Effect of process variables on the properties of air-jet textured yarns using response surface design

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The effect of the main process variables, namely overfeed, air pressure and texturing speed, on the properties of air-jet textured yarns produced from three different polyester POY yarns of 115/36, 115/48 and 115/72 deniers has been studied. The interaction between the process variables has been taken into consideration by using response surface methodology based on the Box-Behnken design without producing samples with all the possible combinations of process variables. The response surface graphs obtained by varying two variables at a time keeping the third variable at a constant level have been studied and some of the graphs for air-jet textured yarns produced from 2 ends of 115/48 denier yarns are presented and discussed. The physical bulk of air-jet textured yarns increases significantly with the increase in overfeed and air pressure whereas it slightly decreases with the increase in texturing speed. The instability increases with the increase in overfeed and texturing speed while it decreases with the increase in air pressure. The tenacity values show a decreasing trend with all the three process parameters, i.e. overfeed, air pressure and texturing speed. The overfeed is found to be the most dominant process parameter out of the three parameters studied. The interaction effect of overfeed and air pressure is maximum on the physical bulk while the interaction of texturing speed and overfeed has the least effect. The interaction effect of texturing speed and overfeed on instability is maximum while that of overfeed and air pressure is the least. The response surfaces of yarn tenacity indicate that there is a significant interaction between air pressure and texturing speed whereas the interaction effect is least in case of overfeed and texturing speed.

Keywords: Air-jet texturing, Box-Behnken design, Physical bulk, Polyester yarn, Response surface design, Tenacity

1 Introduction

Yarn texturing can be described as a technique by which the closely packed parallel arrangements of continuous synthetic filaments are changed into the more open and voluminous structures, and the compact structure of continuous filament yarn is modified to impart texture without cutting and breaking the filament. Since air-jet texturing is a mechanical process, it can be used for a wide variety of yarn deniers and types. The process involves texturing parameters like overfeed, air pressure and texturing speed, which greatly affect the resultant properties like physical bulk, instability and tenacity. Thus, it is a necessity to get the overall picture of the trends that the yarns follow with respect to these process parameters. Several attempts have been made to study the variations in properties with respect to individual parameters. However, these process parameters are not independent of each other. It is, therefore, important to study the effect of individual parameters as well as their interaction effects. In the present work, an attempt has been made to study the individual effect of process variables, namely overfeed, air pressure and texturing speed, and their interaction effects on the properties of air-jet textured yarn by using response surface methodology based on the Box-Behnken design. The Box-Behnken design was chosen to reduce the number of experiments involved.

Response surfaces were generated using the general form of equation of the Box-Behnken design. These allow the study of the response of the property with respect to two variables, keeping the third parameter at a fixed level. So, each response surface gives the effect of two variables on a property simultaneously.

2 Materials and Methods

2.1 Materials

Three PET POY yarns of 115/36, 115/48 and 115/72 deniers were taken for the study. Two ends of the parent yarns were fed together in parallel-end on Eltex-AT-HS air-jet texturing machine using HemaJet
with T110 core. The process parameters used in the production of air-jet textured yarns are as follows:

- Hot pin temperature: 100°C
- Mechanical draw ratio: 1.403
- Heater temperature: 210°C
- Wetting: 0.6 l/jet/h
- Mechanical stretch: 4.44%
- Winding underfeed: 0.7%

Overfeed, air pressure and texturing speed were kept as decided by the Box-Behnken design as discussed in section 2.2.1.

2.2 Methods

2.2.1 Preparation of Samples

Fifteen (15) samples were prepared for every parent yarn at different levels of overfeed, air pressure and texturing speed after the randomisation of the experimental runs of Box-Behnken design (Table 1).

