CRACK BRIDGING FAILURE MECHANISM IN CARBON/CARBON COMPOSITES WITH PYROLYTIC CARBON MATRIX

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Introduction

The understanding of the mechanical behavior of carbon/carbon (C/C) composites with a pyrolytic carbon matrix demands a study of the relationship between matrix microstructure and failure mechanisms. This correlation has been examined up to now only to a limited degree [1,2]**.** Recently, it was pointed out [3] that crack bridging is an important failure mechanism contributing to the toughness enhancement of composites. The objective of this study is the development of an improved understanding of the crack bridging failure mechanisms in carbon fiber felts infiltrated with pyrolytic carbon.

Experimental

A felt consisting of polyacrylonitrile (PAN) carbon fibers with a mean diameter of 12 µm was infiltrated at a temperature of 1100°C [3]. A gas mixture consisting of CH_4 and H_2 with a partial pressure ratio of 7:1 at a total pressure of 20 kPa (specimen felt I) and 30 kPa (specimen felt II) was used. The mechanical testing was performed by three-point bending at room temperature as outlined in [4]. The matrix microstructure after bending was characterized using a Leitz DM RX light microscope and a LEO 1530 scanning electron microscope (SEM) with a Schottky field-emission gun. TEM foils mechanically thinned by dimpling were studied by transmission electron microscopy (TEM) combined with electron-energy-loss spectroscopy (EELS) in an energy-filtering LEO EM 912 Omega transmission electron microscope. Samples of crystalline graphite and amorphous carbon material of lacey TEM-support film were used as the reference materials for EELS studies.

Results and Discussion

Figure 1 demonstrates the correlation between the matrix microstructure and the flexural strength of the infiltrated carbon fiber felts. The matrix (can ?) consists of a preferentially high-textured (HT) layer (felt I) or of alternating low-textured (LT), medium-textured (MT) and HT layers around each fiber (felt II). Due to the effect of multiple crack arresting [5], it can be assumed that the multilayered matrix (felt II) should exhibit an enhanced toughness. However, the stress-strain curves (Fig.1) demonstrate that the composite with matrix consisting predominately of HT carbon (felt I), possesses an increased toughness (dark-grey integral part in Fig.1) as compared with the five-layered matrix composite (felt II).

