Journal of the Mechanics and Physics of Solids 66 (2014) 117–132

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

Multi-scale modeling of delamination through fibrillation

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ARTICLE INFO

Article history:
Received 26 June 2013
Received in revised form
5 November 2013
Accepted 31 January 2014
Available online 14 February 2014

Keywords:
Multi-scale
Fibrillation
Stretchable electronics
Delamination
Cohesive zone

ABSTRACT

Copper–rubber interfaces show extensive rubber fibrillation at the micro-scale during delamination. This constitutes a major problem for identifying unambiguous interface properties, as the micromechanics of rubber fibrillation is not taken into account in conventional (macroscopic) interface characterization methods. As a result, a significant mismatch exists between micromechanical experimental observations, such as fibril length, and the obtained macroscopic cohesive zone parameters.

In this paper, the fibrillation micromechanics is explicitly taken into account in the macroscopic interface description through the use of a multi-scale interface model by means of computational homogenization. In the micro-model physical small scale phenomena such as fibril deformation and debonding are taken into account. The resulting macroscopic cohesive zone parameters are quantitatively coupled to the micromechanical quantities.

The micro-model results show the growth of a fibril, including the drawing of material from the bulk into the fibril, which is accompanied by large strains that are well beyond typical bulk strain values. The micromechanical contributions to the macroscopic work-of-separation are identified. It is concluded that the intrinsic adhesion energy only constitutes a small amount of the total dissipated energy. The main fraction of the work-of-separation consists of elastically stored energy in the fibril, that is dissipated through dynamical release upon instantaneous fibril debonding. Up to the moment of debonding, the fibril micromechanics are virtually unaffected by the intrinsic adhesion properties. The influence of the intrinsic adhesion parameters on the moment of debonding is shown.

1. Introduction

Adhesion is a subject of large interest, both from an industrial and scientific point of view. A recent problem is the adhesion in copper–rubber interfaces, such as applied in stretchable electronics. Stretchable electronics are typically found in electronic textiles and biomedical applications (Coosemans et al., 2006; Li et al., 2005; Khang et al., 2006; Song et al., 2008; Gonzalez et al., 2008). In general, stretchable electronic devices are constructed from small rigid semiconductor islands interconnected by metal, usually copper, conductor lines. These interconnects are embedded in a highly compliant substrate, typically a rubber material. It has been shown that delamination of the copper–rubber interface is a precursor to (mechanical and/or electrical) failure of the device (Hsu et al., 2010). Experimental observations have led to the conclusion

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http://dx.doi.org/10.1016/j.jmps.2014.01.009
0022-5096

that in these samples, delamination occurs through fibrillation of the rubber. This process involves the formation, elongation and failure of rubber fibrils (Hoefnagels et al., 2010).

Because of the detrimental effect of delamination on the performance and life time of the product, knowledge of the interface properties is of key importance for the development of new products. Usually, interface properties are determined through macroscopic (finite element) modeling using cohesive zone (CZ) elements, where a pre-defined constitutive relation between the interface opening and traction (the traction–separation law, or TSL) is employed. By fitting this model on experimental data the CZ parameters are obtained. In earlier work on delamination in copper–rubber interfaces this macroscopic approach proved to be successful (Hoefnagels et al., 2010; Van der Sluis et al., 2011). Good correspondence between the fitted model and the experiments was observed in terms of load-displacement curve, local peel geometry, and the location of the onset of delamination.

However, several issues limit the applicability of these models. The first concern is the lack of a clear quantitative relation between the obtained cohesive zone parameters and the observed fibrillation micromechanics. In fact, it was observed by Hoefnagels et al. (2010) that the occurring fibril length was about 6 times smaller than the obtained cohesive zone critical opening length. This makes it difficult to scrutinize the physical meaning of the established cohesive zone parameters. This problem is caused by the fact that adhesion is a multi-scale phenomenon, whereas it is projected on a single scale when pursuing a macroscopic approach as illustrated in Fig. 1. Evidently, the micromechanics of fibrillation in the experiment is not accounted for in the macro-scale model. In particular, all micro-mechanisms in the vicinity of the interface are lumped into the CZ model, leading to the mentioned mismatch between microscopic experimental observations and macro-scale interface parameters.

