Draft-Cut Wave in Direct Spinning System

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Abstract

Draft-cut length and draft-cut wave are theoretically and experimentally described in this article. Draft-cut length is affected by the draft ratio, breaking elongation and the draft-cut position in which a fiber is broken. Major causes for draft-cut wave are the change and distribution of the breaking position of a fiber in the draft-cut zone.

1. Introduction

The length of fibers broken in the draft-cut system and the draft-cut wave produced in the draft-cut process have been investigated. It is hoped that this inquiry into the reason why the draft-cut wave occurs in the draft-cut process will help in the analysis of experimental results and in the development of direct spinning machines.

The following symbols are used:

- B : Back roller or back roller nip
- b : Drafted length or net drafted length (mm)
- D : Draft ratio
- D_n : Net draft ratio
- E : Mean modulus of elasticity before the fiber is broken (g/den)
- F : Front roller or front roller nip
- h : Distance from front roller nip to breaking position (mm)
- h_0 : Roller gauge (mm)
- h_n : Nip length (mm)
- L_p : Length of period of draft-cut wave (mm)
- l : Length of fiber (mm)
- n_0 : Number of fibers in tow
- n_s : Number of fibers in draft-cut sliver
- p : Tensile stress of a single fiber (g/den)
- p_c : Breaking stress of a single fiber (g/den)
- r : Degree of elasticity
- w : Weight of unit length of draft-cut sliver (mg/cm)
- w_0 : Weight of unit length of tow (mg/cm)
- $\bar{w}$: Mean weight of unit length of draft-cut sliver (mg/cm)
- x : Extruded length from front roller (mm)
- x_c : Extruded length when the fiber is broken (mm)
- ϵ_c : Mean breaking elongation of a single fiber

2. Draft-Cut Length of Fiber

Fig. 1 shows the process of stretching and breaking a single fiber in tow. The fiber in tow is straightened and its leading end proceeds to the front roller nip because the front roller speed exceeds the back roller speed and the front of the fiber is surrounded by higher-speed fibers and the rear of fiber is surrounded by lower-speed fibers (see Fig. (b)).

The fiber in Fig. (b) continues to proceed and its leading end reaches the nip of the front roller. The

Fig. 1 Draft-cutting of single fiber

tensile stress in the fiber is negligible until its leading end is nipped by the front roller. The leading end of the fiber nipped by the front roller continues to be extruded out of the front roller but the rear of the fiber is supplied continuously from the back roller into the draft-cut zone. Because the speed of the front roller exceeds the speed of the back roller, the fiber in the draft-cut zone receives tensile stress. When the tensile stress in this fiber reaches the breaking stress, the fiber is broken as shown in Fig. 1 (e). The broken fiber is unloaded from the tensile stress and shrinks again to its original length (see Fig. 1 (f)).

The broken fiber nipped by the front roller is extruded and the fiber nipped by the back roller is again stretched, broken and drafted in the same process as in Fig. 1 (a~f). The draft-cut fiber is equal in length to the fiber nipped by the front roller shown in Fig. 1(f). Only a single fiber in a fiber bundle is considered in this explanation, but it is not unreasonable to think that the many other fibers are also processed in the same manner.

2-1. Theoretical investigation of draft-cut length

When the front roller rotates over the distance (s) and the back roller rotates over the distance (s/D), the length of the fiber extruded from the front roller is not equal to (s) but equal to (x) which is smaller than (s). The tensile stress (P) of the fiber in the draft-cut zone at this time is expressed by the following equation:

$$P = E \frac{x - \frac{s}{D}}{h - x + \frac{s}{D}}$$

The following expression is given between the element of distance (ds) of the front roller rotation and the element of the extruded length (dx) of the fiber.

$$P = E \frac{ds - dx}{ds}$$

With the aid of these equations, the following formula for calculating the draft-cut length is given:

$$\frac{l}{h_0} = \left\{ \varepsilon_c(1-r) + 1 \right\} \left[\frac{\varepsilon_c + \frac{h}{h_0}}{1 + \varepsilon_c} - \frac{1}{D} \log \left\{ \frac{\frac{D}{1 + \varepsilon_c} + 1}{D - 1} \right\} \right] \quad \dots\dots (1)$$

