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Apparatus for Measuring the Bending Fatigue Properties of High Performance Polyethylene Fibre

Abstract
A test method for bending fatigue has been developed to determine the bending fatigue strength of fibres. This new equipment is capable of performing the bending fatigue testing of fibres under different pre-tensions, bending angles and temperatures. This article presents results from tests on single high performance polyethylene fibre (HPPE) to characterise its bending fatigue behaviour under cyclic loading and temperatures. The curve of the cyclic tension shows that the cyclic tension changes in periods during the cyclic bending process. The S-N and θ-N curves indicated that the pre-tension and bending angle had great influences on the bending fatigue life of HPPE fibre. A CCD camera was utilised to allow observation of the bending fatigue fracture morphology of the fibre. It showed the fracture mechanism of the HPPE fibres. The bending fatigue life of HPPE fibre was tested at different temperatures to show that its bending fatigue strength is strongly influenced by the temperature.

Key words: *HPPE fibre, bending fatigue, apparatus, fracture morphology, temperatures.*

Introduction

The mechanical actions experienced by textile fibres are, in practice, rarely simple, often involving combinations of tensile, bending and torsional deformation. An important method to show the bending property of fibre is the bending fatigue test for major deformation caused by a bending force. Many previous papers focused on the effects of the bending fatigue on fibre and presented the number of cycles-to-failure under a given pre-tension [1 - 4]. Liu tested the bending fatigue lifetime of aramid fibre by using sample bending fatigue apparatus [5] Burgoynet et al used sheave bending apparatus to investigate the bending fatigue of parallel lay aramid ropes [6]. Kohji et al [7] used an environment controllable micro mechanical fatigue machine to test the influence of a vacuum on the bending fatigue of single aramid fibre. Cai tested the bending fatigue property of single PBO fibre [8].

This paper introduces new micro-material test apparatus developed by the Textile Materials and Technology Lab at Donghua University to characterise the bending fatigue behaviour of fibre materials [9]. The design principle of the apparatus is based on the fixed-point bending damage of fibres under different pretensions, bending angles, and temperatures.

HPPE fibre is exploited mainly due to its superior strength and propensity for energy absorption. In this regard, its most important applications are found in products for personal protection, including lightweight ballistic armour, in ropes, cables and filter materials [10, 11]. For some reinforcment applications, HPPE is incorporated in the form of a woven fabric. Many physical properties of fabrics, such as the drape, handle, crease and wrinkle recovery, are dependent on the flexural properties of component yarns, which in turn depend on the properties of individual fibres. However, polyethylene is a typically flexible material with a lower glass-transition temperature and lower melting temperature, even for HPPE. Therefore, study of the bending fatigue behaviour of HPPE at different temperatures is very important for processing and using this kind of thermoplastic fibre.

In the present study, new bending fatigue test apparatus is introduced and the effects of pre-tension, bending angles and temperatures on the bending fatigue of high performance polyethylene fibres using the newly designed apparatus were analysed to provide guidance for using high performance polyethylene fibres.

Experimental

Testing apparatus for bending fatigue of fibre

A real photo of the new bending fatigue test apparatus is shown in ***Figure 1***. The bending fatigue test system, which was developed by the authors at TMT, is comprised of the following parts: 1) upper jaw, 2) positioning pin, 3) lower jaw, 4) running plane, 5)microscope, 6) CCD camera, 7) temperature sensor, and 8) heater. The jaws are used to clamp fibre materials. The positioning pin is used to handhold the fibre and fix the bending point in the bending process. The running plane can bend fibre by rotating different angles. The microscope and CCD camera provide an optical system with which the fibre could be observed. It is also used to observe the bending fatigue fracture morphology of the fibre. The heater and temperature sensor are used to control the temperature of the bending point.

