

Analysis of Effect of Heat-Setting Temperatures on Crimp Parameters in Polypropylene Single-Fibres via Favimat-Robot

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Abstract
The study on the effects of heat-setting temperature on crimp parameters of Polypropylene (PP) single-fibres was initiated by a non-woven manufacturing industry. The study is therefore important as it is addresses the real need raised by the industry to have a better comprehension of effects of heat-setting temperatures in order to optimize and develop a superior end-product. The exploratory research was conducted on non-conventional single-fibre tester Favimat-Robot (Technico), Germany at the Textile Physical testing Laboratory of Vakgroep Textielkunde Universiteit Gent (Ghent University), Belgium. Testing of PP single-fibres was limited to the following crimp parameters: Crimp Force, Crimp Length, Crimp Extension, Crimp Amplitude and Number of Crimps per cm. The collected data was statistically analyzed by the Analysis of Variance test ANOVA, using STATGRAPHICS Centurion XVI.II software, while chart was generated using Microsoft excel program. Major findings of this study reviled that all crimp parameters show a high variation. The study also revealed that the Number of Crimps per cm is increasing with increased temperature, while Crimp Length and Crimp Amplitude are decreasing with increased temperature. From the results it can be also concluded that neither of heat-setting temperatures had a clear effect on Crimp Force and on Crimp Extension. Two crimp parameters-Crimp Extension and Number of Crimps per cm-showed statistically significant difference. For more definite conclusions, the study recommends, in further research-experiments, to break the temperature-range into smaller segments, and to increase subject-temperature from two to five, by incorporating 125,130 and 135^o C.
Keywords: single fibre, Polypropylene, crimp, Favimat, testing.

1. Introduction

1.1. Polypropylene fibres

Polypropylene (PP) is a man-made fibre (a thermoplastic polymer) which, because of its intrinsic properties (it does not absorb water, it has low density, low thermal conductivity, high heat distortion temperature, transparency, flame resistance, dimensional stability, good resistance to different chemicals, and it does not irritate skin, etc.), is increasingly penetrating new markets, and sometimes, at the expense of other polymers (Mansfield, 1999). This is why there is a need in industry of PP fibres for developing new products with new or better properties.

Throughout the history, of the development of man-made fibres, there has always been an explicit tendency to produce fibres which are, as far as possible, similar to properties of natural fibres. One of these desirable properties is the crimping ability and their resulting bulkiness. Crimp is already inherently present in natural fibres; however, it must be artificially introduced into man-made fibres.

1.2. Crimp definitions and function

One of the main disadvantages of man-made fibres is their flat geometry and smooth surface. Straight, slick synthetic fibres would not have sufficient cohesion for carding, combing, drawing, roving, and spinning. Fibre crimp imparted to man-made fibres, which are initially straight, makes it possible to process these fibres with existing machinery designed for natural fibres. The crimping of melt-spun fibres is mainly done by thermo-mechanical means. Texturing methods have been developed to introduce crimp into man-made fibres, while False-twist texturing method being the most common process. These methods incorporate the mechanical deformation of a straight filament into a crimped form, followed by a heat-setting of the deformed configuration. The crimp in man-made fibres can be set, partially set or unset (Stafford, 1977).

Crimp in a textile strand is defined as the undulations or succession of waves, curls, bends or twists along the fibre length, induced either naturally during fibre growth, mechanically, or chemically (ASTM Standards 1996; Brown, 1955). Crimp in a fibre is, thus, considered as the degree of deviation from linearity of a non-straight fibre (Kleinheins et.al., 1975; Alexander, et.al., 1956). Crimp for staple man-made/synthetic fibres is typically two-dimensionally triangular. Parameters currently used to characterize crimp are based on the geometric shape of the fibre crimp, as crimps per length of fibre or as the difference between the lengths of the straightened and crimped fibre (expressed as a percentage of the straightened length), or as the mechanical response of the fibre to an applied force (Baur-Kurz, 2000).

1.3. Importance of crimp (Problem statement and research justification)

Fiber crimp characteristics and behaviour is an important parameter for processing performance and product quality. Crimp also contributes essentially to the properties of intermediate fiber assemblies, yarn and finished fabrics (Rogowin, 1982; Ehrler& Mavely, 1983; Textechno FAVIMAT brochure).