The overfeed values of 17.2, 25.8 and 34.5% (as -1, 0 and +1 respectively); texturing speeds of 300, 400 and 500 m/min; and air pressure of 7, 8 and 9 bars were selected for the study based on the following relationships:

\[
\text{Coded value of overfeed (} X_1 \text{)} = \frac{\text{Overfeed} \% - 25.8}{8.65}
\]

\[
\text{Coded value of air pressure (} X_2 \text{)} = \frac{\text{Air pressure (bars)} - 8}{1}
\]

\[
\text{Coded value of texturing speed (} X_3 \text{)} = \frac{\text{Texturing speed (m/min)} - 400}{100}
\]

Table 1 - Coded levels of variables according to Box-Behnken design

<table>
<thead>
<tr>
<th>Sample</th>
<th>Overfeed (X1)</th>
<th>Air pressure (X2)</th>
<th>Texturing speed (X3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>3</td>
<td>+1</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>4</td>
<td>-1</td>
<td>+1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>+1</td>
<td>+1</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>-1</td>
<td>+1</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>13</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

2.2.2 Test Methods

The prepared samples were tested for the physical bulk (%), instability (%) and tenacity (gpd).

For physical bulk measurement, the parent yarn samples were wound on the package, keeping the draw ratio and winding tension at the same levels as that of textured yarn. The physical bulk \( B_{ab} \) calculated using the package density method \( 7,11,12\) as follows:

\[
\text{Physical bulk} (\%) = \frac{W_p \times (d_1^2 - d_2^2)}{W_t \times (d_1^2 - d_e^2)} \times 100
\]

where \( W_p \) is the net weight of parent yarn wound on the package; \( W_t \), the net weight of textured yarn sample wound on the package; \( d_1 \), the full package diameter; and \( d_e \), the empty package diameter.

The textured yarn samples prepared were tested for instability using DuPont method \( 11,11,12\). The yarn specimen was clamped at the toggle clamp of the instability tester and a 0.01 gpd load was hung to it. One meter length was then marked on the yarn after keeping the initial load for 30 s. The specimen was subjected to a further load of 0.5 gpd for 30 s. The additional load was then removed and the specimen was allowed to recover under the initial load of 0.01 gpd for 30 s. The permanent extension in the length of the specimen was observed using the 1 m length as reference.

The textured yarns were tested for tensile properties on the Instron Tensile Tester (Model 4301), keeping the gauge length at 200 mm and cross-head speed at 500 mm/min.

3 Results and Discussion

The textured yarn samples were tested for physical bulk, instability and tenacity. To observe the effect of individual parameters, the regression equations were formulated using the SYSTAT package. The regression equation takes into account the linear, quadratic and interactive effects. The general form of the equation adopted is given below:

\[
P = C_0 + C_1 X_1 + C_2 X_2 + C_3 X_3 + C_4 X_1^2
\]

\[
+ C_5 X_2^2 + C_6 X_3^2 + C_7 X_1 X_2 + C_8 X_2 X_3
\]

\[
+ C_9 X_3 X_1
\]

where \( P \) is the property being studied; and \( C_0 - C_9 \), the regression coefficients.
The regression coefficients for the model equation as established for the three yarn properties are given in Table 2.

### 3.1 Physical Bulk

Fig. 1 shows the response of physical bulk with air pressure and texturing speed at 25.8% (0 coded level) overfeed. As the air pressure increases, the physical bulk increases. However, with the increase in the texturing speed, the physical bulk slightly decreases. Fig. 2 shows the variation in physical bulk with overfeed and texturing speed at 8 bars air pressure. The response generated indicates that as the overfeed increases, there is a prominent increase in the physical bulk. However, it slightly decreases with the increase in texturing speed. Fig. 3 shows that as the overfeed and air pressure increase, the physical bulk increases at a fixed level of texturing speed (400 m/min).

The increase in physical bulk with the increase in overfeed can be attributed to the more excess lengths of filaments for the loop formation and filament entanglements. As the air pressure increases, the turbulence in the air stream increases, which increases the filament separation and longitudinal displacements with respect to each other and leads to the formation of more loops. The slight decrease in the physical bulk with the increase in texturing speed can be because of the lesser time available for the yarn to remain inside the jet, which decreases the effectiveness of texturing.