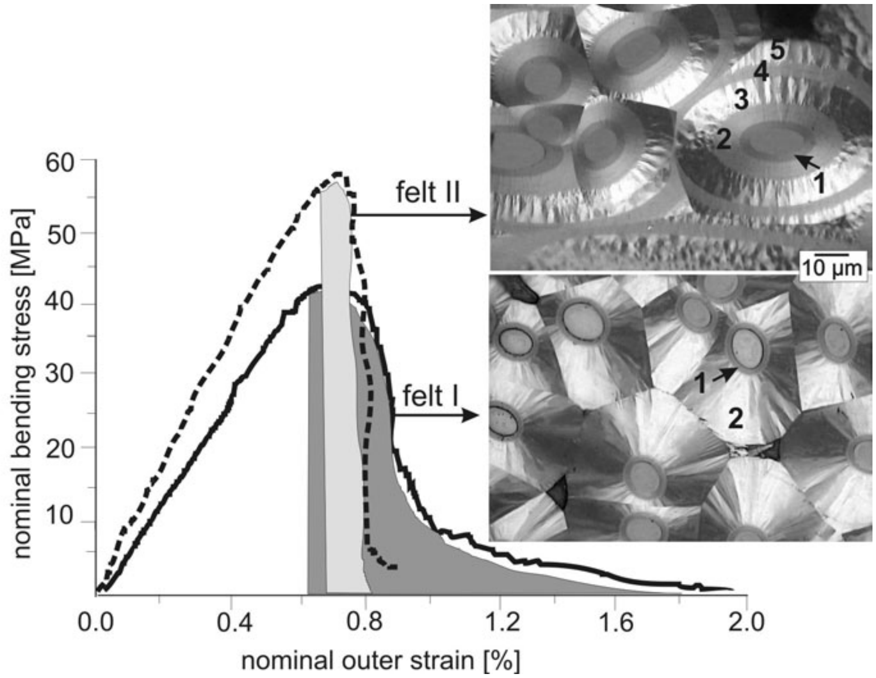

Figure 1. *Stress-strain curves of the composites with different pyrolytic carbon matrices. Matrix layers are: 1-LT, 2 –HT in felt I; 1-LT, 2,4-MT, 3,5-HT in felt II.*

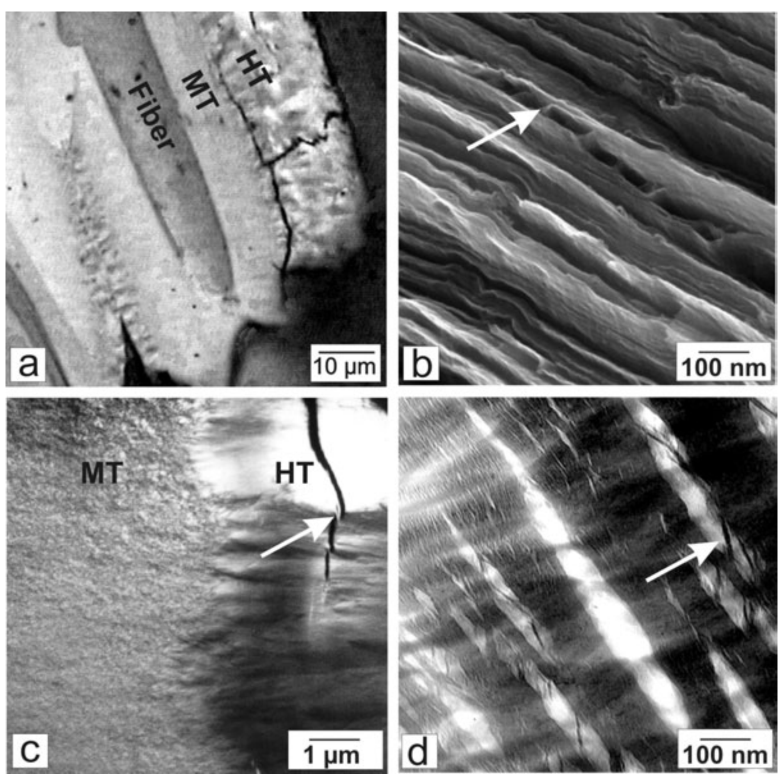

Figure 2. *Crack propagation observed by different microscopical techniques: (a) Optical micrograph of a polished section of a fracture edge; (b) SEM micrograph of a fracture surface; (c) Dark-field 002 and (d) bright-field TEM images of mechanically thinned foils.*

