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THE EFFECT OF FALSE-TWIST TEXTURING PARAMETERS ON THE STRUCTURE AND CRIMP PROPERTIES OF POLYESTER YARN

Article Highlights

- Effect of false-twist texturing parameters on polyester yarn structure and properties were studied
- Texturing speed and heater temperature significantly affected yarn structure and crimp properties
- The effect of draw ratio and *D/Y* ratio on textured yarn structure and properties is less pronounced
- Texturing speed can be significantly increased comparing to industrial standard (1100 vs. 700 m/min)

Abstract

*In this paper, the effect of false-twist texturing parameters (texturing speed, heater temperature, draw ratio and disc-to-yarn speed ratio (*D/Y* ratio)) on the structure and crimp properties of polyester yarn has been studied using a high temperature heater and high texturing speeds. Textured yarn was analyzed and characterized in terms of the degree of crystallinity, degree of orientation and crimp properties (crimp contraction, crimp module and crimp stability). The most important parameters, significantly affecting yarn temperature and its uniformity and thus textured yarn structure and crimp properties, are texturing speed and heater temperature. Depending on these texturing parameters, the degree of crystallinity and orientation varied in the range of 24.48 to 36.66% and 0.371 to 0.595, respectively. The crimp characteristics increase with the increase in heater temperature, and decrease with the increase in texturing speed. The effect of draw ratio and *D/Y* ratio on the textured yarn structure and properties is less pronounced. Obtained results show that partially oriented polyester yarn used in this study can be textured at significantly higher texturing speed (up to 1100 m/min) than the standard texturing speed (up to 700 m/min) used for the yarn count examined.*

Keywords: crimp properties, false-twist texturing, fiber structure, high-temperature heater, polyester yarn.

Trends in the fiber sector are an important indicator of future trends in the textile industry and the global economy. The world fiber production rose to 92.7 million t in 2014. Not surprisingly, the 2014 rise was sustained mainly by growth in man-made fiber

production, which had reached 61.2 million t. Synthetic fibers accounted for most of the increase in man-made fiber production worldwide, and most of the increase in synthetic fiber production was due to growth in the production of polyester fibers. Polyester fiber, with a market share of about 50%, is the most used fiber in the world. The use of polyester fibers is growing very rapidly due to their desirable properties, including ease of processability, low cost, high-strength, thermostability, chemical and light resistance, silk-like hand, good elasticity, wear and tear property, etc. In 2002, polyester fiber demand passed that of cotton fiber and has continued to grow at a significantly faster rate than all

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other fiber types. That is how polyester came to claim a significant share from all other fibers, both man-made and natural, with polyester producers constantly looking at other fibers and their markets to determine if polyester can take further market share [1,2].

For this purpose, a considerable amount of work is being done to modify the existing polyester fibers in order to combine the above-mentioned superior properties of polyester with the features that are unique to natural fibers [3-5]. Texturing is one of the processes that give a crimped and bulky structure, a natural appearance, hand, warmth, stretch and bulk to filament yarns. Among different texturing processes, the false-twist texturing process is mostly used worldwide due to its higher texturing speeds and convenience [6-8].

The false-twist texturing process consists of softening a continuous-filament yarn by heating it above the glass transition temperature to make it more pliable, deforming the softened yarn by twisting, cooling the yarn in the twisted state to set the deformation, and then removing the inserted twist. The temporary twist is imparted to a moving yarn upstream of a twist applicator, such as magnetic spindle, Nip Twister (belt twisting), friction discs, etc. The friction disc twisting technology, introduced in the early 1970s, remains the most common means of twist insertion used in the industry today [6].

The most recent developments in the false-twist texturing process have shown that there is still considerable potential for improvement in that area. In order to increase the texturing speed and, hence, higher yarn speed, either the length or the temperature of the heater have to be increased in order to heat the yarn sufficiently. Since machine producers and users faced many problems with the heater and cooler length of up to 2.5 m, the texturing zone needed to be shortened in order to reduce the investment cost, and, more importantly, to decrease instabilities and to increase the production rate further, as well as to make the setting-up and operability of these machines easier. High-temperature (HT) heaters considerably reduce the residence time required to reach the setting temperature of the polymer. As the texturing zone is shortened, the yarn path is also improved [6-9].

