The Influence of Fiber Fineness on Physical Characteristics of Staple Polypropylene Fibers Spun at Different Pumping Speeds

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ABSTRACT: Melt spinning and pump speed conditions are described for five samples of staple polypropylene PP fibers of different fineness. The influence of fiber fineness or denier on the physical characteristics of staple PP fibers spun at different pump speeds was studied. Optical anisotropy was measured using two-beam interference microscopy. Enthalpy and degree of crystallinity were measured using differential scanning calorimetry technique for studied fibers. The relation between the fiber diameter, crimp ratio, tenacity, and degree of orientation with the fiber denier are given. A selection of microinterferograms of fibers is given for illustration. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 115: 2892–2897, 2010

Key words: melt spinning; staple PP fiber; crimping; fineness; deniers; birefringence; orientation; crystallinity

INTRODUCTION

Part of the modern trend in fiber science research is to alter fiber properties. One of the methods for property alteration involves the spinning process at different conditions. In this process, molten polymer is melted through various spinnerets by extrusion, which passes down a number of fine holes to form fiber or filaments.[1] These fibers are then solidified by air quenching and after application of spin finish are collected in cans or wound on take-up winders. The manufactured fibers are stretched, relaxed, and crimped to be made suitable for various yarn spinning systems. The polymer spinning process speed affects all the fiber properties such as dimensions, crimp ratio, refractive index, birefringence, orientation, degree of crystallinity, tenacity, Young's modulus, elongation, and many other properties. Also, the physical properties of fibers are influenced by the processing techniques used online, from melt conditions to windup speed. However, they are also strongly influenced by the plastic's morphology and fiber deniers. All plastic fibers that are useful in textile applications are usually semicrystalline, irreversibly in an oriented pattern.[2–4]

Polypropylene fibers are manufactured from polypropylene polymer via melt spinning technology[5] like many other thermoplastic polymers. The stretching of the quenched filament yarn causes alignment of the molecular chains and of the crystallites along the fiber axis, and the stretching operation is most important in establishing the properties of final fibers.[6] Drawing is necessary to achieve certain degree of molecular orientation and the overall orientation is influenced by the crystalline structure of unoriented fiber. Furthermore,[6] it is reported that it is easier to stretch an amorphous polymer to the effect that at a given relatively low-draw-ratio, the degree of orientation of the amorphous material may be several times higher than that of a regular crystalline filament. The required degree of drawing is dependent on fiber end-use. It could be fully or partially drawn. In the latter, molecular structures are partially oriented. The crystalline properties of staple fibers are the same as those of filament tows, because they are chopped after drawing process.

Microinterferometry has been recognized as a useful tool in fiber science. It provides useful information about the optical and structural properties of fibers on the molecular level. A detailed survey of the investigations, methods, and techniques of microinterferometry as applied to fibrous materials was given by Barakat and Hamza.[7] Many authors[7–10] used two-beam interferometric techniques for studying the molecular orientation of polymer fibers due to different mechanisms. Recently, Hamza et al.[11] described a method to detect the variations in the geometrical and optical properties of polymer fibers due to cold drawing process.

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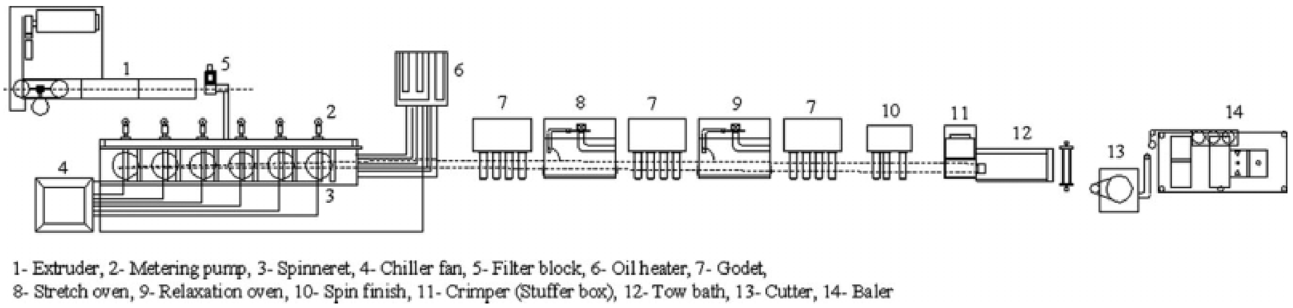


Figure 1 Schematic line diagram of melt spinning of staple fibers.

