The Effect of Hot-Wet Draw Ratio on the Coefficient of Friction of Wet-Spun Acrylic Yarns

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Synopsis

A series of wet-spun poly(acrylonitrile-co-vinyl acetate) yarns that were hot-wet stretched to a draw ratio range of 2.0 × – 7.0 × were made for study of surface morphology and frictional characteristics. These yarns show an increase in molecular orientation and structural compactness at the fiber surfaces with an increase in draw ratio. The fiber to fiber coefficient of friction, measured parallel (line contact), and perpendicular (point contact), increases with draw ratio, giving an excellent correlation between orientation and friction. The effects of hot-wet draw ratio on the surface structure and its frictional behavior are discussed.

INTRODUCTION

Frictional behavior of fibers greatly affects fiber assembly properties, processability, and performance in end use applications. Friction is a surface phenomenon and any factors that modify the surface could also be expected to influence its frictional behavior. Numerous studies have been devoted to measuring the coefficient of friction in fibers, either by sliding a fiber against another fiber or a fiber against another surface. The factors that have been studied thus far could be classified into two main groups, namely, fiber-related and operation-related. The former includes fiber roughness (as varied by addition of pigment), fiber denier, and the state of the surface. The latter includes such factors as the normal load, the sliding speed, the temperature, and the humidity. Little has been published in the area of the effect of structural factors on friction between two fibers. According to the well known Adhesion–Shearing theory of friction,[1] the force of friction between two surfaces is governed by the specific shear strength of the junctions and the true area of contact. Thus any factors that could affect these characteristics of fiber surface could also be expected to affect frictional properties of the fiber. One such factor is the molecular orientation whose effect has not been examined in detail earlier.

In this article, we describe the results of an investigation in which molecular orientation was varied systematically in acrylic yarns and its influence on interfiber friction studied.

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MATERIALS AND METHODS

Materials

The polymer used was a copolymer of acrylonitrile and vinyl acetate, containing about 7.45% by weight of the latter, with a weight average molecular weight of about 118,000. The polymer was dissolved in dimethylacetamide (DMAC) to give a dope containing 25% polymer by weight. The dope was spun in a laboratory-scale spinning line, shown in Figure 1. A positive displacement gear pump metered the dope at a constant volumetric flow rate through a 100 hole spinnerette immersed in a coagulation bath consisting of DMAC and water. The filaments emerge from the spinnerette with a certain jet velocity V_J, and are coagulated in the spin bath and taken up at velocity V_1 by the first rolls. They are washed with pure water and pulled through a boiling water bath by the second rolls at a velocity of V_2. Finally, they are dried at constant length by wrapping over the third hot rolls, rotating at the same speed as the second rolls, and wound up on a bobbin. The yarn is therefore drawn in two stages: (1) jet stretched in the spin bath with a draw ratio of V_1/V_J, and (2) cascade stretched in the orientation draw bath with a ratio of V_2/V_1. The overall draw ratio is, thus, the product of the two numbers, viz., V_2/V_J.

Yarns with different cascade stretches, but the same final denier, were produced by changing both the cascade and the jet stretches so that the overall draw ratio remained constant at 5.0 × (see Table I).

It should be noted that the orientation in the spin bath is generally negligible,[2] that is, the jet stretch is not expected to produce a significant change in yarn orientation. Thus, the majority of the change in molecular orientation is expected to result from a change in the cascade stretch.

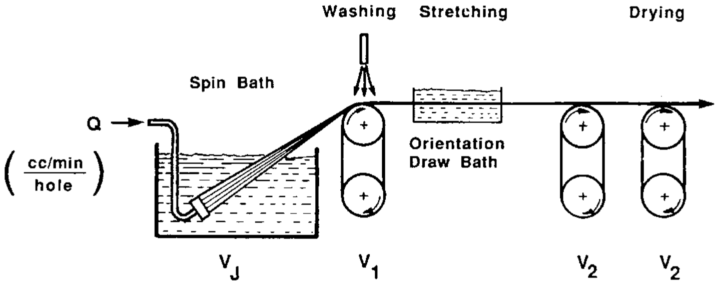


Fig. 1. Schematic diagram of laboratory wet spinning line.