The false-twist texturing process is a multi-parameter process. The most important parameters, considerably influencing textured yarn structure and properties, are: texturing speed, heater temperature, draw ratio and disc-to-yarn speed ratio (D/Y ratio). Studying the correlation between texturing process parameters and textured yarn structure and properties is the first step in process parameter optimization, which is aimed at satisfying product requirements and obtaining a con-

sistent yarn quality, as well as establishing good process performance. When using HT heaters, the operating window for optimizing the texturing process (in terms of filament structure uniformity, broken filament levels, process break-rate, and crimp stability) tends to be smaller than with conventional heaters. This is more pronounced in the case of polyester yarn since it heats up faster and responds more rapidly to heat-settings than polyamide, because of its lower specific heat (approximately 1800 J/(kg K) for polyester *versus* approximately 3300 J/(kg K) for polyamide [9]). Compared to fully oriented polyester yarn (FOY), partially oriented polyester yarn (POY), processed by simultaneous draw-texturing, responds even more rapidly to heat because of the following: the work of drawing and heat of crystallisation additionally raise the temperature of the yarn, and the undrawn POY yarn does not have the stable structure of FOY [6].

According to a literature review, the effect of false-twist texturing parameters on the structure and properties of POY polyester yarn textured using a HT heater and high texturing speeds was studied in smaller scope [10-11] and a comprehensive study about these effects is still missing. Previous approaches were limited to theoretical studies [8,9,12] or using texturing speeds of up to 700 m/min [13,14]. Furthermore, a significantly larger number of studies is dedicated to the texturing of FOY polyester yarn, which is characterized by a stable structure and is less sensitive to texturing parameter changes [15-18], or the texturing of POY polyester yarns, but using other texturing processes [16,18,19]. In this paper, the effect of false-twist texturing parameters (texturing speed, heater temperature, draw ratio and disc-to-yarn speed ratio (D/Y ratio)) on the structure and crimp characteristics of polyester yarn has been studied using a HT heater and high texturing speeds. POY polyester yarn was textured on an industrial false-twist texturing machine. Textured yarn was analyzed and characterized in terms of the degree of crystallinity, degree of orientation and crimp properties (crimp contraction, crimp module and crimp stability).

EXPERIMENTAL

Materials

Single end 167 dtex/36 filaments, polyester POY was used for the study. Chemicals were obtained from commercial sources and were of pro analysis purity.

Texturing conditions

The POY polyester yarn was textured on an industrial false-twist texturing machine FTF 15 HT (ICBT,

France) with a high temperature heater. To study the effect of false-twist texturing parameters (texturing speed, heater temperature, draw ratio and disc-to-yarn speed ratio (D/Y ratio)) on the structure and crimp characteristics of textured polyester yarn, two series of textured yarn samples were prepared at different texturing parameter levels. In the first series of experiments, the first heater temperature levels were 350, 400 and 450 °C. For each heater temperature, the samples were processed at different texturing speed levels: 500, 600, 700, 900, 1000 and 1100 m/min, by keeping other parameters constant at the level considered to be standard for the investigated yarn count (draw ratio of 1.675, D/Y ratio of 2.20 and the second heater temperature of 180 °C). In the second series of experiments, the effect of draw ratio (1.665, 1.675, 1.685) and D/Y ratio (2.15, 2.20, 2.25) on the structure and crimp properties of textured PET yarns were investigated only at higher texturing speeds: 900, 1000 and 1100 m/min, and constant heaters temperature (the first heater temperature 450 °C, and the second heater temperature 180 °C).

Crystallinity measurements

Owing to regular packing of the molecules, the crystalline phase has a higher density than the amorphous phase. Thus the total density of a fiber, i.e. semi-crystalline polymer, depends on the crystallinity of the sample. An accurate measurement of density can be used for estimating crystallinity.

The densities of the fibers/yarns were measured by the flotation method [20]. Short fragments of fibers, i.e., fiber bundles tied in a knot with loose ends snipped off, were immersed in a mixture of carbon tetrachloride and benzene solutions with different densities. After about half an hour they should come to rest at the level representing their density.