Crimp is required in staple fibre processing systems (opening, blending, carding, and web formation) and contributes to fibre bulk. The crimp of a fibre is crucial to its process-ability, especially for the preparatory processes. Crimp provides the gripping of the fibre to the wired cloths of the equipment. A fibre with very high crimp is difficult to process due to the high resistance to mechanical opening. High crimp also creates drafting problems because the drafting force required increases with increasing crimp (Klein, 1994). Too much crimp, in addition, may cause neps during processing and make drafting difficult (Cook, 1984). These neps can reduce fibre mobility and causes difficulty during formation; hence result in lower fabric strength and entanglement. Low crimp fibres, on the other hand, are also hard to process because there is insufficient gripping to the wired cloths. If the crimp is too low the web will break from the lack of cohesion. In addition to this, the crimp affects the loft and tensile properties of the finished fabric. Crimp also provides the cohesive strength of the fibrous web before it is bonded, which is important when transporting the fibre between processes (Bauer-Kruz , 2000).

Fibre crimp improves the following desirable properties of yarns and fabrics, such as knits, wovens and nonwovens: Wool-like aesthetics and visual appearance; Warm, dry, soft handle without slickness; Bulk, loft, hairiness, voluminosity, lightness, tuft; Covering power of yarns and filling capacity of fibres in assemblies; Greater extensibility, compressibility, recovery, elasticity and resilience; Better wrinkle resistance and recovery; Less flexural rigidity, better drape; Good thermal isolation, air permeability, moisture absorption, and higher wear comfort due to porosity (ASTM Standards, 1996; Bauer-Kruz , 2000; Riggert et.al., 1977; Klein, 1994; Miller, 1999; Itoh & Komori, 1991). Crimp is also affects Elongation, Heat Conductivity, Compression Resiliency (The ability to spring back to original thickness after being compressed). Crimp in synthetic staple fibres is a major contributor to processing performance and product properties such as web cohesion and fabric bulk (Baur-Kurz, 2000).

Fabric characteristics such as fullness, bulk, soft handle and high insulating capabilities can be achieved by using fibers with set crimp. Partially-set and unset crimp fibers are most often used for short-staple processing to improve the process-ability of the fibers. They enable easier opening, an improvement in card-ability and a reduction in drafting problems. Partially-set and unset crimped fibers also help to create a better web because the fibers are able to interlock with each other (Klein, 1994).

The crimp of the textile fibres is very critical to determine its properties and voluminisity. In nonwoven processes, crimp and crimp retention during processing are major contributors to processing efficiency, cohesion, fabric bulk and bulk stability (Oxenham & Shiffler, 1997). The microscopic characteristic of the nonwoven fabric is totally depends on the linearity and length of the crimp and the amplitude of the crimp (Singha& Singha, 2013). Fibres used for dry-laid nonwovens typically have medium to high crimp (Temafa , 2006). A comprehensive literature survey on crimp can be found in Baur-Kurz (2000) reference.

In the view of the above, this study was designed to investigate the affect of heat-setting temperatures on the crimp characteristics of single PP fibres. The fibres are to be used in nonwoven textiles and it is of the essence that crimp in these fibres are optimized. This study is important as it will potentially contribute to the body of knowledge on characterization of crimp in single-fibres, which it turn may progress the design of superior PP textile end-products.

2. Materials and Methods

2.1. Parameters tested

The single-fibre crimp testing parameters were limited to the following:

(1) *Crimp extension* (The difference in distance between two points on an un-stretched fibre and the same two points when the fibre is straightened under specified tension). It is expressed as a percentage of the un-stretched length.

(2) *Crimp length* $\boldsymbol{l_c}$, (the average length of fibre in one crimp), which expressed by the following formula (Brand, & Scruby, 1973):

$$l_c = \frac{1}{2}\overline{\lambda} \quad [mm] \text{ or } [inch]$$

(3) *Number of Crimps* (Fibre crimp is the waviness of a fibre and is expressed as waves or number of crimps per centimeter);

(4) *Crimp amplitude* (the maximum distance of a crimp bow from the zero axes), expressed as the ratio of the difference of extended length L_0 and crimped length Lc of a fibre, in percent of the extended length of the fibre L_0 (See Fig.1). Since the measurement of the amplitude of single crimp bows is practically impossible, average crimp amplitude of the fibre is derived geometrically with Pythagoras from length measurements of the crimped and the

un-crimped fibre (Kleinheins, 1975).