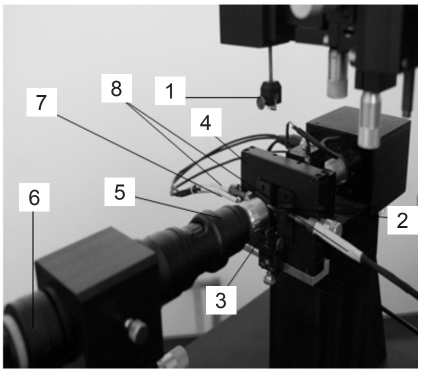

Figure 1. *Real photo of bending fatigue test apparatus; 1. Upper jaw, 2. Positioning pin, 3. Lower jaw, 4. Running plane, 5. Microscope, 6. CCD camera, 7. Temperature sensor, 8. Heater.*

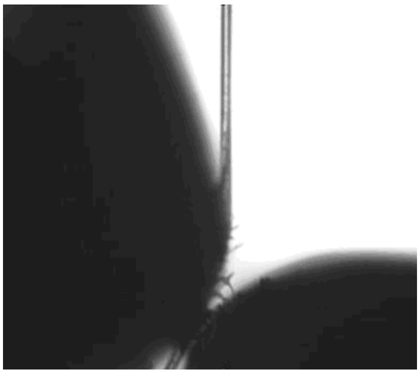

Figure 2. *Real image of HPPF fibre during the bending fatigue process.*

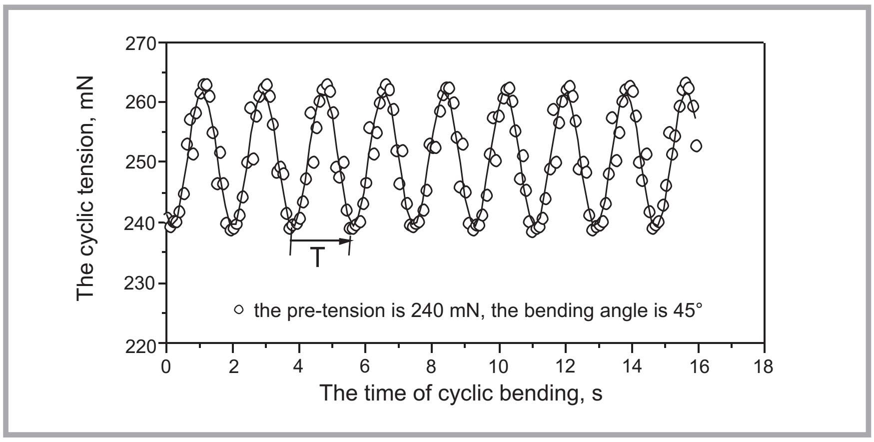

Figure 3. *Curves of cyclic stress during the cyclic bending process.*

The temperature can be regulated electrically from room temperature up to 200 °C.

Pre-tension was applied at various bending angles and frequencies. The cyclic stress σ and number cyclic N were recorded, and the bending fatigue fracture process was monitored in situ using a high-speed CCD camera. ***Figure 2*** (see page 37) shows photographs obtained through in situ observations of the experiments. The bending fracture process and fracture morphology of fibre can be clearly seen in the fibre bending process.

Materials

HPPE fibres were selected for the bending fatigue test. The linear densities of the fibres was 6 dtex. The gauge length adopted for the bending fatigue tests was 60 mm. A fibre was selected randomly from the fibre bundle. The two ends of the fibre were grasped between the upper fixed clamp and lower jaw of the bending fatigue tester and then cut off the paper frame.

