Introduction

The most recent developments in false-twist texturing have shown that there is still considerable potential in the false-twist texturing process [1-3]. In order to increase the texturing speed, the length of the heater and the cooler have to be increased in order to heat the yarn sufficiently. As attempts to increase the production speed have been made, the machines have changed in appearance, mainly due to the use of short high-temperature heaters [4-6]. As texturing zones were shortened, the yarn path has also improved. High-temperature heaters reduce the residence time of the yarn in the heater in order to reach the setting temperature of the polymer.

As false-twist draw-texturing is a process that includes close interactions between machine working parameters and textured yarn properties, the effect of process parameters have so far been widely investigated [7-12]. The most important parameter is the yarn temperature which depends on the heater temperature and the speed of the yarn as it passes through the heating zone. There should be an optimum setting temperature for every supply yarn, and knowledge of the effects of varying heater temperatures on the textured yarn properties facilitates the easy establishment of the desired heater temperature. To ensure proper heat setting of the yarn in the twisted state, efficient cooling is necessary to a degree that the yarn temperature is below 100°C before the yarn is untwisted at the spindle. The effect of the process variables by use of a high-temperature heater on the mechanical and crimp properties of polyester yarn have been investigated and published elsewhere [13]. As the thermoplastic yarn is subjected to mechanical stresses at high temperatures, important structural changes take place. Gupta et al. have studied the structural changes on heat-setting and friction-twisted texturing of commercial nylon-6 yarns over a range of heater temperature and contact time by using a conventional heater [14]. Barnes et al. have studied the effects of heating time and heater length in false-twist draw-texturing of nylon 6.6 yarns by using a single standard heater [15]. Kveder et al. investigated the dynamic mechanical properties, superstructure and texturability of nylon-6.6 partially oriented yarns in order to ascertain the cause of filament breakages during industrial texturing [16]. In a study by Tavanai et al., a practical method of determining the twist levels of fine hosiery nylon yarns in false-twist texturing was developed [17]. In this paper, the effect of the setting variables, such as yarn temperature and texturing speed, on the mechanical and structural properties of polyamide 6.6 yarns in a false-twist draw-texturing machine incorporating a high-temperature heater were investigated. By using this type of heater, a very short texturing zone and the required yarn temperature could be achieved after a short residence time in the heater. Heat transfer in the high-temperature heater requires very stable thread travel, as filament breakage and fusion of the filaments may occur due to thread ballooning. Thread tensions and filament break numbers as a function of the D/Y ratio was also studied, because these influence the stability of the texturing process.

Materials and Methods

All texturing processes were carried out on a laboratory-type false-twist draw-texturing machine (Figure 1) with a Postiorq friction head twisting assembly. The machine is able to run at mechanical working speeds of up to 1500 m/min. The thread path is linear. A Barmag
Texturing variables

Yarn temperature
The texturing trials were performed by taking the actual yarn temperature at the exit of the heater into consideration. For this purpose, the yarn temperature at the exit of the heater was measured using a Luxtron Transmet model temperature measurement system. The temperature measurement is based on heat exchange by convection between the running thread and the measuring head. The measuring head consists of two sensors. The yarn temperature is calculated by normal convection into the surrounding air. The polyamide 6.6 yarn samples were textured from polyamide 6.6 POY with a linear density of 98 dtex/17 f, and textured yarns with a linear density of 78 dtex/17 f were obtained. 3 bobbins were produced for each trial, and the tests were performed for each bobbin. The mean values of the results were taken.

Yarn properties measured
Yarn properties, including mechanical properties such as tenacity, breaking elongation, crimp contraction, crimp modulus and crimp stability, and structural properties such as crystalline orientation function, crystal size and the crystal perfection index were evaluated. During the trials, the number of filament breaks were observed using the Enca Tecnica Fraytec model filament break measurement system.

Tensile tests
The tensile properties, namely tenacity and breaking elongation, were determined on a Textechno Statimat M according to Standard ISO 2062.

