Effect of Heat Setting Process for Polymers

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Heat setting is an important step in the production of synthetic yarns. It imposes a thermo forming on fibres at temperatures higher than their glass transition temperature, and induces changes in fibre crystallinity, chain ordering, etc. These rearrangements are retained in the fibre as a "memory-effect", and affect both the physical properties of the fibres and the degree of dye uptake, shrink resistance, dimensional stability, temperature resistance, and wrinkle resistance. Polypropylene (PP) heat set bulked continuous filament (BCF) yarns is becoming widely used in machine-woven carpet manufacturing as a pile yarns. Normally, man-made fibres are produced without any surface characteristics. In contrast, natural fibres, especially, wool, cotton are not straight, exhibit a marked configuration like helical and ribbon like with a wide inner hollow. However, man-made fibres are lack of natural structure such as resiliency and good appearance of the woven carpets. Heat setting plays a very important role in producing filament yarns with desired properties. This chapter aimed to investigate the effect of heat setting on the structure and properties of industrially produced heat set BCF PP yarns. The increase of temperature from 100°C to 140°C caused a decrease in the strength and elongation values of the BCF PP yarns and an increase in the crimp, shrinkage and yarn linear density values.

Keywords: heat setting; thermoforming; filament yarn; extrusion; yarn mechanical properties; machine-woven carpet

1. Introduction

Fibres are the basic elements of a textile. They can be classified as belonging to one of the following two classes: (a) natural, and (b) man-made. Natural fibres are taken from animal, vegetable, or mineral sources. The most important animal fibres are wool and silk. Cotton and flax are the most important vegetable fibres. All these important natural fibres have been began to use in textile industry for thousands years ago; the bast fibres such as flax, in Egypt at least 7000 years ago; silk in China, wool in Europe and the Middle east, cotton in India and the Americas at least 500 years ago [1,2,3,4]. Manufacturing of man-made fibres began at the end of the thirteen century. Investigations carried-out in the USA on the production of a synthetic polyamide fibre were terminated in 1939 and the following years witnessed the development of manufacturing processes for other kinds of synthetic fibres (polyester, polyacryclonitrile and others). In the course of the last 75 years, about 100 different kinds of man-made fibres were devised, which differ in the initial materials used for their manufacture, the methods of production and their properties [5]. Annual consumption of man-made fibres are increasing day by day because of using a large number of industrial, technical and engineering application. In the future, both world production and absolute fibre consumption per head are expected to rise, but production of natural fibres can be expanded only slowly. The expected substantial rise in the demand for fibres throughout the world during the coming decades must therefore be satisfied by increased use of man-made fibres. The fibres themselves, and hence the know-how involved in processing them, are therefore acquiring steadily greater significance [6].

Polypropylene was the last of the four major man-made fibres of the title to be commercialised. BCF PP man-made yarns are becoming widely used in machine-woven carpet manufacturing as a pile yarns. It is expected that this trend will continue in the near future. The importance of PP as a fiber is easy processing, low production cost and excellent properties. However, it withstands easily footfall, because it is not as resilient as other fibres [7,8].

BCF PP yarn production is a continuous process, consisting melt spinning, drawing and texturing. After being extruded from the spinneret, the molten polymer starts solidifying. Finishing oil is applied to the solidified multifilament yarn, and the yarn is subsequently stretched by about three times in the drawing zones, so that it acquires enough orientation and consequently proper mechanical properties. Texturizing of the continuous filament yarn is emerging from the drawing zone. This process imparts volume, softness, dullness and cover factor of the yarn. After leaving the texturizer, the plug rests on a rotating cooling drum, where the process of setting the rather three-dimensional coils formed as a result of the compression in the plug. Parameters such as cooling air, air pressure and air temperature play an important role in specifying the final properties of textured yarns [2,9,10,11].

2. Heat setting process

Heat setting is a term used in the textile industry to describe a thermal process. A process employing heat and pressure on fabric or carpet yarn to accomplish certain desired results (Figure 1). On fabric made of synthetic fiber (or of natural, chemically treated fibers), it is used to impart a crease or pleat that will last through washings or dry cleanings. Heat setting gives also shrink resistance, shape retention, and dye fastness. It is used on carpet yarns to improve resiliency and to set twist [1,12,13,14].