The objective of this work was to optimize the melt spinning technique to produce five samples of staple PP fibers with different deniers ranging from 7.5 to 17.5 and study the effect of these different deniers on the physical properties of staple PP fibers at pump speeds ranging from 10 to 100 rpm.

EXPERIMENTAL TECHNIQUES

Melt spinning machine

The melt spinning machine that was used to produce five different staple polypropylene fibers was a commercial sized machine. The spinning machine consists of six conventional positions, one-stage melt spinning machine with total nominal capacity of 600 kg/h. Figure 1 shows the schematic line drawing of the melt spinning machine. The "spinnerets" of spinning positions had a doughnut-shaped design, i.e., circular spinnerets, with 3000 holes per spinneret and a total of 18,000 round cross section orifices. The length and diameter of each spinneret hole is 2 mm and 0.5 mm, respectively. Polypropylene polymers were melted and supplied to six individual spinnerets of the spinning machine through an extruder having a 160 mm diameter with a length of 5600 mm, i.e., 35 times L/D. Resistance heating technology was used to heat the extruder at 10 different locations. Extruder speeds ranged from 10 to 100 rpm. Each revolution of the extruder supplied 257 cc's of molten polymer to six individual spinning pumps. The extruder temperature were set from 205 to 230°C, rotating at 40 rpm at a pressure of 67 bars. The spinning pumps were set at 20 rpm for a take-up speed of 46 m/min.

To investigate the effect of denier on the optical and physical characteristics of staple polypropylene fibers, five different samples of polypropylene fibers were spun at five different pump speeds.[12] As it can be seen from Figure 1, fibers from the spinnerets were taken up by the first set of "godet" rollers (heated to 65°C) at a speed of 13.1 m/min. Subsequently, the fibers were stretched between the first set of godets and the second godet rollers, whereas the fibers were traveling through stretch oven with temperature of 110°C at the speed of 45.9 m/min to give draw ratio of 3.5. The fibers were then left to relax at a temperature of 130°C in the relaxation oven, before being taken up by the third set of godet rollers via the "staffer box" method. The third godet traveled at the speed of 43.5 m/min compared with the second godet to allow the fibers to shrink by 5.2%. Fiber tows were introduced to a Lumus-type cutter, so that could be chopped to the required length for further processing.

Stuffer box and crimping

Staple fiber crimp affects the characteristics of the product as well as being beneficial during textile processes. One of the important fiber characteristics in the carpet industry is fiber crimp, firmness, and its frequency. Since synthetic fibers have no crimp, due to the way they are manufactured, they must be crimped, off or online, for most applications. There are several methods that can be used to create crimp in the filament yarn, but stuffer-box technology is the only method used to create crimp in the tow of fibers among others. Crimp in the fiber is achieved by forcing the fiber to crumple in a confined heated compartment. As it can be seen from Figure 2, the feed rollers draw the fiber tow-off the previous unit (Fig. 1) and push it to the preheated chamber to achieve the desirable temperature against the

