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Investigation of Fibre Tension and Fibre Breakage in Simulated Fibre Opening Processes

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Abstract

To reveal the mechanism of fibre damage and breakage in the fibre opening processes, the fibre tension during the interaction between a fibre and a pinned beater has been investigated. Details of the interacting force variations and incident of fibre breakage have been closely examined. Many factors which influence the fibre/pin interacting force have been elucidated. The results highlight the causes of fibre damage and breakage by fibre/pin interactions.

1. Introduction

Much work has been directed towards identifying the mechanisms of fibre breakage in fibre processing stages, such as carding and combing [eg. 1-8]. In a previous study [4,6], pinned beaters were used to simulate the clothed opening rollers, such as the doffer, swift, worker, stripper and comb cylinder. The effect of fibre length, in contact with the beater surface, was discussed only in the case of combing, under the conditions of a relatively short contact length and low combing speed (less than 6.1 m/s). In other processes, such as carding, the fibre contact length (the fibre length in the pin domain) might be longer than the length of a fibre fringe in the comb cylinder, and the fibre/pin interacting speed can be much higher. The picture of fibre/pin interactions at different fibre contact lengths in the pin domain, and at different beater speeds is far from clear.

The frictional force between a fibre and a roller, as expressed by the Equation 1, is closely related to the fibre contact angle with the roller.

\[ \text{Friction force} = F_0 e^{\mu \theta} - F_0 \]

Where
- \( F_0 \), Pre-tension;
- \( \mu \), Frictional coefficient;
- \( \theta \), Contact angle.

In a fibre opening process, however, the fibre-beater interaction is more complicated than the fibre-roller abrasion described above, as the beater is normally covered with metal pins and in most cases \( F_0 = 0 \). It is important to investigate the interacting force between a fibre and the pinned beater, which, to a large extent, determines the fibre damage and breakage during the fibre processing.
It is therefore necessary to conduct a further study to find out the role of pins on the fibre damage and breakage under more extensive conditions with detailed analysis of fibre tension.

To reveal the mechanisms of fibre damage and breakage, the forces experienced by individual fibres during the fibre/beater interaction were measured by a sensitive force transducer and a high speed data acquisition system. The details of fibre breakage and variation of interacting force were captured. The effects of the fibre contact length and the beater speed on fibre/pin interaction forces were investigated. Both the maximum and average fibre interacting forces during fibre/beater interaction were examined.

2. Experimental

2.1 Materials

Three types of fibres, 9 denier polyester filament, mohair fibre and 23μ merino wool fibre, were used in this investigation. All the experiments were carried out under the conditions of (65±5)% r.h. and (20±2)°C.

2.2 Testing system

Figure 1 shows a schematic diagram of the experimental set-up. A Saw-Tooth type Beater (STB) or a Pin/needle type Beater (PB), constructed by previous researchers [4,6] were used to simulate pinned opening rollers. The interaction between the small pinned-beater and a single fibre (or an entangled fibre) was assumed to be a simulated action during the fibre opening process. The highest beater speed was up to 7000 rpm, corresponding to a surface speed of 21.3 m/s (Table 1), which a modern carding machine could possibly reach.

![Figure 1 Experimental set up](image)

A fibre end was attached to a sensitive transducer with a natural frequency of 4 KHz. Leaving a gap of about 25 mm between the head of the transducer and the first fibre contact point with the beater, the rest of the fibre was placed in the pin domain of the pinned beater, alone the beater rotary direction \( \omega \), when the beater was in a static state. The beater was driven by a motor, which
was controlled by an FVR-K7S-EX FUJI programmable inverter. To ensure that the tension signal was acquired at the right time, a synchronous control signal was passed to the computer, when the motor was started. The fibre tension was sensed and converted to an electrical signal during the fibre/beater interaction. The signal was then conditioned, filtered, and finally acquired and processed by a computer data acquisition and signal processing system. The data acquisition and processing program was developed in C language under LabWindows/CVI environment for this study.