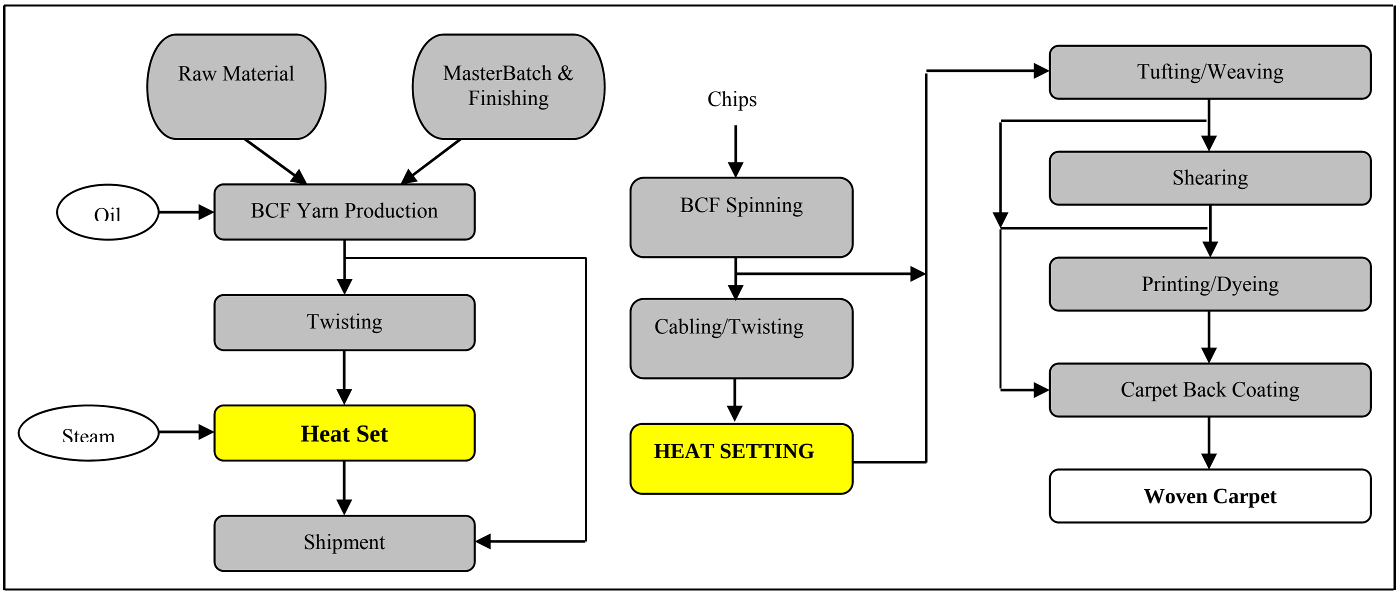

Fig. 1 BCF carpet production process chain from polymer to the product.

The effects of heat setting process bring fibers, yarns or fabrics in dimensional stability, temperature resistance and other desirable attributes like higher volume, wrinkle resistance etc. Heat setting is also used to improve attributes for subsequent processes. Yarns tend to increased torqueing just after spinning, cabling or twisting (Figure 2).

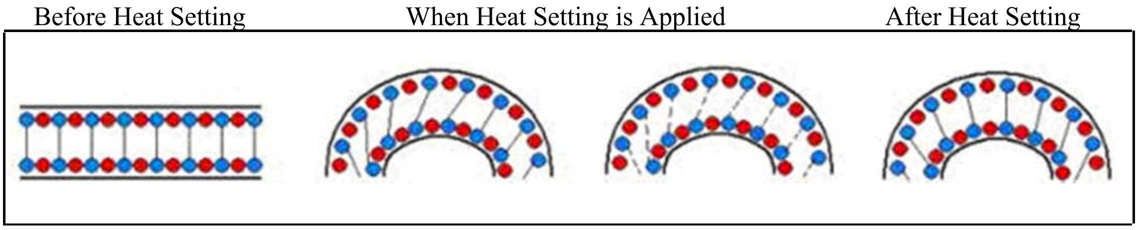

Fig. 2 Stabilization effect of heat setting process.

Heat setting can influence or even eliminate this tendency to undesirable torquing. At the winding, twisting, weaving, tufting and knitting processes, an increased tendency to torquing can cause difficulties in processing the yarn. When using heat setting for carpet yarns, desirable results include not only the diminishing of torquing but also the stabilization or fixing of the fiber thread.

Both twist stabilization and stabilization of frieze effect are results of the heat setting process. Heat setting benefits staple yarns as well as BCF yarns. Heat setting often causes synthetic fibers to gain volume as well. This volume growth is commonly described as "bulk development". All processes using temperature and/or moisture to give textiles one of the above mentioned attributes are known as heat setting. The term "thermal fixation" is used less frequently. In the carpet industry, the process is exclusively called "heat setting".