Crimp tests
Crimp measurements were carried out according to Standard DIN 53840 [18]. Crimp tests were performed on the Textechno Terturmat ME crimp measurement tester. A yarn skin of 2500 dtex was dry-heated at 120°C for 10 minutes, and was then conditioned in standard atmospheric conditions before length measurements on the instrument. Crimp contraction, crimp modulus and crimp stability were calculated from the following equations:

\[ (E\%) = \frac{\left| l_0 - l_c \right|}{l_0} \times 100 \]  \hspace{1cm} (1)

\[ (K%) = \frac{\left| l_0 - l_c \right|}{l_0} \times 100 \]  \hspace{1cm} (2)

\[ (B\%) = \frac{\left| l_0 - l_c \right|}{l_0} \times 100 \]  \hspace{1cm} (3)

Here, \( l_0 \) is the length with loading at 500 cN, \( l_1 \) is the length with loading at 2.5 cN, \( l_2 \) is the length with loading at 25 cN, and \( l_c \) is the length with loading first at 2500 cN for 10 seconds and then unloading to 2.5 cN.

X-ray diffraction measurements
The crystalline orientation function and the crystal size were measured using a Rigaku Dmax III model X-ray diffractometer. CuKα radiations were used along with a Nickel filter for monochromation of x-rays and an alternating voltage of 35 kV with an anode current of 20 mA. For the polyamide, the scanning range was 20=16°-28° with a 0.05° step for equatorial scan and the (200) plane was used for azimuthal scanning.

The crystallite size was measured using the Scherrer equation [19]:

\[ C.S. = K \frac{\lambda}{\beta \cos \theta} \]  \hspace{1cm} (4)

where:
- \( K \) - the Scherrer constant (0.9),
- \( \lambda \) - the wavelength of CuKα X-ray (1.54 Å),
- \( \beta \) - FWHM (full width at half maximum),
- \( \theta \) - the Bragg angle.

The crystalline orientation function was measured using the equation:

\[ f_\theta = \frac{(180° - \text{FWHM})}{180°} \]  \hspace{1cm} (5)

The Crystalline Perfection Index (C.P.I.) of the samples were calculated as:

\[ \text{C.P.I.} = \frac{(d_{200} - d_{002}) - 1}{0.189} \]  \hspace{1cm} (6)
developed, increases with the increase in yarn temperature. In order to explain this, we have to consider two types of deformation imposed on the twisted continuous filament yarns. One is the twist along the length, and the other is the bending of some of the filaments so that they follow a helical path about the yarn axis. As the filaments in the twisted yarn migrate in a helix from the yarn surface to the yarn centre and back again, they are not deformed evenly along their length. Those parts of the filaments that remain on the yarn axis will be relatively straight and are deformed in a torsional way. Those on the yarn surface will have a helical deformation, the radius of which will be equal to the distance from the yarn axis, as well as a torsional deformation. As the yarn is heated in the twisted configuration to set these deformations into the filaments, the twisted yarn becomes torque-free. However, as the yarn is detwisted, the filaments are again restored to a torque-lively condition. The retractive power of the yarn is created mainly by these torsional forces when they are relaxed fully, but the effect of the bending forces in the filaments is predominant in the practical relaxation range of the yarns. By increasing yarn temperature after heating, the helical coils are expected to reduce in diameter, and also to produce higher recovery force in the yarn, because the retractive power of a stretched helical spring is inversely proportional to the square of its diameter [22]. Crimp frequency also increases as a result of the diminishing diameter of the helices, because the coils increase in number as the yarn is untwisted. The yarn crimp contraction and bulk will depend on the retractive power, as well as on the crimp frequency [23].

By varying the texturing speed, the contact time was varied and the cooling time also varied accordingly. The effects of texturing speed on the mechanical and crimp values of the textured polyamide yarn are shown in Figures 4 and 5.

### Results and Discussion

The tenacity and breaking elongation values as a function of yarn temperature after heating are shown in Figure 2. The tenacity value of textured polyamide 6.6 yarn increases until 200°C, and lower values are obtained at 210°C and 220°C. The tenacity increases with the increase in temperature, due to the improvements in orientation and crystal perfection. The breaking elongation decreases.

