

Notes

OBSERVATIONS ON DEFORMATION BEHAVIOR OF HIGH PERFORMANCE FIBERS BY POLARIZING OPTICAL MICROSCOPY

Chang-fa Xiao* and Yu-feng Zhang

Department of Materials Science, Tianjin Institute of Textile Science and Technology,
Tianjin 300160, China

Abstract By means of polarizing optical microscopy (POM), deformation behavior of four kinds of fibers, i.e. ultra high molecular weight polyethylene (UHMW-PE) fiber, polyvinyl alcohol (PVA) fiber, polyethylene terephthalate (PET) fiber, and wholly aromatic (*p*-hydroxybenzoic acid/2-hydroxy-6-naphthoic acid) copolyester [P(HBA/HNA)]/PET (ACPET blend) fiber, in axial compression, axial impacting, and bending was observed. In compression, kink bands formed at an angle of 55~60° to the fiber axis in 10-times-drawn UHMW-PE fiber, 75~80° in 40-times-drawn sample, 80° in PVA fiber, and 90° in the ACPET blend fiber. In impacting and bending, band angles of UHMW-PE, PVA and PET fibers are nearly the same as those formed in compression, indicating that slip systems do not change. For any of the four kinds of fiber, band spacing exhibits great differences in compression, in impacting, and in bending, which may be attributed to the differences in the degrees of strain or stress concentration.

Keywords High performance fiber, Axial compression, Axial impacting, Bending

INTRODUCTION

High performance fibers, made up of extended polymer chains, exhibit high modulus and high strength, though they are of different molecular structure. At the present stage of these high-performance materials, moduli as high as 70%~90% of the theoretical values are achieved, whereas the strength goes up to about 10% of the theoretical values^[1]. One of the serious disadvantages of these high-performance materials is, however, their poor axial compressive strength that limits their applications to fiber composites. For fiber composites, reinforced fibers are required not only having excellent tensile strength, but also having good impact resistance, bending fatigue resistance, and axial compression behavior. There have been many reports on axial compression behavior of high performance fibers^[2~6], but only few on their axially impacting and bending fatigue behavior. Considering that there are similarities among the effects of axial compression, axial impacting, and bending on fibers, it is interesting to compare, therefore, deformation behavior of high performance fibers during axial compression with that during axial impacting and bending fatigue.

In the present work, by means of POM, the deformation behavior of four kinds of high performance fibers, i.e. UHMW-PE fiber, PVA fiber, PET fiber and wholly aromatic copolyester [P(HBA/HNA)]/PET (ACPET blend) fiber, in axial compression, axially impacting, and bending was observed. Kink bands of various band spacing are formed at various angles to the fiber axes, depending on various deformation mechanisms.

EXPERIMENTAL

Fibers

The fibers examined in this study were UHMW-PE, PVA, ACPET blend and PET fibers.

*Corresponding author: Chang-fa Xiao (肖长发), E-mail: cfxiao@public.tpt.tj.cn
Received February 14, 1999; Revised July 4, 1999

By using kerosene and gasoline as the solvent and extraction solvent respectively, two type of UHMW-PE fibers were prepared according to the gel-spinning method described in our previous paper^[7], one with a draw ratio of 10 and the other of 40. PVA fiber was kindly supplied by Kuraray Co., Japan. According to the manufacturer's data, the tensile strength is 13.0 g/d and the tensile modulus is 310 g/d. PET fiber was kindly provided by Tianjin Meilun Liability Ltd. Co., China. having tensile strength of 6.8 g/d and tensile modulus of 158 g/d. In the ACPET blend fiber, the ratio of P(HBA/HNA)/PET is 70/30 and the fiber was used as-spun.

Axial Compression of Fibers

Axial compression of filaments was carried out according to a similar method as described in^[6]. The filaments were immersed in methyl methacrylate (MMA), and then MMA was polymerized for 48 h at 40~98°C using azobisisobutyronitrile as initiator. A cylindrical block, 6 mm in length and 7 mm in diameter, containing the filaments embedded in PMMA was axially compressed manually in a vise at a slow strain rate (< 10% / min) at room temperature. Deformed filaments were removed from PMMA resin block by using acetone as the solvent.

Axial Impact of Fibers

A fiber/resin cylindrical block, 7 mm in length and 7.5 mm in diameter, prepared according to the same method as that described in the above paragraph, was vertically placed on a Paint-Film Impact Tester. A weight of 2000 g was dropped on the sample 20 times from a height of 500 mm.

Bending Test of Fibers

Fiber/resin cylindrical bars, 226 mm in length and 12 mm in diameter, were clamped in a bending fatigue machine model PQ-6. Sample bars were bent as shown in Fig. 1 and rotated. The rotational speed of samples is 3000 rpm.