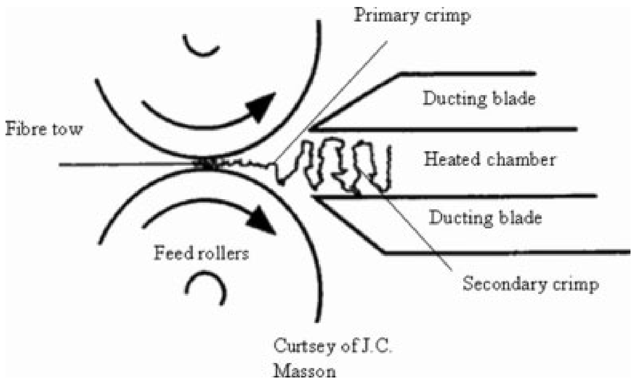
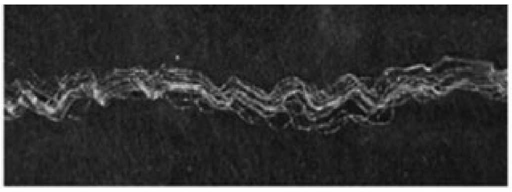
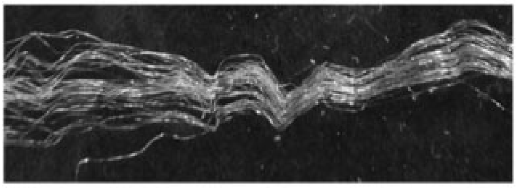


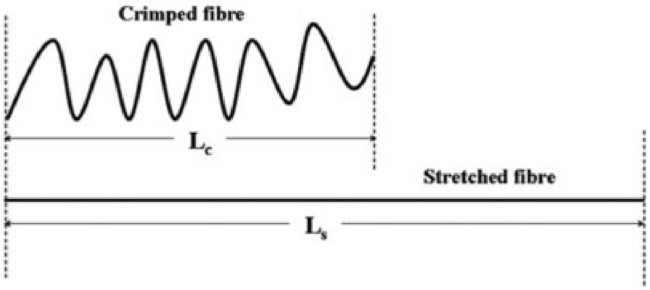
Figure 2 Schematic diagram of staffer box of fiber crimping.



(a) D = 7.5



(b) D = 15



(c)

Figure 3 Crimping measurement; (a) crimped fiber of 7.5 denier, (b) crimped fiber of 15 denier, and (c) schematic diagram of crimped and stretched fibers.

pressure in the stuffer box to buckle the fiber tow. Pressure in the stuffer box against incoming fibers is obtained either by a spring-loaded trapdoor which pivots at the end of the upper doctor blade or tapered ducting blades. This exerts pressure against incoming fibers. The level of crimp per unit of length in the fiber is achieved by adjusting either spring pressure or angle of tapering. However, sharp crimps are created in the collapsed filaments, which are set as they are heated and then cooled. The crimping speed of stuffer-box machine can be as high as 600 m/min.[13] However, with very heavy tow, the linear production may not be high but the mass production remains high.

The major challenge is to provide enough force to make the fibers buckle while the process is continuing. This is to say that one end of uncrimped fiber tow is introduced to the stuffer box; after receiving crimp, it emerges from the other end as crimped tow. In principle, fiber tow is overfed into a heated cavity to soften the filaments, overfeeding causes the heated filaments to buckle.[14] The heat sets the filaments in the acquired configuration as the filaments cool. stuffer-box crimping is a zigzag type of crimping which means it is a two-dimensional crimp, rather like helical (twist set crimp) or air jet crimping.

Man-made staple fibers processability in the textile machinery is governed largely by their cohesion properties, and further improvement on cohesion can be obtained by crimping. A common method of inserting crimp in fiber tow before being chopped into staple fiber (stuffer-box) is mentioned earlier. Two examples of stuffer-box crimped PP namely 7.5 and 15 denier fibers are shown in Figure 3(a,b). To evaluate the staple PP fiber crimp, a method of image processing was adopted. This means, several images from different denier of PP fiber were taken. For the software (Image Pro plus version 4), calibration one image was taken from graduated (1 mm to 100 divisions) microscope slide. After the software has been calibrated, each crimped fiber image was uploaded. Two length measurements were carried out on each fiber. One in crimped state (length L_c frequency) and the other in stretched state (length L_s). By moving the curser on the fiber all the way through, each bit of curvature is shown with the line schematic diagram in Figure 3(c). The following formula was used to calculate the crimp ratio[15]:

$$\text{Crimp ratio} = \frac{L_s - L_c}{L_s} \tag{1}$$

Two-beam interference microscopy

The double refracting interference (Pluta) microscope[16] has been designed especially for monitoring the interferometry of fibers. The microscope serves the purpose of measuring the optical path difference, gradient of the optical path, thickness, refractive index, birefringence, and other physical quantities. This microscope works in two modes; the subtractive and crossed positions. When the microscope is adjusted in the subtractive mode, it can be used to measure directly the double refraction (birefringence). When it is adjusted in the crossed mode, the refractive index in case of light polarizing parallel and perpendicular to the fiber axis can be measured. In our experiments, the microscope is adjusted in the subtractive position. The different samples of PP act as phase objects that produce a modulation in the light transmitted. The birefringence of these fibers can be calculated using the following equation[7]:

$$\Delta n = \frac{\Delta Z \lambda}{bt} \tag{2}$$

where "ΔZ" is thefringe shift inside the fiber, "λ" is the wavelength of monochromatic light used, "b" is the interfringe spacing, and "t" is the fiber diameter.

Differential scanning calorimetry (DSC)

The thermal properties of staple PP fibers were measured using Perkin Elmer jade differential

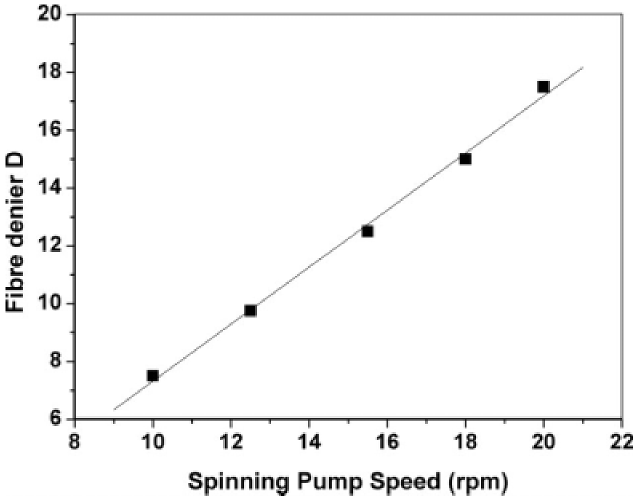


Figure 4 The relation between the fiber denier and the pumping speed.

scanning calorimeter (DSC). The instrument's base line was calibrated using Indium as a standard before each set of DSC experiments. The heat of fusion (melting enthalpy) was measured for the staple PP samples. The degree of crystallinity is related to the heat fusion by the following formula[17]:

$$\chi = \frac{\Delta H}{\Delta H_o} \tag{3}$$

where, ΔH is the heat of fusion (melting enthalpy) of the tested polymer and ΔH_o is the heat of fusion (melting enthalpy) of a 100% crystalline polymer. For a 100% crystalline polypropylene, the value of $\Delta H_o = 207$ J/g[18] was used.

RESULTS AND DISCUSSION

The five samples of spun staple PP fibers were produced with different deniers ranging form 7.5 to 17.5. The pumping speed was varied in the range from 10 to 100 rpm. Figure 4 gives the relationship between the effects of pumping speed on the fiber denier. This relationship implies that an increase in pump speed causes denier of fiber to increase linearly. Figure 5 shows the relationship between the denier and the diameter of the staple PP fiber. As far as we know and as it is clear from the Figure 5, when the value of denier increases, the diameter is also increased. Figure 6 presents the influence of the denier (i.e., diameter) variation on the fiber's crimping. The crimp ratio was calculated using eq. (1) for the five samples at different deniers. It was found that as a result of increasing the fiber denier, the crimping frequency and ratio are both deceased. For example, see Figure 3(a,b) shows the crimping images for 7.5 and 15 deniers, respectively. Corresponding to the reduction in fiber crimping, the tenacity of staple PP fibers was determined using the INSTRON tensile tester and plotted against the fiber