2.3 Methods

The inverter ‘torque boost’ function was set to its maximum value, so that the motor would reach a set speed in a very short time with a linear acceleration character. A small device was designed to measure the beater speed. The beater accelerating time from the beater start-up to a set speed or decelerating time from a set speed to the halt was also measured using the device. Table 1 shows the measured results.

<table>
<thead>
<tr>
<th>Set speed</th>
<th>RPM</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>5000</th>
<th>6000</th>
<th>7000</th>
</tr>
</thead>
<tbody>
<tr>
<td>m/s</td>
<td>3.0</td>
<td>6.1</td>
<td>9.1</td>
<td>12.1</td>
<td>15.2</td>
<td>18.2</td>
<td>21.3</td>
<td></td>
</tr>
<tr>
<td>Time to a set speed (s)</td>
<td>0.08</td>
<td>0.129</td>
<td>0.175</td>
<td>0.253</td>
<td>0.346</td>
<td>0.444</td>
<td>0.472</td>
<td></td>
</tr>
<tr>
<td>Revolutions *</td>
<td>0.75</td>
<td>2.00</td>
<td>4.50</td>
<td>8.50</td>
<td>14.50</td>
<td>22.25</td>
<td>27.50</td>
<td></td>
</tr>
</tbody>
</table>

* refers to the revolutions of the beater recorded when the beater reached the set speed.

A total of 540 tension values was sampled in each revolution of the beater, i.e. the tension signal was recorded with an interval of every 0.337 mm (less than the 1 mm minimum gap between the adjacent pin rows of the PB) of the relative movement of the fibre to the beater surface. By using the high sampling rate for data acquisition, the alterations in fibre tension, especially when the fibre tensile failure occurs during fibre/beater interaction, could be captured precisely.

Fibre length in the pin domain (Fibre contact length as shown in Figure 1) is directly related to fibre/pin contacts, which may reflect its contact angle θ on the beater surface as defined in Equation 1. The fibre/pin interaction tension profiles of different fibre contact length were thus investigated in this paper.

3. Results and Discussion

It was observed that when the STB was used at a high speed, 6000 RPM (18.2m/s) or 7000 RPM (21.3m/s), a single fibre with contact length less than 70 mm would not readily stay in the pin domain. It might be blown out of the beater surface. In this case, if the fibre was forced into the pin domain of a high speed rotating beater, the fibre may be easily broken due to the pin impact force, or it may be blown away from the beater surface again. Such case would seldom occur with the use of pin beater. Therefore, the pin beater (PB) was used more often than the saw tooth beater (STB) in this part of investigation, although the saw tooth clothing is more commonly used in industrial practice.

3.1 Interacting force
In early stage wool processing, fibres are subjected to frequent stretching due to its interactions with pins. Figure 2 presents two examples of the tension profiles generated from a filament/PB interaction at different speeds. The maximum interacting tension at the low interacting speed (e.g., 6.1 m/s in Figure 2A) is very low. While at the high speed (21.3 m/s in Figure 2B), it is 3.6 cN.

Figure 2  Tension Profiles of Filament/PB Interaction

Figure 3 is the tension signal of a filament, obtained by interacting with the STB. Unlike the tension profiles of fibre/PB interaction in Figure 2, the pattern of the interacting force in Figure 3 is almost identical in each revolution due to the helical wrapping of saw teeth around the beater. The mean interacting tension is around 1.5 cN and the maximum interacting tension is about 2.6 cN.

Figure 3  Tension Profiles of Filament/STB Interaction
cN.

Figures 2 and 3 only illustrate a short period of the interactions. For a long period of the interactions, the tension signal may vary with the interacting time. Furthermore, the interacting force in Figures 2 and 3 is lower than the fibre breaking load generally known, thus no fibre breakage is supposed to occur. However, the fibre breakage, in fact, may still occur, especially at a high interacting speed as discussed in the following section. Fibre breakage may also occur after taking longer interacting time to induce the fibre fatigue failure.