The degree of crystallinity is calculated by the following equation:

$$X(\%) = 100 \left[\frac{\rho - \rho_a}{\rho_c - \rho_a} \right] \frac{\rho_c}{\rho} \quad (1)$$

where X is the mass fraction of the crystalline phase in %; ρ , ρ_a and ρ_c are densities of the given sample, amorphous and crystalline phases, respectively. The literature values of ρ_a and ρ_c (i.e., the densities of a perfectly amorphous and a perfectly crystalline sample) for poly(ethylene terephthalate) are 1.335 and 1.515, respectively [21].

Birefringence measurements

The birefringence (Δn) was measured using a MIN 8 polarizing microscope, an average of 10 single

filaments were tested to maintain the reproducibility of the results. The birefringence was measured using the following relationship:

$$\Delta n = \Delta / d \quad (2)$$

where Δ is the ray-motion difference and d is the thickness of fiber in the compensation zone [22]. The optical orientation factor (f , in terms of Herman's orientation factor, can be calculated as the ratio of the birefringence of the fiber (Δn) to that of an ideal fiber (Δn_{\max}) in which the molecules are oriented in a perfectly parallel manner to the fiber axis. In the present study, a value of 0.24 has been used as the maximum birefringence value for the fully oriented poly(ethylene terephthalate) sample [23,24].

Morphology investigation

The yarn/filament morphology, i.e., the longitudinal view and cross section of filaments, was investigated by a light microscope (Kruess, Germany) in order to determine filament flattening and cross-sectional uniformity.

Yarn crimp measurement

Crimp contraction (CC), crimp module (CM) and crimp stability (CS) were determined in accordance with the standard DIN 53840-1 [25]. Briefly, a yarn hank of 2500 dtex was dry heated at 120 °C for 10 min and then conditioned in the standard atmospheric conditions before length measurement on the Texturmat instrument. Crimp contraction, crimp module and crimp stability were calculated from the following equations:

$$CC(\%) = 100 \frac{l_0 - l_1}{l_0} \quad (3)$$

$$CM(\%) = 100 \frac{l_0 - l_2}{l_0} \quad (4)$$

$$CS(\%) = 100 \frac{l_0 - l_3}{l_0 - l_1} \quad (5)$$

where 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_3 is the length with loading first at 2500 cN for 10 s, followed by unloading to 2.5 cN.

RESULTS AND DISCUSSION

Effect of heater temperature and texturing speed on the yarn structure and crimp properties

Characterisation of the structure in the bulk state is essential for the process conditions-structure-property correlation of polymers and fibers. The packing of long polymer chains in a three-dimensional structure is

largely governed by their molecular characteristics (such as flexibility, structural regularity, etc), intermolecular interactions and external constraints (such as temperature, stress, etc.) [21,26].

POY polyester (polyethylene terephthalate) yarn used in this study is partially orientated yarn with a very low degree of crystallinity (less than 5%) and thus its structure and properties can be varied through manipulation of the texturing process parameters. The most important parameters are texturing speed and heater temperature, both of them affecting yarn temperature and its uniformity, and thus textured yarn structure. The effect of texturing speed and heater temperature on the structure of false-twist textured yarn, *i.e.*, degree of crystallinity and birefringence of textured polyester yarn is shown in Figure 1. The texturing speed and heater temperature have been varied between 500 to 1100 m/min and 350 to 450 °C, respectively, while other texturing parameters have been kept constant. The degree of crystallinity of POY polyester false-twist textured filament yarn varies in the range of 24.48 to 36.66% depending on the texturing parameters. It can be seen that the degree of crystallinity increases with the increase in heater temperature and texturing speed up to 900 m/min. However, in this study, the degree of crystallinity decreases after peak point, and starts to increase again with increasing the texturing speed. At lower texturing speeds, increase in the degree of crystallinity can be explained by the re-crystallization process at an elevated temperature. As the yarn temperature increases, the intermolecular forces become weak, facilitating the mobility and flexibility of the macromolecular chains and structural elements, allowing the crystallites to align more easily. The observed decrease in crystallinity can be explained by the facts that during the false-twist texturing process POY polyester yarn is subjected to externally applied forces, namely

drawing and twisting forces, and internal stress, *i.e.*, contraction stresses due to relaxation processes and increased molecular mobility with increasing temperature. The ability of the yarn to resist these forces depends on changes in the yarn temperature, which is determined by both texturing speed and heater temperature. The effect of these two parameters on the yarn stress is opposite. The increasing temperature interrupts more and more molecular interactions and softens the material; as a consequence, the yarn stress diminishes. On the other hand, the increase of texturing speed increases both externally applied forces and internal yarn stress [10,27].

