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The effect of dislocations on crack propagation in wrinkled gold film deposited on polydimethylsiloxane

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Crack propagation in a wrinkled thin film of gold deposited on polydimethylsiloxane (PDMS) was affected by the presence of folding defects—the ripple dislocations. The ripple pattern, ripple dislocations, and the crack were simultaneously formed after the tensile load applied on the PDMS substrate was removed. The crack, however, was unstable and propagated forward. The propagation rate increased when the crack passed by the ripple dislocations, but less significantly when it advanced near a ripple dislocation dipole. Such crack dislocation interaction implies that the ripple dislocation has an internal stress field. The measured data of the rate process were analyzed based on the theory of fracture mechanics, and an empirical relationship between the crack velocity and the crack extension force was presented. © *2008 American Institute of Physics*.
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Wrinkled thin films on soft substrates are used as stretched interconnects for flexible electronics and in biological assays.[1–3] Studies on their formation and properties have been extensive in recent years.[4–11] In the wrinkled films, there is a micron defect besides the crack and lattice dislocation. This defect is formed when a wave crest is terminated along an interior line inside the wave pattern. Because of its similarity to the shape of an edge lattice dislocation (see Fig. 3 of Ref. 8), we shall term it as "ripple dislocation." Recently, Efimenko *et al.*[12] showed that when the uniaxially stretching polydimethylsiloxane (PDMS) was exposed to ultraviolet/ozone radiation, the ripple dislocations, cracks, and skin wrinkles were simultaneously formed. Ohzono and Shimomura[13] reported the observation on the motion of ripple dislocation due to the directional change of the applied stress. However, the elastic properties of ripple dislocation are not yet well known. In the present work, we intend to explore more information about ripple dislocations and, in particular, on their interaction with other defects. Our results show that the ripple dislocation, similar to the lattice dislocation, has an internal stress field; it interacts with the neighboring crack. It is also demonstrated that the crack velocity is related to the dislocation-generated crack extension force by a power law.

PDMS gels were obtained from Sil-More Industrial Ltd., Sanchung, Taiwan. A mixture of PDMS gels and curing agents with a wt % ratio of 15:1 was placed in a vacuum chamber for 30 min to eliminate the bubbles. A silicon wafer with a diameter of 4 in. was subsequently cleaned in acetone, isopropyl alcohol, and de-ionized water using an ultrasonic cleaner and then blown to dry in nitrogen gas. The mixture of PDMS gels and curing agents was coated on the wafer using a spin coater with two stages. The spinning speeds of the first and second stages are 100 and 300 rpm, respectively. Each stage was maintained for 30 s. The silicon wafer coated with PDMS sol-gel was placed in a vacuum chamber to cure for two days. Then the PDMS plate with a thickness of 0.2 mm was detached from the silicon wafer.

The PDMS plate was cut into dog-bone-shaped samples with gauge length of 8 mm and width of 2 mm. Each sample was subjected to a tensile load of 78.4 MPa and elongated to 110% (or strain $\varepsilon=0.1$). A thin film of gold with a thickness of 34 ± 5 Å was deposited at room temperature on the elongated PDMS sample using a Hitachi E-1010 sputter under a pressure less than 10 Pa and electric current of 10–20 mA. After the load was completely removed, the thin layer became rippled by contraction. A crack of depth 360 ± 40 nm propagating normal to the ripple crests in the neighborhood of the ripple dislocations was observed. The rate of the crack propagation was recorded in a sequence of micrographs using an Olympus optical microscope with a charge coupled device camera. The crack tip positions were measured as a function of propagation time t.

Figure 1 shows a micrograph of the rippled surface of

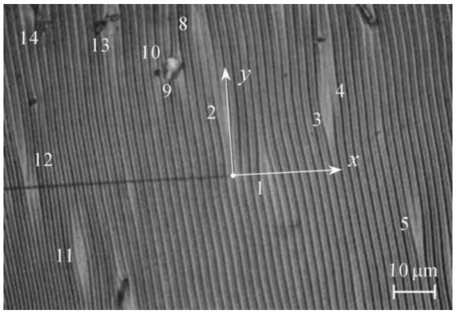

FIG. 1. Light microscopy image taken at the time $t=0$ showing a running crack in the neighborhood of 14 ripple dislocations in the Au/PDMS sample (dislocations 6 and 7 are not seen in this frame). The origin of the coordinate system $0xy$ is set at the crack tip.