3. Experimental Results

In this chapter, 12 bobbins of BCF PP yarns (1600, 2000 and 2500 dtex, 44 filaments) are produced on an industrial production line. Tree different yarn linear density BCF yarn is produced by changing only flow rate of pump with same drawing ratio. The natural colour with trilobal filaments are produced by gravimetric feeding of 96 % polypropylene granulates (MFI=20) and 2.6 % master batch to a Neugmac BCF machine. Properties of PP granulates are given in Table 1.

Table 1 Properties of PP polymer granulates.

Melt Flow Index (MFI (gr) at 228 ºC)	20
Melting Point (ºC)	152
Polymer Density (kg/lt)	0,74
Heat Conduction Coefficient (J/ms ºC)	0,15
Specific Heat (kJ/kg ºC)	2,10

The production parameters of BCF yarn are given in Table 2. Spinning, twisting and heat setting processes of filament yarns are operated in the mill conditions. So that, analyze of heat setting effect on yarn properties have been carried out on yarns which have used to produce as machine-woven carpets. For this purpose, four different setting temperatures (100, 120, 130 and 140 ºC) are used as analysis variances.

Table 2 Production parameters of BCF yarns.

SPINNING (Neumag-NPT 2000)	
Extruder temperature (ºC)	190, 200, 210, 220, 225 and 228
Extruder pressure (bar)	130
Draw ratio	1:2.84
Temperature of texturizer (ºC)	140
Pressure of texturizer (bar)	8,5
Cooling air temperature (ºC)	17
Cooling air humidity (rH)	70 %
Cooling air velocity (m/s)	0,8
Yarn speed (m/min)	1100
Weight of cylindirical bobbin (kg)	3,5
TWISTING (Volkman-050C8.02)	
Yarn twist (turn/m)	100
Twist type	2 for 1
Winding speed (m/min)	52,4
HEAT SET (Power Heat-Set GKK2500)	
Setting temperature (ºC)	100-120-130-140

For experiments, mechanical properties of 100% PP carpet yarns have been tested according to ISO and ASTM standards. Yarn linear density is measured ISO 2060: 1994 Textiles; Yarn from packages- Determination of linear density (mass per unit length) by the skein method. Direct yarn numbering system (dtex) is used. Yarns are randomly selected from the BCF specimens. Test results are reported and yarn numbers are calculated. Yarn strength and elongation are measured ISO 2062: 1993 Textiles; Yarns from packages- Determination of single-end breaking force and elongation at break. Crimp contraction and shrinkage are measured Textured Yarn Tester (TYT) by Lawson Hemphill by ASTM D-6774-02; Crimp and Shrinkage Properties for Textured Yarns Using a Dynamic Textured. Prior to the tests, the samples are conditioned in the standard atmosphere for testing textiles, i.e. a relative humidity 65 % ± 2 % and a temperature of 20 ºC ± 2 ºC for 24 h. All tests are repeated 10 times for each sample.

4. Discussion

4.1 Strength and Elongation

Mechanical properties of filament yarns are the most important properties for end-products. The purpose of tensile tests is to investigate yarn properties and to estimate their suitability for pile, to estimate how strength. Heat setting causes the structural change of fiber orientation. The principal focus of this study is to explore the effect of heat setting on the mechanical properties of BCF PP yarns.

In Figures 3 and 4, the change against yarn strength under four different heat settings temperature of BCF PP yarn at three different yarns linear densities are shown. Heat setting generally decreases the strength and elongation of BCF PP yarns. However the effect of temperature in the range from 100 to 130 ºC is particularly small, where at 140 ºC, the effect becomes more noticeable. Because during the heat setting process while the temperature is increasing, the molecular structure both amorphous and crystalline phase is changing. It can be said that heat setting generally leads to restructuring. Due to the temperature of the heat-setting, the distance between crystalline centers and the number of bonds between molecules in fibers decreased. It could be explained that the decreased tensile properties were correlated with more unoriented chains in amorphous and crystalline region, and more irregular yarn structure. Structural change may lead to change strength and elongation of BCF PP yarns. As a consequence, yarn strength and elongation is declined.