The birefringence values of POY polyester false-twist textured filament yarn are shown in Figure 1b. The birefringence values vary in the range of 0.089 to 0.143, depending on the texturing parameters. Since the birefringence is a measure of overall orientation, the increase in birefringence values shows that the orientation also increases; the optical orientation factor varies in the range of 0.371 to 0.595, depending on the texturing parameters. From the data obtained, it is clear that the birefringence shows tendency to increase with increasing temperature. This can also be explained, as in the case of the degree of crystallinity, by the fact that higher yarn temperature facilitates the mobility and flexibility of the macromolecular chains and structural elements, wherefore they are oriented more easily. Concerning the effect of texturing speed on the birefringence, an increase in the texturing speed, which corresponds to a decrease in contact time in the heater, decreases the birefringence and orientation; however, there is no clear correlation since at higher texturing speed an increase in birefringence and orientation has been again observed. This can be explained by the fact that, in addition to yarn temperature, there are two more factors influencing the degree of

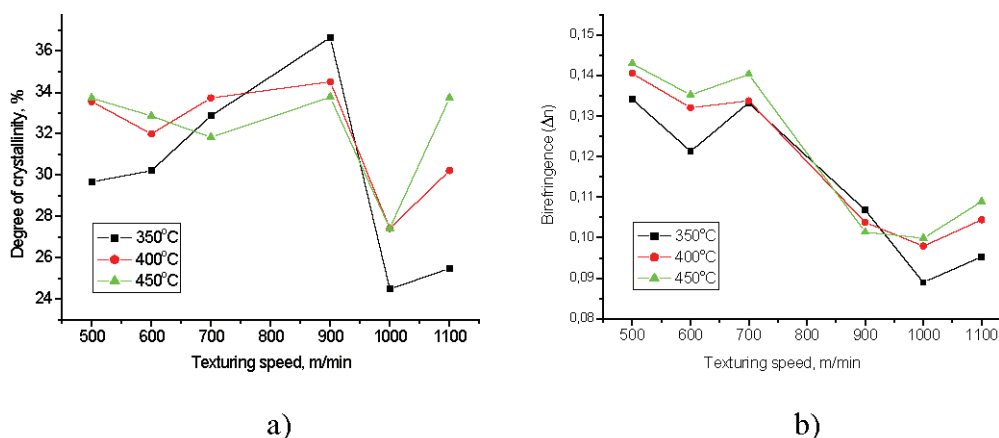


Figure 1. Effect of texturing speed and heater temperature on: a) degree of crystallinity and b) birefringence of textured polyester yarn (draw ratio of 1.675, D/Y ratio of 2.20).

orientation of textured yarn: the torsional stresses that help to disorient the macromolecules chains, and the tensile stresses that orient crystalline and amorphous sections of the chains further [6,7]. In general, POY PET yarn textured at the lowest texturing speed (*i.e.*, 500 m/min) and highest temperature (450 °C) shows the highest birefringence and consequently orientation, possibly due to the fact that at a higher temperature and lower texturing speed segments of macromolecules have higher mobility and sufficient time for orientation under the tensile stresses.

The yarn/filament morphology investigation revealed differential crimp existing in the individual filaments (Figure 2a and b), relatively straight and deformed in a purely torsional way the filament parts staying on the yarn axis (Figure 3a), the filament flattening and filament fusion (Figure 3b and c), as well as the filament cross-sectional non-uniformity (Figure 3d). Observed morphological non-uniformities can be explained by the fact that texturing of the multifilament yarn with a large number of filaments leads to obtaining a more compacted, denser filament bundle before its entry into the heater. As a consequence, proper migration of constituent filaments within the twisted bundle in the texturing zone is difficult due to the high number of filaments, resulting in yarn temperature cross-sectional non-uniformity (filaments on the outside of the bundle receive more heat than those on the inside) and an asymmetric distribution of tensile and twisting forces, which also affects the amount of crimp development in the different individual filaments and the filament cross-section shape uniformity [6,7].