Crimp values as a function of yarn temperature after heating are shown in Figure 3. Crimp contraction and crimp stability increase until 200°C, and then they begin to decrease. With the increase in heater temperature, the heat input in the yarn increases, which thereby facilitates the mobility of the macromolecular chains. The dissolution of hydrogen bonds in nylon is also facilitated by the increase in heater temperature; consequently, the extent of deformation and relaxation experienced by the filaments is also greater. Due to more deformation and better relaxation, more crimping occurs in the yarn with the increase in heater temperature [21]. Crimp contraction, which is the reduction in length of a textured filament yarn as a result of its cramped structure when the crimp is

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Textured yarn temperature</th>
<th>Texturing speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenacity</td>
<td>46.57 &gt; 4.46 &gt; 2.86</td>
<td>11.14 &gt; 7.69 &gt; 4.07</td>
</tr>
<tr>
<td>Breaking elongation</td>
<td>58.1 &gt; 4.46 &gt; 2.86</td>
<td>20.69 &gt; 7.69 &gt; 4.07</td>
</tr>
<tr>
<td>E %</td>
<td>62.43 &gt; 4.46 &gt; 2.86</td>
<td>13.35 &gt; 7.69 &gt; 4.07</td>
</tr>
<tr>
<td>K %</td>
<td>37.27 &gt; 4.46 &gt; 2.86</td>
<td>12.18 &gt; 7.69 &gt; 4.07</td>
</tr>
<tr>
<td>B %</td>
<td>26.54 &gt; 4.46 &gt; 2.86</td>
<td>26.12 &gt; 7.69 &gt; 4.07</td>
</tr>
</tbody>
</table>

The results of the analysis of variance are given in Table 2. From the results, it can be seen that the effects of textured yarn temperature and texturing speed on tenacity, breaking elongation and the crimp values are significant.

The temperature of the yarn at the end of the cooling plate increases as the texturing speed increases. The yarn temperature must be decreased to a temperature as close as possible to the glass transition temperature ($T_g$), so the yarn speed should be selected accordingly to obtain sufficient cooling. Setting occurs in cooling, and an efficient cooling, to a degree that the yarn temperature is below 100°C before the yarn is untwisted at the spindle, is necessary [24]. The cooling of the yarn is obtained by the passive cooling method through normal contact with the cooling plate by heat conduction from the yarn into the cooling plate and by normal convection into the surround-

![Figure 2](https://via.placeholder.com/150)

*Figure 2. The effect of yarn temperature after heating on tenacity and breaking elongation (D/Y: 2.2, texturing speed: 600 m/min) [20].*

![Figure 3](https://via.placeholder.com/150)

*Figure 3. The effect of yarn temperature after heating on crimp properties of textured polyamide 6.6 yarn (D/Y: 2.2, texturing speed: 600 m/min) [20].*

![Figure 4](https://via.placeholder.com/150)

*Figure 4. The effect of texturing speed on the tenacity and breaking elongation of textured polyamide yarns (D/Y: 2.2, yarn temperature after heating: 200°C).*

![Figure 5](https://via.placeholder.com/150)

*Figure 5. The effect of texturing speed on the crimp properties of textured polyamide yarns (D/Y: 2.2, yarn temperature after the heating: 200°C).*
ing air. The higher the speed, the more important is additional forced cooling. It should be noted that, in these trials, the length of the cooling bar is 0.8 metres, which is a very short length. Forced cooling would provide lower temperatures at the entrance to the twisting aggregate.

An increase in the texturing speed, which corresponds to a decrease in contact time in the heater and in the cooling plate, decreases tenacity, crimp contraction, crimp modulus and crimp stability. As the contact time increases, higher thermal input is achieved and there is more time for crystalisation. In addition, the contact time in the cooling plate and cooling time also increases. This leads to more efficient cooling and setting of crimp in the textured yarn. In a simulation programme by Wulfhorst & Meier, the theoretically shortest possible heating times were found as a function of polymer and yarn denier. For polyamide 6.6, this minimum heating time ranges between 3 ms and 15 ms for yarn fineness ranges of 20 dtex and 100 dtex respectively. The heating times for the conventional contact heaters used at present are between 200 and 250 ms [4]. In our trials, the heating times ranged between 64 and 100 ms.