TABLE I
Jet Stretch, Cascade Stretch, and Total Stretch Values of the Samples

Sample	Jet stretch	Cascade stretch	Total stretch
1	2.50	2	5.00
2	1.68	3	5.03
3	1.25	4	5.02
4	1.00	5	5.02
5	0.84	6	5.04
6	0.72	7	5.02

Methods

Sonic modulus has been used to effectively characterize the polymer chain orientation in acrylic fibers.[2-5] A parameter, "molecular orientation factor," α, has been proposed that is based on the values of sonic modulus and that gives an average value of orientation for all molecular segments in both crystalline and amorphous regions. This parameter is given by

$$\alpha = 1 - E_u/E \tag{1}$$

In this, E is the sonic modulus of partially oriented fiber and E_u is the sonic modulus of unoriented fiber. The sonic modulus tests were conducted on a dynamic modulus tester PPM-5R (marketed by H. M. Morgan Co.). E_u was determined by extrapolation of the curve giving sonic modulus dependence on the degree of shrinkage to 100% shrinkage. The value of E_u found for acrylic yarns was 2.65 N/tex (30 g_f/den). The value of the orientation factor α was calculated for various yarns of this investigation by using eq. (1) and this value of E_u.

The coefficient of friction is a material property in materials that deform plastically, but, in materials such as fibers that deform elastically or viscoelastically, it not only varies with the material properties but also with the applied normal force and mode of contact.[6] In this investigation, therefore, the coefficient of friction was measured by both the line and the point contact methods and, in each of these, at two different levels of normal force. For the line contact measurements, the twist method proposed by Gralén and Lindberg[7] was used. A simple device[8] adapted this method for use on Instron. Essentially, the method involves twisting two fibers together by a given number of turns (n), tensioning one end of each fiber by a given amount (T_0), and increasing the tension on the other ends to a value T at which slippage starts to occur. If β is the twist angle between the fibers, then the coefficient of interfiber friction, μ, is given by

$$\mu = (\pi n \beta)^{-1}(\ln T - \ln T_0) \tag{2}$$

For the point contact friction measurements, a modification of the classical capstan method[9] was utilized. A fiber was held in a bow and another passed over it at right angles (Fig. 2). The angle of wrap, θ, was kept very small. The very small diameter of the fiber combined with small angle of wrap restricted the area of contact to a very small value.

In this set up, thus, if T_0 is the fixed tension and T the tension required to slide one fiber over the other, then the coefficient of friction, μ, is given by

$$\mu = (\theta)^{-1}(\ln T - \ln T_0) \tag{3}$$

The measurement of friction by both the line and the point contact methods was carried out on an Instron machine using a rate of traverse of 0.5 in./min. A record of withdrawing tension against time gave a typical stickslip trace from which the average value of the tension T could be determined. This value was used in the above equations to calculate the values of the coefficient of friction.

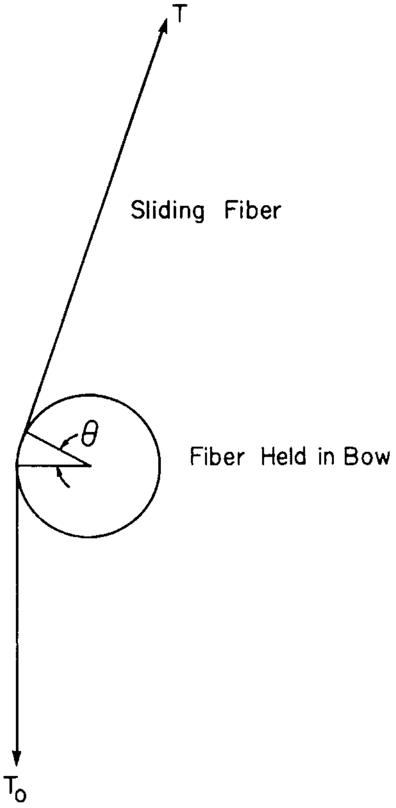


Fig. 2. Setup for the measurement of interfiber friction by the point contact method.

In general applications of textile fibers, the forces imposed are usually of small magnitude. It was, therefore, decided to carry out the present friction measurements against low forces. Accordingly, the values of T_0 used were 108 mN (11 g_f) and 245 mN (25 g_f), which gave tensions per unit linear density of approximately 4.9 and 11.1 mN/tex, respectively.

RESULTS AND DISCUSSION

Table II lists the average values of the coefficient of friction for the line and the point contact methods and for the two levels of the initial tensions. Also given in this table are the values of the sonic modulus orientation factor. The value of the orientation factor increased with cascade stretch, but the rate of increase gradually dropped with increase in stretch ratio as has been reported before.[1,3] The values of the coefficient of friction are plotted against orientation factor in Figure 3.

