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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 phtolihography [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 μm and h_c=6 μm (Fig. 1(b)), respectively. The length of the parallel segments is l_c= 3100 μm. The thickness of the polymer membrane is h_p= 60 μm with the length and width of a_p=7 mm and b_p= 5 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 GPa and v_c=0.33, respectively. For the polymer substrate, the elastic modulus E_p and the Poisson ratio v_p are 3.08 GPa and 0.31 [17], respectively.

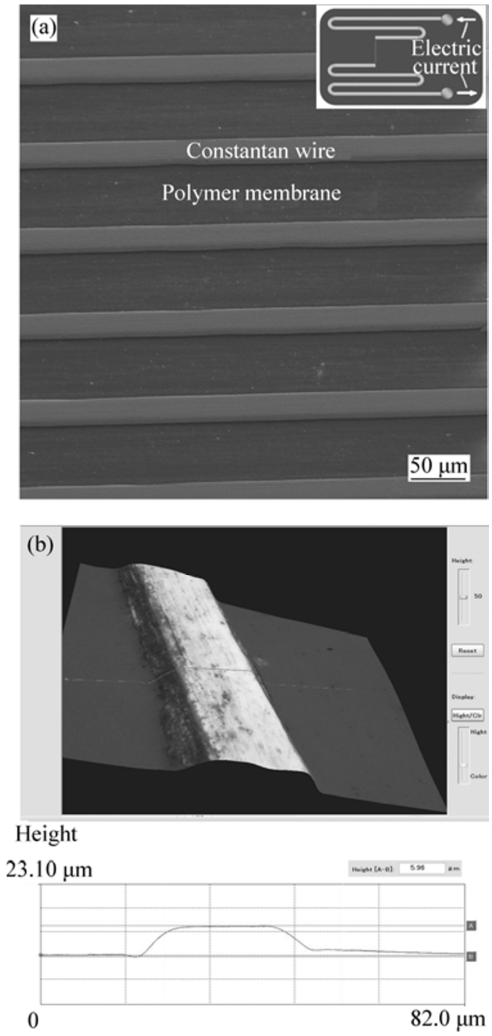

Fig. 1 SEM image of constantan-wire/polymer structure (a), and 3D super-depth digital microscope image for determining height of constantan wire (b)

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

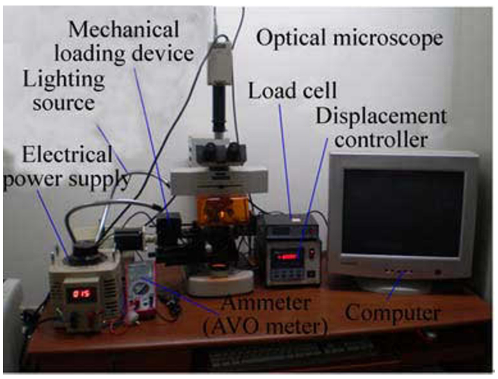

Fig. 2 Experimental setup for combined electrical and mechanical loading, where electrical loading was applied to constantan wire and mechanical loading was imposed on sample supporter