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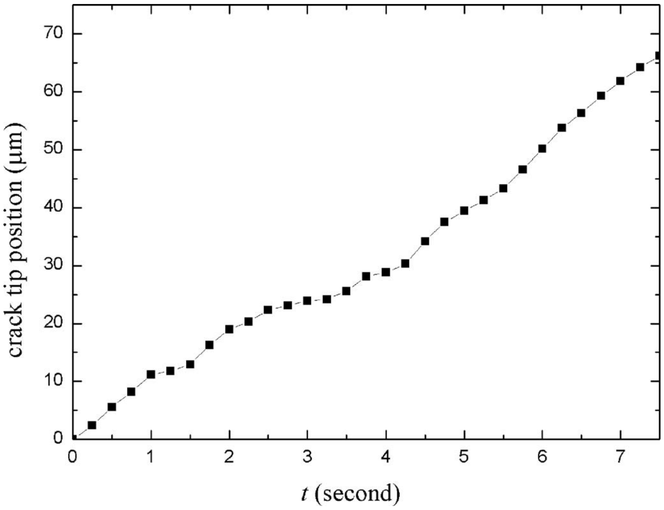

FIG. 2. The crack tip position *x* as a function of time *t*.

the Au/PDMS sample taken at $t=0$. The crack is propagating along the positive *x* axis in the neighborhood of 14 ripple dislocations (dislocations 6 and 7 are located below dislocation 5, but not seen in this frame). From the recorded micrographs, the position of the crack tip *x* was determined as a function of time *t* and the results are shown in Fig. 2. Using the obtained data and the method of central difference of distances, the crack speed v at a given time was computed and is represented by the solid square on the top curve in Fig. 3. The computation errors are contained in the error bar. As seen in Fig. 3, the local maximum speed was found at $t=0.5$ s when the crack approached ripple dislocation 1 and at $t=5.75$ s when it passed by ripple dislocation 5. A local minimum speed was observed at time $t=2.75$ s. This happened when the crack advanced near the ripple dislocation dipole (ripple dislocations 3 and 4). Obviously, these variations in crack propagation are the result of the interaction of ripple dislocations with the running crack.

It is understood that upon unloading, the elastic strains were totally relaxed, while the plastic strains were retained in lattice dislocations. When a large number (perhaps thousands or more) of lattice dislocations of the edge type are grouped in a close neighborhood, they may form a ripple dislocation. At present, the elastic properties of the ripple dislocation, especially its internal stress field, have not been fully explored. In an attempt to provide a quantitative illustration of its interaction with the crack, we assume that the ripple dislocation has an internal stress field of the same characteristics as an edge lattice dislocation. Further, the ripple dislocation, as well as the accompanying lattice dislocations, may be considered as an entity or a superdislocation even though it may not be as mobile as a lattice dislocation. The Burgers vectors of the super dislocations may vary slightly and may be as large as the wavelength of the crests.

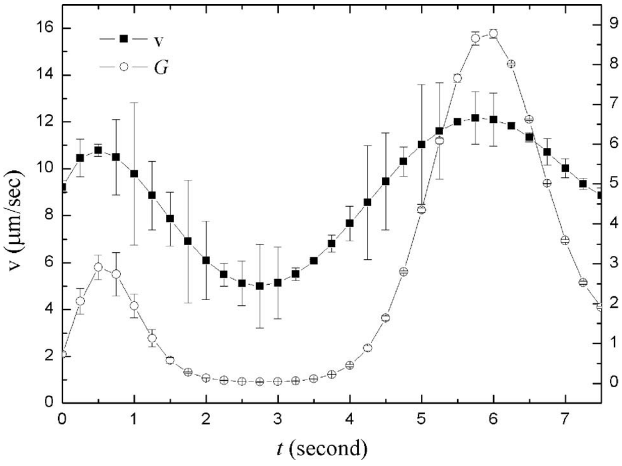

FIG. 3. The crack velocity v and the crack extension force *G* as a function of time *t*. The low values of v and *G* in the time period of 2–4 s result from the weak interaction between the crack and the ripple dislocation dipole.