Barnes & Morris [15], in their investigation of the effects of heating time and heater length in the processing of nylon 6.6 yarns, draw-textured 96 dtex/34 fil nylon 6.6 yarns and obtained a textured yarn fineness of 78 dtex/34 fil. using a standard heater of 1-metre length, a water-cooled cooling plate of 1-metre length and a Positorq friction twisting unit. Texturing speeds ranged between 100 and 600 m/min, so yarn dwell times ranged between 0.6 and 0.1 seconds respectively. It was observed that the high speeds clearly reduced the crimp stability, especially at lower processing temperatures. A setting time of no less than 0.2 seconds and temperatures as high as practicable were found to be necessary in order for the draw-textured yarn to retain a good proportion of its crimp in fabric manufacture, dyeing and finishing. In our trials, the dwell time ranged between 0.1-0.064 seconds, and acceptable levels of crimp stability were achieved even at 0.064 seconds at a textured yarn temperature of 200°C.

As the working principle of friction draw-texturing is based on surface friction between the yarn and the disc, this results in filament damage. Broken filaments are one of the main problems in friction draw-textured yarns [8]. In order to investigate the occurrence of broken filaments, the yarn tensions and number of filament breaks at different D/Y ratios and at two different yarn texturing speeds are given in Table 3.

It can be seen from Table 3 that as the D/Y ratio decreases, the tension of the yarn after the friction discs increases, and the number of filament breaks increases. At a low D/Y ratio, the ratio of disc speed to yarn speed decreases, and the yarn is stretched between the false-twisting device and the exit roller. Therefore the T2 value increases. As the D/Y increases, the forwarding action of the aggregate increases, and the tension ratio defined as T2/T1 moves to less than one, providing that the yarn is being effectively overfed by the aggregate. The D/Y ratio generally falls within the region of 1.4 to 3.0 for most existing systems [23]. The higher the D/Y, the higher the disk speed in relation to the yarn speed, and so more torque is transferred to the yarn. This leads to more twist in the yarn. However, after a point, more slippage between yarn and disk occurs, resulting in the increasing instability of the texturing tension.

![Figure 6. Change of crystalline orientation function with the yarn temperature after heating (D/Y: 2.2, texturing speed: 600 m/min).](image)

![Figure 7. Change of crystallite size (Angstrom) with the yarn temperature after heating (D/Y: 2.2, texturing speed: 600 m/min).](image)

![Figure 8. Change of Crystal Perfection Index (C.P.I.) with yarn temperature after heating](image)

Therefore, the upper limit of the D/Y ratio also has to be chosen carefully.

In a comparison of the surging speed limits between a conventional heater and a high-temperature heater for draw-texturing polyamide 6.6 yarns, the surging speed limit was found to be 900 m/min for a conventional heater, whereas it was found to be 1100 m/min for a high-temperature heater for 78 dtex polyamide 6.6 yarns. Also, lower texturing tensions were obtained due to the straight and shorter yarn path [25].

The changes in crystalline orientation function (fC), crystallite size and crystal perfection index with the temperature of the yarn after the heater are given in Figures 6, 7 and 8 respectively.

**Table 3.** The T1 and T2 tensions (tensions before and after friction discs, respectively) of polyamide 6.6 yarn textured at different D/Y ratios and at two texturing speeds, T2/T1 ratio and number of filament breaks (yarn temperature after the heater: 200°C).

