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ANALYSIS OF STABILITY OF STRAIGHT SIDE BUCKLES ON ELASTIC SUBSTRATES

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ABSTRACT

We deposited 150nm thick aluminum films on organic glass (PMMA) substrates by using the magnetron sputtering process. The parallel straight side buckles are produced by an axial compressive load of the film/substrate set. The buckle’s pattern is recorded using an optical microscope (2000X). The transformation from straight side buckles to telephone cord buckles is investigated and simulated. A finite element model for quasi–static buckling is introduced to analyse the instability of straight side buckles. It is found that the secondary buckling (bifurcation) of straight side buckles is influenced by the residual stress in the longitudinal direction.

Keywords: thin film, buckling, finite element method

INTRODUCTION

Thin film materials are widely used in many fields, such as, micro-electro-mechanical systems, thermal barrier coatings, magnetic recording media etc. However, delamination and buckles at the interface of the thin film and the substrate are observed because of the compressive residual stresses which are generally introduced in the thin film during manufacturing processes. As a result, some patterns of buckles, such as the circular buckles (Moon, 2002; Wang, 2010), straight-sided buckles (Coupeau, 2008) and telephone cord buckles (He, 2011), are formed. In most experiments related to delamination, the telephone cord buckles are frequently observed.

A mechanism of instability causing undulations of the straight side buckle is pointed out, which can be the basic phenomenon explaining the telephone cord pattern. A transition to a varicose pattern, which is unobserved until now, is also predicted when the film has a weak Poisson ratio (Audoly, 1999).

In comparison with the adhesion state, all the stress components of the telephone cord buckle are decreased in magnitude. It is known that the straight side buckle, also known as Euler buckling, only releases the initial biaxial compressive stress in the...
transversal direction. However, typical initial strains in the film can be as high as a few percent, so that compression in the film may be far beyond the buckling threshold. As a result, this residual stress can induce a secondary bifurcation of the Euler column (Audoly, 1999).

Using a scanning x-ray micro diffraction technique developed at a third generation x-ray synchrotron source, the thin film internal stress maps are obtained for circular blisters and telephone chord buckling with micrometric spatial resolution. It is evidenced that residual stress relaxation is associated with the film buckling (Goudeau, 2003).

In the present paper, we produced straight side wrinkles by applying axial compression to Ti/PMMA samples and then investigated the buckling propagation under cyclic load and static compression (Wang, 2010; Wang, 2011). Al films with 150nm thick have been deposited on PMMA substrates by magnetron sputtering process. The parallel straight side buckles are obtained by axial compressive load. After axial compression release (unloading), the transformation from straight side buckles to telephone cord buckles, which is caused by the residual stress in the longitudinal direction, is investigated using an optical microscope (see figure 1). In order to explain this phenomenon, secondary buckling and post-buckling calculations have been carried out by the finite element method.

![Fig.1 Optical images of the transformation from straight side buckles to telephone cord buckles during the unloading process](image)

**MODELING OF THIN FILM BUCKLES**

Quadratic thin shell elements with 5 degrees of freedom at each node and with reduced integration are used. All inelastic effects are not taken into account in a linear eigenvalue buckling analysis and the contact conditions at the straight side of buckling are fixed in the base state. We have used imperfections based on the random combination of buckling eigenmodes for the analysis of thin film buckles, and found the final results (wavelength and amplitude) to be independent of the perturbations with only with some differences at the bifurcation point. The imperfections are always small enough to ensure that the solution is accurate. Once a mode has formed, its shape is virtually independent of details of imperfection since the imperfection amplitude is very small. In that way, the nonlinear effects of large deformation analysis can be used to perform the buckling analyses of structures that show linear behavior prior to (bifurcation) buckling.
To simulate the release of stress in post buckling, we used the boundary displacements for loads, which are the in-plane deformations caused by the biaxial residual stress on the thin film, instead of the residual stresses. Considering a well bonded strip having a residual compression in the equi-biaxial state with the size, $L \times 2b$, that is also the size of the buckling area. We discretize an original rectangular domain with edges $(L + \Delta Y) \times (2b + \Delta X)$, where $\Delta Y$ and $\Delta X$ are the in-plane deformations of the strip obtained by removing the biaxial residual stress in the area $L \times 2b$. The thickness of the film is $h = 150nm$. The buckling width $2b$ is a given data, resulting from the delamination of the film, and which is supposed to remain constant during the secondary buckling of the wrinkle. In order to make sure that any buckling of the film with penetration inside the substrate is impossible, the substrate is assumed to be rigid and plane. The two boundaries of the straight-sided wrinkle are thus clamped at $x = 0$ and $x = 2b + \Delta X$. The grid in Fig. 3 is attached to rigid substrate outside the strip. Symmetry boundary conditions are applied at $y = 0$ and $y = L + \Delta Y$. The entire calculation process is divided into two steps (see figure 2). In step 1, the displacement $\Delta X$ is applied at $x = 2b + \Delta X$ to produce straight side buckles; In step 2, the displacements $\Delta Y$ are applied at $y = Y + \Delta Y$ to produce the secondary bifurcation.

