Kink bands by compression of ultra-drawn linear polyethylene

Kink band formation in oriented crystalline polymers has been studied by many authors. Kink bands were observed in oriented nylon deformed by compression [1, 2] and by twisting [3] in oriented polyethylene (PE) deformed by compression [4–6], by shearing [7, 8], by tension [9, 10], and by twisting [3]. Kink bands have also been studied in other crystalline polymers, e.g., polypropylene [3] and polyethylene terephthalate [9]. Various molecular mechanisms have been proposed to interpret the kink band fromation and deformation stress–temperature relations, e.g., crystallographic slip in a paracrystalline lattice [1], pseudotwin [8], remelting at a pseudotwin boundary [4] and intracrystalline and intermicrofibril slip [5, 6]. The significance of this work is to provide additional evidence for interfibrillar motion as a possible kink mechanism in highly oriented polyethylene. The work on linear polyethylene with intermediate draw ratio [9] clearly demonstrated that the deformation inside the kink bands was of the continuum type. Similar behaviour would not be expected in the ultra-drawn sample, however, because of its highly anisotropic nature and well-defined microfibrillar structure.

Linear polyethylene (Alathon 7040; $M_n = 21 \times 10^3$ and $M_w = 71 \times 10^3$) was oriented at 80° C using the radial compression technique developed by Griswold *et al.* [11]; the draw ratio reached 37. The resultant sample was transparent, and the density had increased from 0.960 to 0.975. Crystalline orientation measured from the (2 0 0) and (0 2 0) diffraction maxima showed a value of 0.990. A lamellar spacing of 250 Å is indicated by the small angle X-ray pattern (Fig. 1); the strong meridional streak can be interpreted in terms of a microfibrillar structure [12, 13]. Weak lateral cohesive strength permitted the bristle to be split easily. A scanning electron micrograph (Fig. 2) of the split surface shows clearly that fibrillar structure is the predominant morphological entity.

Kink bands in the bristle were generated by compression at room temperature. The sample was fractured longitudinally at liquid N_2 temperature, and the fractured surface was coated with gold/palladium for SEM examination. It was observed that the kink bands had an average width of about 3 μm. Some of the kink bands existed only in the outer surface, with no indication of kink in the fibrils somewhat removed from the bristle surface (Fig. 3). This micrograph strongly suggests that the ultra-drawn PE bristle is composed of fibrils which can move independ-

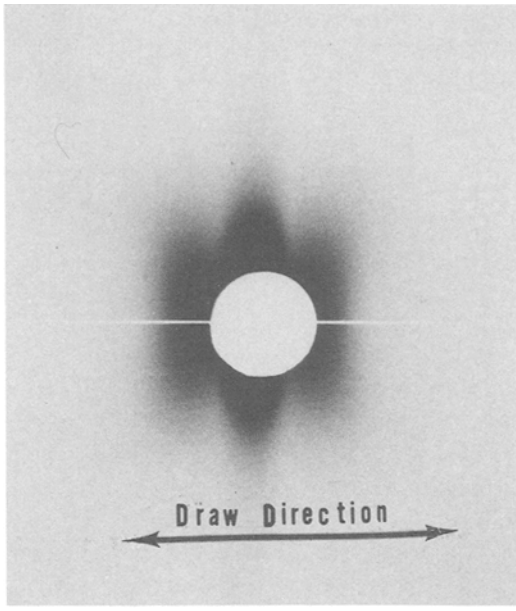

Figure 1 Small-angle X-ray diffraction pattern of ultra-drawn linear polyethylene.

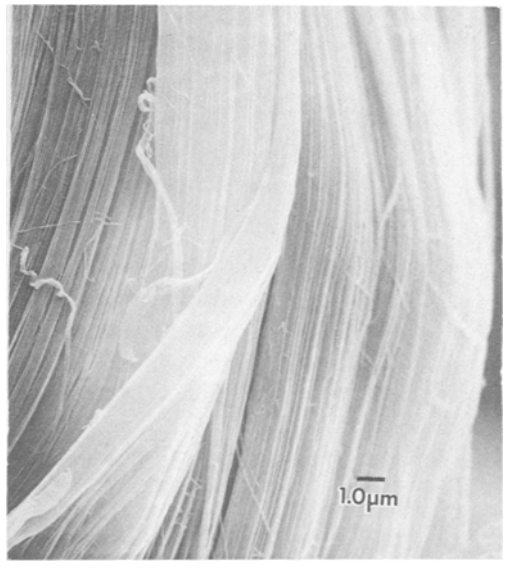

Figure 2 Fibrillar structure of a typical split surface of ultra-drawn linear polyethylene.