Figure 2. Longitudinal view of yarn textured at 700 m/min, draw ratio 1.665, D/Y ratio 2.15 and heater temperature: a) 400; b) 350 °C (magnification 40 \times).

Filament damage (*i.e.*, filament flattening and filament fusion), mainly observed during texturing at higher heater temperature and lower texturing speed, occurs on the filaments located on the outside of the twisted bundle as a result of their contact with higher surface temperatures on the HT heater. Figure 3d shows the textured filament cross-section deviation from the round cross-section of the parent POY yarn. The polygonal or elliptical form of these filaments is a

result of their deformation in the twisting unit, and it will also affect filament optical properties.

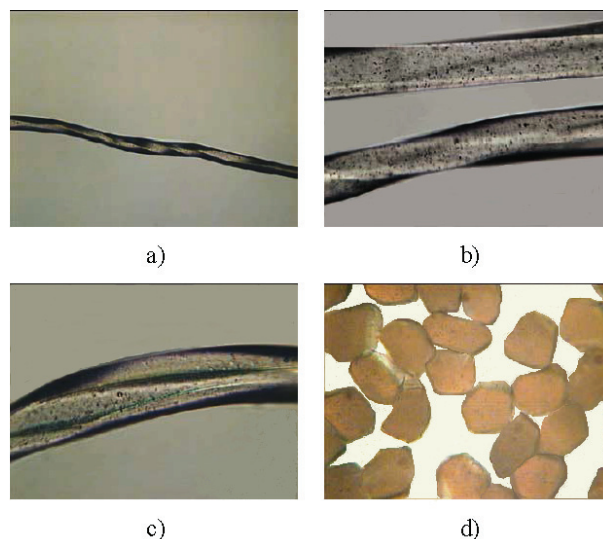


Figure 3. Longitudinal view of single filament textured at 700 m/min (a and b), heater temperature 350 °C, draw ratio 1.685, D/Y ratio 2.25 (magnification 100 and 400 \times , respectively); c) single filament textured at 500 m/min, heater temperature 400 °C, draw ratio 1.685, D/Y ratio 2.25 (magnification 400 \times); d) cross-section of yarn textured at 600 m/min, heater temperature 350 °C, draw ratio 1.675, D/Y ratio 2.25 (magnification 400 \times).

Discussed differential crimp existing in the individual filaments and the structural changes in the polymer and filament yarn developed during the texturing process both affect crimp properties of the textured yarn. Crimp properties are a measure of the structural stability and relaxation of yarn tensions remaining from previous treatment steps that affect textured yarn performance during further processing (knitting, warping, weaving or tufting) and, knowing them, it is possible to predict how a yarn will perform during fabric formation and finishing [6,7]. The obtained results for crimp contraction, defined as the reduction in length of a textured filament yarn as a result of its crimped structure when the crimp is developed; crimp module, which characterises the elongation behavior of the textured yarn in the range of crimp elasticity; and crimp stability, defined as the ratio of the retraction of a hank of yarn after and before defined loading; are shown in Figure 4. The results indicate that in general the crimp contraction, crimp module and crimp stability increase as the heater temperature increases. On the other hand, the crimp contraction, crimp module and crimp stability decrease as the texturing speed increases. This can be explained by yarn instability and decrease in orientation (Figure 1a). Furthermore, the absence of a clear correlation between crimp properties and texturing speed could be

explained by different types of deformation imposed on the twisted continuous yarns: the tension occurring above glass transition temperatures which inhibits macromolecule mobility and consequently lowers the yarn's ability to relax during texturing; the twist along the length of the filaments, resulting, as it has been mentioned, in relatively straight filaments deformed in a purely torsional way; and, finally, the bending of some filaments, which thus follow a helical path about the yarn axis [11].

