Behavior of interface crack in layered structure under actions of both stress wave and residual stress

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Abstract The propagation characteristic of stress wave impinging at the interface between initially stressed film and substrate is analyzed to reveal the effect of residual stress on the fracture behavior of such layered structure. In particular, the response of the layered structure to both stress wave and residual stress is investigated based on an axis-symmetric model including a centric coin-shape interface crack. The dispersion of the stress wave and the dynamic stress concentration around the interface crack tip are discussed with the crack surface contacting behavior being involved in the model. It is revealed that the strain energy release rate at the crack tip would be dependent on the interface crack length. The results also indicate that the residual stress would influence greatly the in-plane stress of the film and therefore determine the fracture pattern of the film.

Keywords Layered structure, Residual stress, Stress wave, Interface crack

1. Introduction

The impact method with coated bullet was developed by Wu et al [1] to evaluate the interface adhesion of film to substrate. In such measurement, an initial compressive stress pulse is produced by impacting the substrate of the specimen under test with the coated front end, of which the reflection would induce tensile stress around the tested interface. Theoretically, the initial compressive pulse can be calculated as

$$p_0 = -v_0(\rho c)_1(\rho c)_2 / ((\rho c)_1 + (\rho c)_2)\,. \tag{1}$$

Where v_0 is the relative impinging velocity of the bullet to the specimen, $(\rho c)_1$ represents the acoustic impedance of the bullet coat and $(\rho c)_2$ the acoustic impedance of the specimen substrate [2]. The experimental results have revealed that the reflection of the input compressive pulse could separate the film off the substrate clearly [2]. Moreover, it is also indicated that the initial stress state of the specimen may influence the fracture behavior of the film and the interface. Generally speaking, the initial stress, also known as residual stress, varies according to the material treatment processes. Actually, the previous research verified that the film stress and the interface stress around the impact region edge will be greatly changed by the initial stress state in the specimen subjected to coated bullet impact [3].

The fracture may arise first within the film or at the interface depending on the comparison of the stress level to the toughness of the film or the interface. Once the interface crack exists before the specimen is impacted, the interface crack may influence the propagation and evolution of the impinged stress pulse. Therefore, this present work focus on the behavior of the interface crack between the film and substrate under impact test. First, the axis-symmetry cracked model was set up to investigate the impact responses of the structure with treating the initial impact as an input compressive stress pulse as shown in Fig. 1. Then, the propagation and evolution of the stress pulse and thereafter the deformation, stress and strain energy of the specimen are calculated for the cases of different crack length. Finally, the influence of the residual stress on the impact response of the cracked specimen is investigated for the three cases of initially stress free, initially compressed and initially tensioned film.

2. Theoretical formula and modeling

The axis-symmetry model sketch is shown in Fig. 1, in which the symbol *t_s=5mm* and *t_f* =0.25mm represents the thickness of the substrate and film, respectively; *r_s=50mm* is the radius of the specimen, *r_b=7.5mm* indicates the coverage radius of the impact region. And *l_c* represents the interface crack length and will be set as 10~100 percent of the magnitude of *r_b*. Moreover, the two parameters defining the compressive pulse are $\Delta\tau$ =0.05μs and p_0 =800MPa. The symmetry constraints are applied at the symmetry axis and the displacement at the boundary of the circular specimen are restricted as shown in Fig. 1.

The densities of the substrate and film are 7850kg/m^3 and 8800kg/m^3, respectively. The ideal elasticity is assumed for the specimen and the elastic modulus of the substrate and film are 200e9 Pa and 210e9 Pa, respectively. The Poisson's ratio of the substrate and film are 0.29 and 0.31 respectively.

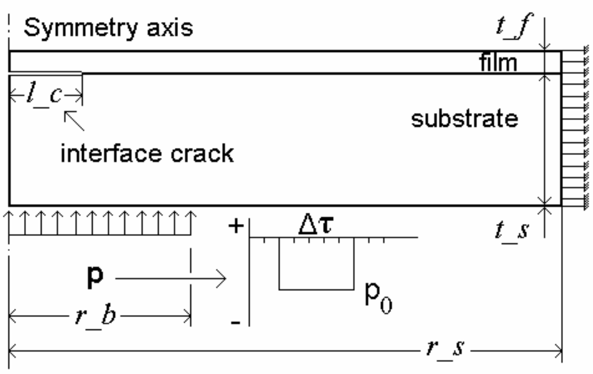

Fig. 1 Model sketch of the system of film and substrate with interface crack

The discretized model is shown in Fig. 2. In detail, the film is divided as five segments through its thickness. Thus, the linear element size is nearly one fifth of the film thickness. The contact elements are adopted at the crack surface for both the film and substrate, for which the coulomb friction law is used to simulate the probable surface friction induced shearing between the crack surfaces.

