buckled wire, presented in Fig. 6(b) with compressive strain 0.083. The folding results from the fact that the buckled constantan wire is further extruded by the mechanical compressive stress. Moreover, when the applied mechanical compressive strain is large, the polymer membrane will buckle from the supporter and fracture under the buckled bending stress of the polymer membrane along with the folding of the buckled constantan wire, see Fig. 6(c) with compressive strain 0.102. All of the above instability modes are tended to realize energy minimization of the samples.

4 Conclusions

1) The buckling driven delamination of the constantan wire from the polymer membrane can emerge under both electrical-tensile and electrical-compressive loadings. When the applied mechanical loading is slightly greater, the polymer membrane tends to fracture along with the buckling of the constantan wire.

2) The fracture of the buckled constantan wire will appear under electrical-tensile loading. There are also several interesting instability modes under electrical-compressive loading, including the buckling towards the inside of the polymer membrane and the folding of the buckled constantan wire.

3) The instability mechanisms are analyzed and the interfacial toughness is estimated from the buckling morphology.

4) Although the research results about the buckling-related instability behaviors of metal-wire/polymer structures under the coupled electrical-mechanical loading are preliminary, this work is promised to provide potential guidance in structure design, interface optimization and reliability evaluation of micro film-wire/flexible-substrate structures.

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聚合物膜上的微尺度金属导线 在力电耦合作用下的屈曲行为

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摘 要: 研究一种典型的微尺度康铜线/聚合物膜结构在力电耦合作用下的屈曲行为。根据卸载后康铜线从聚合物基底上屈曲的现象, 评估康铜线与聚合物基底间的界面韧性。此外, 力电耦合作用还会诱发新的失稳模态。在电载荷和拉伸载荷作用下, 康铜线易在屈曲时发生断裂。在电载荷和压缩载荷作用下, 康铜线易在屈曲区域的顶部发生折叠, 偶尔还会向聚合物基底内部方向发生屈曲。分析了这些失稳模态的产生机理。

关键词: 屈曲分层; 失稳模态; 电载荷; 机械载荷; 界面韧性

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