<table>
<thead>
<tr>
<th>Yarn texturing speed, m/min</th>
<th>D/Y</th>
<th>Yarn tension T1, g</th>
<th>T2, g</th>
<th>T2/T1</th>
<th>Number of filament breaks/10 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>2.2</td>
<td>16</td>
<td>10</td>
<td>0.62</td>
<td>0</td>
</tr>
<tr>
<td>600</td>
<td>2.0</td>
<td>16</td>
<td>11</td>
<td>0.69</td>
<td>1</td>
</tr>
<tr>
<td>600</td>
<td>1.8</td>
<td>16</td>
<td>12</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>600</td>
<td>1.6</td>
<td>16</td>
<td>16</td>
<td>1.00</td>
<td>3</td>
</tr>
<tr>
<td>700</td>
<td>2.2</td>
<td>16</td>
<td>9</td>
<td>0.56</td>
<td>0</td>
</tr>
<tr>
<td>700</td>
<td>2.0</td>
<td>16</td>
<td>11</td>
<td>0.69</td>
<td>1</td>
</tr>
<tr>
<td>700</td>
<td>1.8</td>
<td>17</td>
<td>14</td>
<td>0.82</td>
<td>2</td>
</tr>
<tr>
<td>700</td>
<td>1.6</td>
<td>20</td>
<td>18</td>
<td>0.90</td>
<td>4</td>
</tr>
</tbody>
</table>
In Figure 6, it can be seen that the crystalline orientation function of the yarn increases with the increase in the yarn temperature after heating within the temperature range between 160 and 200°C. This effect is significant ($F_0=22 > F_{0.05,6,14}=2.86; F_{0.01,6,14}=4.46$). With an increase in temperature for any contact time in the heater, the heat input in the yarn increases, and the mobility of the macromolecular chains is facilitated. As the temperature increases, intermolecular forces become weak. Therefore, the exibility of the macromolecules and the motion of structural elements increase. As the stiffness of the filaments will be lower, the crystallites will align more easily [8]. It is expected that while drawing above the glass transition temperature, the molecular chains will tend to align the crystallites along the axis, resulting in an improvement in molecular orientation. The orienting influence of the tensile force, due to the applied draw ratio, will enhance the molecular orientation. [11]. These results also correlate well with the tenacity values of the textured samples.

The crystalline orientation function of textured polyamide yarns increase with the increase in yarn temperature until 200°C, and they decrease at 210 and 220°C. These values also correlate well to the tenacity values at the corresponding temperatures. In considering this trend in crystalline orientation function, the changes in the fine structure of polyamide yarns upon heat-setting under tension should be taken into account. At temperatures above 140°C, moisture is rapidly desorbed from the polyamide, and the formation of new amide-amide interactions can occur comparatively unhindered by the presence of water molecules when the segments of two parallel chains come into close proximity. In this way, a slight increase in the total order in the structure occurs. At temperatures of about 200°C, the rotational energy of molecular segments not bonded to one another is sufficient to permit the chains to attain a random coil configuration with the lowest entropy state, and this will introduce contractive forces in the structure. At the same time, this temperature is not sufficiently high to cause any extensive rupture in the partly and fully ordered regions. The result is an increase in the orientation of the ordered regions when the fibre is under tension during dry-heat setting. At higher temperatures, the partly ordered regions undergo a form of melting, and disorder occurs [26].

The crystallite size at (002) plane increases by the increase in temperature until 200°C, and decreases at 210-220°C. The results are significant ($F_0=22.67 > F_{0.05,6,14}=2.86; F_{0.01,6,14}= 4.46$) A random pattern is observed for the (200) plane.

At increased temperatures, the C.P.I. increases, but it shows a slight decrease at 210 and 220°C. The change of crystal perfection index with textured yarn temperature is significant, as $F_0=10.2 > F_{0.05,6,14}=2.86; F_{0.01,6,14}=4.46$).

The reason that bigger crystals are obtained at higher temperatures is that smaller, imperfect crystals grow easily at higher temperatures. These smaller, imperfect crystals then melt, and so ultimately the growth of bigger crystals is facilitated at higher temperatures [7]. From these results, it was found that crystalline orientation function and crystal size increase as the temperature increases. The crystal size and C.P.I. showed a maximum at 200°C, and at 210 and 220°C they tended to decrease.