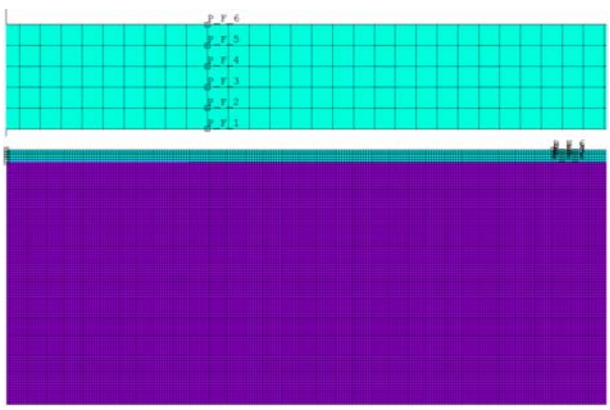
Fig. 2 Discretized model of the film and substrate

As far as the initial stress state is considered, three cases are analyzed. That is, the results denoted by NRS represents the case of the initially stress free film; TRS represents the case of that the film being initially biaxial tensioned to 300MPa; CRS corresponds to the case that the film being initially biaxial compressed to -300MPa.

3. Results and discussion

The interface normal stress acting at the center point of the impacted region is shown in Fig. 3, which is named as SY_I and the symbol '+' and '-' represent the film side of the interface crack surface and the substrate side, respectively. It is indicated that the interface crack would permit the transmission of compressive stress pulse while deny the transmission of tensile stress. It is also shown that the normal stress is almost continuous across the interface, as one can see that the two curves corresponding to the results of the two nodes across the interface almost identical.

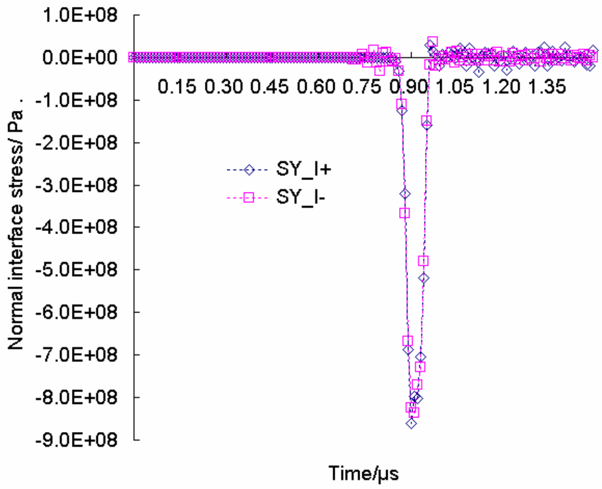

Fig. 3 Normal stress acting at the interface center point

The interface normal stress acting at the third interface node numbered from the interface crack tip is shown in Fig. 4, which is denoted by SY_INTE2 with the symbols '+' and '-' of the same meaning as aforementioned. Great tensile stress pulse appears after the reflection of the transmitted part of the input stress pulse at the free surface of the film. This is thought to be the principle driving force for the interface crack extension.

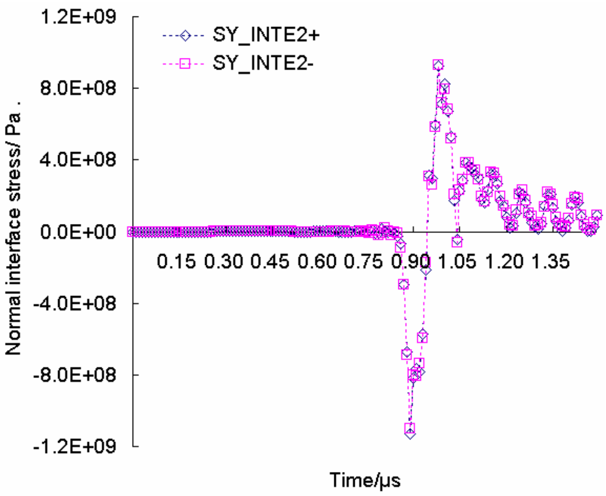

Fig. 4 Normal stress acting at the outer node close to the interface crack tip

The normal stress and shear stress contours for the time point t=1.03μs are shown in Figs.5 and 6, respectively. It is to be noted that the deformation is magnified by 100 times to reveal the details of the interface crack. Obvious crack open displacement and stress concentration can be found around the crack tip. Moreover, the difference in the normal stress acting where before and after the crack tip the obstructing effects of the interface crack on the propagation of the tensile stress pulse.