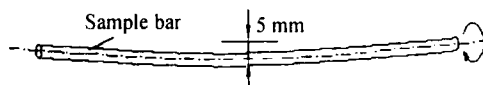


Fig. 1 Schematic illustration of the fatigue bending of fibers

Observation on Deformed Fibers

Axially compressed, axially impacted and fatigue bent high performance fibers, removed from deformed fiber/resin block (bars) by treating them with acetone, were examined by means of POM which was carried out with an XP1D polarizing optical microscope.

RESULTS AND DISCUSSION

Deformation Behavior of Fibers in Axially Compression

Figure 2 shows POM microphotograph of axially compressed fibers. Various kink bands are observed in all the four kinds of fibers that were removed from the axially compressed resin/fiber composites. The compressional strains of the composites were estimated to be about 40%. Figures 2a) and 2b) demonstrate the POM microphotographs of UHMW-PE fibers with draw ratios of 10 and 40.

In the 10-times-drawn UHMW-PE fiber, kink bands of 10 μm thickness were formed at angles of 55~60° to the fiber axis. It can be readily confirmed by rotating a sample on the stage of the microscope that the molecular axes of polyethylene in the kink bands were sharply bent from their original direction by an angle of ca. 70°. This result is very close to that in the compressional extrudates of linear polyethylene obtained by Shigematsu *et al.*^[8], in which kink bands were formed at an angle of 50~55° to the extruding direction but molecular axes in the kink bands were still bent from their original direction by an angle of ca. 70°. This indicates that there exist similarities between the superstructures of the two. According to the investigations on the superstructure of UHMW-PE gel fiber^[7, 9] and the extrudates of linear polyethylene^[8], both are mainly composed of stacked lamellae with c-axis oriented along the fiber axis, so we can use Shigematsu's model to approximately demonstrate the superstructure of 10-times-drawn UHMW-PE fiber. According to Shigematsu's model, the kink band formation is assumed to proceed by the combined mechanisms of uniform c axis shear of the crystal and

inter-crystallite and/or inter-microfibrillar slip. On the other hand, because of the high degree of solvation in the gel fiber, the lamellar crystals in it stack very loosely. When they are compressed, the lamellar crystals in the gel may deformed more gently than those in extrudates do, which results in the inclination of lamellar crystals by ca. 50°, a little smaller than those in extrudates. The kink band angle, thus, is ca. 60°, a little larger than that in the extrudates. As shown in Fig. 3, Shigematsu's model can account well for the mechanisms of kink band formation in the 10-times-drawn UHMW-PE fiber.

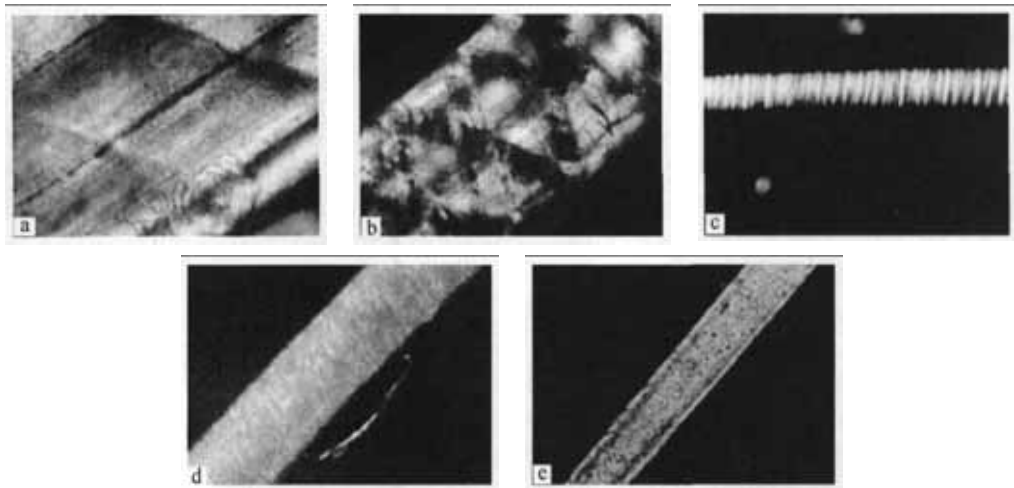


Fig. 2 microphotographs of axially compressed fibers observed from POM
a) 10-times-drawn UHMW-PE fibers; d) 40-times-drawn UHMW-PE fibers;
c) PVA fiber; d) ACPET blend fiber; e) PET fiber