Some of the trends in these results (Table II, Fig. 3) are generally as to be expected. The value of μ is a function of the initial tension. A higher value of μ at lower value of T_0 is an expected result in viscoelastic materials. The line contact method yields a substantially higher value than the point contact method. These two results are an interesting demonstration of the fact that the coefficient of friction in viscoelastic materials is a highly technique-cum-

TABLE II
Effect of Cascade Stretch on the Sonic Modulus Orientation Factor and the Coefficients of Friction of the Yarns

			Average coefficient of friction			
			Line contact		Point contact	
Sample	Cascade stretch	Sonic modulus orientation factor	108 mN	245 mN	108 mN	245 mN
1	2 ×	0.6949	0.186	0.167	0.134	0.125
2	3 ×	0.7316	0.221	0.183	0.135	0.127
3	4 ×	0.7556	0.230	0.202	0.136	0.128
4	5 ×	0.7725	0.235	0.208	0.138	0.132
5	6 ×	0.7847	0.238	0.211	0.138	0.130
6	7 ×	0.7918	0.243	0.217	0.141	0.132

procedure dependent parameter. They also illustrate the fact that, for the frictional results in fibers to be meaningful, the conditions used in measuring friction should, as nearly as possible, simulate the conditions encountered in actual use. A structural model of the fiber friction developed recently by two of the authors (B. S. G and Y. E. E.)[10] show a direct relationship between the coefficient of friction and the geometric area of contact. The line contact method involving significantly larger area of contact, thus, could be expected to lead to a relatively higher value of the coefficient of friction.

The most interesting result of the study and the one that has not been observed before is, however, the effect molecular orientation produced on the value of the coefficient of friction. The increase in molecular orientation as characterized by the sonic orientation factor caused approximately a linear increase in coefficient of friction (Fig. 3). Linear regression equations fitted on

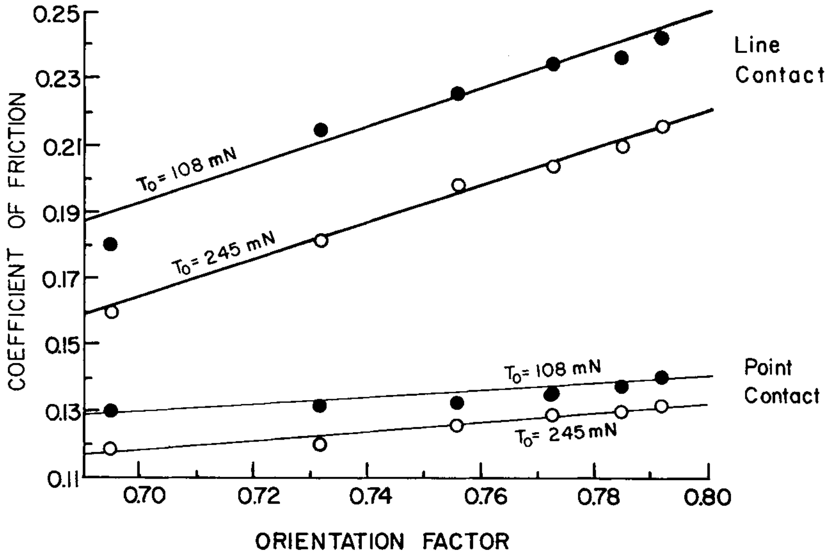
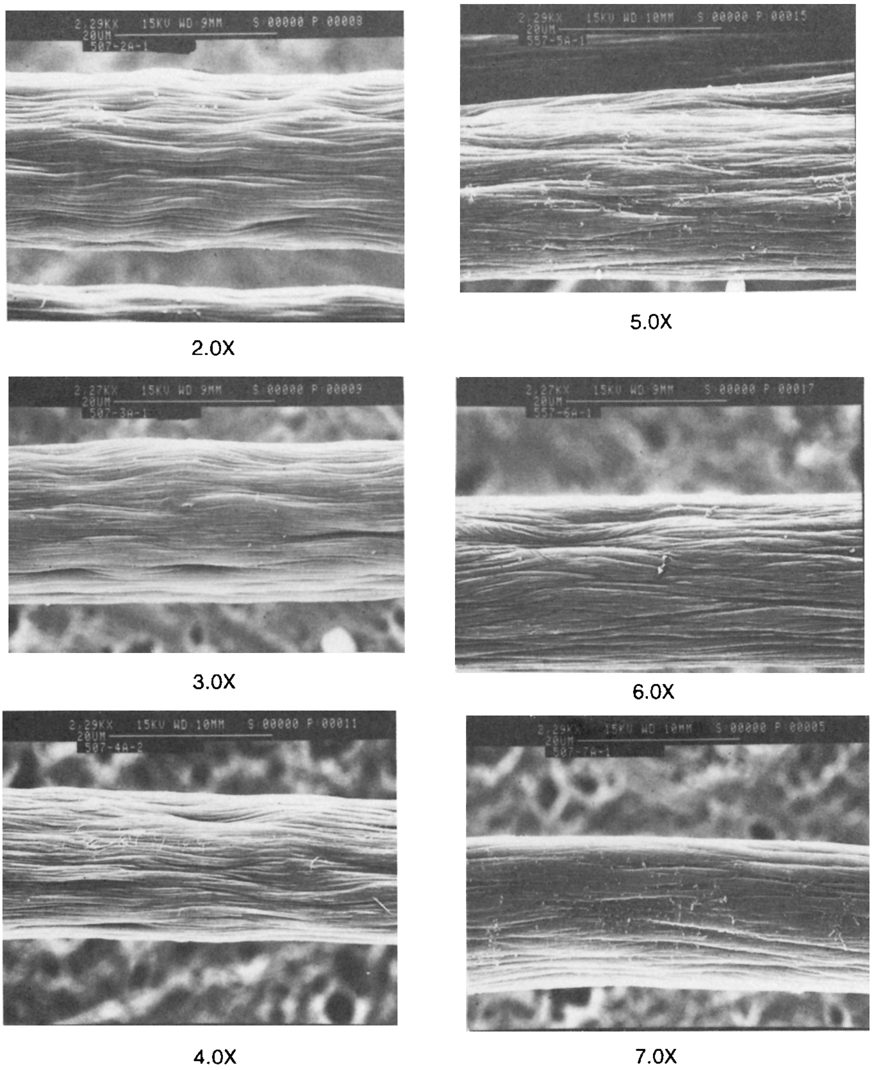