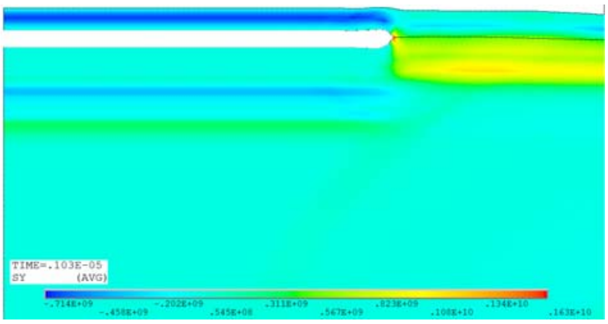

Fig. 5 Magnified contour of stress component SY at the time point t=1.03μs

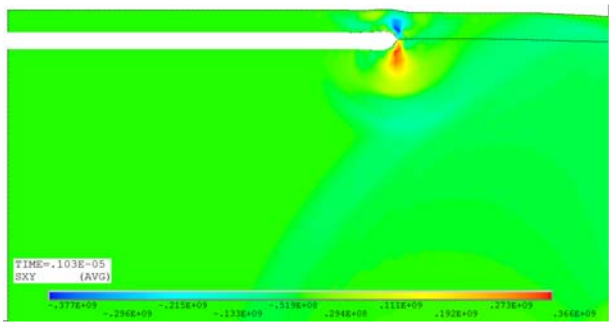

Fig. 6 Magnified contour of stress component SXY at the time point t=1.03μs

The crack open displacement at the node 5μm away from the crack tip is further shown in Fig. 7. It is verified again that the crack is always open after the compressive pulse transmits across the interface crack, although some slight fluctuation arises due to the quick reciprocating of the film under impacting.

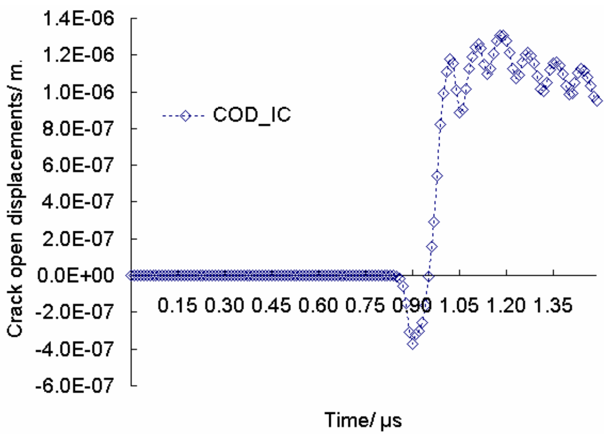

Fig. 7 Crack open displacement at the inner node 5μm away from the crack tip

The peak values of normalized dynamic strain energy release rate [4] (DSERR) versus crack length are shown in Fig. 8 for the model under the three initial stress states, in which the time value in bracket denote the time point when the peak value arises. One can see that the maximum DSERR appears when the crack length if about 65 percent of the impact region radius. One can also see that the peak value of DSERR almost all appears around the time point t=1μs if the crack length is less than 75 percent of the impact region radius, while the time when peak value arises will be postponed obviously with the increasing of crack length. This may partly due to the dispersion of the stress wave around the impact region edge.

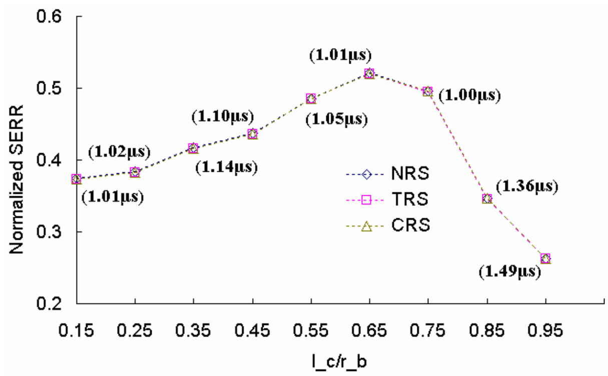

Fig. 8 Peak values of normalized strain energy release rate versus crack length

Anyway, these results in Fig. 8 indicated that the strain release rate is not altered by the in-plane residual stress in the film. Moreover, the interface stresses are neither influenced by the residual stress, as shown in Figs.9 and 10. However, the film stress will be greatly dependent on the residual stress states, which can be found in Fig. 11. A high degree of similarity of the three curves corresponding to the three initial stress states is also in the nature of things considering the ideal elasticity consumption adopted in this model.