Results and discussion

Cyclic tension of fibre in the bending process

Figure 3 shows the cyclic stress curve of HPPE fibre during the bending fatigue process under a per-tension of 240 mN and bending angle of 60°. The elongation of the fibre changes with the bend, which results in stress fluctuating. We can find that the curve of cyclic stress changes in periods when the fibre bends repeatedly. It can be assumed that the period of the waveform is T, and the number of cycles N ($N = t/T$) can be acquired when the fibre fatigue rupture time t is known. The varying bending angles caused changes

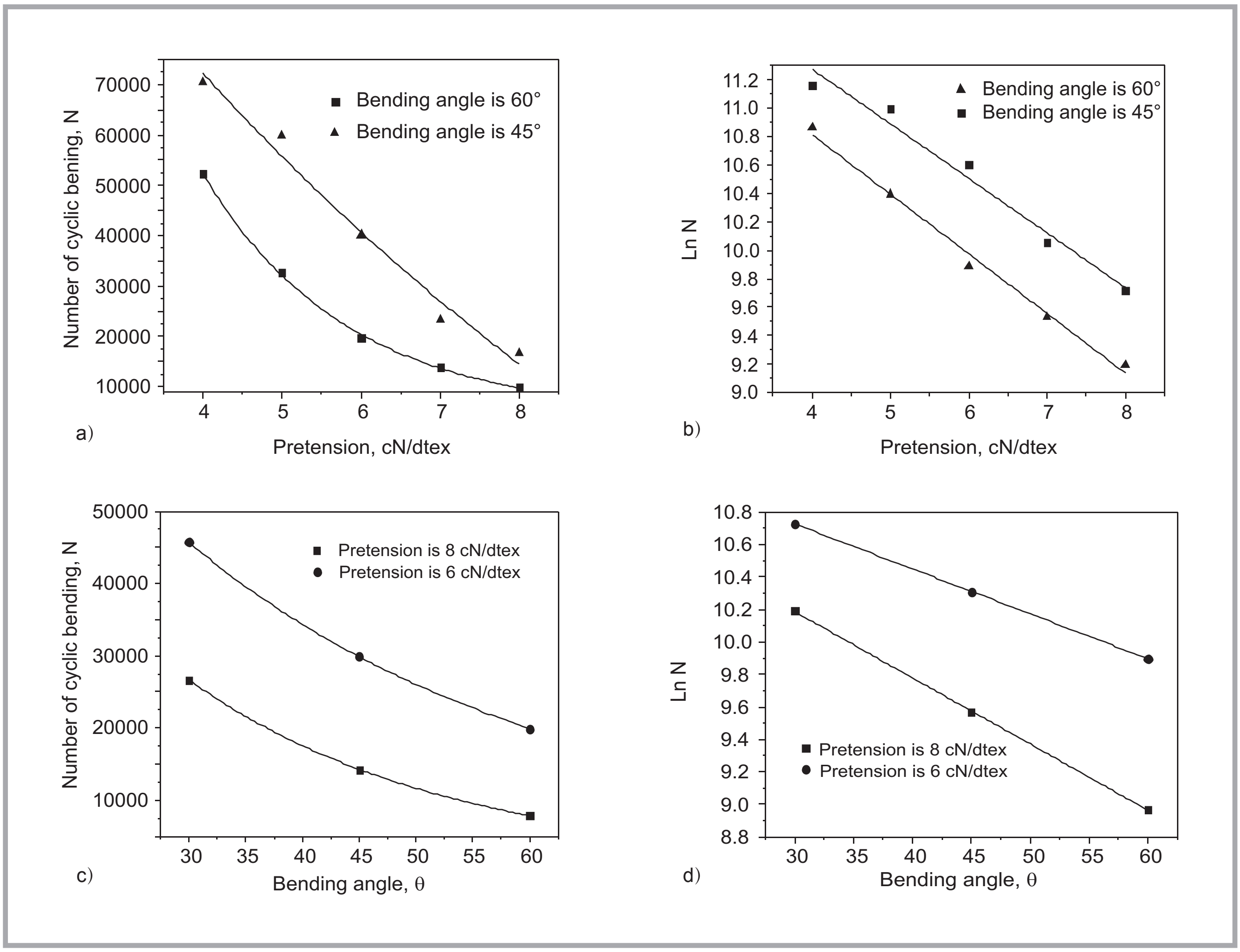

Figure 4. *Curves of the HPPE fibre; a) S - N, b) S - ln N, c) θ - N, d) θ - ln N.*

in the cyclic strain when the fibre cyclic bends, then the cyclic stress changes.