After secondary bifurcation, the wrinkle is transformed into a distribution of telephone cord buckles supposed to follow a periodic repartition. The purpose is to evaluate the stress distribution in telephone cord bucking and to discuss when the Euler mode is stable under an equi-biaxial residual stresses.

**RESULTS AND DISCUSSIONS**

The investigations show that the Al films contain large compressive stresses which results in formation of several telephone cord buckles in this film system. The secondary buckle (bifurcation) is caused by the residual stress in the longitudinal direction.
Fig. 3 (a) The buckling evolution from straight side wrinkle to telephone cord buckling as the stress $\sigma_{yy}$ increases; (b) the stress map after residual stresses release.

Fig. 3 (a) illustrates the progression under increasing film stress from Euler mode to undulating mode with young’s modulus $E_f = 75.0\,\text{GPa}$, Poisson’s ratio $\nu_f = 0.25$ and film thickness $h_f = 150\,\text{nm}$. In this example, the initial imperfection is random that includes both symmetric and anti-symmetric components such that both undulating mode can be triggered. The imperfections can also been seen thought the roughness and flatness of the sample surface that depend on the preparation technology. For the imperfections (about 0.1% of the plate thickness), the Euler mode gives way directly to the telephone-cord mode as $\sigma_{yy}$ increases at the bifurcation point; finally change into the telephone-cord buckle is observed. In experiments, no film is absolutely flat and perfectly smooth. It is consistent with the fact that Euler modes are hardly observed experimentally under equi-biaxial film stress states. Fig. 3(b) illustrates the membrane stress of the telephone cord buckling. In this simulation, when a film is well bonded, the initial residual stress is equi-biaxial, that is chosen as $\sigma_{xx} = \sigma_{yy} = 1.5\,\text{GPa}$. Fig.3 (b) shows the contour plots of the released membrane stress of the nonlinear stability analysis, taking into account this compression. The
stresses illustrated in Fig.3 and Fig. 4, \( \sigma_{xx} \) and \( \sigma_{yy} \), are the equivalent stresses related to the in-plane deformation occurred in the thin film.

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\begin{align*}
\sigma_{xx} &= 1.5 \text{ GPa} \\
\sigma_{yy} &= 0.0 \text{ GPa}
\end{align*}
\]

In all the cases considered in this paper, the unbuckled plate is subject to boundary deformation calculated from the equi-biaxial compressive stresses. The finite element program has been applied to analyze a tapered film clamped along the edges. In this way, it can be determined that the critical width of Euler mode which can keep the straight side wrinkles stable under the initial residual stress 1.5 GPa. The transition from telephone cord mode to the Euler mode is illustrated in Fig. 4. It is evident that in this calculation, the stable width of straight side wrinkle is about no more than 4.949 \( \mu \text{m} \).

CONCLUSION

In this paper, we studied the instability of straight side buckling. The evolution from Euler mode to telephone cord buckling is calculated by FEM. When the Euler column is formed, the buckling of the film mostly releases the transversal stress. Prior to delamination, the initial compression of the film was biaxial; the longitudinal compression therefore remains presently in the Euler column. It is found that, for relatively small values of the compression, the column becomes unstable, as it undergoes a secondary buckling in the longitudinal direction at which the residual stress releases. The critical width of straight side wrinkles is also determined by calculating a tapered film clamped along the edges.

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REFERENCES