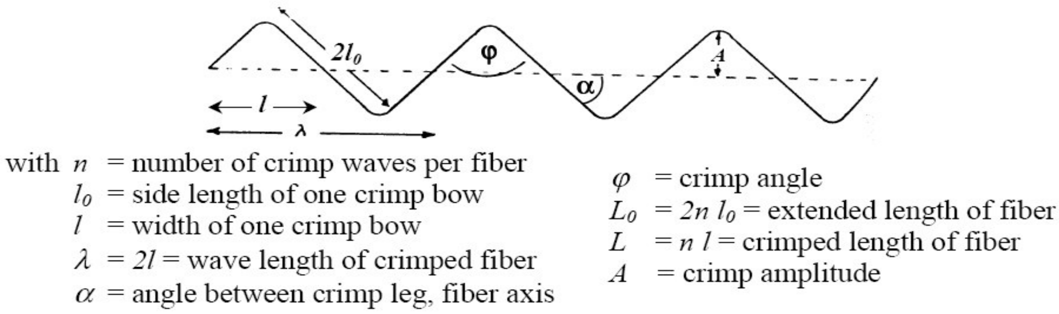

Figure1. Idealized geometry of the crimped fiber (Brand& Kende, 1970)

(5) The *crimp force* F_0 is either approximated as the force corresponding to the elongation at the intersection of the prolonged Hookean slope line with the horizontal axis, or as the force where the curve peels-off from the straight Hookean slope, see Figure 2. It is considered as the force necessary to un-crimp the fibre (Alexander et.al., 1962)

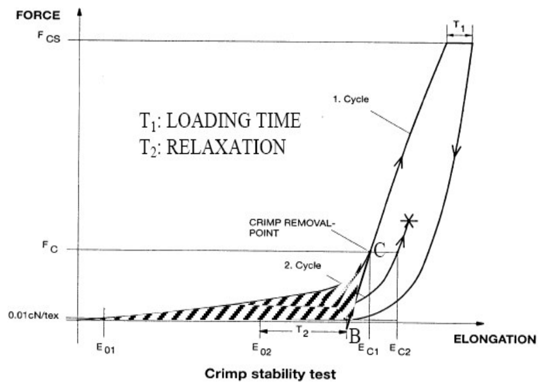

Figure 2: Force-Extension Curve in the Crimp Stability Test (Evans& Montgomery, 1953).

2.2. Subject- Samples

PP fibres were being produced by the same manufacturing company, on the matching equipment, under the similar processing conditions, of the same linear density and within the limited time-frame. An oven with controlled heating-rate was used (the temperature inside the oven was monitored using hp 3497 Data acquisition system).

Three sets of representative samples of PP single-fibres were prepared in accordance with BS 2545(subject-sample #1- reference; sample#2- set at 120ºC, and sample#3- set at 140 º C).

Fifty fibres (on average) from each of the subject-samples were tested according to the Favimat-Robot Standard Test procedure (Textechno, 1999). In particular, for sample #1- 55 single-fibres were tested (5 tests were reported as not possible), while for sample# 2- 59 tests were conducted, out of which 9 tests reported as not possible. For sample# 3- 52 tests were done (2 tests were reported as not possible).

2.3. Equipment and settings used.

Testing of single-fibres was conducted at Textile Physical testing Laboratory of Vakgroep Textielkunde Universiteit Gent (Ghent University), Belgium. The Favimat-Robot (Textechno) single-fibre tensile tester (see Fig. 3) was used to test crimp parameters (due to its excellent length- and force resolution (down to 0.1 μN)). The Favimat-Robot is semiautomatic, microprocessor-controlled testing equipment, working according to the principle of constant rate of extension (DIN 51221, DIN 53816, and ISO 5079). Opto-electronic sensor integrated in the FAVIMAT enables the creation of a digital image of the crimped fibre, which is held between the two clamps, and the subsequent evaluation of the crimp geometry regarding crimp number and crimp amplitude. For comprehensive procedure of testing and conditioning used, on Favimat, refer to Starovoytova, et.al. (2015). Pre-calibration was done according to Textexhno (1999).

