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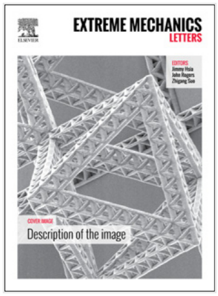

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An algorithmic approach to multi-layer wrinkling

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Abstract

Wrinkling, when a thin stiff film adhered to a compliant substrate deforms sinusoidally out of plane due to compression, is a well understood phenomenon in bi-layer systems. However, when there are more than two layers, the wrinkling behavior of the multi-layer system is, at present, not fully understood. In this paper, we provide an analytical solution for wrinkling in tri-layer systems where the additional layers can contribute to either the film stiffness or substrate stiffness. Then, we provide an algorithmic approach for extending our tri-layer analytical solution to systems with multiple additional layers. Our analytical solution and algorithmic approach are verified numerically using the finite element method. Using our methodology, wrinking can be predicted and controlled in multi-layer systems, with applications ranging from stretchable electronics to biomimetic design. In this paper, we demonstrate that our model can be used to understand wrinkling behavior in epidermal electronics.

Keywords: Wrinkling, Epidermal electronics, Geometric instability

1. Introduction

Though wrinkling in bi-layer systems is a well understood phenomenon [1–7], the study of wrinkling in multi-layer systems is incomplete. Multi-layer systems, as illustrated in Fig. 1, do not necessarily have a single layer clearly defined as the film or a single layer clearly defined as the substrate. Instead, there are multiple layers some of which may contribute to the axial and bending stiffness of the film and some of which may contribute to the stiffness of the substrate [8–10]. Understanding wrinkling in multi-layer systems is important for interpreting the wrinkling behavior of some biological systems, such as the gut [11–13], the skin [14–16], or the lungs [17, 18]. The patterns which emerge from these biological multi-layer systems can inspire engineering design, such as engineering surfaces which utilize wrinkling to access multiple length scales and increase surface area [19–21]. In buckling based metrology, a better understanding of wrinkling in multi-layer films will enhance the study of novel multi-layer systems [22–25]. In addition, in engineering stretchable electronics, a deeper understanding of multi-layer wrinkling can be used to design systems in which wrinkling is used to prevent high levels of strain in stiff or brittle layers [26, 27]. In this paper, we use epidermal electronics [28–32] as an example to motivate the study of multi-layer wrinkling. Epidermal electronics are a strong motivation because, as seen in Fig. 2, they connect to multi-layer wrinkling in two ways. First the electronic devices themselves are often multi-layer systems [28, 33]. Second, the skin is a multi-layer structure thought to have as many as six mechanically distinct layers which influence its wrinkling behavior [34, 35]. We present a multi-layer model suitable for capturing the wrinkling behavior of the skin-device system.

With regard to previous research specific to multi-layer wrinkling [8], we primarily build on four previous works to construct our approach to multi-layer wrinkling. First, Stafford *et al.* [37] proposed a method for combining thin, experimentally observed, surface layers of finite thickness with the film layer by treating the film as a composite beam. Second, Jia *et al.* [9] provided an analytical solution verified by numerical results to account for an intermediate layer that will combine with either the film or the substrate depending on the geometric and material properties of the system. Third, Huang *et al.* [38] demonstrated that after a finite substrate depth is reached, substrate depth no longer influences wrinkling behavior. Finally, in our

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