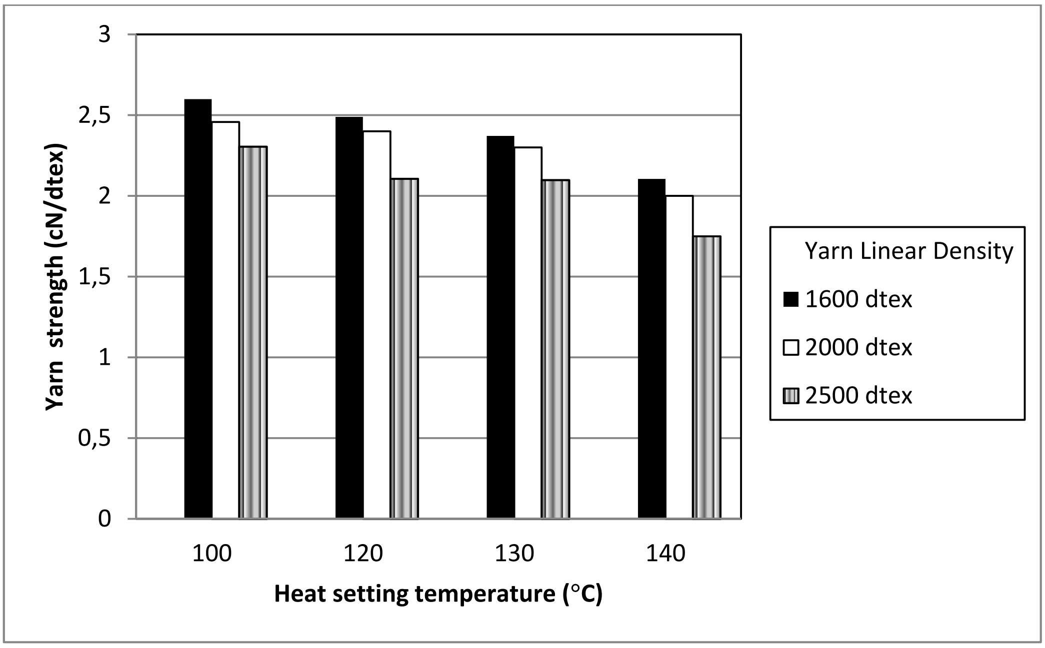

Fig. 3 Changes on strength properties of BCF PP yarn.

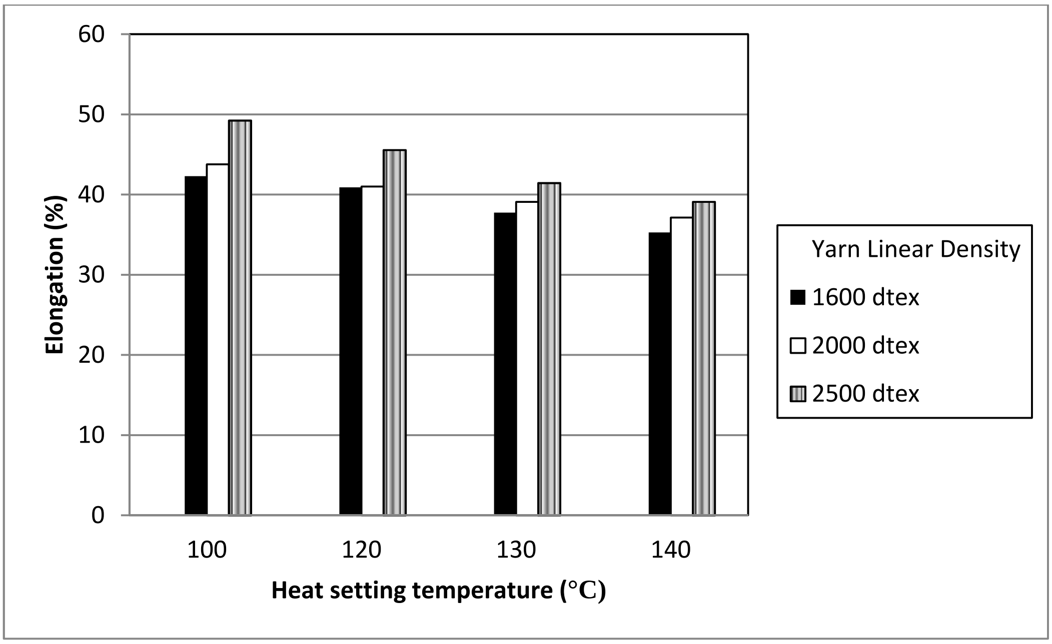

Fig. 4 Changes on elongation properties of BCF PP yarn.

4.2 Crimp

Crimp is a physical change in the structure of the individual filament. Crimp is a relatively unstable mechanical structure of individual filaments, which together with other filaments, have a volume. Changes in crimp result in variations of the yarn's geometry. The crimp structure has a decisive influence on the appearance of the yarn in the carpet. The introduction of yarns with different crimp levels into the same fabric will change the reflectance of light off the surface of the fabric, producing dye shade differences. The shrinkage level influences the dye uptake or the dispersion of dyestuff particles into the molecular spacing, causing an increase or decrease of adhesion of the dyestuff particles into non-crystalline regions. Crimp is also particularly useful in carpet pile yarns. More crimp yarn has excellent bending recovery. Bending recovery is indicated of how well a yarn can bounce back to its original geometry after a load has been removed. The higher the percent recovery, the more the yarn is able to return to its original geometry.

