Grain-Size Growth Model Validated by *In Situ* Measurements of Nucleation and Growth

Using *in situ* heating transmission electron microscopy (TEM) methods, a team of researchers at Yale University has devised a technique to predict the microstructure resulting from crystallization. This ability allows researchers to tailor material properties that are sensitive to microstructure and is important to a broad range of fields that includes materials science, geology, physical chemistry, and biochemistry. There are theoretical models to predict the grain size and also experiments to monitor the growth of individual crystals. However, this research is the first to check the validity of theoretical predictions by comparing them to experimental observations that can separate the effects of nucleation and growth. These methods would enable researchers to predict grain size and the associated material properties that are dependent on microstructure.

In the September 19 issue of *Applied Physics Letters* (#124102; DOI: 10.1063/1.2053348), the Yale team of H.-J. Lee, H. Ni, D.T. Wu, and A.G. Ramirez reported a method of predicting grain size from the direct measurement of nucleation and growth rates. The researchers sputter-deposited amorphous 200-nm-thick equiatomic NiTi films onto silicon nitride TEM membrane samples, annealed them at various temperatures within a 200-kV field-emission TEM microscope, and took images during heating at 2-s intervals.

The researchers were able to monitor the crystallization events in real time. The amorphous NiTi films underwent polymorphic crystallization during annealing and transformation times that increased drastically from a few seconds to over an hour from the highest to the lowest temperatures. The researchers determined the nucleation rate and the growth rate by measuring the number of crystals and their size as a function of time. These results were compared with values derived from the conventional Johnson–Mehl–Avrami–Kolmogorov (JMAK) method of determining the area fraction and were found to be consistent. To verify their approach, the researchers compared the activation energies of nucleation and growth with the overall activation energy determined by the JMAK method and found these values to agree.

In contrast to the JMAK method, the novel contribution of this work is that the nucleation and growth rates are measured separately. This information allowed the researchers to use the mathematics of crystallization in a new way, namely, to deter-

Serpentine-Patterned Compliant Thin Films of Stiff Materials Reduce Strain During Stretching

Flexible electronic devices that can be stretched or bent have significant potential for numerous applications and are a major focus of current research activity. Most electronic materials, such as semiconductors, metals, and dielectrics, however, are stiff, and they fracture at small strains, typically under 1%. A possible way to create flexible electronics is to form thin films of these materials on an elastomeric substrate. However, the strains induced in these thin films would still be too large for various deformation modes, in particular, stretching. T. Li and Z. Suo, both from Harvard University, and S. Lacour and S. Wagner, from Princeton University, have now demonstrated that by patterning the thin film in the form of a serpentine on an elastomeric substrate, a large elongation may induce just a small strain in the film. Under appropriate conditions, the strain can be mitigated by out-of-plane twisting of the serpentine. Using finite element modeling, the researchers have shown that this principle can indeed be used for stretchable electronics.

In their article published in the December 2005 issue of the *Journal of Materials Research* (p. 3274; DOI: 10.1557/JMR.2005.0422), the researchers propose that a thin film of a stiff material can be patterned as a wide serpentine on a flat elastomeric substrate. This could serve as a platform on which electronic circuits can be fabricated using planar microfabrication technology. The finite element code ABAQUS was used to model and analyze the structure. The ratio of the Young's modulus of the substrate, E_{sub}, to that of the film, E_{film}, was assumed to range from 10^{-5} to 10^{-3}. For a relative elongation of 25%, the maximum strain in the film was shown to be <3.5% for a very compliant substrate with $E_{\mathrm{sub}}/E_{\mathrm{film}} = 10^{-5}$. On the other hand, for $E_{\mathrm{sub}}/E_{\mathrm{film}} = 10^{-3}$, the maximum strain was calculated to be 11.6%. Thus, the substrate needs to be sufficiently compliant for a smaller strain in the film. For a very compliant substrate, the maximum strain was also shown to be insensitive to the width and thickness of the serpentine, but was sensitive to the amplitude-to-period ratio. The larger the amplitude-to-period ratio of the serpentine, the smaller the strain levels in the film. In addition, the more compliant the substrate, the smaller were the maximum interfacial stresses.

The study showed that a thin film of a stiff material can be appropriately patterned on a sufficiently compliant substrate. Such a film would elongate by twisting out of plane so that large elongations of the substrate only induce small strains in the film (see Figure 1). The researchers said that such patterned films could serve as platforms on which entire electronic circuits could be fabricated. Such circuits are expected to function without appreciable fatigue, even when the substrate is subjected to repeated deformation. While only uniaxial elongation was considered in the study, the researchers said that the same principle can be extended to biaxial elongation.

Gopal Rao

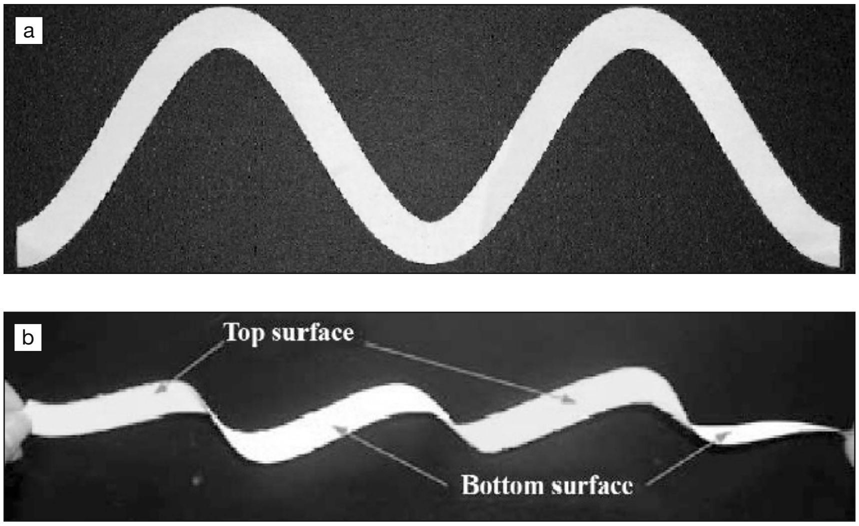

Figure 1. (a) A piece of paper is cut into a serpentine. (b) When pulled, the serpentine elongates by twisting out of plane.