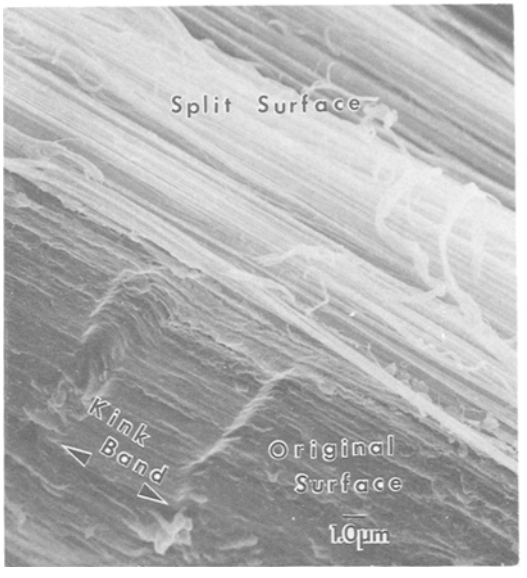

Figure 3 Kink band present on the outer surface but not in the interior of the sample.

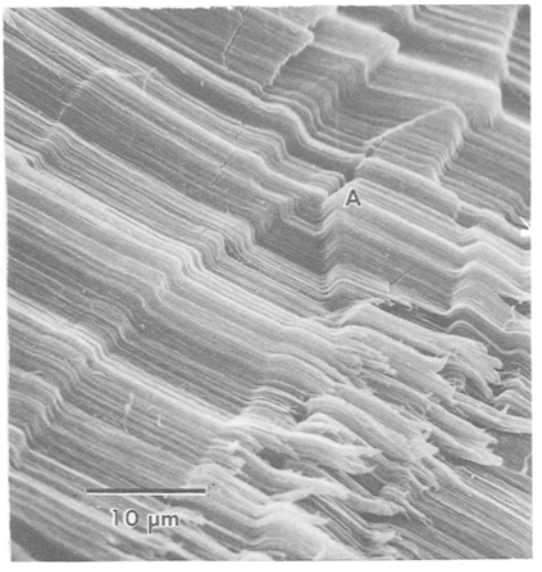

Figure 4 Kink bands within the sample interior.

ently with respect to each other. The strain associated with the kink bands on the outer surface is believed to be dissipated in the interior by interfibrillar slippage. This is not an unexpected result in view of the high longitudinal modulus of the fibril of this draw ratio [14] and the weak interfibrillar bonding.

On the other hand, there are other areas on the split surface where the kink bands clearly penetrate through the interior fibrils as shown in Fig. 4. The fibrils deformed coherently at the kink bands, and the bands do not stop abruptly inside the sample as shown in Fig. 3. The cause of these different types of kink band formation is not understood as yet.

The boundary of the kink observed on an individual fibril in Fig. 5 does not seem to be as sharp as has been observed by other workers [5, 8]. It is possible that the kink boundaries observed in our work are composed of small consecutive kinks as suggested in Fig. 5 (arrows). Elucidating the molecular mechanism of kinking in an individual fibril is beyond the scope of this work.

Another interesting feature is shown in Fig. 4: two kink bands intersect at point A and a trough exists beyond the intersection A. The fibrils in this region must be bent severely at the bottom of the trough. It is possible that the local strain developed around the trough bottom of the fibrils

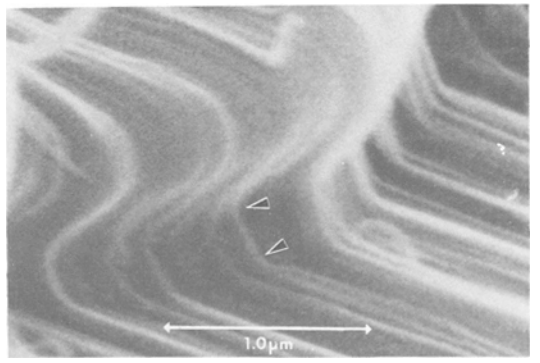

Figure 5 A higher magnification view of a typical kink band boundary.

exceeds the fibril fracture strain limit. There is no clue as to whether the fibrils around intersection A are broken or not. There are, however, a number of fibril broken ends present at the right lower corner of Fig. 4, with the broken ends arranged vaguely in rows. It is therefore proposed that fibril failure due to a large bending strain induced by the intersection of kink bands may be an important fracture mechanism of highly oriented polymeric fibres with a microfibrillar structure. Kevlar 49 fibres are known to be susceptible to kink band formation under compression [15]; they are also known to have relative low compression fatigue life compared with nylon and polyester fibres [16]. The fibril failure mechanism

proposed in this work could probably play an important rôle in the fatigue of Kevlar and similar fibres deformed in compression.

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