Temperature Effect on Frictional Force when an Acrylic Fiber is Pulled out of Parallel Fiber Bundles

Tooru Nogai, Motozoo Ihara and Yutaka Narumi*, Members, TMSJ

Faculty of Engineering, Shizuoka University, Hamamatsu, Shizuoka Pref.

Based on the Journal of the Textile Machinery Society of Japan, Transactions, Vol. 30, No. 7, T119-T124 (1977)

Abstract

Experiments were made in the temperature range from 20 to 100°C to determine the frictional force acting on an acrylic filament pulled out from paralleled fiber bundles of cotton, viscose rayon, or polyester fibers, and following results were obtained:

(1) The temperature influence on the frictional force varies according to the kinds of fibers. The friction when pulled out from cotton fiber bundles has the minimum at 80°C, while that from viscose rayon or polyester fiber bundles reaches the maximum at 80°C.

(2) The pulling out frictional force from fiber bundles, f_s (g/cm), is expressed by the equation:

$$f_s = K_0 P^\alpha$$

where P (g/cm²) is the external force applied on parallel fiber bundles, K_0 and α are experimental constants affected by the kinds of fibers, temperature, and compressive properties of fiber bundles.

1. Introduction

In our previous papers^[1,2], we measured the frictional force when fine metallic wires are drawn through parallel fiber bundles in the temperature range from 20°C to 130°C, and obtained the following relation

$$f = K (P/\sqrt{\xi})^\beta \quad \dots\dots\dots(1)$$

where f is the frictional force (g/cm), P the external pressure (g/cm²) applied on the bundle, ξ the volumetric ratio of the bundle, K and β are experimental constants.

In this paper, we measure the frictional force when an acrylic filament is pulled out from parallel fiber bundles of cotton, viscose rayon, or polyester fibers by the same way as reported in the previous paper^[2], and try to confirm whether or not eq. (1) is applicable to an acrylic filament. It is another purpose of us to obtain an experimental equation concerning the frictional force when the compressive characteristic is considered.

2. Experiment

2.1 Samples

Samples are made from card slivers of cotton (mean diameter: 18 μ m, mean fiber length: 30 mm, fiber density:

1.54 g/cm³), viscose rayon (11 μ m, 44 mm, 1.51 g/cm³) and polyester fibers (12 μ m, 38 mm, 1.38 g/cm³). After disentangling these slivers, we cut the slivers at the length 100 mm and put these in a rectangular channel (width: 40 mm, length: 100 mm, height: 50 mm). The sample weighing 7 g in general and 3 g in case of polyester fibers is first divided into two halves, and one of them is put in the channel. Then an acrylic filament (mean fiber diameter: 14 μ m) is put on the surface of the bundle, and then the remaining half is put in the channel.

In the case of viscose rayon and polyester fibers, such clean samples are used as the lubricants on which are removed by the same way as used in the previous paper^[2].

2.2 Experimental Apparatus and Procedure

The apparatus used in this study is the same as used in our previous study^[2].

The sample is stored in a oven kept at a constant temperature for 30 min, and then the experiment is started to measure the frictional force at the temperature between 20 and 100°C. The external pressure range is from 3.9 to 38.9 g/cm² in general, but from 1.9 to 19.3 g/cm² in case of polyester fibers.

The relation between the volumetric ratio ξ in eq. (1) and the height of the parallel fiber bundle h (cm) is expressed by

$$\xi = W (\rho Ah)^{-1} \quad \dots\dots\dots(2)$$

* Present Address: Aichi Institute of Technology, Toyota, Aichi Pref.