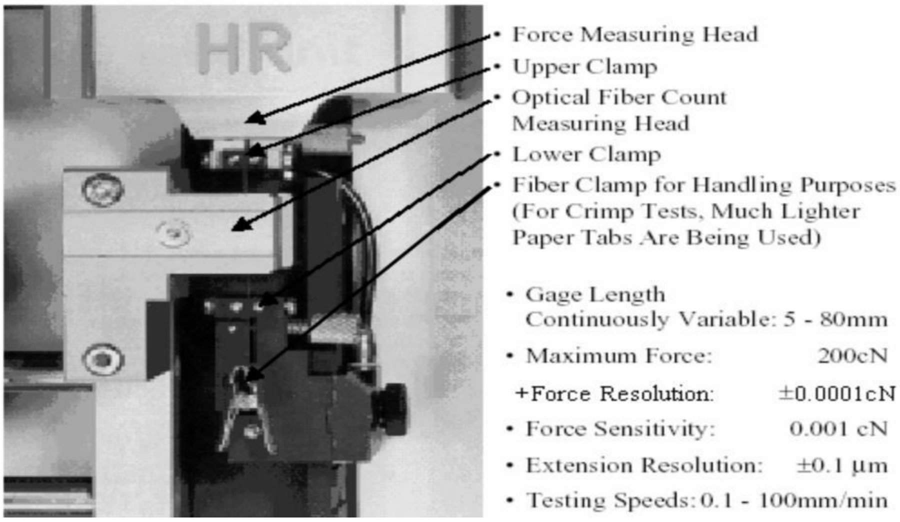

Figure 3: Favimat-Robot single-fibre tester (Bauer-Kurz, 2000).

Settings used: Favimat-Robot with load cell 210 cN, Gauge length 20mm, and Nominal L.D. 16.00 dtex. For crimp test **(**test speed 20 mm/min, recovery time 5 sec, crimped status at 0.010 cN/tex, crimp overload 3.0 cN/tex, and margin 0.020mm), while for crimp number **(**sensitivity 0.10 mm, and pretension 0.01 cN/tex) was used. Crimp number is determined through an optical-electrical sensor that evaluates the fibre under 0.03cN/tex. Linear density test (Test speed 20 mm/min, and Pretension 0.80 cN/tex).

2.4. The sequence of testing

Before testing, specimens were conditioned, without any stress, in standard atmosphere (20 ± 2 °C, 65 ± 2 % relative humidity) for at least 24 hours. Twenty-five fibres (one full magazine) of the three samples were tested twice using the Favimat-Robot Standard Tensile Test procedure (Textechno, 1999).

Single PP fibres (black in color) were carefully removed from the bulk sample with tweezers in order to minimize any fibre stretching or crimp pullout before the test. A small tuft of fibres from one temperature-group was laid onto a white velvet board. Using forceps, a single-fibre was randomly separated from the group of fibres and placed in the Favimat-Robot magazine for testing. To assist handling, a paper clip (<3 mg) was attached to the fibre end before clamping it in the measuring unit. In order to measure the individual fibre count without disturbing the actual crimp removal test, the following procedure was used: First, the fibre was stressed up to a target load at a constant rate of extension. The target load was then applied for a defined time period, and the fibre was released again at a constant rate. A load of 0.001cN/tex was applied for a defined time period. The fibre was then stressed again, at a constant rate of extension, up to a pre-set tension for the count measurement, which was then completed according to vibro-scopic method ASTM D1577 (ASTM Standards, 1996).

The sequence of a crimp test with count measurement on the FAVIMAT-Robot is as follows (Bauer-Kurz, 2000):

1. Fibre is pre-tensioned with paper weight (approx. 0.01cN/tex)
2. Load sensor at upper clamp is calibrated to zero
3. Fibre is clamped (initial gage length e.g. 20 mm)
4. Position of lower clamp is adjusted, so that fibre is exactly pre-tensioned with 0.001 cN/tex referred to nominal count
5. Actual crimp test starts:
    -- Lower clamp moves downwards at constant rate of extension (e.g. 20 mm/min)
    -- Until preset "crimp force" (e.g. 1 cN/tex) is reached.
    -- Lower clamp moves upwards
    -- Until preset gage length is reached
6. Count test is done:
    -- Fibre is loaded at a predefined rate
    -- Fibre is excited acoustically & resonance frequency is detected
7. Fibre is loaded until it breaks
8. Lower and upper clamp open, fibre drops
9. Lower clamp moves upwards to initial position

Note: Out of the 5 crimp parameters, the data for Crimp Force, Crimp Amplitude and Number of Crimps were generated (print format) by Favimat-Robot for each of the tested fibres, while Crimp extension and Crimp Length were calculated by the Textechno software for all of the three subject-samples.