Heat set temperature has a predominant role in crimp properties as shown in Figure 5. It shows the variation of the percentage crimp versus temperature of heat set. It is clear from the Figure 5 that the crimp of BCF PP yarns increases with increased heat-setting temperature. Various researches have also shown that hot air set the yarn into its new configuration and so changes the crimp of BCF PP yarns [14,15,16,17,18].

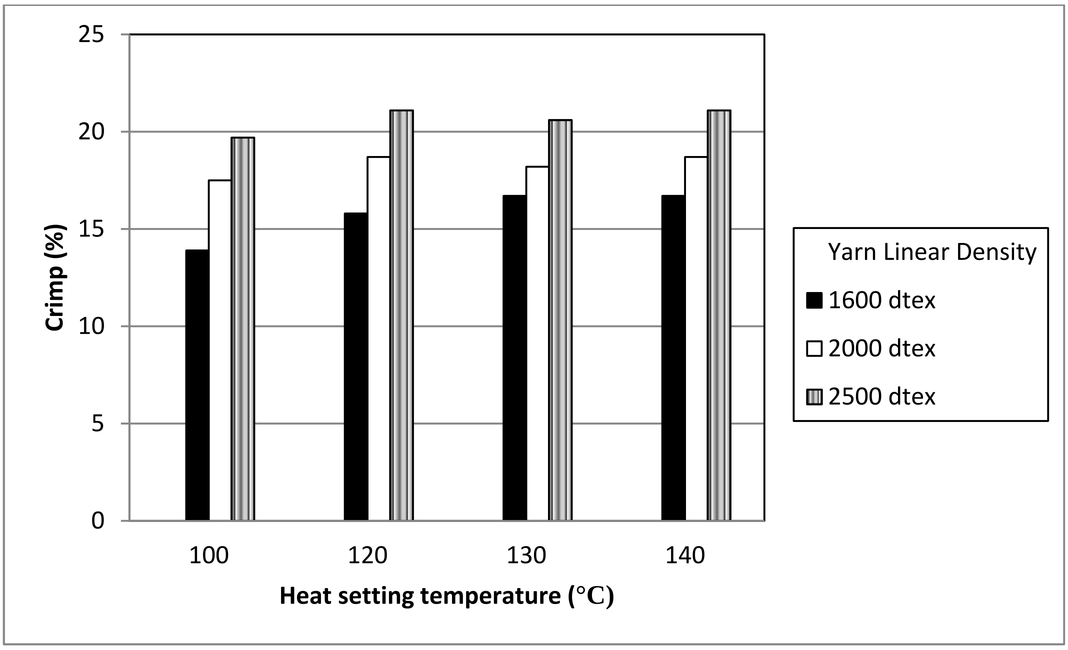

Fig. 5 Changing on crimp properties of BCF PP yarn.

4.3 Shrinkage

Non-heat setting and/or non-uniform heat setting can induce disorientation in the fiber morphology and is responsible for the fiber length change, leading to problems in applications, such as streaks in finished products. Therefore, shrinkage is a useful property for determining dimensional stability. The amount of fiber shrinkage will affect the processing behaviour of yarns and dimensional changes in the fabrics made from these yarns. Differences in shrinkage behaviour of threads may lead to wrinkle appearance in the fabric after finishing of the products.

In Figures 6, the change against shrinkage under 4 (four) different heat setting (100, 120, 130 and 140 ºC) of BCF PP yarn at three different yarn linear density is shown. As can be seen in Figure, the shrinkage of the yarns increases considerably by increasing heat setting temperature. As the heat-set temperature increases, the microstructure of BCF PP yarn is unstabilized. Molecular orientation is increased. Amorphous and crystalline regions are changed. However, the shrinkage value of 2500 dtex BCF yarn is decreasing at 140 ºC because of irregular raw material molecular orientation, instability raw materials, irregularity of drawing zone e.g. godet surface starching and not exactly adhesion spin finish pump to the raw material.