Table 1. Constants C and δ in eq. (3)

Sample	Cotton		Viscose rayon fiber				Polyester fiber			
Temp.	<i>C</i>	δ	non-cleaned <i>C</i>	δ	cleaned <i>C</i>	δ	non-cleaned <i>C</i>	δ	cleaned <i>C</i>	δ
20°C	1.2×10^{-2}	0.44	1.7×10^{-2}	0.42	2.0×10^{-2}	0.38	1.9×10^{-2}	0.46	1.8×10^{-2}	0.52
40	1.2	0.44	1.9	0.42	—	—	1.9	0.47	—	—
60	1.2	0.44	2.4	0.38	2.5	0.36	1.9	0.48	1.9	0.50
80	1.2	0.44	2.8	0.34	—	—	2.1	0.49	—	—
100	1.2	0.44	2.9	0.33	2.7	0.33	2.3	0.49	2.2	0.52

where W is the mass (g) of the sample, ρ the density (g/cm³), and A the crosssectional area (cm²) of the rectangular channel.

3. Experimental Results and Discussions

3.1 Relation between Volumetric Ratio and External Pressure

As in our previous paper^[1,2], the relation between ξ and P (g/cm²) is expressed by

$$\xi = CP^\delta \quad \dots\dots\dots(3)$$

Fig. 1 Relation between pulling out frictional force and external pressure

Fig. 2 Relation between pulling out frictional force and external pressure

where C and δ are experimental constants determined by the kind of fibers and the temperature, the numerical values of which are shown in Table 1.

The range of P in this study corresponds approximately to the low compression region reported in our previous paper^[5] roughly from 2 to 30 g/cm². Compared with that region, the values of C and δ in Table 1 are larger. It means that the bundles in this study are more easily compressed. It is thought that the deformation of fibers in the previous paper is more difficult than that of parallel fiber bundles in this study, because the arrangement of fibers in the previous paper is random. The change of C and δ in this study by temperature rise is less than that in the previous paper. It is thought this is due to the difference of the sample structure and experimental conditions, namely the compression in this study is done in the rectangular channel, while in the previous study is done without the container.

3.2 Frictional Force

The frictional force (abbreviated as W.F.F. in figures) for cotton fibers and viscose rayon fibers measured is shown in Figs. 1 and 2. f_s (g/cm) means the maximum static friction. Because the dynamic friction shows the same tendency as the static friction, only the case of the static friction is represented here.

From these figures, it is clear that f_s increases with the increase of P (g/cm²) concavely to the pressure axis. This almost agrees with the results for viscose rayon fiber bundles in the low pressure range obtained by S. Kinoshita et al., and shows the same tendency as in our previous study for fine metallic wires^[2].

The influence of temperature on f_s is shown in Fig. 3. f_s of viscose rayon and polyester fibers increases with temperature rise and decreases when the temperature is over 80°C. f_s of cotton fibers decreases with temperature rise, and increases when the temperature is over 80°C. This temperature 80°C at which the tendency of f_s changes is near the glass transition temperature of acrylic fibers^[4]. Even in the previous paper^[1], it is observed that the pulling out force changes abruptly at about that temperature when a fine metallic wire is pulled out from acrylic parallel fiber bundles. Therefore it is thought that the temperature

Fig. 3 Relation between pulling out frictional force and temperature

Fig. 4 Relation between pulling out frictional force and inter-fiber force parameter

dependency of f_s is affected strongly by the property of the material pulled out.

The relation between f_s and the inter-fiber parameter $P/\sqrt{\xi}$ (g/cm^2)^[2] is shown in Fig. 4. From this figure, eq. (1) is satisfied in the P region treated in this study. The same

tendency is obtained also in case of cotton and polyester fibers^[8,9]. So, the measured results are substituted into eq. (1), and experimental constants β and K are obtained as shown in Table 2.

Unlike the previous papers^[1,2], β varies with temperature similarly as K . But its tendency is different from K . Because the inter-fiber force parameter is determined by the compressive characteristic of each fiber bundle, it seems that the temperature dependency of β and K is different from that between f_s and temperature.