2.5. Data analysis' tools

The collected data was analyzed by Analysis of Variance ANOVA test, using STATGRAPHICS Centurion XVI.II software, while charts were generated using Microsoft excel program.

3. Results

The following Table 1, 2 and 3 show the crimp test results for sample#1, sample#2, and sample#3 respectively.

Table 1: Results for sample#1

Statistics	-N-	-X-	-S-	-CV-	-Q(95%)-	-MIN-	-MAX-
Linear density	1	16,00dtex					
Crimp extension	50	11,89%	4,55	38,29	1,29	3,85	26,05
Crimp Force	50	1,80cN	0,35	19,34	0,10	1,22	2,71
n Crimps	50	2,72/cm	0,80	29,53	0,23	1,24	5,77
Crimp length	50	1,82mm	0,54	29,85	0,15	0,80	3,96
Crimp amplitude	50	0,50mm	0,20	39,90	0,06	0,24	1,44

Table 2: Results for sample#2

Statistics	-N-	-X-	-S-	-CV-	-Q(95%)-	-MIN-	-MAX-
Linear density	1	16,00dtex					
Crimp extension	50	8,61%	3,57	41,43	1,01	0,95	15,81
Crimp Force	50	1,59cN	0,36	22,67	0,10	0,97	2,71
n Crimps	50	2,66/cm	0,96	36,25	0,27	1,18	4,92
Crimp length	50	1,94mm	0,71	36,43	0,20	0,95	4,18
Crimp amplitude	50	0,56mm	0,35	61,93	0,10	0,21	1,76

Table 3: Results for sample#3

Statistics	-N-	-X-	-S-	-CV-	-Q(95%)-	-MIN-	-MAX-
Linear density	1	16,00dtex					
Crimp extension	50	6,84%	2,80	40,88	0,79	1,41	13,92
Crimp Force	50	1,53cN	0,41	26,50	0,12	1,05	2,89
n Crimps	50	2,96/cm	0,78	26,38	0,22	1,79	5,85
Crimp length	50	1,65mm	0,41	24,69	0,12	0,83	2,55
Crimp amplitude	50	0,49mm	0,29	59,72	0,08	0,20	1,72

4. Data Analysis

Figure 4 shows the mean values ("central tendency") for the crimp subject-parameters (generated by Microsoft Excel program).