With the above considerations we proceed to provide a quantitative basis for the ripple dislocation–crack interaction in the Au/PDMS system. From the extensive study of lattice dislocation–crack interaction,[14,15] the mode *I* stress intensity factor K_I at the crack tip arising from the uniformly applied stress and the internal stresses of the nearby edge dislocations can be determined by the equation

$$K_I = K_{IA} + K_{ID}, \tag{1}$$

where K_{IA} is the stress intensity factor due to the applied stress σ, given by

$$K_{IA} = \sigma\sqrt{\pi a}, \tag{2}$$

and a is the dimension of the crack. K_{ID} is the stress intensity factor due to the ripple dislocations for the plane stress condition[14,16] and is given by

$$K_{ID} = -\frac{E}{2(2\pi)^{1/2}}\sum_{i=1}^{14}\frac{b_i}{r_i^{1/2}}\left\{\frac{1}{2}\sin\left(\phi_i+\frac{\theta_i}{2}\right) - \frac{3}{4}\sin\left(\frac{\theta_i}{2}-\phi_i\right)+\frac{1}{4}\sin\left(\frac{5\theta_i}{2}-\phi_i\right)\right\}, \tag{3}$$

where r_i is the radial distance from the crack tip to the *i*th dislocation with Burgers vector b_i . In reference to the Cartesian coordinate frame 0*xy*, the crack is lying on the *x* axis with its tip sitting at the origin. θ_i and ϕ_i are respectively the angles between r_i and the positive *x* axis and between b_i and *x*. **E** is Young's modulus of the medium (for gold $E=82$ GPa). Furthermore, from Eq. (1) we have the crack extension force[17]

$$G = K_I^2/E. \tag{4}$$

In the present case, the interaction of the dislocations with the crack takes place after the load is released. Thus $K_{IA}=0$. Also, as the crack advances with time, the relative distribution of the ripple dislocations is changed accordingly. Using Eqs. (3) and (4) and the data of r_i, θ_i, and ϕ_i (a total of 30 sets in the time range), the crack extension force as a function of time was computed and is also shown in Fig. 3. There are two peaks found from the computation: one is located at $t=0.5$ s and the other is at $t=5.75$ s. As shown in Fig. 3, the two pairs of peaks on the *G* and v curves coincide on the same time frame. In the computation of *G*, the Burgers vectors were assumed to be 2 μm, the average wavelength of the ripple crests.

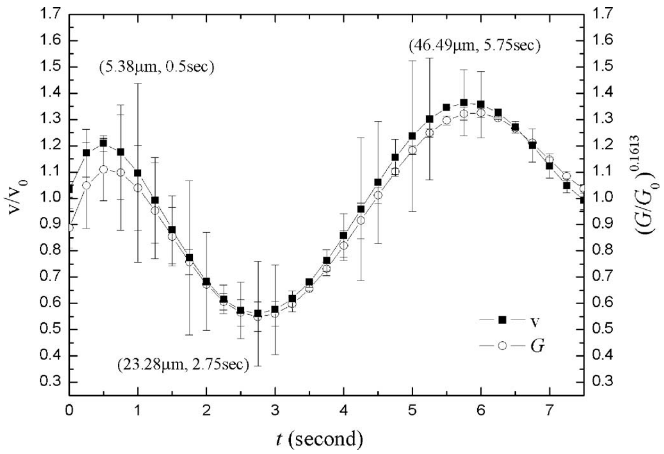

FIG. 4. Comparison of the crack velocity v and the crack extension force G. The crack tip position and propagation time at maximum (or minimum) v and G are given in parentheses.

To establish a functional relationship between the crack extension force G and crack velocity v, we propose, in analogy to dislocation dynamics,[18] a power law given by

$$v/v_0 = (G/G_0)^n, \tag{5}$$

where G_0, v_0, and n are constants. A best fit of the two sets of data, v vs t and G vs t, gives $n=0.1613$, $v_0=8.9$ μm/s, and $G_0=1.535\times10^{-2}E/8\pi$, with units of G_0 and E being MPa μm and MPa, respectively (see Fig. 4). The same n value was also obtained from the plot of log v vs log G.

In summary, the crack propagation in a wrinkled gold film deposited on PDMS was affected by the presence of ripple dislocations after unloading. The propagation rate was faster when the crack was near a ripple dislocation. The effect was much less significant when the crack was passing by a ripple dislocation dipole. Such crack-dislocation interaction would imply that the ripple dislocation has an internal stress field.

The experimental data of crack propagation were analyzed based on the theory of fracture mechanics. It was demonstrated that the crack velocity is related to the dislocation-generated crack extension force by a power law.

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