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Mechanism for controlling buckling wrinkles by curved cracks on hard-nano-film/soft-matter-substrate

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ABSTRACT

A study on the surface wrinkling of thin stiff film/soft substrate by patterning the film/substrate with curved cracks is introduced in the present work. From abundant experimental consequences, it is revealed that on the concave side of the curved crack the wrinkling is suppressed, and on the convex side the wrinkling is induced. Based on the fundamental theory of elastic mechanics, the analysis reveals that on the concave side the compressive stress is released and on the convex side the compressive stress is concentrated, and this analysis could offer explanation on the suppression and induction effects of the curvature. Meanwhile, from our carefully designed experiment, we find when the curvature is sufficiently small, curvature of the curves cannot afford to suppress the wrinkling even at the concave side.

1. Introduction

Thin stiff film/soft substrate system is a fundamental format in flexible structures [1,2]. Buckling wrinkle is an important failure mode, which is generally induced by the environmental factors (e.g., the temperature, mechanical force, PH value, electric field) in the thin film/soft substrate system [3]. Such phenomena have been reported extensively in the past decades [4–9].

In recent years, with the development of micro/nano manufacturing technique, the research on the formation of wrinkling draw attention of a number of academic disciplines [10–12]. The phenomena are mainly studied by experiments, and meanwhile the mechanisms are explored by theoretical and simulation analysis [13–17]. For practical application, the wavy configuration of the ferroelectric thin film supported on the soft substrate supports to achieve reversible, linear elastic responses as effective sensors [13]. And the stimulus-induced shape/surface morphology is used to produce complex structures [18]. Besides, the sophisticated fabricating technique of wrinkling can be used to fabricate high frequency optical gratings [19]. On the other hand, the wrinkling can be used to measure the elastic properties of the thin stiff film supported on the soft substrate [20], for which the buckling wavelength needs to be measured accurately.

The preferred properties of the wrinkling are promising in applications for biology engineering, flexible structures and microfluidics, etc. [21–24]. Fabrication of the wrinkling and analysis of the mechanism have been the mostly concerned issues [19,20], among which the controlling of the buckling configuration of the wrinkling has been a hot topic and studied systematically [10,11,22].

As to the controlling of the buckling wrinkles, an equally significant research topic is the buckling distribution [4,5] except the buckling configuration. However, less attention has been focused on this research topic. It is worth to be noted that regulating the occurrence of wrinkles is useful in the micro/nano manufacturing field [25]. In recent experiments we have found that wrinkling of the film on the soft substrate can be regulated (Fig. 1) by patterning the substrate with curved cracks [26]. The influence of the curvature of the crack in the film has been investigated by experiments. In Fig. 1, on the concave side of the curved cracks wrinkles are suppressed, and on the convex side the wrinkles are stimulated. Such phenomena have been called the “shielding effect” and “inductive effect” [26]. The mechanism of such phenomena is to be interpreted in this paper and more experimental observations are provided as proofs. The theoretical analysis will be combined with the experiment to reveal the essence of the shielding effect and inductive effect. The shielding effect may be attributed as the release of compressive stress. Accordingly the inductive effect may be attributed as the concentration of compressive stress. Finally the speculations will be validated by further experimental results.

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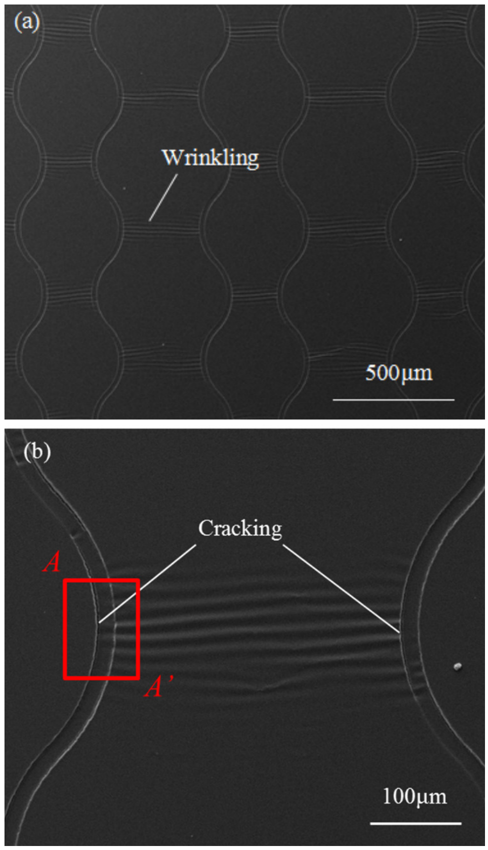

Fig. 1. (a) The curved crack patterns fabricated on the soft substrate and wrinkles regulated by the curved cracks in thin hard film; (b) cracks induced in the thin hard film along the convex side and normal direction of the boundaries of the curved cracks.