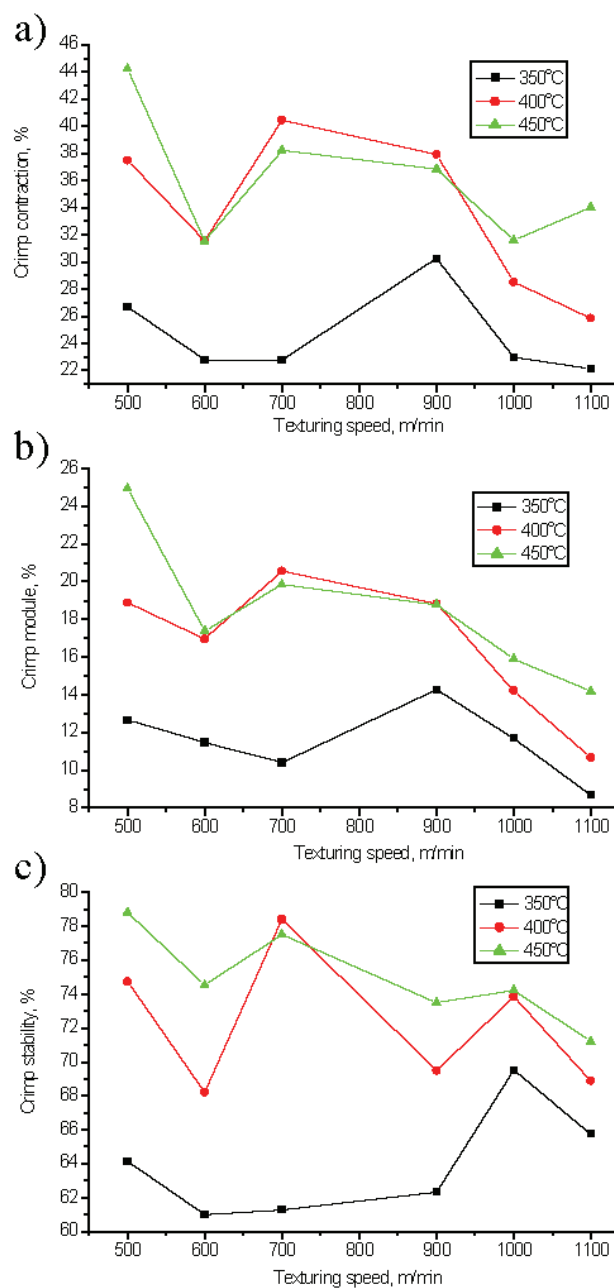


Figure 4. Effect of texturing speed and heater temperature on: a) crimp contraction, b) crimp module and c) crimp stability of textured polyester yarn (draw ratio of 1.675, D/Y ratio of 2.20).

The results obtained in the first set of experiments aimed at satisfying product requirements and establishing good process performance at a higher texturing speed (up to 1100 m/min), clearly show that by increasing the heater temperature (from 350 to 450 °C), it is possible to obtain textured polyester yarn with improved crimp properties (*i.e.*, increased CC , CM and CS parameters).

Effect of draw and D/Y ratio variations on yarn structure and crimp properties

The second part of the study has been conducted in order to clarify effects of small changes of texturing parameters (draw and D/Y ratios) on structure and crimp properties of polyester yarn textured at a higher texturing speed (900–1100 m/min), but also to explore the possibility of improving textured yarn properties by varying these two parameters. The degree of changes of these parameters has been governed by the stability of the process on the texturing machine. The draw and D/Y ratios have been varied in the range of 1.665 to 1.685 and 2.15 to 2.25, respectively, while other texturing parameters have been kept constant. The effect of false-twist texturing parameters: draw and D/Y ratios on the structure, *i.e.*, degree of crystallinity and birefringence of textured polyester yarn is shown in Figure 4. The degree of crystallinity varies in the range of 25.48 to 34.51%, while birefringence varies in the range of 0.0842 to 0.1089, depending on the texturing parameters. Increasing the draw ratio means that more tensile stress is generated into the yarn, while increasing the D/Y ratio means that the discs are rotating faster and more twist is inserted into the yarn [7]. Furthermore, if the D/Y ratio is low, the yarn tension before the twisting unit will be low and the tension after twisting unit will be high, which can cause yarn damage [13]. Figure 5a gives a clear indication of the effect of draw ratio on the crystallinity and orientation of the textured yarn, *i.e.*, extending the yarn below or above the optimum value (draw ratio of 1.675) results in decrease of both structural parameters. It should be noted that the D/Y ratio has a similar effect on these two structural parameters of textured yarns (Figure 5b).