(a) Maximum length of draft-cut fiber

When a fiber is broken at the back roller nip, its draft-cut length is maximum and equal to the extruded length and the length of the fiber that

exists in the draft-cut zone.

$$l = l_{max} \text{ for } h = h_0$$

$$\frac{l_{max}}{h_0} = \left\{ \varepsilon_c(1-r) + 1 \right\} \times \left[1 - \frac{1}{D} \log \left\{ \frac{\frac{D}{1 + \varepsilon_c} + 1}{D - 1} \right\} \right] \quad \dots\dots (2)$$

(b) Minimum length of draft-cut fiber

When a fiber is broken at the front roller nip, its draft-cut length is minimum and equal to the extruded length of the fiber.

$$l = l_{min} \text{ for } h = 0$$

$$\frac{l_{min}}{h} = \left\{ \varepsilon_c(1-r) + 1 \right\} \left[\frac{\varepsilon_c}{1 + \varepsilon_c} - \frac{1}{D} \log \left\{ \frac{\frac{D}{1 + \varepsilon_c} + 1}{D - 1} \right\} \right] \quad \dots\dots (3)$$

(c) Approximated formula for calculating the draft-cut length of fiber

The breaking elongation of a fiber, as far as our present discussion is concerned, is about 0.1~0.2 and the degree of elasticity (r) is nearly equal to unity, i.e., $r=1$. To break the fiber in the draft-cut zone, the draft ratio must exceed $(1+\varepsilon_c)$. When the draft ratio is below $(1+\varepsilon_c)$, the fiber in the draft-cut zone is not broken but only stretched. The values of (r), (ε_c) and (d) have the range mentioned above, and eqs.(2) and (3) can, therefore, be approximated as follows:

$$\frac{l_{max}}{h_0} = -\frac{D-1}{D-(1+\varepsilon_c)} \quad \dots\dots (4)$$

$$\frac{l_{min}}{h_n} = \frac{\varepsilon_c}{1 + \varepsilon_c} \times \frac{D}{D-(1+\varepsilon_c)} \quad \dots\dots (5)$$

$$l_{max} = \infty, \quad l_{min} = \infty \quad \text{for } D = 1 + \varepsilon_c.$$

2-2. Experiments on draft-cut length

Figs. 2 and 3 show the maximum, minimum and mean lengths of a draft-cut fiber. These values are divided by the nip length. The curves for l_{max}/h_n , l_{min}/h_n in these figures are calculated by formulas (4) and (5).

Here, $\varepsilon_c = 12.66$ for 1.2×4000 den. tow
 $\varepsilon_c = 12.06$ for 1.5×4000 den. tow
 $h_0 = h_n + 10$ (mm)

The draft-cut length of a fiber decreases hyperbolically with an increase in the value of $(D+1)$. The curves for the fiber length drop steeply between the values $D=1.5$ and $D=5$ and stop decreasing when the draft ratio reaches the value $D=10$.

When the staple diagram of a draft-cut sliver

has, theoretically, a trapezoidal form, its mean length is denoted by the following expression :

$$\frac{l_{mean}}{h_n} = 0.5 \left(\frac{l_{max}}{h_n} + \frac{l_{min}}{h_n} \right)$$

$$\frac{l_{mean}}{h_n} = 0.5 \frac{(D-1)(1+\epsilon_e) + D\epsilon_e}{(1+\epsilon_e)\{D-(1+\epsilon_e)\}}$$

Fig. 2 Draft-cut length

Generally, a staple diagram obtained by experiments has not a trapezoidal form, and the mean length of fibers obtained by experiments had better be expressed by the following formula :

$$\frac{l_{mean}}{h_0} = K \frac{(D-1)(1+\epsilon_e) + D\epsilon_e}{(1+\epsilon_e)\{D-(1+\epsilon_e)\}} \quad \dots\dots (6)$$

Fig. 3 Draft-cut length

Fig. 4 Draft-cut length and nip length

Fig. 5 Draft-cut length and nip length

Now, when the constant K is below 0.5, the experimental staple diagram has more short fibers than does a trapezoidal staple diagram. When the value K is above 0.5, the experimental staple diagram has more long fibers than does a trapezoidal staple diagram. In this experiment,

$$K=0.471 \quad \text{for } 1.2 \times 4000 \text{ den. tow}$$

$$K=0.457 \quad \text{for } 1.5 \times 4000 \text{ den. tow.}$$

The experimental value K is about 7% below the theoretical $K=0.5$. The curves l_{max}/h_n in Figs. 2 and 3 are drawn with the experimental value K shown above.