### 3.2 Fibre breakage caused by a high speed interaction

It was observed that wool fibres had more chances to break in the latter case than the former. An example showing both cases is given in Figure 5B. During the interaction of a wool fibre with the pin beater, the fibre might break at point $d$, where the fibre tension became zero, followed by an immediate return of the fibre to the pin domain. A similar phenomenon of the fibre escape by the tension level between $b$ and $c$ might then escape from the beater at point $e$. The escape and return, rather than fibre breakage, is supposed to occur. However, the fibre breakage, in fact, may still occur, especially at a high interacting speed as discussed in the following section. Fibre breakage may also occur after taking longer interacting time to induce the fibre fatigue failure.

**Figure 4** Filament breakage caused by fibre/pin interaction

Figure 4 and 5 illustrate a short period of the interactions. For a long period of the interactions, the tension signal may vary with the interacting time. Furthermore, the interacting force in Figures 2 and 3 is lower than the fibre breaking load generally known, thus no fibre breakage is supposed to occur. However, the fibre breakage, in fact, may still occur, especially at a high interacting speed as discussed in the following section. Fibre breakage may also occur after taking longer interacting time to induce the fibre fatigue failure.

**Figure 5** Wool fibre tension experienced during fibre/PB interaction from the beater start-up to fibre breakage (PB set speed = 6000 RPM)
position c and onwards is only 25 mm, which was measured afterwards. The high tension with such short fibre contact length between the fibre escapes might result from the impact force when the fibre suddenly entered the high speed pin domain. Since in a carding process, fibres were transferred from one pin domain to another, they may experience a large impact force during the transfer process and cause a higher degree of fibre damage than the other process in early stage wool processing.

On the whole, the interactions between fibres and a pinned beater cause considerable amount of fibre breakages at a high speed, even for the fibre with a relatively high breaking load, such as a polyester filament.

3.3 The mean and maximum interacting force

The mean interacting force has been generally used to express the actual tension experienced by fibres and to further interpret the fibre fatigue during processing. In this study, however, the maximum interacting force on an individual fibre is considered to be a more appropriate factor affecting the fibre breakage than the mean tension value. Figure 6A shows statistical values of the mean forces caused by filament/PB interactions. In order to record the tension precisely, each

Figure 6  Effect of PB speed and filament contact length on the interacting tension

[Graph showing data for mean and maximum interacting force as a function of beater speed for different contact lengths.]

mean represents the average of 378000 tension values, which are equivalent to 700 revolutions’ interaction time at the set speed. It can be seen that the mean interacting tension increases with
an increase in the beater speed and fibre contact length. Furthermore, all of the mean values are less than 2 cN, which is far less than the breaking strength of the fibres used (The breaking load of a wool fibre is around 8 cN and that of a filament is around 20-45 cN). Based on the mean values obtained, it might be postulated that no fibre breakage would occur. As discussed in Section 3.2, the averaging way is not a proper method to examine fibre breakage during fibre opening processes.

When the maximum interacting tensions on the individual fibres were analysed, however, the tension amplitude is different from the average as plotted in Figure 6B, which represents the maximum forces, in the period of the beater start-up to 710 revolutions of running time at the set speed. It can be seen that the maximum interacting force also increases with an increase in the beater speed and fibre contact length. However, under the conditions of a high beater speed and a long fibre contact length, the maximum impact force is so high that it may reach the wool fibre breaking load, indicating the possibility of a fibre breakage. In addition, fibre breakage may occur when the interaction force is less than the fibre breaking load due to the fibre fatigue and structural flaws.

3.4 Study of the time when maximum tension appears during the fibre/pin interaction

In addition to the maximum amplitude of the interacting force, the time when the maximum force appears is also helpful to understand the mechanism of fibre breakage. Table 2 gives a distribution of the maximum tension during the beater start-up to 720 revolutions of full speed running. The test fibre was initially positioned parallel to the beater rotary direction before the fibre/PB interaction started.