Effects of pre-tension and bending angle on the bending fatigue lifetime of HPPE fibre

The factors influencing the bending fatigue of fibre materials include the bending angle, pre-tension and bending frequency. Many investigations have discussed the fatigue of polymer. These investigations are based on the Zhurov kinetic concept of the mechanical deterioration of polymers, defined by the general equation:

$$\tau = \tau_0 \exp[(U_0 - \alpha\sigma)/KT] \qquad (1)$$

Where τ is lifetime of materials under σ load, σ - the mechanical stress, applied T the absolute temperature τ_0 - the period of thermal fluctuations of atoms; T – the absolute temperature, U_0 - the energy of the rupture of an interatomic bond, α - the coefficient of overstress in the bond being ruptured, and K is the Boltzmann constant. We can obtain the equation:

$$\ln N = A - B\sigma \qquad (2)$$

Where $A = \ln \tau_0 + U_0/KT - \ln (2\pi/\omega)$, $B = \alpha/KT$ in ***Equation 2***.

The bending fatigue lifetime of HPPE fibre was plotted as a function of the pertension σ using the N - σ and ln (N - σ) scales. The experimental results are shown in ***Figures 4.a*** and ***4.b***. The bending lifetime N decreased with the increasing pre-tension. Furthermore the ln N decreased linearly with the increasing pre-tension. These experimental results are consistent with the function indicated in ***Equation 2***. The experimental results, shown in ***Figures 4.c*** and ***4.d***, illustrate the θ - N and θ - ln N curves of HPPE fibre. It is shown that the bending lifetime of N decreased with the increasing bending angle in degree, while the ln N decreased linearly with the increasing bending angle. There is also a linear relationship between the bending angle and fatigue lifetimes in the natural logarithm.

We can also observe that an action of the large pretension and small bending angle can be comparable with an action of the small pre-tension and the large bending angle to the influence of the fatigue life. Hence, fibre bending should be avoided under a high pretension or at a large bending angle, particularly when both the pre-tension and bending angle have high values.

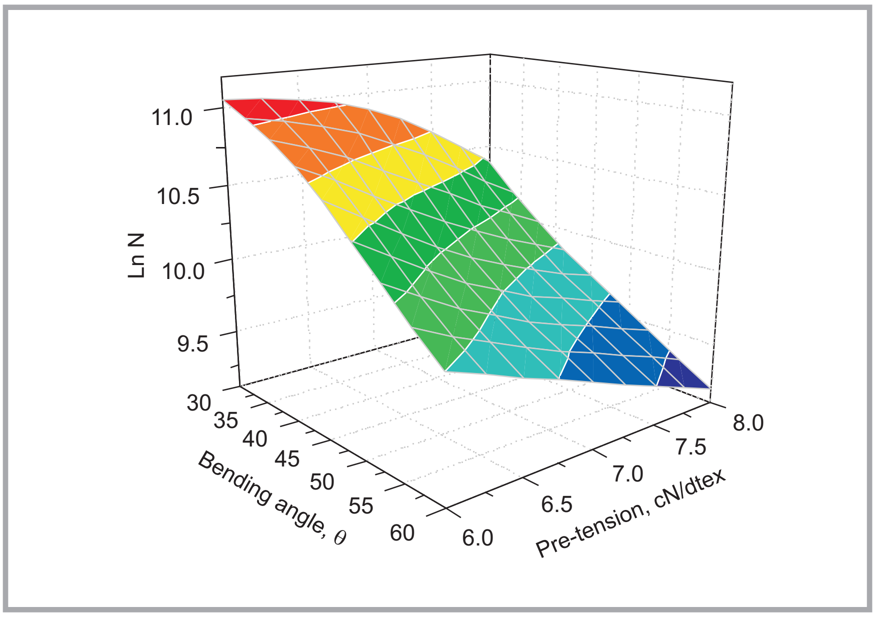

Figure 5. *Relationship between the pre-tension, bending angle and fatigue lifetime of HPPE fibre.*