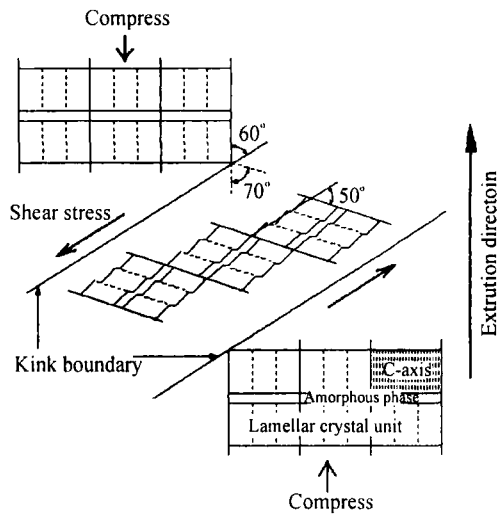


Fig. 3 Shigematsu model for the formation of kink bands in 10-times-drawn UHMW-PE fiber in compression

In the 40-times-drawn UHMW-PE fiber in compression, kink bands formed at an angles of 75~80° with respect to the fiber axis direction were observed. The formation of the kink bands in 40-times-drawn fiber is radically different from that in the 10-times-drawn one because of their different superstructure. In the fiber with a draw ratio of 40, the polymer chains tend to extend and orient along the fiber axis highly to form highly developed fibrils and the degree of crystallization is much higher than that of 10-times-drawn one^[7]. When it is

compressed, crystalline slips may play an important role in the formation of kink bands. Takahashi *et al.*^[3] has reported that kink bands are formed, respectively at 90° and $75\sim 80^\circ$ to the draw axis, in compressional doubly oriented high-strength high-modulus UHMW-PE films. It was suggested that $(110)\langle 001 \rangle$ slip plays the dominant role in the formation of the 75° kink bands, while $(100)\langle 001 \rangle$ slip, in the formation of 90° kink bands. Because the crystal structures of both highly drawn UHMW-PE films and highly drawn fibers are orthorhombic crystalline system, we suggest, accordingly, that the formation of kink bands in the 40-times-drawn fiber could be mainly due to the $(110)\langle 001 \rangle$ crystalline slip.

Figure 2c) shows a POM photomicrograph of axially compressed PVA fiber removed from PMMA resin block. Kink band with ca. $10\ \mu\text{m}$ spacing are helically formed around the fiber axis at the angles of ca. 80° to fiber axis. Generally, band angles, angles between bands and the fiber axis, are mainly dependent on the slip systems, crystallographic or noncrystallographic slip. If noncrystallographic slip plays an important role in the formation of the banded structure of gel-drawn or compressed PVA fibers, the kink bands might be formed at the angles favorable for shear stress, that is at about 45° to the fiber axis. According to Orowan's consideration^[10] and the crystal structure of PVA proposed by Bunn^[11], Takahashi calculated the band angles for the $(101)\langle 010 \rangle$ slip and concluded that $(101)\langle 010 \rangle$ slip plays an important role in the formation of the bands at angles of $\sim 75^\circ$ to the fiber axis^[4].

An investigation^[5] on the axially compressional behavior of wholly aromatic copolyester [P(HBA/HNA)] fiber revealed that at the initial stage of the compression of the fiber, kink bands are formed on the P(HBA/HNA) fibers at an angle of ca. 60° to the fiber axis. It can be predicted that two slip systems, $(110)\langle 001 \rangle$ and $(100)\langle 001 \rangle$, are responsible for the formation of the kink bands. With progressive compression, new kink bands were formed near the kink bands that were formed in the initial stage of the compression, indicating the compressional stress is concentrated at regions near the kink bands, and the band angle is close to $85\sim 90^\circ$. When compressed further, massive lateral displacement occurred from place to place along fiber axis and finally ACPET blend fiber became out of shape. Inter-microfibrillar slip was assumed to play an important role at this stage of compression.

In this study, the axial compression behavior of ACPET blend fiber and PET fiber were continually investigated. The results show that compressive deformation of ACPET blend fiber, similar to that of P(HBA/HNA) fiber, also developed in three stages. At the initial stage of compression (about 10%), the band angles are 60° , and the larger the deformation of the fiber compressed, the larger the band angles formed. Fig. 2d) shows the POM microphotograph of ACPET blend fiber with a relatively high compressive deformation (45%). It can be seen that the bands are formed at angles of nearly 90° with respect to the fiber axis, very close to that of P(HBA/HNA) fiber with the same deformation. The bands spacing, however, is $\sim 3\ \mu\text{m}$, much smaller than that of the P(HBA/HNA) fiber, which may indicate the effect of PET composition, flexible polymer chains, on the deformation behavior of the ACPET blend fiber. In axially compressed PET fiber much thinner and denser bands are observed (cf. Fig. 2e)). The mechanism of the effect of PET on the deformation behavior of the ACPET blend fiber is not very clear yet.