2. Idealized experiments and theoretical analysis

2.1. Compressive stress mode in cracked film

A typical case is the aluminum film deposited onto the PDMS (polydimethylsiloxane) substrate by thermal evaporation [26]. During the deposition process, the surface of the substrate is heated. After the process is accomplished, the dropping of temperature will lead to contraction of the substrate, inducing compressive stress in the film. Suppose that a cell element is cut from the film/substrate system (Fig. 2(a)). The stress state in the film of the cell element is shown in Fig. 2(b). When the compressive stress exceeds the critical value [4] σ_c, disordered wrinkles will appear (Fig. 2(c)).

For the case shown in Fig. 1(a) with the curved patterns fabricated onto the PDMS substrate, the film on the substrate is partitioned by the curved cracks (Fig. 1(b)) and the stress state is more complicated. To analyze the stress state around the curved crack, the red frame *A-A'* (Fig. 1(b)) is selected to be analyzed. A schematic of this portion is shown in Fig. 3(a). At the edge of the crack (Fig. 3(b)), the stress component vertical to the crack is released and $\sigma_x = 0$. In the former work by Bowden et al. [4], the stress state near the straight ridge is that $\sigma_y > \sigma_x = 0$. So the wrinkling is induced with the wrinkles ridging vertical to the crack. For straight ridge, the stress distribution has been deduced theoretically and at the two sides of the straight ridge, the stress distribution is consistent. But at the two sides of the curved crack, the stress distribution is obviously different from the experimental result shown in Fig. 1.

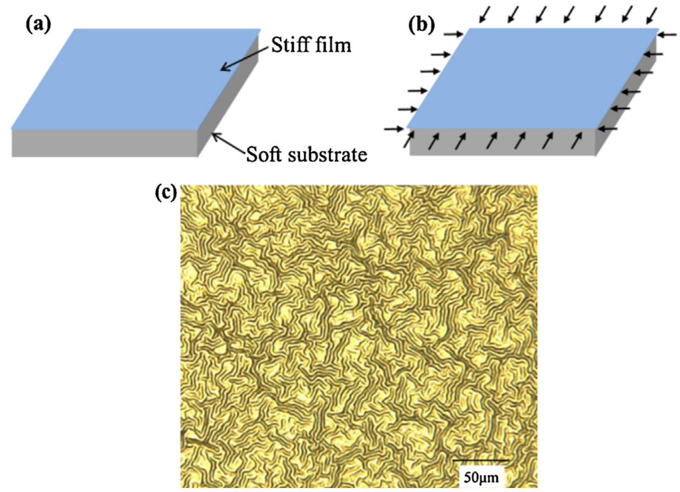

Fig. 2. (a) Schematic diagram of a unit cut from the film/substrate system; (b) the stress state of the unit; (c) the disordered wrinkling formed in the aluminum film/PDMS substrate.

2.2. Theory in elastic mechanics

To analyze the stress distribution around the curved edge, the mechanical model shown in Fig. 4 is applied. In Fig. 4(a), the plate with a notch *bcd* is subject to uniaxial compression. According to the stress boundary condition, the stress component vertical to the edge of the notch is 0 at the edge of the notch. While the other stress component $\sigma > \sigma_0$ due to the stress concentration effect around the notch based on the theory in elasticity.

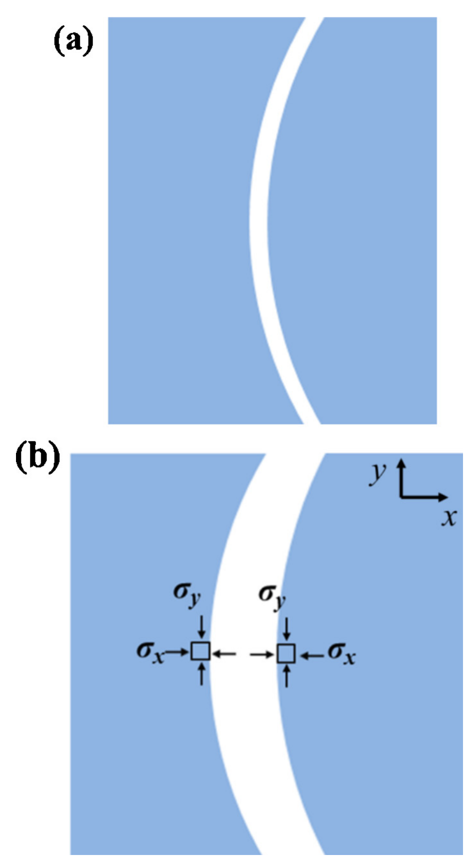

Fig. 3. (a) A schematic diagram of the part cut from the film/substrate system; (b) the stress state of the film at the edge of the crack.