Combined effects of the pre-tension and bending angle on the bending fatigue lifetime of HPPE fibre

The combined effects of the pre-tension and bending angle on the fatigue lifetime of HPPE fibre can also be expressed by the multivariate nonlinear mode. The regression equation can be expressed as:

$$\ln N = 14.516 - 0.36\sigma - 0.0390\theta + 0.000345\sigma\theta, \quad r^2 = 0.9865 \qquad (3)$$

The equation indicates that the pre-tension and bending angle are the two most important factors influencing the fatigue lifetime. The σθ has little effect on the ln N due to the coefficient being only 0.000345, which can be ignored. The relationship between the fatigue lifetime, pre-tension and bending angle is shown in ***Figure 5***. We can also observe that the large pre-tension and small bending angle act similar to the small pretension and the large bending angle to the influence of the fatigue lifetime. Hence, fibre bending should be avoided under high pretension or at a large bending angle, especially when both the pre-tension and bending angle have high values.

Effect of temperature on the bending fatigue lifetime of HPPE fibre

The bending fatigue performance of HPPE fibre under different temperatures was examined by the heating bending point method. In this experiment, we

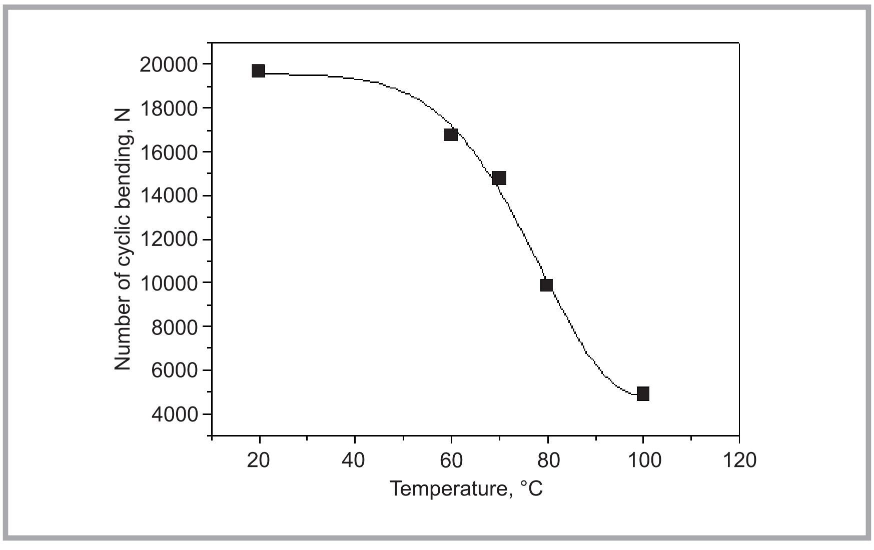

Figure 6. *Bending fatigue life comparison of HPPE fibre under different temperatures.*

