Advances in Necking-Assisted Controlled Fragmentation by Composite Cold Drawing

Dong Li[1]*, Huajian Gao[1,2], Lei Wei[1], Zhixun Wang[1], Ming Chen[3], Tingting Wu[1]

*[1]Nanyang Technological University, Singapore, [2]Institute of High Performance Computing, A*STAR, Singapore*
[3]Chinese Academy of Sciences, China
** Presenting Author email: dong.li@ntu.edu.sg*

Abstract

Fracture of materials has been regarded as the major danger to structures and is to be avoided in design, manufacture and maintenance. However, the application of classical cold drawing technique to advanced composites consisting of brittle semiconductor/glass/2D materials and ductile polymers prone to necking enables controlled fragmentation of the target component, resulting in structured patterns in micro- down to nano- scales. The controlled fragmentation can thus be taken advantage of to produce microstructures in large scale. Mechanism of controlled fragmentation and key parameters for tuning fragment size are revealed through theoretical modeling, experiment and finite element analysis. Effects of the addition of a sacrificial layer/capping layer on fragment size to improve capability of the cold drawing technique will also be discussed.

1. Introduction

Cold drawing is a widely used processing technique for metals and polymers to improve mechanical properties of the materials. However, only in recent years does cold drawing of advanced composites start to be focused on and developed as an emerging technique for mass production of microstructures. Although abundant experiment results and potential applications have been reported, appropriate modeling is lacking to fully understand how the controlled fragmentation can be achieved and to guide the design and optimization processes. This work develops a theoretical model to reveal the underlying mechanisms of controlled fragmentation and to predict fragment size using material and interfacial properties. Addition of a capping layer/sacrificial layer is expected to improve performance of the composite cold drawing method. The relevant models together with numerical simulations and experiments are promising to the development of a technical platform for large-scale manufacturing of functional structures at micro- and nano- scales.

2. Methods and Results

The cold drawing systems of interest include a cylindrical fiber with the core embedded in the center of the cladding and a thin film deposited on substrate. The core and thin film are typically brittle target materials, while the cladding and substrate are ductile matrices that can form a neck under drawing. The necking matrix experiences a fast hardening stage which pushes the neck to propagate along the loading direction without damage induced in the matrix. The load is transferred from the matrix to the target layer through interfacial shear which is characterized by a constant strength τ_{int}.

For the core-cladding system, since there is a substantial strain gradient across the necking zone in the cladding, the core stress distribution is different from that in the shear lag model. It turns out that the interface can be divided into three regions: a shear lag zone near the loading edge, a sticking zone far from the load and a reverse shear lag zone in between the two. The occurrence of the reverse shear lag zone causes a peak tension at its boundary with the shear lag zone, which is a sticking point (Fig. 1a, b). The peak tensile stress is also observed in experiment. As drawing the shear lag zone expands, and the peak tensile stress increases until fracture strength of the core is reached. After the core fractures at position of the peak tension, the rest portion of system will repeat this process to form sequential fragmentation.

The fragment size is predicted to be $l_{\text{frag}} = (Er/2\tau_{\text{int}})[1 - \exp(-\sigma_{\text{s}}/E)]$ where E, σ_{s} and r denote Young's modulus, fracture strength and radius of the core, respectively. By increasing interfacial interaction and/or reducing dimensions of the core, the fragment size is expected to be reduced down to nanoscale, which is crucial for widening application scope of the structures produced by composite cold drawing. The analysis for a film-substrate system is similar, and the major difference is the curved shape of the thin film after deformation which can be resolved by a coordinate transformation.

In the uniaxial tension test which can be described by the conventional shear lag model (Fig. 1c), stress in the target layer is accumulated in the shear lag zone and forms a plateau in the sticking zone. Due to the variation in strength distribution, random fracture happens in the target layer. By contrast, in the necking affected shear lag case (Fig. 1d), huge strain gradient makes the matrix to “drag” the target layer to the opposite direction in the normal and reverse shear lag zones, leading to a peak tension in the middle. Therefore, the fragment size in this case is determinate and controlled.

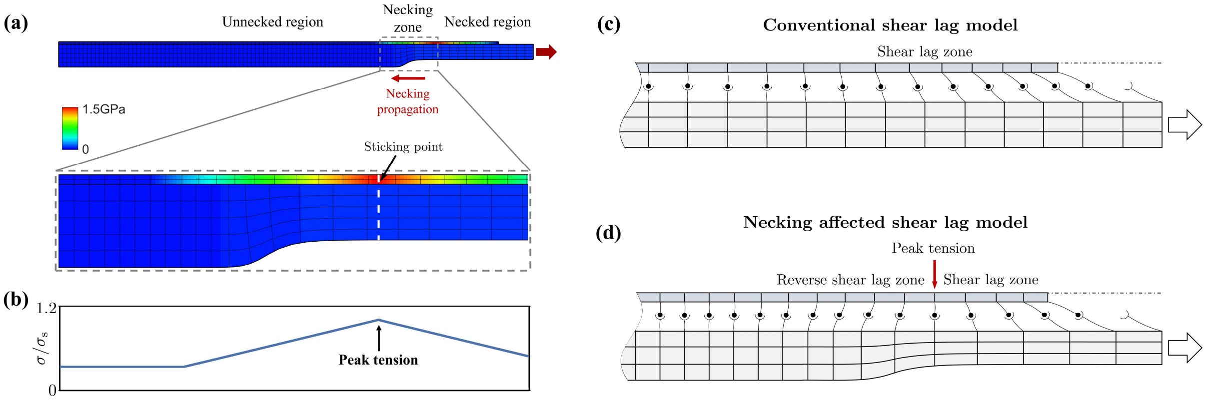

Fig. 1. (a-b) Stress distributions in the cold-drawn core-cladding fiber system. (c-d) Interfacial deformations in the conventional and necking-affected shear lag models

A prerequisite for controlled fragmentation is to keep the target material intact before the formation of necking, i.e., in the elastic deformation stage; otherwise, random premature fracture would happen to the target layer, which is common for highly brittle materials. It is found that in film-substrate systems a capping layer covering the thin film can provide the film effective resistance to the substrate deformation. In the neck propagation stage, however, this resistance is not enough as deformation in the necking zone increases dramatically, and controlled fragmentation can be achieved as normal. On the other hand, when the target material is ductile, damage is difficult to develop with the continuously deformed matrix, or intergranular cracks with random deflections are dominant in the film-substrate system. To this end, a brittle sacrificial layer is inserted between the target layer and matrix. The sacrificial layer will fracture first and facilitates ordered intragranular cracks in the target layer due to the stress concentration induced by fracture of the sacrificial layer.

3. Conclusions

The theoretical model explains how the controlled fragmentation by cold drawing is achieved through the necking-induced peak tension, in contrast to the random fracture in uniaxial tensile test without necking. Interfacial shear strength and target layer size are found to determine the fragment size. A capping layer can protect the target material from premature fracture in the elastic deformation stage, while the addition of a sacrificial layer facilities controlled intergranular fracture to prevail for ductile target materials.

Acknowledgements

D.L. and H.G. acknowledge support from the Singapore Ministry of Educaton (MOE) AcRF Tier 1 (Grant RG120/21). H.G. acknowledges support as a Distinguished University Professorship from Nanyang Technological University and Scientific Directorship at Institute of High Performance Computing from the Agency for Science, Technology and Research (A*STAR).