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Effect of lateral dimension on the surface wrinkling of a thin film on compliant substrate induced by differential growth/swelling

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ABSTRACT

Surface wrinkling in thin films on compliant substrates is of considerable interest for applications involving surface patterning, smart adhesion, liquid/cell shaping, particle assembly, design of flexible electronic devices, as well as mechanical characterization of thin film systems. When the in-plane size of the system is infinite, the critical wrinkling strain is known to be governed by the moduli ratio between the film and substrate. Here we show a surprising result that the lateral dimension of the film can play a critical role in the occurrence of surface wrinkling. The basic phenomenon was established through selective UV/Ozone (UVO) exposure of a strain-free PDMS slab via composite copper grids with different meshes, followed by treatment using mixed ethanol/glycerol solvents with different volume fractions of ethanol. To understand the physics behind the experimental observations, finite element (FE) simulations were performed to establish an analytical expression for the distribution of shear tractions at the film–substrate interface. Subsequent theoretical analysis leads to closed-form predictions for the critical growth/swelling strain for the onset of wrinkling. Our analysis reveals that the occurrence of surface wrinkling and post-wrinkling pattern evolution can be controlled by tuning the lateral size of the thin film for a given moduli ratio. These results may find broad applications in preventing surface wrinkling, creating desired surface patterns, evaluating the interfacial shear strength of a film/substrate system and designing flexible electronic devices.

1. Introduction

Differential growth/swelling or thermal expansion in a film/substrate system may cause biaxial in-plane compression of the film and lead to intriguing surface wrinkling patterns. This problem has received considerable attention in recent years

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among physicists, biologists, mathematicians, material scientists and engineers (Bowden et al., 1998; Breid and Crosby, 2009; Audoly and Boudaoud, 2008a, 2008b, 2008c; Cai et al., 2011; Li et al., 2012). The wrinkling patterns can endow the solid with unique physical properties and therefore have wide technical applications, ranging from mechanical characterization of thin films, surface patterning, smart adhesion, tunable hydrophobicity, liquid/cell shaping, particle assembly, optical surfaces, to flexible electronic devices (Stafford et al., 2004; Huang et al., 2007; Vella et al., 2010; Bowden et al., 1998; Chan et al., 2008; Koch et al., 2009; Zang et al., 2013; Genzer and Groenewold, 2006; Li et al., 2012; Fleming et al., 1999; Texeira et al., 2003; Jeong et al., 2014; Harrison et al., 2004; Khang et al., 2006; Choi et al., 2007; Rogers et al., 2010). In addition, the surface wrinkling behavior of a soft material with hard skin can help understand the formation of surface patterns in some biological systems, e.g. the tissue-shaping instabilities occurring in animal epithelia (Li et al., 2011; Ben Amar and Jia, 2013; Shyer et al., 2013) and tissue morphology during brain development (Budday et al., 2014a, 2014b). In most previous studies (Chen and Hutchinson, 2004; Audoly and Boudaoud, 2008a, 2008b, 2008c; Cai et al., 2011; Cao and Hutchinson, 2012; Zhao et al., 2015) attention has been focused on the case where the in-plane sizes of the film and the substrate are much greater than the wrinkling wavelength, in which case the critical condition for the onset of surface wrinkling is mainly dominated by the mechanical parameters, e.g. the moduli ratio between the film and substrate. For an infinite stiff film resting on a compliant substrate, the wrinkling strain could be very small. For instance, for a gold film resting on a crosslinked poly(dimethylsiloxane) (PDMS) substrate subject to thermal load, surface wrinkling may occur even when the compressive strain in the film due to thermal mismatch is smaller than 0.1%, which corresponds to a variation in temperature less than 10 °C when taking the thermal expansion coefficient of gold as $1.42 \times 10^{-5}(1/^{\circ}C)$ and that of the PDMS as $1 \times 10^{-4}(1/^{\circ}C)$. Although the periodic wrinkling patterns have many applications as mentioned above, it should be pointed out that surface wrinkling may lead to delamination of a film from its substrate (Mei et al., 2011) and this sometimes leads to the failure of the structure and should be avoided in many circumstances. Besides, surface wrinkling should be avoided as much as possible during the process of transfer printing involved in the design of flexible electronic devices (Feng et al., 2007; Carlson et al., 2012). To create desired wrinkling patterns or prevent the occurrence of surface wrinkling related performance failure of a structure/system, it is of great importance to understand the critical conditions for the onset of surface wrinkling due to various internal or external stimuli.

Experiments involving selective UV/Ozone (UVO) exposure of a strain-free PDMS slab through composite copper grids with different meshes are carried out, the detailed set-up and observations of which are described in Section 2. The results (Fig. 1) show that for a given moduli ratio in a film/substrate system, the in-plane size of the film has marked effects on the onset and evolution of the wrinkling patterns caused by differential swelling. Breid and Crosby (2009) also observed in their

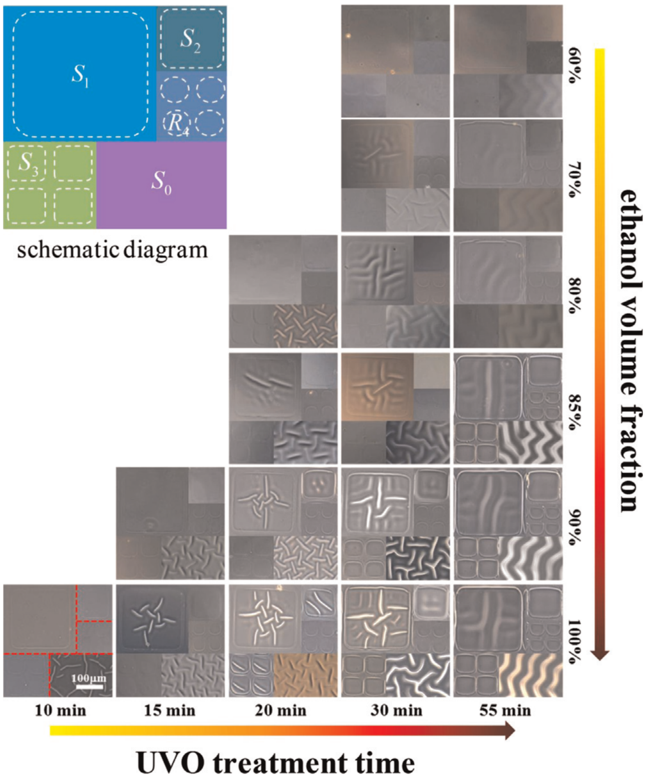

Fig. 1. Optical images of the surface morphological evolution under different conditions of UVO treatment time and volume fraction of ethanol in the ethanol/glycerol mixed solvents. Each image is stitched with five parts as shown by the schematic diagram in the top left corner. The regions S_0, S_1, S_2, S_3 and R_4 represent the blank region, S100, S200, S300 and R400, respectively. The scale bar of 100 μm applies to all images.