As for cotton fibers, the temperature dependency of β and K agrees with that of f_s , because their compressive characteristic does not vary with temperature. However, as the compressive characteristics of viscose rayon and polyester fibers depend on temperature, the temperature dependency of β and K is a little different. β of viscose rayon fibers has the same tendency as f_s , but their K becomes concave to the temperature axis and has the maximum value at about 40°C. β of polyester fibers has the inverse tendency to f_s , and K has the maximum value at about 60°C. Because the temperature at which each fiber has the maximum value of K agrees approximately with the glass transition temperature for each fiber composing the bundle, it is expected that K is a parameter depending on the surface nature of materials used for friction. Contrary to this, β seems to be a factor governing the mechanism of friction as mentioned in the previous paper, and is thought to depend on the property of the filament pulled-out.

3.3 Effect of Lubricants

The relations between f_s and P or the inter-fiber force parameter for cleaned viscose rayon fibers are shown in Figs. 5 and 6.

From Fig. 5, f_s seems to decrease a little with temperature rise. Compared with non-cleaned samples, the difference is large in the region at low temperature, and little in the region at high temperature. Samples of polyester fibers have a similar tendency in the region at low temperature.

From Fig. 6, eq. (1) seems to be satisfied also by cleaned samples of viscose rayon, fibers, and similarly by cleaned polyester samples. β and K are shown in Table 2. These

Table 2. Constants β and K in eq. (1)

Sample	Cotton		Viscose rayon fiber				Polyester fiber			
			non-cleaned		cleaned		non-cleaned		cleaned	
Temp.	β	K	β	K	β	K	β	K	β	K
20°C	0.76	7.8×10^{-3}	0.75	5.6×10^{-3}	0.098	2.8×10^{-3}	0.90	3.4×10^{-3}	0.90	3.0×10^{-3}
40	0.78	6.5	0.77	6.3	—	—	0.83	5.4	—	—
60	0.84	4.5	0.88	4.4	0.98	3.0	0.80	6.6	0.89	4.0
80	0.93	2.5	0.96	3.4	—	—	0.87	5.4	—	—
100	0.92	3.3	0.97	3.0	0.91	3.8	0.95	2.9	0.97	3.5

Fig. 5 Relation between pulling out frictional force and external pressure

values are different a little in case of non-cleaned samples.

As mentioned above, it is clear that the lubricant exerts influence upon the pulling-out friction.

In case of viscose fibers, the lubricant has low viscosity and is adhesive little because the most lubricant is animal^[2]. So, the friction is in the state of boundary lubrication. Therefore the frictional force decreases with increase of the lubricant viscosity, in other words, by lowering temperature. In case of polyester fibers, because antistatic agents are added to the lubricant in addition to slickners, the frictional behavior is in the state of hydrodynamic lubrication rather than the boundary lubrication. Therefore the frictional resistance increases with temperature rise.

3.4 Discussion

The relation between the surface frictional force f_d and the external pressure for general high polymer solids is represented by the following expression based on the adhesion theory;

$$f_d = aP^n \quad \dots\dots\dots(4)$$

where a and n are constants depending on the materials, and n is the value from (2/3) to 1.0.

It is clarified that eq. (4) is also satisfied in case of the friction between staple fibers. For example, Mazur^[10] showed that, by measuring the fiber fiber friction of nylon

Fig. 6 Relation between pulling out frictional force and inter-fiber force parameter

and viscose rayon fibers, n is between 0.80 and 0.94. Okajima et al.^[6] showed that eq. (4) is satisfied in case of the fiber to metal friction of rabbit fibers. Lord^[7] showed that eq. (4) is satisfied in case of the friction between cotton bouldes.

The relation between f_s and P is plotted on a logarithmic figure, by the data from Figs. 1 and 2, and a linear relation is obtained as follows:

$$f_s = K_0 P^\alpha \quad \dots\dots\dots(5)$$

K_0 and α calculated from experimental results are shown in Table 3. Eq. (5) is formally the same as eq. (4). Therefore the frictional mechanism is explained microscopically by the adhesion theory of general high polymer solids.