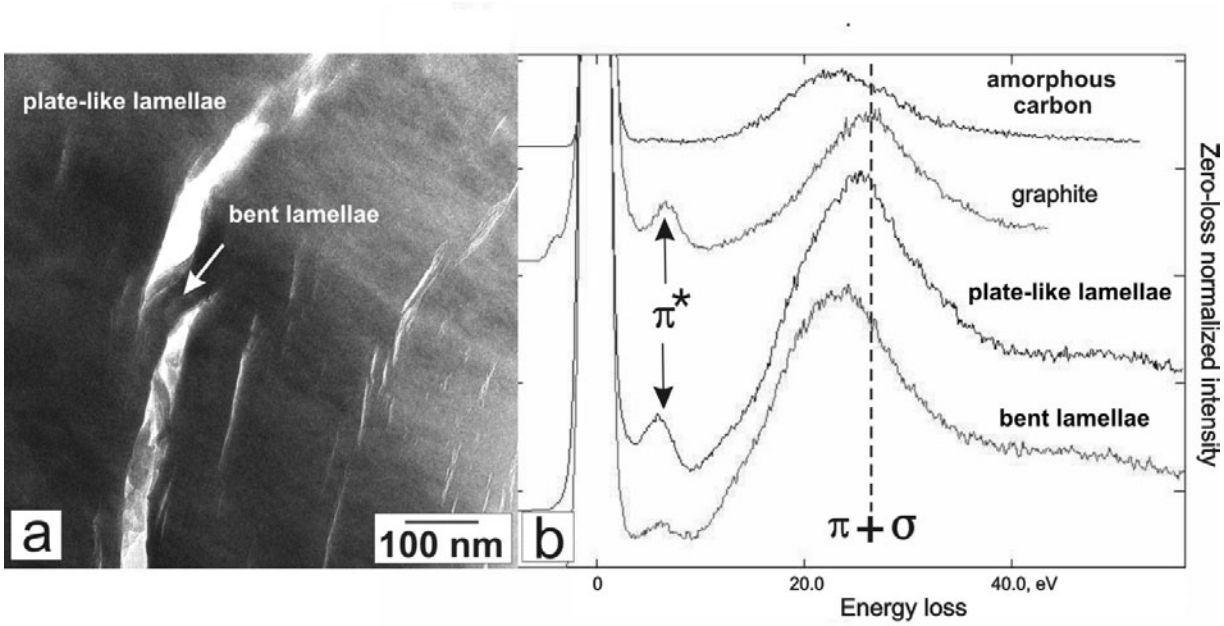

Figure 3. *TEM micrograph of a mechanically thinned foil (a) and EELS spectra (b) of the cracked region. The dashed line in (b) indicates the shift of the bulk plasmon resonance in the regions of interest in comparison with the reference specimens of amorphous carbon and graphite.*

Figure 2a shows an optical micrograph of the fracture surface edge of felt II fractured by three-point bending. The cracks do not penetrate through the fiber, exhibit curved paths in the HT layer, and seems to be deflected in the interfacial region between the MT and HT layers. Figure 2b is a high-resolution SEM micrograph showing interlaminar crack bridging (arrow) within the HT layer. Figures 2c and 2d are TEM images of the mechanically thinned (dimpled) samples. The interface between the HT and MT layers is free of cracks while crack bridging within the HT layer (arrow in Fig.2c) is observed. An intensive material splitting and crack bridging by lamellae exhibiting an increased flexibility is observed at higher magnification within the HT layer (Fig.2d).
Figure 3 presents results of EEL spectroscopy in the low-loss region. In the case of bent lamellae the main plasmon $\pi+\sigma$-resonance is shifted towards 22 eV and the π^*-peak is weakly developed, i.e. this material exhibits amorphous–like features. Within the plate-like surrounding material, the low-loss spectrum is more similar to the graphite spectrum.
Possible explanations of the observed signal fluctuations in EEL spectra are as follows.
The degradation of the graphite planar structure in bent lamellae can be associated with the presence of tiny polymer-like (soft) areas with a lower graphitization degree [6]. Another possible explanation is the presence of spherical- or polyhedral-like irregular zones with the increased curvature of the graphene planes [7].

Conclusions

1. Composites with a higher content of the high-textured matrix exhibit the highest toughness.

2. Crack bridging within high-textured lamellae by bent lamellae is frequently observed on freshly-fractured surfaces by SEM and in mechanically thinned foils by TEM.

3. TEM observations show that the bridging (bent) lamellae can be deformed plastically.

4. The EELS analysis of the shape and energetic position of the bulk plasmon excitations indicates that the bent lamellae are more amorphous-like in comparison with the graphite-like material located within the plate-like lamellae.

5. The increased flexibility of bent lamellae can be associated with the degradation of the graphite planar structure.

6. Crack bridging is an important failure mechanism contributing to the toughness enhancement of infiltrated carbon fiber felts.

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