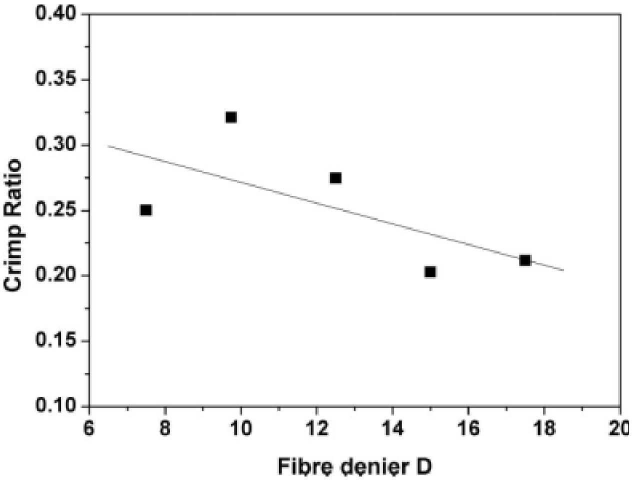


Figure 6 The relation between the crimp ratio and fiber denier.

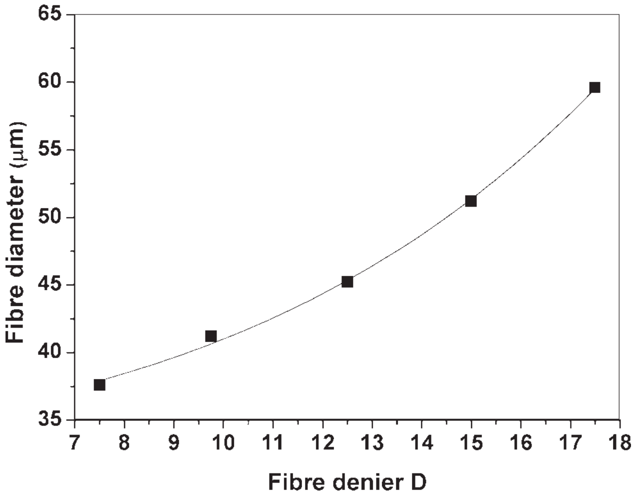


Figure 5 The relation between the fiber denier and the fiber diameter of the staple PP fiber.

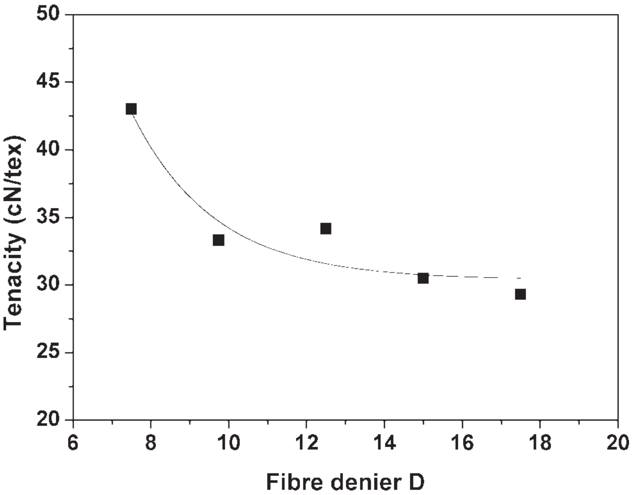


Figure 7 The relation between the fiber tenacity and the fiber denier.