Because of the fibrillation process, the macroscopic interfacial dissipation (work-of-separation) consists not only of the thermodynamic work of de-adhesion between the two materials (i.e. resulting from the intrinsic adhesion), but also of the energy dissipated in the fibrillation process (Crosby and Shull, 1999; Lakrout et al., 1999; Creton et al., 2001; Brown et al., 2002). This can lead to work-of-separation values that are several orders of magnitude larger than the thermodynamic work of de-adhesion (Hoefnagels et al., 2010; Van der Sluis et al., 2011).

Associated to this, and severely limiting the practical use of the obtained interface parameters, is the fact that the fibrillation micromechanics, and thus the associated dissipation, depend on the loading conditions (Brown et al., 2002; Van der Sluis et al., 2011). As a result, the obtained macro-scale interface properties are system properties instead of interface properties. This problem can only be resolved by taking into account the fibrillation micromechanics in the macro-scale interface description. This encompasses the development of a model of the fibrillation micromechanics and a method to couple this model to the macroscopic interface description.

To address the above-mentioned issues, a multi-scale interface method is used. Micromechanical modeling of crack growth in viscoelastic media was achieved through an analytical description of the fibrillation process by Allen and Searcy (2001). In the present paper, the multi-scale interface concept introduced by Matouš et al. (2008) is used. The method has later been used to describe a variety of interfaces, see e.g. Hirschberger et al. (2009), Verhoosel et al. (2010) and Cid Alvaro et al. (2010). The method was initially developed to describe adhesive layers with known thickness. However, since there is no adhesive layer in the copper–rubber interface, some modifications need to be made.

In the multi-scale method the macro-scale interface is still described by a cohesive zone formulation. However, the TSL is no longer defined a priori, but is obtained from a micro-model through a numerical homogenization scheme. Hence, this method allows the explicit modeling of the fibrillation micromechanics and simultaneous application of the obtained response at the macro-scale. Clearly, in this way the obtained TSL is quantitatively coupled to the micromechanical quantities, e.g. maximum fibril length. Since no closed form solution is aimed for in the present paper, it is more appropriate to refer to a ‘traction–separation response’ rather than a TSL.

The fibrillation micromechanics has received considerable attention, especially for viscoelastic pressure-sensitive adhesives (PSAs). Zosel (1998) and later Creton and co-workers used tack tests to gain insight into the parameters that control the fibrillation process, see e.g. Lakrout et al. (1999), Brown et al. (2002) and Shull and Creton (2004). In their tests a rigid cylindrical punch was brought into contact with a layer of PSA, and after establishing good contact the punch was retracted. Their experiments show that the fibrillation process consists of several phases. The first phase is homogeneous

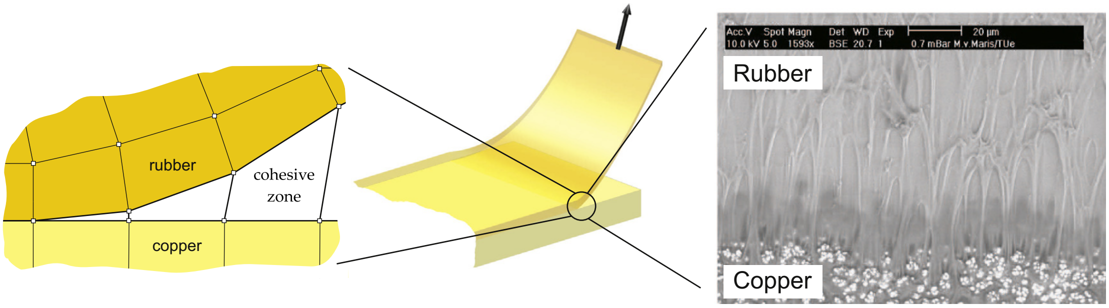

Fig. 1. Peel test. Left: finite element model. Right: in situ SEM image of fibrillation during peel test.