Fig. 3. Correlation between the sonic modulus orientation factor and the coefficient of interfiber friction.


2.0X 5.0X

3.0X 6.0X

4.0X 7.0X

Fig. 4. Scanning electron microscope photographs showing surface morphology of acrylic fibers giving different levels of cascade stretch.

the four sets of data provided correlation coefficients which ranged from 0.91 to 0.99.

The morphology of fiber surfaces was examined under SEM. Figure 4 includes micrographs of fibers spun with cascade stretch ratios of 2 × – 7 × . The morphology of the surface is seen to gradually change with stretch. With increase in the latter, the macrofibrils at the surface, formed during coagulation and collapse of the fiber skin in the earlier spinning stages, stretched out into alignment, packed more compactly, and made the surface smoother. This should bring two fibers into a more intimate contact at any given transverse pressure. The increase in the area of contact due to this reason could be expected to result in an increase in the value of the coefficient of friction. It is noteworthy that a greater portion of visual change in surface morphology took place as stretch ratio increased from 2 × to 4 × . This coincided directly with the rate of change that took place in the values of μ for the line contact with stretch ratio. From the line contact values in Table II one could show that approximately 70% of the total increase in μ occurred when stretch ratio increased from 2 × to 4 × and only about 30% of the change came with stretch ratio increase from 4 × to 7 × . In the point contact method, the total area of contact being very small and the contact being at right angle to the direction of molecular orientation, the effect of orientation and surface smoothening on the value of μ could not be expected to be as high, but the effect is present and is statistically significant.

CONCLUSIONS

A linear correlation is found between the molecular orientation, characterized by the sonic modulus orientation factor and the interfiber coefficient of friction in wet spun and hot-wet drawn acrylic yarns. Examination of surfaces under SEM brings to light the most plausible explanation for this relationship, namely, the smoothing out of the surface leading to a more intimate or greater area of contact with increased draw ratio. The mutual dependence of both molecular orientation and surface morphology on the hot–wet draw ratio points to the existence of an interrelationship between the structures at the microscopic and the macroscopic levels in these yarns, and, also importantly, to the availability of a convenient mechanism for effectively modifying surface properties with the cascade stretch process.

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