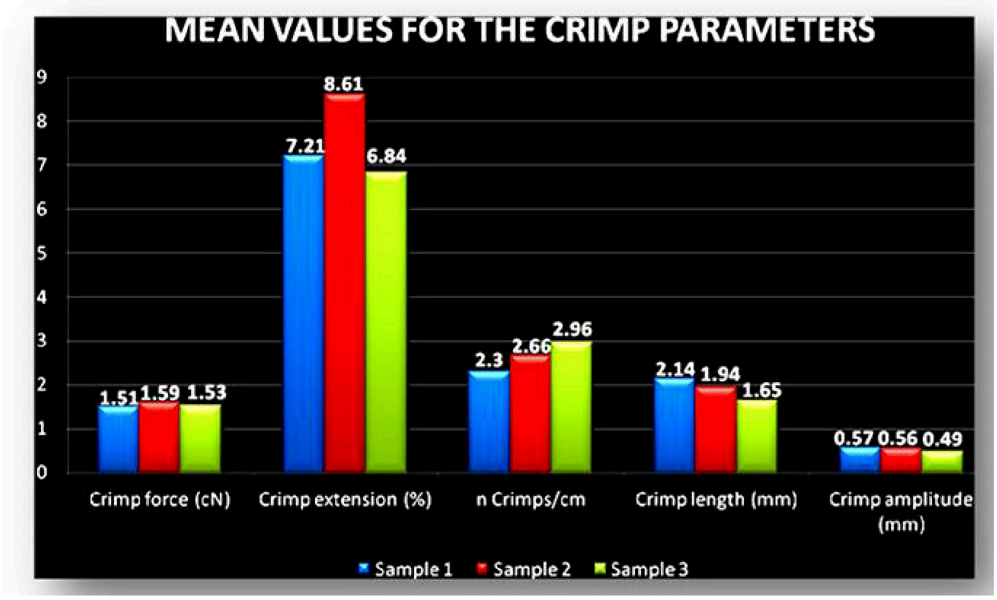

Figure 4: Mean values for the crimp subject-parameters

The following scatter plots and means graphs were generated by STATGRAPHICS Centurion XVI.II software. Figure 5 shows Scatter plot for Crimp Force; Figure 6- Crimp Extension, while Figure 7 shows Number of Crimps per cm results. Table 4 shows the results of ANOVA data analysis.