The discussed structural changes in the polymer and filament yarn occurred during the texturing process have a surprisingly minor effect on the crimp properties of the textured yarn, as it is shown in Figure 6. According to literature [7], increases in orientation should reduce the capability of polymer chains to buckle and deform in the friction unit, thereby restricting the degree of crimp that can be developed in the yarn. Polyester yarn textured at a texturing speed of 900 m/min shows the highest crimp characteristics

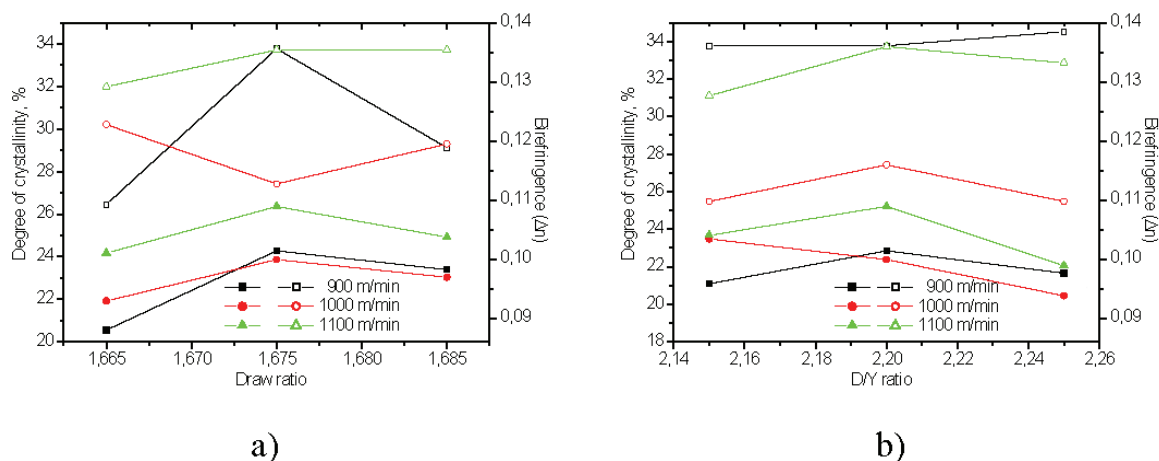


Figure 5. a) Effect of texturing speed and draw ratio on degree of crystallinity (empty symbol) and birefringence (solid symbol) of textured polyester yarn (heater temperature 450 °C, D/Y ratio of 2.20) and b) effect of texturing speed and D/Y ratio on degree of crystallinity (empty symbol) and birefringence (solid symbol) of textured polyester yarn (heater temperature 450 °C, draw ratio of 1.675).

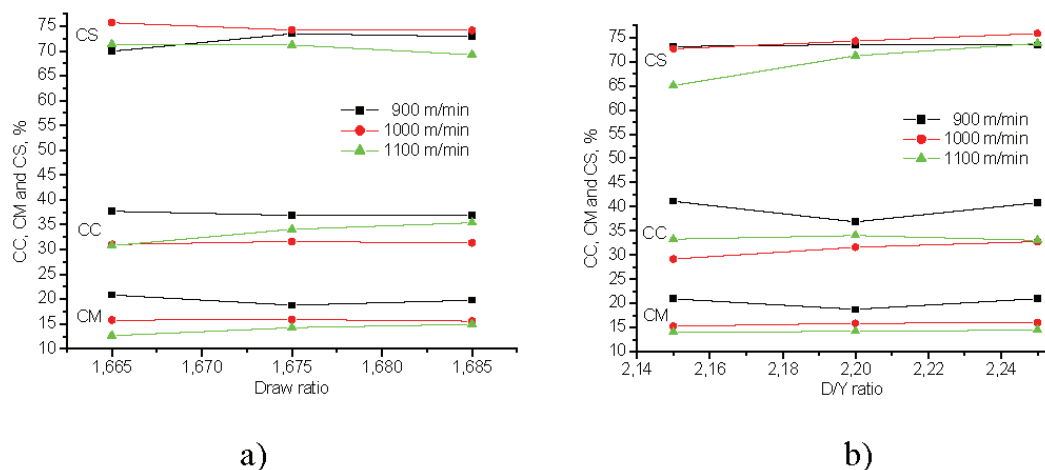


Figure 6. a) Effect of texturing speed and draw ratio on crimp contraction, crimp module and crimp stability of textured polyester yarn (heater temperature 450 °C, D/Y ratio of 2.20) and b) effect of texturing speed and D/Y ratio on crimp contraction, crimp module and crimp stability of textured polyester yarn (heater temperature 450 °C, draw ratio of 1.675).

