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# Rolling wrinkles on elastic substrates

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ABSTRACT

We present and develop a patterning technique that relies on the contact mechanics and geometry of rolling to create mechanically tunable wrinkled surface structures. A plate-to-roll (P2R) geometry was used to laminate a thin film onto a soft substrate. First, a soft substrate is draped around a roller and pressed into contact with a thin film supported on a plate. Once the plate begins to translate, the thin film preferentially laminates onto the soft substrate. During this process the deformation of the soft substrate due to contact load, as well as deformation due to bending around the roller, can induce wrinkling. Importantly, we demonstrate that the amplitude of wrinkles can be controlled by applied contact load and roller curvature. We demonstrate this using a 150nm poly(styrene) thin film supported on a silicon wafer and a 2mm thick poly(dimethyl siloxane) rubber substrate. Wrinkle feature size consists of amplitudes of $0.2 - 4\mu m$ and wavelengths of $15 - 20\mu m$. We develop semi-empirical equations to describe the effect of applied contact load and roller curvature on the wrinkle aspect ratio. To support experimental relationships between contact conditions and strain at the roll/plate interface, finite-element modeling (FEM) of a soft substrate in full-friction rolling contact with a rigid plate is conducted.

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## 1. Introduction

Surface wrinkling is an instability that arises from the in-plane compression of a thin film attached to a soft substrate. There is a plethora of work that has been done to understand and control the morphology of wrinkles [1–5], as well work done to define the limits of the wrinkling instability [6–10]. In addition, there have been numerous proposed applications that utilize surface wrinkling as a patterning technique, including diffraction gratings [1,11,12], optoelectronics [13,14], stretchable electronics [15–20], microlens arrays [21–23], responsive windows [23,24], tunable adhesives [25–29], wetting and antifouling surfaces [30–33,24,34], microfluidics [35–37,23], particle sorting [38,39], cell growth and motility [40–45], and material metrology [46–52]. However, the production of surface wrinkles with controlled order and micron scale dimensions in a scalable manufacturing process is challenging. To address these challenges, we demonstrate a robust method to create surface wrinkles using the contact mechanics of rolling, which could prove quite useful in the development of a roll-to-roll (R2R) surface wrinkling manufacturing process.

Previous studies have utilized a similar rolling technique for transfer printing of fragile devices [53,54], as well as for fabricating wrinkled membranes [55]. However, these studies do not assess the capability to actively control the aspect ratio, the ratio of amplitude to wavelength, of surface wrinkles—a necessity for the realization of the proposed applications that utilize the wrinkling instability [9]. Here, we control both the aspect ratio and periodicity of surface wrinkles by adjusting applied strains through applied normal load and roller radius. A numerical contact mechanics model is developed using materials properties and geometric parameters to confirm results from lab-based experiments.

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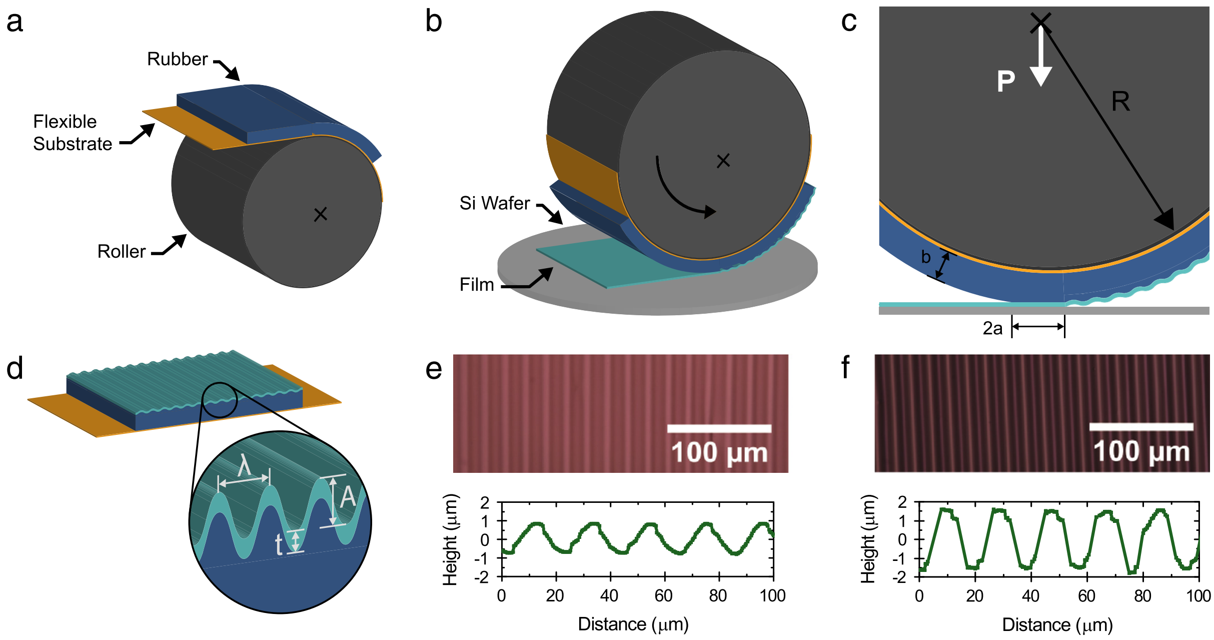