The above findings also give an indication that the overfeed is the most dominant process parameter out

<table>
<thead>
<tr>
<th>Property</th>
<th>Total feed (POY denier/dpf)</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C₀</td>
<td>C₁</td>
</tr>
<tr>
<td></td>
<td>230/96</td>
<td>214.661</td>
</tr>
<tr>
<td>Instability, %</td>
<td>230/72</td>
<td>2.860</td>
</tr>
<tr>
<td></td>
<td>230/96</td>
<td>2.750</td>
</tr>
<tr>
<td></td>
<td>230/144</td>
<td>2.580</td>
</tr>
<tr>
<td>Tenacity, gpd</td>
<td>230/72</td>
<td>1.122</td>
</tr>
<tr>
<td></td>
<td>230/96</td>
<td>1.272</td>
</tr>
<tr>
<td></td>
<td>230/144</td>
<td>1.244</td>
</tr>
</tbody>
</table>
of the three parameters studied. The interaction effect of overfeed and air pressure is maximum on the physical bulk while the interaction of texturing speed and overfeed has the least effect.

3.2 Instability

Fig. 4 shows the response of instability to the variations in air pressure and texturing speed. At the lower texturing speeds, the instability either remains constant or increases to some extent with the increase in air pressure. However, at the higher texturing speeds, the instability decreases with the increase in air pressure. Fig. 5 shows the change in instability with overfeed and texturing speed. The increase in overfeed and texturing speed leads to an increase in instability. Fig. 6 depicts the response of instability with overfeed and air pressure. As the overfeed increases, the instability increases while it decreases marginally or remains nearly constant as the air pressure increases.

For the individual parameters, as the overfeed increases, the instability increases because the higher excess length of filaments is available for the loop formation and the frequency of loops will be higher and the yarn compactness will be lower as reported earlier. This leads to the increased instability with the increase in overfeed. The increase in air pressure leads to the increase in the turbulence and formation of more compact yarn structure. This leads to a decrease in instability. As the texturing speed increases, the yarn has lesser time in the air stream, resulting in less effective filament separation and entanglements and this leads to an increase in instability.

3.3 Tenacity

Fig. 7 shows the variation in tenacity with air pressure and texturing speed. The tenacity decreases with the increase in both the air pressure and texturing speed. Fig. 8 shows that there is a decrease in tenacity with the increase in overfeed; however, the tenacity remains nearly constant or decreases marginally with the increase in the texturing speed. Fig. 9 shows that the tenacity decreases with the increase in air pressure and overfeed.

The decrease in tenacity with higher overfeed can be attributed to the excess length of filaments
available to form loops, higher loop size and loop frequency which lead to lesser availability of straight load bearing filaments. As the air pressure increases, there is an increase in non-uniform flow velocity of air impinging on the filaments which implies better texturing and thus lesser number of straight load bearing filaments in the yarn. The decrease in tenacity with texturing speed may be because of the less compact yarn structure with higher obliquity of filaments in the yarn core.

The response surfaces indicate that there is a significant interaction between air pressure and texturing speed whereas the interaction effect is least visible in the case of overfeed and texturing speed.

4 Conclusions
The physical bulk of air-jet textured yarns increases significantly with the increase in overfeed and air pressure whereas it slightly decreases with the increase in texturing speed. The instability increases with the increase in overfeed and texturing speed while it decreases with the increase in air pressure. The tenacity values show a decreasing trend with all the three process parameters, i.e. overfeed, air pressure and texturing speed.

For the individual effect of parameter, the overfeed seems to have the maximum effect, followed by air pressure and texturing speed. For the interaction effects, the interaction of air pressure and overfeed...
dominates for the physical bulk while the interaction effect of texturing speed and overfeed is maximum for instability. The response surfaces indicate that the interaction effect of texturing speed and overfeed affects the instability to the maximum extent while the interaction of overfeed and air pressure is the least. The yarn tenacity response surface indicates that there is a significant interaction between air pressure and texturing speed whereas the interaction effect is least visible in the case of overfeed and texturing speed.

References