over almost all texturing conditions. It is important to note that the increases in draw ratio can be used to increase crimp contraction, while the increases in D/Y ratio can be used to increase crimp stability at the highest texturing speed applied in this research. In such instances, texturing parameters have to be compromised, mainly taking into account texturing speed and yarn crimp properties. Our results show that POY polyester yarn fineness of 167 dtex f36x1 used in this study can be textured at significantly higher texturing speeds than the standard texturing speed for the yarn count examined (up to 700 m/min).

CONCLUSION

The false-twist texturing of POY polyester yarn is a process that includes close interactions between

process parameters and textured yarn structure and properties. The most important parameters are texturing speed and heater temperature, both of them affecting textured yarn structure and crimp properties. The degree of crystallinity increases with the increase in heater temperature and texturing speed reaching peak point at 900 m/min. The birefringence and orientation show a tendency to increase with increasing temperature, while an increase in the texturing speed decreases the birefringence and orientation. At a higher texturing speed, above 1000 m/min, an increase in birefringence and orientation has been observed. A similar tendency has been observed for crimp properties, they increase as the heater temperature increases and decrease as the texturing speed increases. Small changes of draw and D/Y ratios affect to a higher extent the structure of the textured polyester yarn,

while their effect on the crimp properties is surprisingly minor. Obtained results show that texturing parameters have to be compromised, mainly taking into account the texturing speed and yarn crimp properties. POY polyester yarn used in this study can be textured at significantly higher texturing speeds than the standard texturing speed used for the yarn count examined, while maintaining the same textured yarn characteristics.

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NAUČNI RAD

UTICAJ PARAMETARA PROCESA TEKSTURIRANJA LAŽNIM UPREDANJEM NA STRUKTURU I KARAKTERISTIKE KOVRDŽAVOSTI TEKSTURIRANOG POLIESTARSKOG PREDIVA

U ovom radu proučavan je uticaj parametara tekstuiranja lažnim upredanjem (brzina tekstuiranja, temperatura grejača, stepen istezanja, kao i odnos površinske brzine diska i linearne brzine prediva (D/Y odnos)) na strukturu i karakteristike kovrdžavosti poliestarskog prediva tekstuiranog uz korišćenje visokotemperaturnog grejača i pri velikim brzinama tekstuiranja. Tekstuirano predivo je okarakterisano sa aspekta novodobijene strukture (stepen kristalnosti i stepen orijentisanosti) i karakteristika kovrdžavosti (stepen kovrdžavosti, karakteristična kovrdžavost i stabilnost kovrdža). Najznačajniji parametri, koji u najvećem stepenu utiču na temperaturu prediva i njenu ravnomernost, a samim tim i na strukturu i svojstva kovrdžavosti tekstuiranog prediva, su brzina tekstuiranja i temperatura grejača. Zavisno od ovih parametara tekstuiranja, stepen kristalnosti i stepen orijentacije varirali su u rasponu od 24,48 do 36,66% i 0,371 do 0,595, redom. Karakteristike kovrdžavosti se povećavaju sa povećanjem temperature grejača, a smanjuju sa povećanjem brzine tekstuiranja. Uticaj stepena istezanja i D/Y odnosa na strukturu i svojstva tekstuiranog prediva je manje izražen. Dobijeni rezultati su pokazali da se delimično orijentisano poliestersko predivo, korišćeno u ovom radu, može tekstuirati pri značajno većim brzinama tekstuiranja (do 1100 m/min) u odnosu na standardne brzine tekstuiranja (do 700 m/min) koje se koriste za preradu prediva ispitivane finoće.

Ključne reči: poliestarsko predivo, struktura vlakana, svojstva kovrdžavosti, tekstuiranje lažnim upredanjem, visokotemperaturni grejač.