Gupta et al. [27] assumed that the forces acting on the yarn during texturing are the determining parameters for the structural changes taking place. The yarn is subjected to a tensile force and friction torque at texturing. In addition, the contractile stress is applied on the yarn as the main internal stress that arises within the fibre due to texturing, since the thermoplastic yarn is heated above the glass-transition temperature. These forces are acting on the yarn at the texturing temperature, and at this temperature some melting of crystallites followed by recrystallisation occurs. It is assumed that in the twisted form of the yarn, the nuclei for the recrystallisation will also be oriented in this form, and that the crystallites grown from these nuclei will therefore be bent and twisted. The same force will be applied in the opposite direction at the twisting stage, but at a lower temperature, probably close to the glass-transition temperature. The crystallites would become relatively rigid, since they have been set to a great extent at this stage. Consequently, the twisting force would further distort the crystallites.

In a comparison of the structural changes in heat-set and textured samples, it was observed that in heat-setting, the filament is under tension only, and therefore recrystallisation under tensile stress takes place. In texturing, bending and torsional forces are also present in addition to the tensile force, and these forces will not allow crystallinity to develop to the same extent as in the case of heat-set filaments. This is because simple tension will assist in the formation of a lattice, while bending and torsion will tend to distort the lattice [14].

Statton [28] has investigated the effect of tension on annealing of fibres. It is reported that when the fibre is heated, the intermolecular bonds with the most energy will melt, and the short-length molecule will move from more stable inter-molecular bonds, which will provide better perfection of the crystals. The local melting will allow recrystallisation into folded segments, following the folds that are already present as nuclei for crystallisation. The amount of tension during heat treatment greatly in unces the amount of refolding. Tension inhibits the refolding process, and also disrupts the crystal perfection during annealing treatment. Fibre heated at high tension restricts the growth of large and perfect crystals, and the degree of crystallinity is low. Therefore, in our textured samples crystal growth and crystal perfection is not as high as could be expected from heat-setting.

**Summary and Conclusions**

Polyamide 6.6 yarns were textured on a false-twist draw-texturing machine. We produced textured yarns with acceptable crimp and mechanical qualities with a laboratory false-twist texturing system equipped with a high-temperature heater. The required heater residence time was thus reduced to as short as 0.064 seconds for polyamide 6.6 yarn of 78 (final) dtex. As a high-temperature heater was used, the texturing speeds were higher and yarn dwell times in the heater were shorter when compared with conventional heaters. In contact heaters, the heaters have become very long in order to increase speed, and the long process path causes rapid changes in threadline tension to occur. The increased speed potential is one of the benefits of this heating technology. With the increase of heat transfer effectiveness in the heating zone, the yarn residence time requirement can be decreased.
With these shortened heater and cooler zones, a straight yarn path arrangement became possible, resulting in a reduction of threadline instability due to the reduced torque required for texturing.

The effect of temperature and texturing speed (as well as dwell time in the heater) on the mechanical and structural properties were as follows. It was seen that as the temperature of the yarn after heating increases, so do the tenacity, crimp values, crystalline orientation function and crystal size. The crystal perfection also improves. Texturing at 200°C gives the highest tenacity and crimp values. However, the tenacity, crimp contraction and crimp stability together with the crystalline orientation function, crystal size and C.P.I. decrease at 210°C and 220°C.

The texturing speed determined the dwell time of the yarn in the heater; and as texturing speed increases, the yarn residence time in the heater decreases. This leads to a decrease in crystalline orientation function and crystal size for polyamide yarn, due to the fact that the time of heat setting is decreased.

With an increase in the D/Y ratio, broken filaments decreased, as an increased D/Y ratio helps to stabilise the texturing process. Therefore, we can state that a proper D/Y ratio must be selected in order to obtain acceptable levels of broken filaments.

In contact heaters, the actual yarn temperatures are significantly less than the heater temperature, re-ecting the problem of heat transfer to a rapidly moving threadline. One important point to be recommended when working with high-temperature heaters is that the measurement of actual yarn temperature is very important. Therefore, an instrument for temperature measurement would be desirable for producers of textured yarn.

Processing with a high-temperature heater did not necessarily improve textured yarn characteristics; however, due to the straight and shorter yarn path, we obtained lower texturing tensions, and as a result the speed limits could be increased while maintaining the same textile characteristics.

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