a) Relation between draft-cut length and nip length

Roller gauge h_0 is a distance from the center of the front roller nip to the center of the back roller nip. The length of the draft-cut zone is theoretically equal to roller gauge h_0 . In practice, the length of the draft-cut zone is not equal to the roller gauge, because the top roller covered with rubber is deformed by contact with the bottom roller under high pressure. The actual length of the draft-cut zone is equal to the length of the difference between the roller gauge and the nip width. The length of this difference is called the nip width (or nip length). This nip width, in our experiments, is a constant 10 mm. Figs. 4 and 5 show that the draft-cut length is proportional to the nip length.

3. Draft-Cut Wave in Fiber Bundle

Now to look into the reason why the draft-cut wave occurs in the draft-cut process. This inquiry, it is hoped, will help in the analysis of experimental results or in the investigation of the performance of a direct spinning machine.

The draft-cut system converts tow into slivers in three stages of process—stretching, breaking and drafting. The drafting process is closely related to the breaking position. Fibers broken in the back of the draft-cut zone are highly drafted. Fibers broken at the front receive low drafting. The breaking position distributes over the whole or part of the draft-cut zone. Therefore, the amount of draft (net draft or drafted length) varies with the breaking position. Variations in the amount of draft are the greatest factor conducive to the draft-cut wave in the draft-cut system. The draft-cut wave is generated even if tow has no thickness variations.

3-1. Variations in net draft ratio as a cause for the draft-cut wave

Assume that, when the filaments of tow are broken in an arbitrary position, the fiber nipped by the front roller shrinks to length l_f' , and that the fiber nipped by the back roller shrinks to length l_b' . Fiber-lengths l_f' and l_b' , then, are denoted by the following expressions:

$$l_f' = \frac{h}{1+\epsilon_c} \left\{ \epsilon_c(1+r) + 1 \right\}$$

$$l_b' = (h_0 - h) \frac{\epsilon_c(1-r) + 1}{\epsilon_c + 1}$$

The distance between the tail of fiber l_f' and the leading end of fiber l_b' is calculated thus:

$$h_0 - (l_f' + l_b') = \frac{\epsilon_c r}{\epsilon_c + 1} h_0$$

The distance $h_0 \epsilon_c r / (\epsilon_c + 1)$ results from the recovery elongation of fibers after breaking, not from draft.

Fig. 6 Calculation of the length of net draft

"The amount of net draft" is the definition we give to the distance between the tail end of fiber l_f' and the leading end of fiber l_b' when the latter reaches the nip point of the front roller. The amount (length) of net draft is calculated as follows: The leading end of fiber l_b' exactly reaches the front roller nip after the time $(h_0 - l_b')/v_B$ (sec) and the tail end of fiber l_f' proceeds, in that time, over the distance

$$\left(\frac{h_0 - l_b'}{v_B} - \frac{l_f'}{v_F} \right) \times v_F$$

apart from the front roller nip. Therefore, this distance represents the amount of net draft.

Assuming the amount of the net draft to be equal to $h_0(D_n-1)$, the following equation is obtainable:

$$h_0(D_n-1) = \left(\frac{h_0-l_b'}{v_R} - \frac{l_f'}{v_F} \right) \times v_F = D(h_0-l_b')-l_f'$$

By substituting the value of l_f' and l_b' in the foregoing equation, the net draft ratio is determined as follows:

$$D_n = (D-1) \times \frac{h}{h_0} \times \frac{\varepsilon_c(1-r)+1}{\varepsilon_c+1} + D \frac{\varepsilon_c r}{\varepsilon_c+1} + 1. \quad \dots (7)$$

The net draft ratio (D_n), then, varies with the change of the breaking position (h/h_0). For example, when the filament is broken at the back roller nip ($h=h_0$), the net draft ratio (D_n) slightly exceeds the draft ratio (D).

$$D_n = D + \frac{\varepsilon_c r}{\varepsilon_c+1} > D.$$

Since the amount of the net draft includes the distance resulting from the shrinkage of broken fiber, the net draft ratio (D_n) is larger than the draft ratio (D). When the filament is broken at the front roller nip ($h=0$), the net draft ratio (D_n) is very small compared with the draft ratio (D).