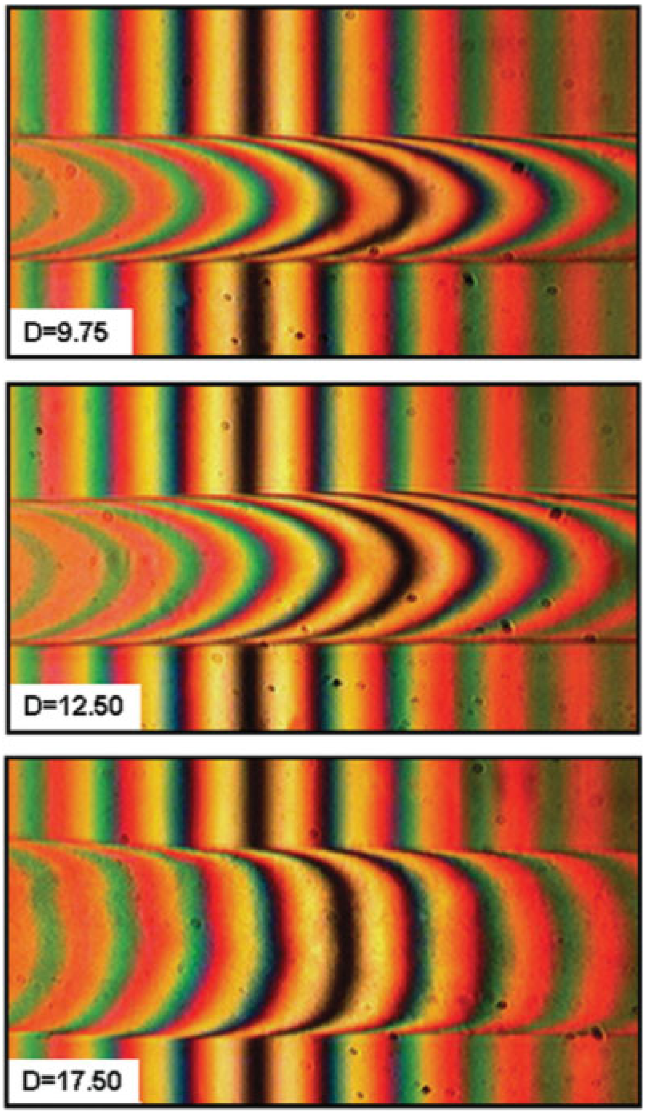


Figure 8 Microinterferograms of three samples of staple PP fibers with different deniers taken by the Pluta microscope. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

denier as shown in Figure 7. It is clear that increasing the fiber denier as well as increasing pumping speed reduces the fiber tenacity exponentially.

To characterize the fibers structurally, two-beam interferometry was used. Figure 8 gives some of the microinterferograms obtained for staple PP fibers at different deniers. The wavelength of light used was 550 nm. To obtain quite clear images at ambient temperature of 22°C immersion oil having refractive index of 1.5 was used. Using these microinterferograms and eq. (2), the birefringence Δn was calculated for the different samples. Figure 9 shows the relationship between the fiber birefringence and the fiber deniers. The birefringence of staple PP fibers was found to decrease as the fiber denier increased; this is an expected trend as the fiber diameter and denier are increased. Spinning the fibers with same, the conditions except pump speed will change the fiber diameter and hence its birefringence [see eq. (2)]. The error in the determination of the birefringence cannot be better than 0.003–0.001.[16]

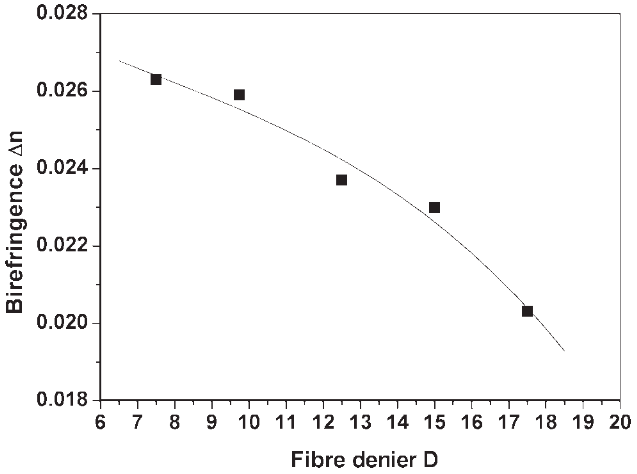


Figure 9 The relation between the fiber birefringence and the fiber denier.