<table>
<thead>
<tr>
<th>Speed (RPM)</th>
<th>Number of tests</th>
<th>Beater speed region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of tests</td>
<td>Start-up</td>
</tr>
<tr>
<td></td>
<td>Start/ Full</td>
<td>0/100</td>
</tr>
<tr>
<td>1000</td>
<td>66</td>
<td>6.06</td>
</tr>
<tr>
<td>3000</td>
<td>71</td>
<td>15.49</td>
</tr>
<tr>
<td>4000</td>
<td>76</td>
<td>17.11</td>
</tr>
<tr>
<td>5000</td>
<td>82</td>
<td>18.29</td>
</tr>
<tr>
<td>6000</td>
<td>136</td>
<td>69.85</td>
</tr>
<tr>
<td>7000</td>
<td>90</td>
<td>58.89</td>
</tr>
</tbody>
</table>

It is noted that, at a low speed, for example less than 5000 RPM (15.2m/s), the maximum interacting force occurs more or less randomly at different stages, or more frequently at the early stage of the interaction (e.g., from beater start-up to the first 100 revolutions at the set speed). However, when the beater speed is 6000 RPM (18.2m/s) or over, the maximum interacting force
occurs in the beater accelerating period, i.e. before the set speed is reached. The results indicate that in a high speed fibre opening process, the tensile failure or fibre breakage is more likely to occur in the initial stage of the fibre’s contact with the clothing elements.

3.5 **Fibre tension in the period of the beater acceleration and deceleration**

As discussed in Section 3.1, the fibre tension is strongly influenced by the fibre/pin interacting speed, and the tension increases with an increase in the interacting speed (by comparing Figure 2A and Figure 2B). The effect of interacting speed on fibre tension can be examined from the fibre tension variation in the period of the beater acceleration (eg. Figure 5) and deceleration. The alterations of the interacting force from the beater start-up to a set speed are shown in Figures 7 and 8. It is clear that the interacting force during the period of the beater acceleration always increases as the beater speeds up.

![Figure 7 Mohair fibre/PB interacting force during PB accelerating](image)

![Figure 8 Filament/STB interacting force during STB accelerating](image)

The alteration of the interacting force in the period of the beater deceleration (from a full set speed to halt) is shown in Figure 9. As expected, the interacting force decreases as the beater slows down.
On the whole, the fibre/pinned beater interacting tension increases almost linearly with an increase in the beater speed, indicating that single fibre strength is a key factor to limit the fibre processing speed for less fibre breakage.

3.6 Interacting tension of an entangled wool fibre

To form an artificial ‘entanglement’, a wool fibre of 85 mm in length as a tangling fibre, was tied up to a main wool fibre as shown in Figure 10. The main fibre had a contact length (in the pin domain) of 85 mm. The knot was formed at 60 mm from the free end of the main fibre and at the middle point of tangling fibre. The ‘entanglement’ attached fibre was then put in the pin domain without any entanglement with pins. About 100 ms after the beater start-up, one of the fibre free ends was broken and a peak A appeared on the tension signal (Figure 11). The following peak B was caused by the breakage of the main fibre at the position where a knot was formed for attaching the fibre to the transducer. The main fibre was broken in less than half a second and that the beater had not yet reached its set speed. This suggests that an entangled fibre may break easily during fibre opening.

![Figure 10 Illustration of a fibre with an artificial ‘entanglement’](image-url)
4. Conclusions

In order to better understand the mechanism of fibre damage and breakage in the early stage of fibre processing, the fibre tension during the interaction of a fibre and a pinned beater has been studied. A high speed data acquisition system for measuring the fibre tension on a simulating equipment was introduced. Details of the interacting force variations and incident of fibre breakage have been captured by the advanced data acquisition system. The interaction between a fibre and a pinned beater under various conditions has been closely examined. Many factors which influence the fibre/pin interacting force have been elucidated. The results highlight the causes of fibre damage and breakage generated by fibre/pin interactions.

The effect of fibre contact length on the interacting forces has been investigated. The interacting speed has a significant effect on the fibre tension. A high interacting speed generally results in a high fibre tension (interacting force), increased fibre damage and breakage under the conditions examined.

Study on the fibre tension in the period of the beater acceleration and deceleration reveals that the interacting force increases dramatically, as the beater is accelerated from the beater start-up to a set speed, or decreases when the beater is decelerated from a high set speed to zero. When fibre breakage is a concern, single fibre strength determines the maximum fibre/pin interacting speed.

Interacting an entangled fibre with pins will increase the fibre tension rapidly and cause the fibre breakage.

5. References