$$D_n = 1 + D \frac{\varepsilon_c r}{\varepsilon_c+1} < D.$$

Fig. 7 is drawn with eq.(7). Variations in the net draft ratio are clearly expressed relative to

Fig. 7 Variations in net draft ratio with change of breaking position

the breaking position. The degree of elasticity (r) of a fiber and the breaking elongation (ε_c) has only slight effects on the variations in net draft. Long fibers broken in the back are drafted heavily; short fibers broken in front are drafted slightly. Thus, variations in net draft (D_n) with the change of the breaking position are one of the principal causes for the draft-cut wave in the draft-cut process.

3-2. Concentrated breakage of fibers in one position

All fibers are equal in length when tow is broken continuously in a fixed position in the draft-cut zone. By arranging broken fibers along the length of a sliver as shown in Fig. 8, we obtain a series of parallelograms made of fibers. The number of fibers contained in the parallelograms is equal to the number of fibers in tow, and the distance between parallelograms is equal to $h_0(D_n-1)=b$, which is defined as the amount of net draft.

Fig. 8 Draft-cut diagram

One of the parallelograms built of fibers is defined as, and called, an "element of draft-cut diagram." The arrangement of fiber parallelograms shown in Fig. 8 is called the draft-cut diagram. It expresses the fiber length, the number of fibers in a cross section of a sliver and the draft-cut process. By connecting the draft-cut diagrams with one another, we get the draft-cut sliver diagram (Fig. 9). The draft-cut sliver diagram shows the length of a fiber and the number of fibers in a cross section of the sliver. The inclination of the sliver diagram depends on net draft. If the net draft ratio is high, the slope of the sliver diagram approaches the level.

Fig. 9 Draft-cut sliver diagram

When the breaking positions are concentrated, the length and number of fibers in a cross section of a sliver are constant, and the sliver has no draft-cut wave. The number of fibers (n_s) in the sliver can be calculated with the draft-cut diagram shown in Fig. 10.

Fig. 10 Calculation of the number of fiber in sliver

$$\frac{n_s}{n_0} = \frac{l}{l+b}$$

while

$$\frac{b}{h_0} = (D_n - 1) = (D - 1) \frac{h}{h_0} \times \frac{\varepsilon_c(1+r)+1}{\varepsilon_c+1} + D \frac{\varepsilon_c r}{\varepsilon_c+1}$$

and

$$\frac{l}{h_0} = \left\{ \varepsilon_c(1-r)+1 \right\} \left\{ \frac{\varepsilon_c + (h/h_0)}{\varepsilon_c+1} - \frac{1}{D} \log \frac{D - (\varepsilon_c+1)}{(D-1)(\varepsilon_c+1)} \right\}$$

then

$$\begin{aligned} \frac{n_s}{n_0} = & \left[\left\{ \varepsilon_c(1-r)+1 \right\} \left\{ \frac{\varepsilon_c + (h/h_0)}{\varepsilon_c+1} - \frac{1}{D} \log \frac{D - (\varepsilon_c+1)}{(D-1)(\varepsilon_c+1)} \right\} \right] \div \left[\left\{ \varepsilon_c(1-r)+1 \right\} \right. \\ & \left. \left\{ \frac{\varepsilon_c + (h/h_0)}{\varepsilon_c+1} - \frac{1}{D} \log \frac{D - (\varepsilon_c+1)}{(D-1)(\varepsilon_c+1)} \right\} \right. \\ & \left. + D \frac{\varepsilon_c r}{\varepsilon_c+1} + D \frac{h \{ \varepsilon_c(1-r)+1 \}}{h_0(\varepsilon_c+1)} \right] \dots (8) \end{aligned}$$

Even if the breaking positions are fixed, sliver thickness varies with the draft ratio.

Fig. 11 shows the variations in the thickness of a sliver as concerns the breaking position and the draft ratio. Slivers whose fibers are broken at the front of the draft-cut zone are about 10~30% thicker than slivers whose fibers are broken in the back. The explanation is that fibers broken at the front receive a low net draft, while fibers broken in the back receive a high net draft. However, if the draft

Fig. 11 Variations in thickness of sliver as relates to breaking position

ratio is high, *e.g.*, $D=10$, and the breaking positions of filaments range between $h/h_0=0.5$ and 1.0, (back half of the draft-cut zone), the thickness of the sliver is nearly uniform.