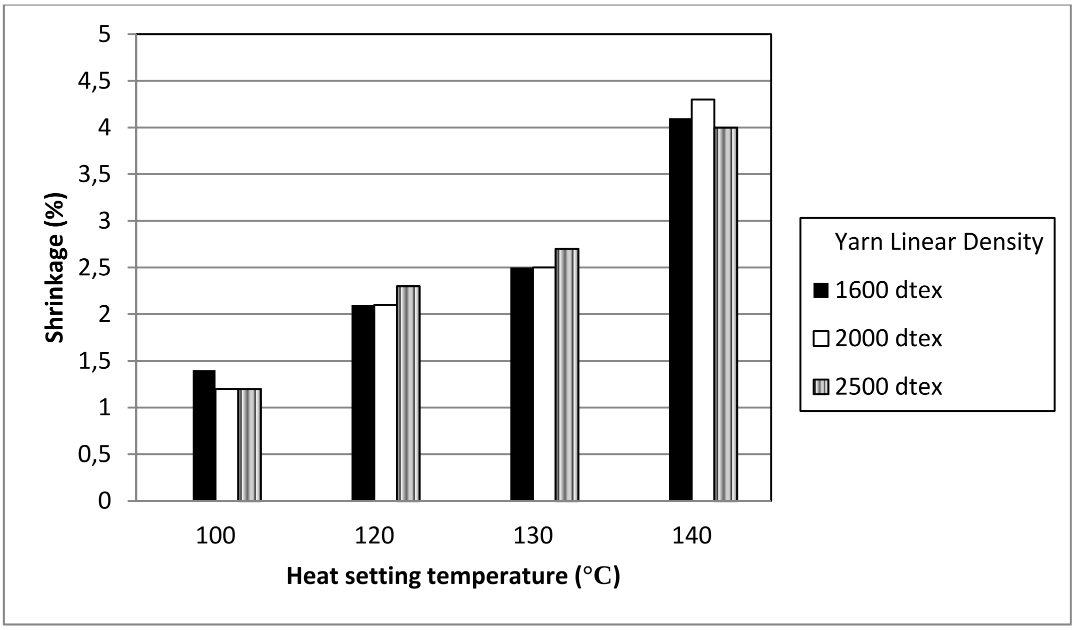

Fig. 6 Changing on shrinkage properties of BCF PP yarn.

4.4 Yarn linear density

As expected temperature of heat setting increase the linear density of the yarns as shown in Figure 7. When heat set is applied to yarn, length of yarn is decreasing, it is seen that as heat-setting temperature increases, so does diameter. It is also found that after heat treatment BCF PP yarn became slightly thinner and more even in density. Heat setting leads to restructuring. In other words, heat set change the molecular structure of yarn. Amorphous and crystalline regions are changed by heat setting. Disorientation in the amorphous and crystalline regions causes fiber length changes and diameter. On the other hand, weight of yarn is not changing, because PP fiber is not hold the humidity on it. Therefore, according to yarn count system dtex which is the mass in grams per 10,000 meters is depend on metric system, yarn linear density is increasing.

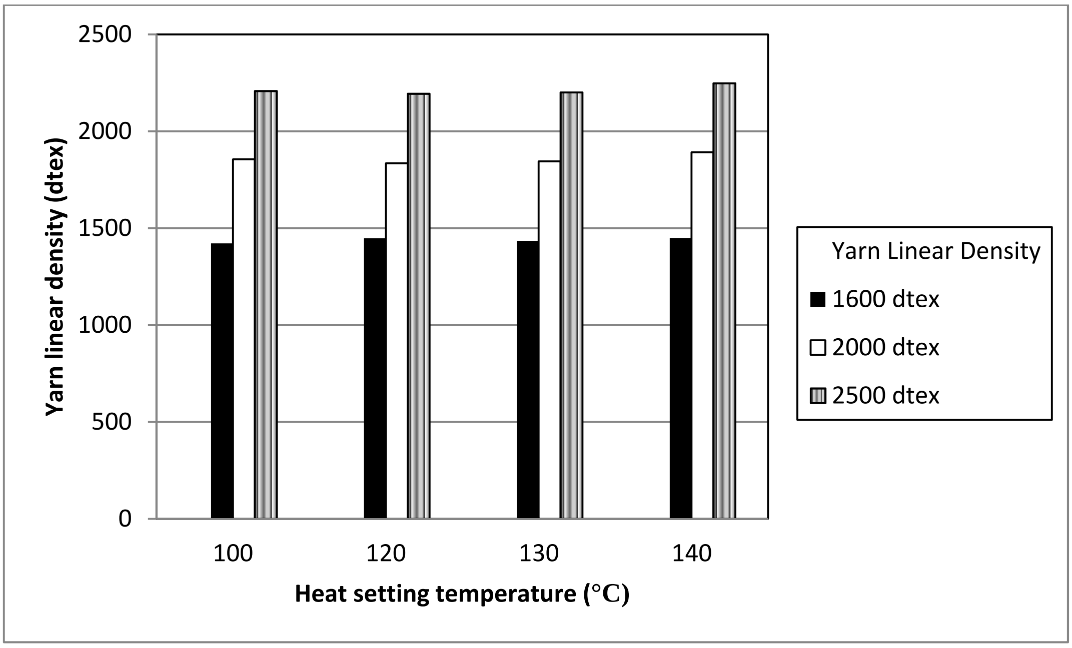

Fig. 7 Yarn linear density of BCF PP yarn.