Deformation Behavior of Fibers in Impacting

Whether axially compressed or axially impacted, fibers bear axial compressive stress and are deformed axially, but in the case of axial impacting, the deformation rate is much higher than that in axial compression. The total deformation of fibers in impacting is an accumulation of many impacts. In this paper the deformation behavior of fibers in impacting was observed.

Figure 4 shows the deformation of fibers during impacting. It can be seen that except in the blend fiber, band angles in all the other fibers are almost the same in impacting as in compression. This indicates that the slip systems in most of the fibers except ACPET blend fiber do not change in impacting. However, the widths of the bands and/or the band spacing are changeable.

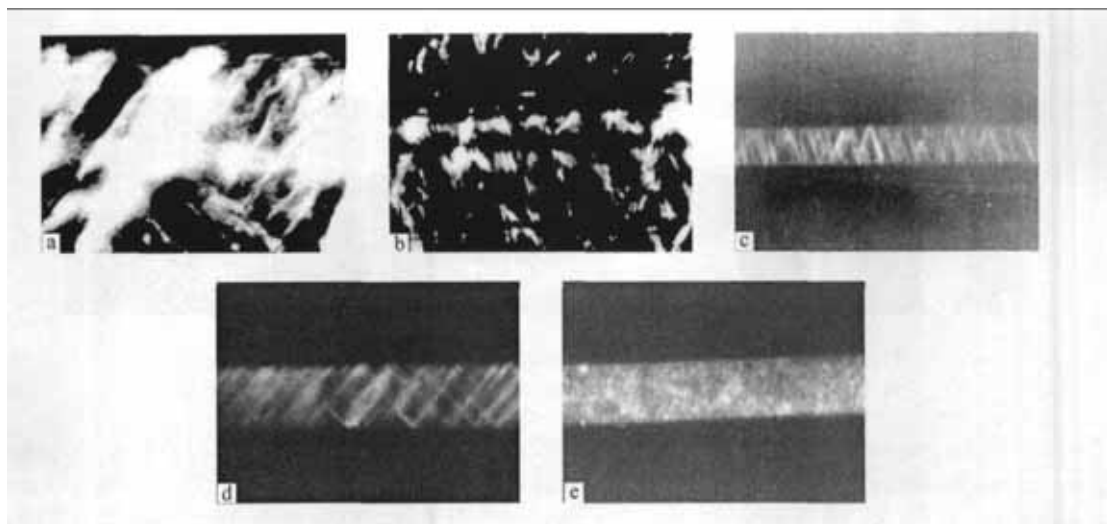


Fig. 4 POM microphotographs of axially impacted fibers
 a) 10-times-drawn UHMW-PE fibers; b) 40-times-drawn UHMW-PE fibers;
 c) PVA fiber; d) ACPET blend fiber; e) PET fiber.

During the impacting of 10-times-drawn UHMW-PE fiber, kink bands are formed more widely than during the compression (Fig. 4a)), indicating compressional stress concentration is much stronger in impacting than in compression. New kink bands formed predominantly near the original ones and developed into wider ones.

While in the high drawn UHMW-PE fiber composed of well-developed microfibrils, lateral fibril-to-fibril contact is not enough for transmitting the internal stress to the adjacent microfibrils, and accordingly growth of the band around the fiber axis might be inhibited. New kink bands, i.e., new points of crystalline slips are formed continually with progressive impacting no longer near the original ones, which results in thinner and denser kink bands, as shown in Fig. 4b).

Figure 4c) shows the result of impacting on PVA fiber. On comparing with Fig. 2c), the band angles are ca. $80\sim 85^\circ$ and the band spacing is larger. This may result from smaller stress during impacting. The deformation mechanism, however, is the same as that in compression.

Figure 4d) shows the deformation behavior of ACPET blend fiber during impacting, which is very similar to that of compressed blend fiber of small deformation (10%). The kink bands formed at angles of $50\sim 60^\circ$ to the fiber axis but the band spacing is ca. $\sim 8\ \mu\text{m}$, a little longer than that of the compressed one. One can conclude from this result that the slip system does not change either, that is the same as during its compression. The smaller band spacing of ca. $\sim 8\ \mu\text{m}$ may be attributed to the cushion effect of composition of PET in the blend fiber, because no differences between the deformation of PET fiber in impacting (Fig. 4e)) and in compression (Fig. 2e)) were observed. In general, the deformation behavior in impacting of ACPET blend fiber is basically the same as that at the initial stage of its compression to a small deformation of about 10%.