3-2. Uniform distribution of breaking positions

Other typical distributions of breaking positions are, in our opinion, these: (1) a case where breaking positions change their locations, (2) a case where the breaking number of fibers changes in time, (3) a case where the breaking positions having a uniform distribution over a certain range and (4) a case where the breaking positions distributes generally in the draft-cut zone. In these cases, the causes and features of the draft-cut wave can be theoretically described. In this article, however, only the results of theoretical investigation with a uniform distribution of the breaking positions are described.

If breaking positions have a uniform distribution as a mean in time, breakings ought to take place in all positions in the distributing range at any moment. Therefore, an element of the draft-cut diagram must be a trapezoidal form if the breaking positions change their locations.

A uniform distribution of breaking positions is analogous to a case where breaking positions change their locations periodically within the distribution range.

To simplify the description, assume that breaking positions change rapidly from one end to the other

in the distributing range while the number of breakages becomes equal to the number of filaments in tow. The draft-cut diagram, in this case, is shown by Fig. 2(a). The left-end element of the draft-cut diagram shows that breaking positions change their locations rapidly from back to front. The second element shows that breaking positions change their locations from front to back. The above process is repeated. The fiber length l , l' and the length of net draft b , b' are calculable.

The draft-cut sliver diagram in Fig. 12(b) is built by two characteristic curves: one wave-like, the other approximately straight.

Fig. 12(c), drawn from the draft-cut sliver diagram, shows thickness variations of a sliver and the structure of fibers in the sliver. The curve is characterized by a tendency to have a low gradient on one side and to be steep on the other. There are comparatively many short fibers in the neck of the sliver.

The ratio of the maximum number of fibers in a cross section of a sliver to the mean number of fibers, the ratio of the minimum number of fibers to the mean number of fibers, variations in the draft-cut wave and the length of the period of the draft-cut wave can be calculated theoretically by the following expressions, obtained from Figs. 12 and 13:

Fig. 12

Fig. 13

$$\frac{n_{max}}{n_{mean}} = \frac{D}{1 + \frac{D\epsilon_c \{D - (1 + \epsilon_c)\}}{(D-1)(1 + \epsilon_c)}} \quad \dots\dots (9)$$

$$\frac{n_{min}}{n_{mean}} = \frac{D}{1 + \frac{\{D(1 + \epsilon_c) - 1\} \{D - (1 + \epsilon_c)\}}{D\epsilon_c}} \quad \dots\dots (10)$$

$$\frac{n_{max} - n_{min}}{n_{mean}} = D \frac{1}{1 + \frac{D\epsilon_c \{D + (1 + \epsilon_c)\}}{(D-1)(1 + \epsilon_c)}} - \frac{1}{1 + \frac{\{D(1 + \epsilon_c) - 1\} \{D - (1 + \epsilon_c)\}}{D\epsilon_c}} \quad \dots\dots (11)$$

$$\frac{L_p}{h_0} = \frac{(D-1)(1 + \epsilon_c) + D\epsilon_c}{(1 + \epsilon_c) \{D - (1 + \epsilon_c)\}} + \frac{\{D(1 + \epsilon_c) - 1\} + D\epsilon_c}{(1 + \epsilon_c)} \quad \dots\dots (12)$$

3-3. Experiments on draft-cut wave

The draft-cut wave is theoretically defined as a periodic variation in number of fiber in a cross section of draft-cut sliver, but actually it is more convenient to consider it as a periodic variation of the weight of the unit length of a draft-cut sliver. If the specific weight of fibers in a sliver are all equal, the variations in cross-sectional number of fibers is proportional to the variations in the weight of the unit length of a draft-cut sliver.

a) Mean value of draft-cut wave

In this experiments, the variations in weight of the unit length of a draft-cut sliver are measured as the draft-cut wave. The mean weight of the unit length of a draft-cut sliver is not equal to the value (w_0/D) (w_0 is the mean weight of the unit length of tow) but equal to the value (w_0/D_n) (here (D_n) is the mean net draft ratio).

