EFFECTS OF RESIDUAL STRESS ON PMD OF SPUN FIBERS

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Abstract *Effects of residual torsional stress on PMD of spun fibers are analyzed. It is found that the residual stress significantly affects the PMD of unidirectional spun fibers, but does not change the PMD of bidirectional spun fibers.*

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Introduction

Fiber spinning is an effective technique for reducing polarization mode dispersion (PMD) of single mode fibers. Several papers have presented theoretical and experimental studies on the fiber spinning mechanism [1-7]. Effects of external lateral load and twist on spun fibers [8], as well as statistical natures of spun fibers [9-10] have also been reported.

The fiber spinning can be classified into two categories: unidirectional spinning [1,6], and bidirectional spinning [2-5], which have very different characteristics. In the fiber spinning process, the fiber is rotated around its central axis by a torsional force applied to the fiber. The rotation is frozen into the fiber when it is cooled down, causing the fiber birefringent axes rotating along the fiber. In this process, a small amount of residual torsional stress is inevitably frozen into the fiber. However, in analyzing spun fibers, it is normally assumed that the spinning does not introduce any torsional stress in fiber for simplicity. This assumption is valid only when the fiber intrinsic birefringence is much bigger than the birefringence induced by the residual torsional stress. With the improvement in fiber manufacturing technology in the past a few years, the fiber intrinsic birefringence has become much lower. For low intrinsic birefringent fibers, even a small amount residual stress is expected to contribute significantly to the total PMD. However, the impact of the residual stress on fiber PMD has not been well understood yet.

This paper studies effects of residual stress on fiber PMD reduction of spun fibers using the coupled-mode theory. Differences in response to residual stress between unidirectional and bidirectional fiber spinning are examined.

Theoretical approach

To study the effects of residual stress on fiber PMD, we modified the coupled-mode model [2] that we developed for spun fibers by incorporating residual stress into the coupling matrix. In this model, the complex electric field amplitudes of the two orthogonal polarization modes A_1 and A_2 that describe the polarization change satisfy the coupled-mode equation:

$$\frac{d}{dz}\begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = ik \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} \quad (1)$$

where k is a 2x2 coupling coefficient matrix. Using the circular polarization mode basis, the coupling coefficient matrix of a spun fiber with residual torsional stress is expressed by the following equation:

$$k = \frac{1}{2}\begin{pmatrix} d(z) & \Delta b_0 \exp[2i\int_0^z a(z')dz'] \\ \Delta b_0 \exp[-2i\int_0^z a(z')dz'] & d(z) \end{pmatrix} \quad (2)$$

where Db_0 is the intrinsic linear birefringence, $a(z)$ is the spin function, and $d(z)$ is the circular birefringence induced by the residual stress due to fiber spinning, which is proportional to the spin rate:

$$d(z) = r_s g a(z) \quad (3)$$

where g is a constant related to photo-elastic coefficients of glass, r_s is a factor that describes how much residual stress frozen in the fiber. When r_s =1, Eq.(3) represents the circular birefringence induced by pure mechanical twist of fiber after the fiber drawing.

Integrating the coupled-mode equation (1) with the initial conditions of $A_1(0)$=1, $A_2(0)$=0, we get the amplitudes $A_1(z)$ and $A_2(z)$ along the fiber. The fiber PMD is calculated from the amplitudes using the following equation:

$$t = \frac{2}{z}\sqrt{\left|\frac{dA_1(z)}{dw}\right|^2 + \left|\frac{dA_2(z)}{dw}\right|^2} \quad (4)$$

To describe PMD reduction, a parameter called PMD reduction factor (PMDRF) is defined as the ratio of PMD of spun fiber (t) to that of unspun fiber (t_0): PMDRF=t/t_0. A PMDRF of 1 means no PMD improvement, while a PMDRF of 0.2 indicates a PMD improvement by factor of 5.

Results and discussions

Using the coupled mode equations outlined above, unidirectional and bidirectional spun fibers are analyzed. The spin function for unidirectional spin is a constant

$$a(z) = a_0 \quad (5)$$

where a_0 is the spin amplitude. For bidirectional spin, a sinusoidal spin function is used

$$a(z) = a_0 \sin\left(\frac{2p}{\Lambda} z\right) \quad (6)$$

where a_0 is the spin amplitude, and L is the spin period. In our analysis, we varied the residual stress factor r_s between 0 and 14%.