Fatigue Behavior of Fibers in Bending

A cylindrical fiber/resin bar was subjected to a bending test. When it is bent, one side of the bar is compressed while the other is stretched. If fibers are not situated in the center along the resin bar, when the bar is bent reversely and repeatedly, the fiber in the bar will be compressed and stretched alternately. Because the frequency of stretching-compression in this study is so high (up to $3000\ \text{min}^{-1}$) that a certain amount of heat generated will sharply raise the temperature of fibers, which is sufficient to affect the deformation behavior of fibers. By means of POM, this fatigue behavior of the four kinds of fibers in bending was observed.

Figure 5a) is a POM microphotograph exhibiting the deformation of UHMW-PE fiber with a draw ratio of 40 in a bending test. It can be seen that band angles hardly changed, but the width of bands and the band spacing are larger compared with the compressed or the impacted one. Only one reason resulted in this result may be interpreted as the steep rise of temperature of the fiber during bending leads to the melting of slip system and

stress concentration.

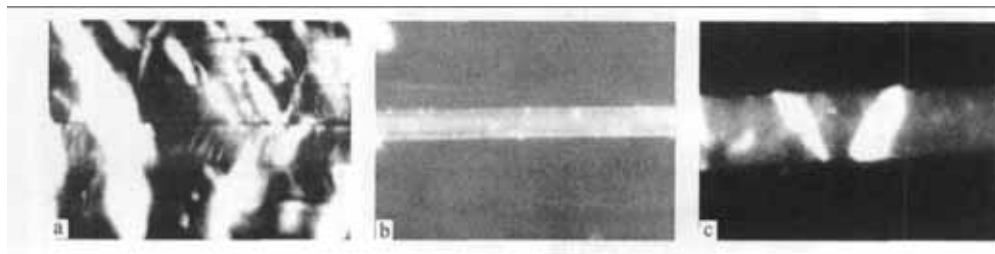


Fig. 5 POM microphotographs of bending deformed fibers
a) 40-times-drawn UHMW-PE fibers; b) PVA fiber; c) ACPET blend fiber

Unlike the fatigue behavior of UHMW-PE fiber, that of PVA fiber is almost the same as its behavior in compression but no effect of heat on its deformation was observed in the bending test. Fig. 5b) shows the POM microphotograph of PVA fiber in bending test. One may attribute this to its high melting point (230°C) and high glass transition temperature (80°C).



Fig. 6 POM microphotographs of fibrillated ACPET blend fiber in bending

Figure 5c) shows the bend fatigue behavior of ACPET blend fiber. It is evident that bands of ca. 15 μm , much wider than those in compressed or in impacted ACPET blend fibers, scattered sparsely along the fiber. This is probably due to softening of PET composition during bending test, which induces the stress concentration. In addition, fibrillation of the blend fiber was observed in bending test under POM (Fig. 6)). It is known that polyarylate fiber is easily fibrillated^[12].

REFERENCES

- 1 Ohta, T., *Polym. Eng. Sci.*, 1983, 23: 697
- 2 Deteresa, S.J., Porter, S.R. and Farris, R.J., *J. Mater. Sci.*, 1988, 23: 1886
- 3 Takahashi, T., Suzuki, K. and Sakurai, K., *J. Macromol. Sci.-Phys.*, 1990, B29: 101
- 4 Takahashi, T., Suzuki, K., Aoki, T. and Sakurai, K., *J. Macromol. Sci.-Phys.*, 1991, B30: 101
- 5 Takahashi, T., Xiao, C.F. and Sakurai, K., *Sen-i Gakkaishi*, 1991, 47: 397
- 6 Takahashi, T., Miura, M. and Sakurai, K., *J. Appl. Polym. Sci.*, 1983, 28: 579
- 7 Xiao, C.F., Zhang, Y.F., An, S.L. and Jia, G.X., *J. Appl. Polym. Sci.*, 1996, 59: 931
- 8 Shigematsu, K., Imada, K. and Takayamagi, M., *J. Polym. Sci. Polym. Phys. Ed.*, 1975, 13: 73
- 9 Pennings, A.J. and Smook, J., *J. Mater. Sci.*, 1984, 19: 3443
- 10 Orowan, E., *Nature*, 1942, 149: 643
- 11 Bunn, C.W. and Garner, E.V., *Proc. Roy. Soc.*, 1947, A189: 39
- 12 Roche, E.J., Takahashi, T. and Thomas, E.L., *ACS Symposium Series*, 1980, 141: 303