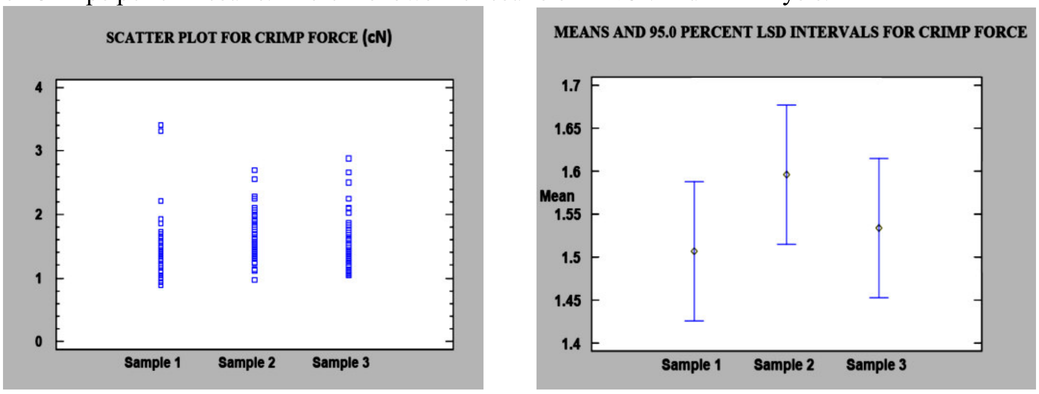

Figure 5: Crimp Force results

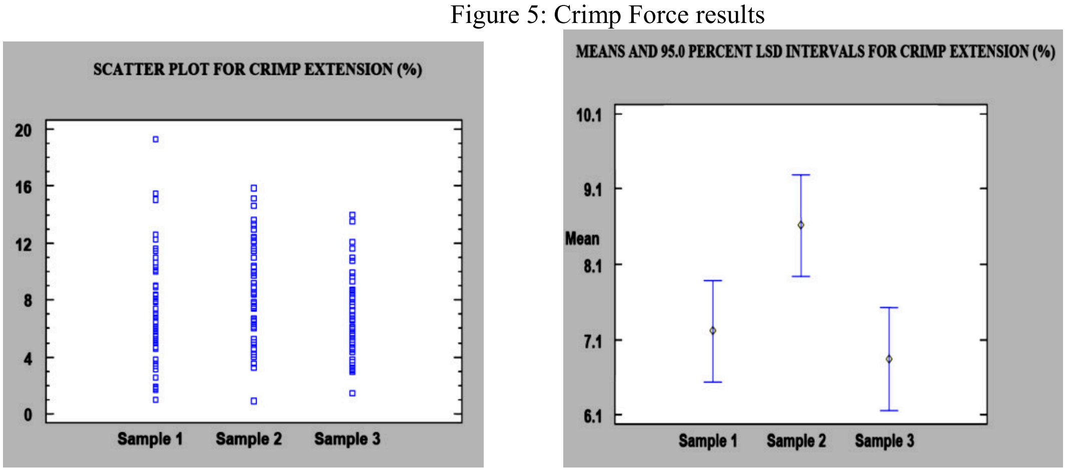

Figure 6: Crimp Extension results

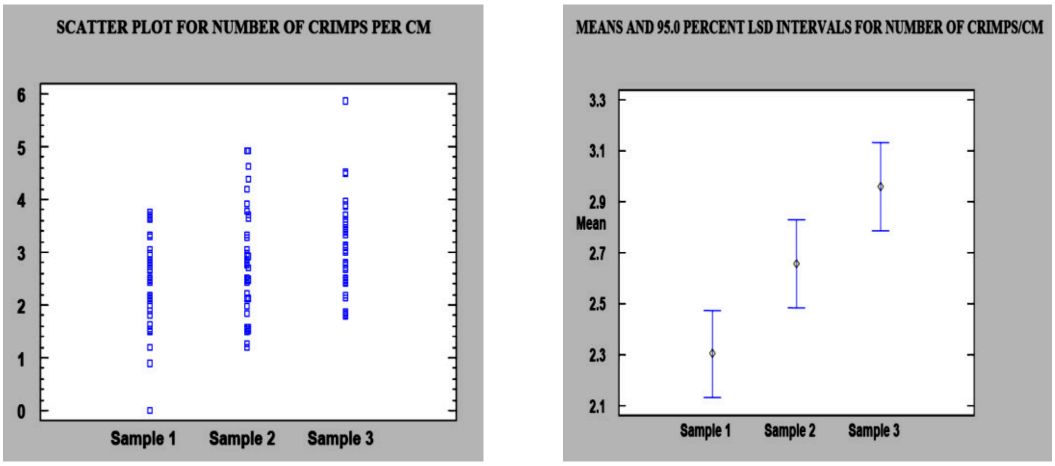

Figure 7: Number of Crimps results

Table 4: Summary of Analysis of Variance ANOVA test-results

Parameter	F-Ratio	P-Value
Crimp force (cN)	0.62	0.5384
Crimp extension (%)	3.70	0.0270
n Crimps/cm	7.13	0.0011

5. Discussions and Recommendation

From Tables 1, 2 and 3, the first observation that should be made is that all crimp parameters show a high variation. For Crimp Amplitude it is the highest, ranging CV from 39.9 to 61.93; the next highest CV is for Crimp Extension (38.29-41.43); followed by Crimp Length (24.69-36.43); Number of Crimps (26.38-36.25); and the least variation with CV ranging from 19.34 to 26.5 is observed for Crimp Force. The fiber damage and breaking was observed in the PP single-fiber testing (according to Favimat self-report, 16 fibes (9.6%) were broken or damaged), contributing to the variability in test-results. The high variability (intra-individual) is confirmed by other authors (Baur-Kurz, 2000; Foulk& Mcalister, 2002; Shenai, 1988).

Figure 4 revealed that the Number of Crimps per cm is increasing with increased temperature, while Crimp length and Crimp Amplitude is decreasing with increased temperature. From the results it can be also concluded that neither of heat-setting temperatures had a clear effect on Crimp Force and on Crimp Extension.

From Table 4 it is revealed that only the Crimp Force shows P-values greater than 0.05 hence we can conclude that there is no statistically- significant difference between the means of the three variables at the 95% confidence level however, Crimp Extension and Number of Crimps per cm give P-values less than 0.05, therefore there is a statistically-significant difference between the means of the 3 variables at the 95.0% confidence level.

This concise study was restricted to just two subject-temperatures (120°C and 140 °C) and in addition, it is manifested high variability of its test-results, accordingly, the study was incapable to achieve the required level of conclusiveness, and consequently, to categorically identify the optimum heat-setting temperature and to ascertain any influences of heat-treatment temperatures on crimp parameters of PP single-fibres. The study, therefore, recommends, in further research-experiments, to break the temperature-range into smaller segments by increasing subject-temperature from two to five, with inclusion of 125,130 and 135° C. In addition, a separate study should investigate the reason (s) behind high breakage- and damage-rates during testing of PP fibres.

6. Conclusion

The influence of heat-treatment temperatures on PP single-fibres has been studied through the high-resolution and -sensitivity testing equipment FAVIMAT-Robot by Textechno. It was observed that all crimp parameters show a high variation. The study also revealed that the Number of Crimps per cm is increasing with increased temperature, while Crimp Length and Crimp Amplitude are decreasing with increased temperature. From the results it can be also concluded that neither of the heat-setting temperatures had a clear effect on Crimp Force and on Crimp Extension. Two crimp parameters-Crimp Extension and Number of Crimps per cm-showed statistically-significant difference.

The study recommends, in further research-experiments, to break the temperature-range into smaller segments, and to increase subject-temperatures from two to five, by adding 125,130 and 135° C.

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