5. Statistical significance analysis

The experimental results have been statistically evaluated by using the Design Expert Analysis of Variance (ANOVA) software with F values of the significance level of $\alpha = 0.05$, with the intention of exploring whether there is any statistically significant difference between the variations obtained. We evaluated the results based on the F-ratio and probability of F-ratio (prob>F). The lower the probability of F-ratio, it is stronger the contribution of the variation and the more significant the variable. The best models for each fabric were obtained and the corresponding regression equations and regression curves were fitted. The test results of the related fabrics were entered into the software for the analysis of the general design [19].

Table 3 summarizes the statistical significance analysis for all the data obtained in the study which have been evaluated separately. In the table, variables are yarn linear density (dtex) and heat set temperature (ºC). Moreover, abbreviations in Table 3: F-V is the F-Value, P-V is the P-Value, A-Yarn Linear Density (dtex) and B- Heat Set Temperature (ºC), $R_a{}^2$ –Adjusted R^2, $R_p{}^2$- Predicted R^2. Here, the p values of models smaller than .are considered to be significant. The ANOVA table also indicates the significant interactions between filament yarn properties and heat setting conditions. The term A and B in this table is independent variables (numerical factors), whereas the mechanical properties are dependent parameters. The term "model" is the sum of the model terms in the ANOVA table. The regression equations were also developed by considering the ANOVA table.

When ANOVA table (Table 3) is examined, it can be seen that heat set temperature and yarn linear density have significant impact on strength, elongation, crimp, shrinkage and yarn linear density values. In addition, according to the table, the R^2 value of the model turned out to be approximately 0,98. In this case, terms in the model can explain the model at 98 % ratio. This case shows that the model created for response values (strength (cN/dtex), elongation (%), crimp (%), shrinkage (%), yarn linear density (dtex)) can express with rather high accuracy the relation between independent variables and dependent variable and that experimental work results were acceptable as accurate.

Table 3 Statistical significance analysis (ANOVA Table).

	Strength (cN/dtex)		**Elongation (%)**		**Crimp (%)**		**Shrinkage (%)**		**Yarn Linear Density (dtex)**	
Factor	**F-V**	**P-V**	**F-V**	**P-V**	**F-V**	**P-V**	**F-V**	**P-V**	**F-V**	**P-V**
Model	39,17	0,0002	42,88	0,0001	79,55	<0,0001	32,49	0,0003	1027,92	<0,0001
A	113,79	< 0,0001	163,55	<0,0001	38,43	0,0008	152,42	<0,0001	6,38	0,0449
B	64,74	0,0002	64,40	0,0002	355,41	<0,0001	0,0003	0,9581	4974,08	<0,0001
A^2	18,73	0,0049	3,71	0,1024	4,00	0,0925	14,80	0,0085	6,22	0,0470
B^2	10,83	0,0166	13,84	0,0099	10,23	0,0186	0,0925	0,9266	104,93	<0,0001
AB	0,025	0,8800	2,97	0,1355	7,42	0,0344	0,19	0,6812	0,060	0,8149
R^2	0,9703		0,9728		0,9851		0,9644		0,9988	
$R_a{}^2$	0,9455		0,9501		0,9728		0,9347		0,9979	
$R_p{}^2$	0,8842		0,8880		0,9360		0,8876		0,9909	

A normality test (normal distribution test) was also applied on the data obtained from mechanical properties by changing yarn linear density (dtex) and heat setting temperature (ºC). In general probability plotting is a graphical technique for determining whether sample data conform to a hypothesized distribution based on a subjective visual examination of the data. The assessment is very simple. From the data, which are scattered around the normality line as shown in Figure 8, we can see that they conform to normal distribution. This analysis also supports the conformity of chosen model.