**Fig. 1.** Schematic of the Plate-to-Roll (P2R) Process. (a) A rubber-like layer attached to a flexible substrate, or web, is wrapped around a roller. (b) The roller with the rubber-like layer and web is pressed into contact with a thin, rigid film supported by a silicon (Si) wafer. The thin film is transferred from the Si wafer to the rubber-like layer in this plate-to-roll (P2R) technique. (c) During the film transfer process, several parameters such as contact load per unit width, $P$, roller radius, $R$, rubber-like layer thickness, $b$, and contact width, $2a$, are considered. Once contact is released, the thin film wrinkles. (d) When the final film/rubber/web composite is released from the roller, a wrinkled surface with a larger amplitude emerges. Peak-to-peak distance, wavelength ($\lambda$), peak-to-valley distance, amplitude ($A$), and film thickness ($t$) are highlighted in the expanded schematic of the wrinkled surface. (e) An optical micrograph of a wrinkled surface after rolling, (b)–(c). The plot is a line profile along the scale bar, quantified using optical profilometry. (f) An optical micrograph of a wrinkled surface after (d). The plot is a line profile along the scale bar, quantified using optical profilometry. There is a clear increase in amplitude between the line profiles of (e) and (f).

## 2. Wrinkling background

When a thin film attached to a soft substrate is compressed beyond a critical strain, the thin film will attempt to buckle out of plane. If the adhesion between the thin film and soft substrate is sufficient, the soft substrate must stretch to accommodate the thin film buckling. An energy balance between the thin film buckling and the soft substrate stretching results in a periodic pattern with a minimum wavelength [56].

In the small strain limit, the minimum wavelength, $\lambda$, depends on the plane strain modulus of the film, $\overline{E}_f$, the thickness of the film, $t$, and the plane strain modulus of the soft substrate, $\overline{E}_s$ [57].

$$\lambda = 2\pi t \left( \frac{\overline{E}_f}{3\overline{E}_s} \right)^{1/3}. \tag{1}$$

The critical strain, $\varepsilon_c$, required to wrinkle such a composite depends solely on the materials properties of the film and the substrate, as long as the modulus of the film is much greater than the modulus of the substrate [57,10].

$$\varepsilon_c = \frac{1}{4} \left( \frac{3\overline{E}_s}{\overline{E}_f} \right)^{2/3}. \tag{2}$$

The wrinkle amplitude, $A$, depends on applied strain to the film, $\varepsilon$, as well as critical strain for wrinkling and thin film thickness [57].

$$A = 2t \left( \frac{\varepsilon}{\varepsilon_c} - 1 \right)^{1/2}. \tag{3}$$

Therefore, when a materials system is chosen, active control of wrinkle amplitude will depend only on applied compressive strain to the film. In our process, we control both applied load and roller radius to change the applied compressive strain to the film.

## 3. Wrinkling process

We propose a wrinkling method that utilizes a plate-to-roll (P2R) geometry, consisting of a free-rolling cylinder, a flexible inextensible substrate coated with a rubber-like layer, a translating plate with a releasable thin film, and the actuation of force when the rubber-like coating and plate come into contact (Fig. 1(a)–(c)). In the proposed P2R geometry, the compressive strain on the film can be created from either contact deformation of the rubber-like coating and plate during the rolling process or draping the rubber-like coating around the curved roller surface. Fig. 1 highlights the P2R transfer process. Fig. 1(e) shows evidence of a wrinkled surface while the composite is on the roller, formed due to contact deformation ($\varepsilon_{contact}$). Fig. 1(f) shows an increase in wrinkle amplitude due to the imposition of bending strains ($\varepsilon_{bending}$). By tuning the

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