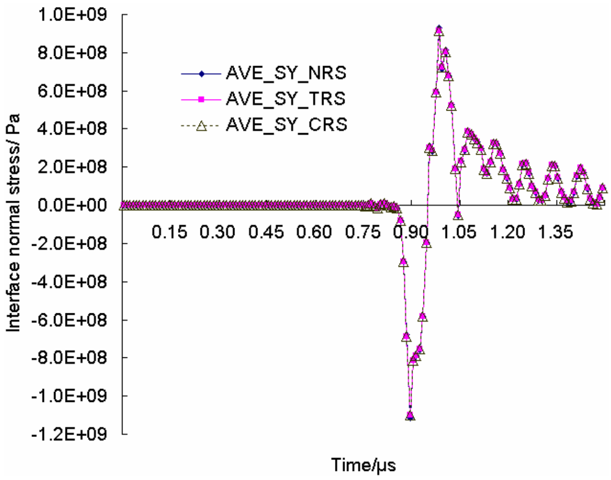

Fig. 9 Normal stress acting at the outer node close to the interface crack tip for the three initial states

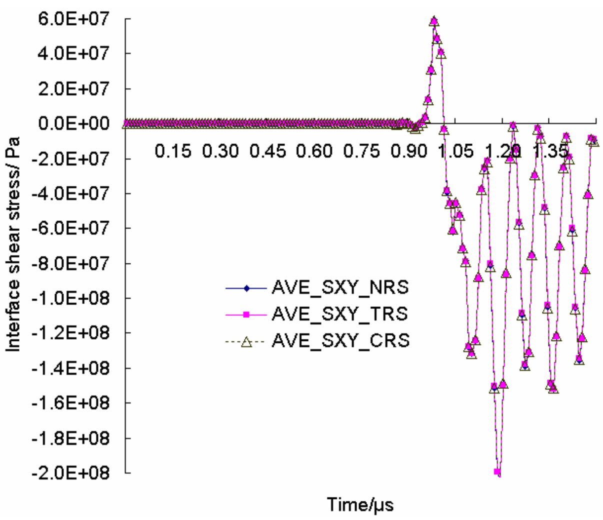

Fig. 10 Shear stress acting at the outer node close to the interface crack tip for the three initial states

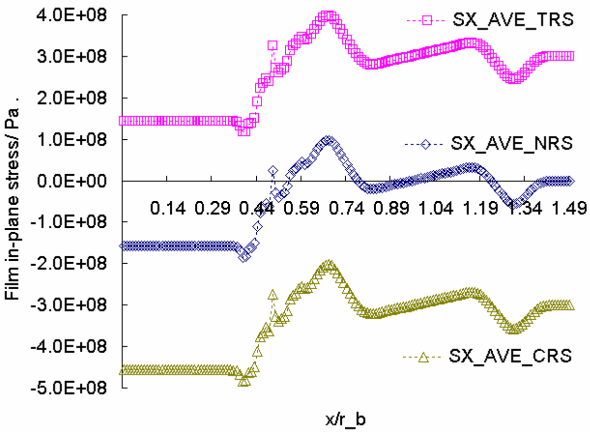

Fig. 11 Film stress at the instant t=1.03μs for the three initial states

For the moment, these results may be theoretically explained by the fact that the action direction of the residual stress is parallel to the interface. Therefore, the load component contributing to the interface separation developed by the in-plane residual stress would be slight when the deflection of the coating is small as considered in the present article. Even so, we hope more physical experimental outcome can be obtained to further support the present cognizance. Actually, a group of relevant tests are undertaken though much difficulty arises in the many sides of it, especially at the quantitative definition of the residual stress and the observation of the interface crack state.

It is also worthwhile to note that these theoretical results are basically drawn from linear dynamic analysis. Such linear modeling could not include the large deformation of the coating, which may lead to more obvious effect of the in-plane residual stress on the interface stress and therefore the interface crack behavior. Moreover, as reveled by Wu [3], the residual stress would influence greatly the total in-plane stress in the coating, which will affect the cracking of the coating under impact. Once the coating fractures around the impact region edge, the interface crack would be arrested around the edge. In comparison, if the coating can endure the impact and maintain intact, the partially released residual stress would affect greatly the interface crack behavior.

4. Conclusions

The model was set up to investigate the behavior of interface crack between the film and substrate subjected to stress wave, in which the crack surface contacting was considered. The dynamic deformation, stress and strain energy versus different crack lengths are calculated for the cases of three initial stress states, that is, initially stress free film, initially compressed film and initially tensioned film.

The history of the normal stress acting at the interface center node indicate that the interface crack permits the transmission of compressive stress while denies the transmission of tensile stress. The dynamic open displacement at the inner node 5μm away from the crack tip further reveals that the crack surfaces seldom contact after separating by the first compressive pulse.

The initial stress state would almost not influence the strain energy release rate of the interface crack or the interface stress around the crack tip if only small strain is taken into account in the modeling. Anyway, the film stress will be greatly changed by the residual stress, which will ultimately determine the fracture of the film.

Acknowledgements

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