During the melt spinning of PP staple fibers, most of the molecules are considered to be aligned uniaxially in the drawing direction and the rest are randomly arranged transversely. For evaluating this molecular alignment, the optical anisotropy or birefringence Δn of fiber is one of the well-known parameter to reflect the overall orientation (Hermans) factor,[19] which can be determined as follows:

$$\mathbf{F}(\theta) = \frac{\boldsymbol{\Delta}\mathbf{n}}{\boldsymbol{\Delta}\mathbf{n}_o} \tag{4}$$

where Δn_o is the intrinsic maximum birefringence which corresponds to the case where all the molecules are perfectly aligned. For fully oriented fibers, the optical orientation factor $F(\theta)$ would be 1. For

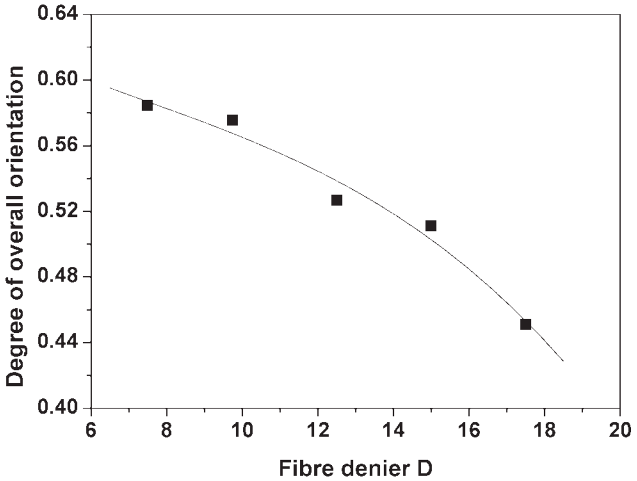


Figure 10 The relation between the overall orientation of staple PP samples and fiber denier.

TABLE I
DSC Results of Staple PP Fibers at Different Deniers

Denier (D)	Enthalpy (ΔH) J/g	Crystallinity (χ)
7.50	92.51	44.69 ± 0.43
9.75	98.59	47.63 ± 0.04
12.5	95.11	45.95 ± 0.39
15.0	98.30	47.49 ± 0.18
17.5	98.13	47.41 ± 0.02

isotropic system where there is no orientation $F(\theta)$ would be 0. The value of Δn_o for PP fiber was taken to be 0.045.[20] Figure 10 shows the relationship between the optical orientation factor of staple PP samples and fibers deniers. It is clear that as denier value increases, the optical orientation factor is decreased. This indicates that the molecules constituting the fibers become less oriented upto the higher values of denier and correspondingly an increase in the angle of orientation (average angle between the polymer chains and the fiber axis). The higher the fiber denier the higher disorientation thus, the lower orientation would be the expected.

The enthalpy of fusion, also known as the heat of fusion, is the amount of thermal energy which must be absorbed or evolved for 1 mole of a substance to change states from a solid to a liquid or *vice versa*. It is also called the latent heat of fusion or the enthalpy change of fusion, and the temperature at which it occurs is called the melting point. In addaition, Enthalpy H is an arbitrary concept but the enthalpy change ΔH is more useful because it is equal to the change in the internal energy of the system, plus the work that the system has done on its surroundings.[21] Table I gives the measured enthalpy (heat of fusion) and degree of the crystallinity of staple PP fibers at different deniers. It is obvious that there is no significant trend for both of the enthalpy and the crystallinity degree versus denier values. The reason behind the insignificant variation of crystallinity, it might be due to the drawing conditions of fibers which melt spun with the same draw ratio (D.R. ≈ 3) and the main variable parameter was the speed of metering pump which varies both of the fiber diameter and denier and doesnot affect heat fusion and hence degree of crystallinity.

CONCLUSIONS

The melt spinning technique is the most suitable method for production of staple PP fibers under various conditions. The influence of pumping speed and denier values on the physical properties of staple PP fibers was investigated. Two-beam microinterferometry and differential scanning calorimetry were found to be appropriate techniques for characterization of the fibers. From the results, the following conclusions may be drawn:

1. Increasing denier values leads to a decrease in the tenacity, birefringence, and orientation of the staple PP fiber.
2. Increasing of the pump speed during the spinning process increases the fiber denier values.
3. The increase in the pumping speed results in molecular disorientation along the fibers axis, i.e., higher the fiber denier the higher disorientation the lower orientation would be the expected.
4. No significant variation in the melting enthalpy and degree of crystallinity versus fiber denier.

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