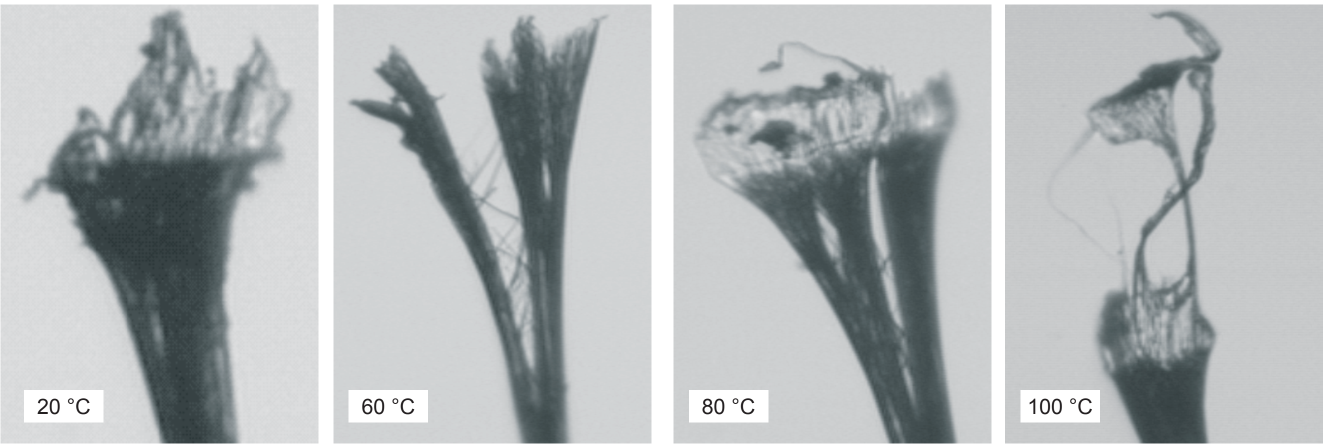

Figure 7. *Fracture-end morphology of HPPE fibre at different temperatures.*

selected 20, 60, 70, 80, and 120 °C, set the pretension at 6 cN/dtex and bending angle and 60°. ***Figure 6*** (see page 39) is a comparison of the bending fatigue life of HPPE fibres under different temperatures. It can be seen that the bending fatigue life of HPPE fibre decreased with the increasing bending point temperature. When the temperature reached 120 °C, the bending fatigue life was less than 30% at 20 °C. Therefore the bending fatigue of HPPE fibre under high temperature should be avoided.

The bending fatigue fracture end morphologies of HPPE fibre under different temperatures are shown in ***Figure 7***, which shows the effects of testing at progressively increasing temperatures. ***Figure 7.a*** is the fracture end morphology of HPPE fibre at 20 °C. It can be seen that the fracture end had slight fibrillation, insignificant fibril splitting, and accumulated plastic deformation. ***Figure 7.b*** shows the bending fatigue fracture end at 60 °C. There were some fibre fibrillations in the HPPE fibre. When the temperature continuously increased to 80 °C (***Figure 7.c***), some fibrils started melting, and a bent hook-like end was finally formed, resulting from increasing the temperature of the bending point. When the temperature reached 100 °C (***Figure 7.d***), a melting extraction filament fracture end formed after a number of bendings. The bending point temperature and accumulation of heat of the bending point increased with an increase in the number of cyclic bendings. When the temperature reached the melting point, the molten fibre ruptured easily under the force because of the low glass transition and melting temperature of HPPE fibre.

Conclusions

New test apparatus was successfully applied to determine the characteristics of bending fatigue. The test apparatus made it possible to examine the effects of pre-tension, the bending angle, and temperature on the bending fatigue life of high performance polyethylene fibre. The bending rupture morphology of the fibre during the dynamic bending process could be monitored in situ through a CCD camera. The curve of cyclic stress changed in periods when the fibre was repeatedly bent.

Some measurements were conducted to determine the bending fatigue of high performance polyethylene fibre. The pretension and bending angle have a great influence on the bending fatigue life of fibre. The experiment results showed that the bending lifetime N decreased with the increasing pre-tension and $\ln N$ decreased linearly with the increasing pre-tension. The bending lifetime of N decreased with an increasing in the bending angle. The bending fatigue life of fibre is especially low when the pre-tension and bending angle have high values.

The temperature of the bending point had a great influence on the bending fatigue life of HPPE fibre. When the temperature of the bending point reached 120 °C, the bending fatigue life of HPPE fibre was less than 30% at room temperature.

Acknowledgments

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