When breaking positions distribute uniformly over the whole of the draft-cut zone, the mean net draft ratio (D_n) is expressed by the following equation:

$$\bar{D}_n = \frac{2\varepsilon_e + 1}{2(\varepsilon_e + 1)} (D+1)$$

Put $D=2\sim 8$ and $\varepsilon_e=0.12$, then the mean value of net draft ratio

$$D_n = 0.533(D+1) = 1.7 \sim 5.0$$

is obtained.

When the draft ratio is $D=2$, 85% of the draft ratio is used to shuffle (or drafting) draft-cut fibers and the other 15% to stretch and break fibers. When the draft ratio is $D=8$, the net draft ratio is only 63% of the draft ratio.

The mean net draft ratio (D_n) is smaller than the draft ratio (D) and is ordinarily about 15~63% of the draft ratio. Accordingly, the mean weight of the unit length of a sliver exceeds the weight (w_o/D).

Fig. 14

Fig. 15

Figs. 14 and 15 show the experimental results on the mean weight of the unit length of sliver; it is obviously larger than (w_o/D). The theoretical ratio of the mean weight of the unit length of the draft-cut sliver to the mean weight of the unit length of tow is expressed by the following formula:

$$\frac{\bar{w}}{w_o} = \frac{1}{\frac{1}{2} \left(1 + \frac{\varepsilon_e}{1 + \varepsilon_e} \right) (D+1)}$$

The calculated ratio is as follows:

$$\frac{\bar{w}}{w_o} = \frac{1}{0.6(D+1)}$$

and experimental ratio is:

$$\frac{\bar{w}}{w_o} = \frac{1}{0.7(D+1)}$$

Fig. 16

Fig. 17

The experimental mean weight of a sliver is about 20% smaller than its theoretical weight.

b) Maximum and minimum values of draft-cut wave

The maximum and minimum weights of the unit length of a sliver, w_{max} (mg/cm) w_{min} (mg/cm), are plotted in Figs. 16 and 17. These weights of a sliver decrease with an increase in the draft ratio. The mean weight of sliver, as we have already said, exists between these two curves.

c) Variations in draft-cut wave

Variations in the draft-cut wave are defined by the following expression in this article:

$$(\text{Variations in draft cut wave}) = \frac{w_{max} - w_{min}}{w}$$

Fig. 18 shows experimental results on variations in the weight of the draft-cut wave as relates to the draft-cut ratio.

Fig. 18

Formula (11) is for investigating variations in the draft-cut wave when breaking positions distribute uniformly in the draft-cut zone, but the experimental results were obtained when the breaking positions did not always distribute uniformly in the draft-cut zone. Accordingly, variations obtained from experiments are much smaller than those obtained by calculation. The experimental values are about one sixth of the calculated values. Formula (11) gives the maximum variation theoretically conceivable.

d) Length of period of draft-cut wave

The theoretical length of the period of the draft-cut wave is expressed by the following formula:

$$L_p = (l_{max} + b_{max}) + (l_{min} + b_{min}).$$

and the theoretical mean length of the period of the draft-cut wave is as follows:

$$\frac{\bar{L}_p}{h_n} = \frac{(D-1)(1+\epsilon_e) + D\epsilon_e}{(1+\epsilon_e)\{D-(1-\epsilon_e)\}} + \frac{D\epsilon_e + \{D(1+\epsilon_e)-1\}}{(1+\epsilon_e)}$$

Fig. 19 shows that the experimental mean length of the period coincides fairly well with its calculated length. From these experimental values the following relation is obtained:

$$L_p = h_n \times D.$$

Fig. 19

4. Summing Up

The characteristics and the mechanisms of the generation of the draft-cut wave produced in the draft-cut process has been investigated. In a direct spinning machine or a draft-cut machine in service, the draft-cut wave occurs in more complex manner. The investigation, it is hoped, will help in inquiry into the causes for the draft-cut wave or in efforts to improve the direct spinning machine.

The conclusions deducible from the above investigations are: The process of the draft-cut may be divided into three stages—stretching, breaking and drafting. A part of the draft ratio works as the stretching and breaking processes. The draft-cut wave is explained by the net draft ratio, which is lower than the draft ratio and has a close relation with the breaking position of filaments. This is the first reason why a draft-cut sliver has a draft-cut wave in it.