Substituting eq. (3) into eq. (1), and replacing K_0 and α with the following expressions

$$\left. \begin{aligned} K_0 &= KC^{-(\beta/2)} \\ \alpha &= (1 - \delta/2)\beta \end{aligned} \right\} \quad \dots\dots\dots(6)$$

eq. (1) becomes the same as eq. (5). Therefore it seems that eq. (1) expresses the frictional component and eq. (3) the compressive component of the pulling out frictional characteristic, respectively.

Table 3. Constants α and K_0 in eq. (5)

Sample	Cotton		Viscose rayon fiber				Polyester fiber			
	α	K_0	non-cleaned		cleaned		non-cleaned		cleaned	
Temp.			α	K_0	α	K_0	α	K_0	α	K_0
20°C	0.59	4.2×10^{-2}	0.59	2.6×10^{-2}	0.79	1.9×10^{-2}	0.69	2.0×10^{-2}	0.67	1.8×10^{-2}
40	0.61	3.6	0.61	2.9	—	—	0.63	2.8	—	—
60	0.66	2.9	0.71	2.3	0.80	1.8	0.63	3.2	0.67	2.3
80	0.73	1.9	0.80	1.9	—	—	0.66	2.9	—	—
100	0.72	2.5	0.81	1.6	0.76	2.0	0.72	1.8	0.73	2.2

5. Conclusion

We investigate experimentally the temperature dependency of the frictional characteristic when an acrylic filament is pulled out from parallel fiber bundles made of cotton, viscose rayon and polyester fibers, and the following results are obtained:

(1) The temperature influence on the frictional force varies according to the kinds of fibers. The frictional force when pulled out from cotton fiber bundles has the minimum value at 80°C, while that from viscose rayon and polyester fiber bundles reaches the maximum at 80°C.

(2) The pulling out frictional force f_s (g/cm) for each fiber is expressed by a power function of the inter-fiber force parameter ($P/\sqrt{\xi}$).

(3) Substituting the compressive characteristic of parallel fiber bundles to the inter-fiber force parameter, f_s is denoted as a power function of the external pressure;

$$f_s = K_0 P^\alpha$$

where K_0 and α are experimental constants. From this, it can be deduced that the pulling out friction is the aggregate of the fiber fiber frictional phenomena based on the adhesive theory.

(4) The effect of lubricant is large, and the temperature dependency of the frictional force varies with the viscosity

and add-on of lubricant.

We thank to Hamamatsu members of Nisshin Spinning Co., Ltd., who offered slivers used in this study, and Messrs. H. Hattori, K. Mimura, T. Kimura and K. Mihara who carried on the experiments together with us.

Literature Cited

- [1] T. Nogai, Y. Narumi; *J. Text. Mach. Soc. Japan*, **26**, T84 (1973)
- [2] T. Nogai, Y. Narumi, M. Ihara; *ibid.*, **27**, T65 (1974)
- [3] S. Kinoshita, T. Takizawa; *Sen-i Gakkaishi*, **15**, 455 (1959)
- [4] Handbook of Fibers, Part of Materials, 251, Sen-i Gakkai (Maruzen)
- [5] T. Nogai, Y. Narumi; *J. Text. Mach. Soc. Japan*, **25**, T180 (1972)
- [6] S. Okajima, S. Ikeda, T. Inoue; *Sen-i Gakkaishi*, **14**, 400 (1958)
- [7] E. Lord; *J. Text. Inst.*, **46**, P41 (1955)
- [8] T. Nogai, Y. Narumi, M. Ihara; Print presented at the 29th Annual Meeting of the Text. Mach. Soc. Japan, 49 (1976)
- [9] T. Nogai, Y. Narumi; Print presented at the 28th Annual Meeting of the Text. Mach. Soc. Japan, 39 (1975)
- [10] J. Mazur; *J. Text. Inst.*, **46**, T712 (1955)