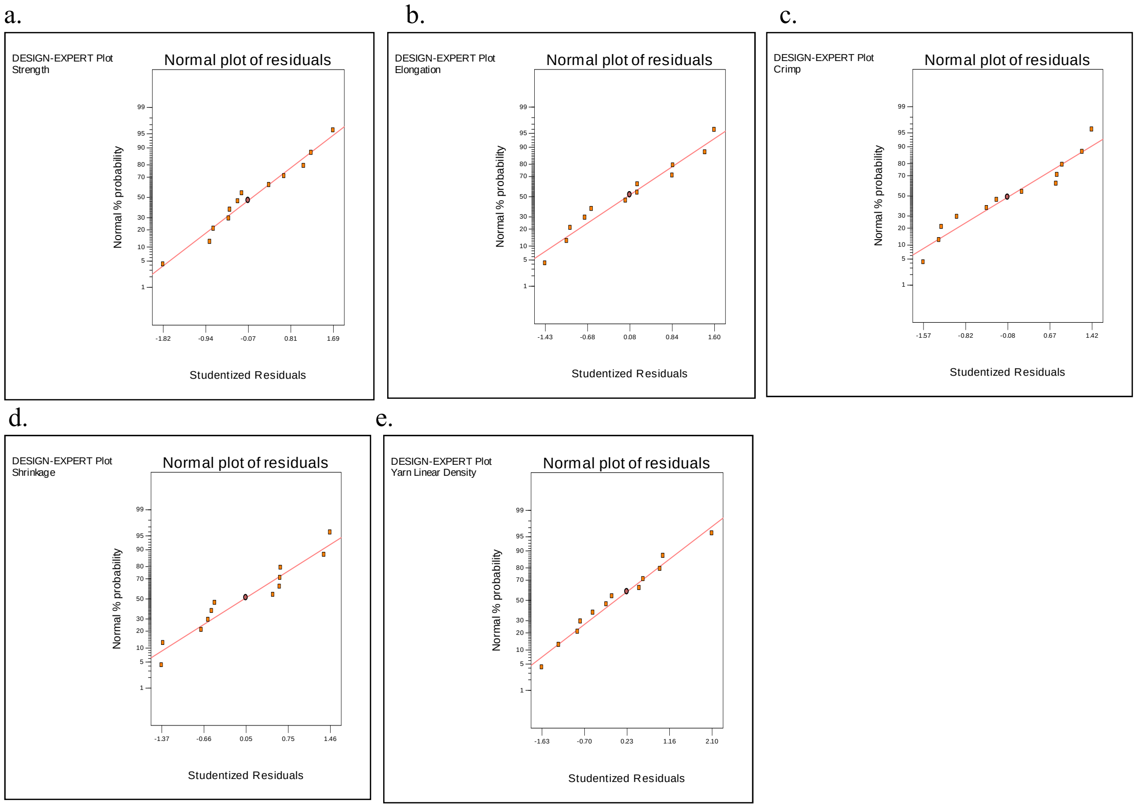

Fig. 8 Normality test for heat set of samples (a. Strength, b.Elongation, c. Crimp, d. Shrinkage, e. Yarn Linear Density).

The regression equations for determining heat set temperature are presented below.

$$\mathit{Strength} = +2{,}39 - 0{,}16{*}A - 0{,}24{*}B - 0{,}044{*}A^2 - 0{,}16{*}B^2 - 8{,}998E\text{-}003{*}A{*}B \quad (1)$$

$$\mathit{Elongation} = +41{,}62 + 2{,}50{*}A - 4{,}11{*}B + 0{,}95{*}A^2 - 1{,}08{*}B^2 - 0{,}87{*}A{*}B \quad (2)$$

$$\mathit{Crimp} = +18{,}71 + 2{,}48{*}A + 0{,}84{*}B - 0{,}35{*}A^2 - 0{,}48{*}B^2 - 0{,}41{*}A{*}B \quad (3)$$

$$\mathit{Shrinkage} = +1{,}96 + 7{,}8E\text{-}003{*}A + 1{,}37{*}B + 0{,}011{*}A^2 + 0{,}70{*}B^2 + 0{,}038{*}A{*}B \quad (4)$$

$$\mathit{Yarn\ Linear\ Density} = +1885 + 386{,}77{*}A + 15{,}59{*}B - 75{,}18{*}A^2 + 24{,}85{*}B^2 + 1{,}82{*}A{*}B \quad (5)$$

6. Conclusions

We have examined the heat setting effect and mechanical properties of BCF PP yarn treated at various heat setting conditions. An analysis of the effect of heat setting process showed that heat set temperature is the most critical variables for quality of yarn. From the results of test on the samples, it can be concluded that the properties on structure of yarn are affected at different heat set temperatures. For production of stable yarn, immediately after drawing, a heat setting process is required. Drawing brings the structure to a stable state and heat setting improves the uniformity and stability of the structure. In other words, restructuring is responsible for the heat setting process. As a result of heat setting, the mechanical properties of the treated BCF PP yarns, such as strength and elongation decreases. Crimp, shrinkage and yarn linear density increases as a result of heat setting.

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