We study first the unidirectional spinning by increasing the fiber intrinsic beatlength from 1 to 100 m. It is found if the fiber beatlength is shorter than 5 m, the residual stress has negligible effects on the PMD. When the intrinsic fiber beatlength is longer than 5 m, the residual stress starts to show effects on the PMD. As an example, Figure 1 shows the PMDRF change as a function of spin amplitude for constant spinning. The intrinsic fiber beatlength in this figure is 10 m. It can be seen that for spin amplitudes less than 2 turns/m, the effect of residual stress is very small. When the spin amplitude increases, the PMDRF becomes bigger with the presence of residual stress, which is in contrast to the case without residual stress. For the same spin amplitude, the PMDRF increases with the residual stress level.

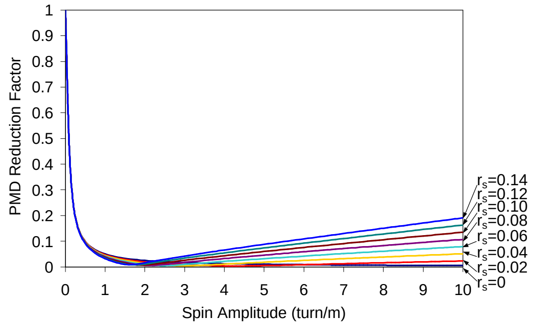

Figure 1. PMDRF change with spin amplitude for a unidirectional spun fiber. The beatlength is 10 m.

The stress effect becomes more pronounced when the intrinsic fiber beatlength is even longer. Figure 2 is another example of constant spinning for a fiber with a beatlength of 50 m. In this case, the stress effect shows up for a spin amplitude as small as 0.5 turns/m.

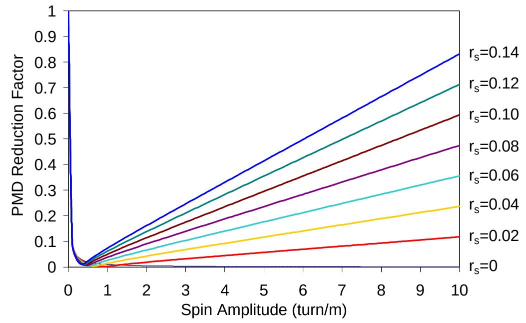

Figure 2. PMDRF change with spin amplitude for a unidirectional spun fiber. The beatlength is 50 m.

On the other hand, the bidirectional spinning has a very different response to the residual stress. Numerical results show that the residual stress does not affect the PMDRF for bidirectional spun fibers. For example, in Figure 3, we plot the PMDRF as a function of spin amplitude for different residual stress levels for a sinusoidal spun fiber with 50 m intrinsic fiber beatlength. The lines for different stress levels are almost identical, which means that the sinusoidal spinning is not sensitive to the residual stress.

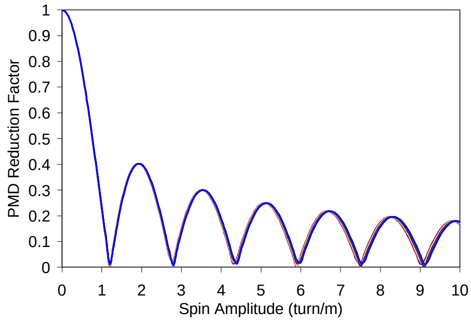

Figure 3. PMDRF change with spin amplitude for a sinusoidal spun fiber. The beatlength is 50 m. The spin period is 1 m.

The difference in response to the residual stress between the unidirectional and bidirectional spinning can be understood by examining residual stress evolution along the fiber. For unidirectional spin, Eq.(3) tells us that the stress is a constant for a constant spin amplitude. The stress effect accumulates linearly along the fiber, which contributes to the overall fiber PMD. For a sinusoidal spinning, the stress oscillates between a positive and negative value. The integration of the stress along the fiber is zero, which does not contribute to the overall fiber PMD.

Conclusions

In conclusion, we have studied effects of residual torsional stress on PMD reduction of unidirectional and bidirectional spun fibers. Numerical modeling results show that the residual stress can affect the PMD of unidirectional spun fiber significantly, especially for fibers with low intrinsic birefringence. On the other hand, bidirectional spun fibers are not affected by the residual stress.

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