Investigation of deformation properties of textured multifilament PES yarns

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ABSTRACT – REZUMAT

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In the process of texturing, smooth filaments are formed into crimpy yarns. By combining thermal and mechanical action, thermoplastic fibres acquire a permanent wavy shape.

Since textured multifilament yarns, formed from POY PES filaments, produced on machines with high-temperature heaters, are insufficiently studied, this paper analyses the deformation characteristics of yarns produced in industrial conditions using different process parameters (primary heater temperature, yarn speed, yarn stretching, peripheral speed of friction discs). Special attention is paid to the characteristics at the elastic limit, then at the creep limit, yield and breaking of multifilament textured yarns. A method is proposed which can determine the key points of deformation in the process of stretching textured polyester multifilament yarn, as well as the relationship between the values of force and elongation at the limits of elasticity, creep, end of creep zone, yield and break.

Keywords: *textured yarn, false twisting, elastic limit, creep limit, yield point, breaking force*

Investigarea proprietăților de deformare ale firelor multifilament texturate din PES

În procesul de texturare, filamentele netede sunt transformate în fire ondulate. Prin combinarea acțiunii termice și a celei mecanice, fibrele termoplastice capătă o formă ondulată permanentă.

Întrucât firele multifilament texturate, formate din filamente POY PES, produse pe mașini cu încălzitoare de temperatură înaltă, sunt insuficient studiate, această lucrare analizează caracteristicile de deformare ale firelor produse în condiții industriale folosind diferiți parametri de proces (temperatura încălzitorului primar, viteza firului, întinderea firului, viteza periferică a discurilor de frecare). O atenție deosebită se acordă caracteristicilor la limita elastică, apoi la limita de fluaj, deformarea și ruperea firelor texturate multifilament. Se propune o metodă prin care se pot determina punctele cheie de deformare în procesul de întindere a firului multifilament de poliester texturat, precum și relația dintre valorile forței și alungirii la limitele de elasticitate, fluaj, capătul zonei de fluaj, deformarea și ruperea.

Cuvinte-cheie**:** *fir texturat, torsiune falsă, limită elastică, limită de fluaj, punct de deformare, forță de rupere*

INTRODUCTION

In the process of texturing, the yarn is exposed to high temperatures and tensile and torsional forces, which affect the structure of the yarn and thus its properties (geometric, physical-mechanical, physical-chemical, etc.) [1, 2].

Modern technological solutions of frictional texturing by false twisting, are characterized by short heating zones with increased temperatures on the heaters and with a shortening of the heating time.

Texturing parameters significantly affect the properties of textured multifilament yarn, and thus their behaviour in subsequent processes of production of textile materials. The tensile forces of textured multifilament yarn in the production processes of textile materials significantly affect the final quality of the finished products. Poor quality of textile materials is very often obtained, although all preconditions in the process of preliminary design have been met. The reasons for such shortcomings should be sought in the irregularities in defining the tensile forces of textured multifilament PES yarns in the production processes of textile materials. The problem is especially pronounced in the texturing of partially oriented PES filament (POY – Partially Oriented Yarn), about which there is not enough data in the literature. Data from the literature mainly refer to data from laboratory conditions [3–5]. In paper [6], the influence of the parameters of the false twisting texture process on the structure and crimping properties of textured multifilament PES yarns produced in industrial conditions on a machine with high-temperature heaters were analysed.

The literature also contains information on the influence of texturing process parameters on the properties of multifilament POY PES yarns produced on texturing machines with classical primary heaters [7–10].

The literature offers a lot of information on the texturing of stretched polyester filament (FOY – Fully Oriented Yarn) which is less sensitive to changes in the parameters of the texturing process [11]. Also, there is information on the application of different texturing processes: Fully Oriented Yarn texturing procedures [12, 13].

In addition, the possibility of using recycled polyethylene terephthalate to make filament textured yarns was investigated and the properties of recycled PET filament yarns were compared with filament yarns made of new fibre-grade PET [14].

Since the properties of textured multifilament PES yarns produced on machines with high-temperature heaters are insufficiently studied, in this study the influence of texturing process parameters on the deformation properties of textured PES multifilament yarns produced in industrial conditions was analysed. Experiments in industrial conditions should enable the selection of optimal parameters of the texturing process, with the aim of increasing productivity and achieving energy savings. The obtained results should contribute to the economy of production of multifilament textured PES yarns.

MATERIALS AND METHODS

The experimental material was made in industrial conditions. Polyester multifilament yarn is produced on a machine for stretching friction texturing with high-temperature heaters: FTF-15 (ICBT, France). Technical-technological characteristics of the machine are: maximum speed of texturing: 1500 m/min; length of the first heater: 1.050 m; length of the second heater: 1.60 m; cooling zone: 1.24 m; friction aggregate: ICBT aggregate 1-5-1; working (5 pcs.) PU discs; C profile.

Samples of textured PES yarns of yarn count 167f36x1 dtex and 165f36x1 dtex were produced from POY PES multifilament of yarn count 278f36x1 dtex, manufactured by TWD Fibers (Germany). The POY polyester filament (poly (ethylene terephthalate)) used in this study is partially oriented with a very low degree of crystallinity (less than 5%), so its structure and properties can vary greatly by changing the parameters of the texturing process. A total of 108 industrial tests were performed, during which the texturing speeds (*v*) were changed, as follows: 500 m/min, 600 m/min, 700 m/min, 900 m/min, 1000 m/min and 1100 m/min. Then, the primary heater temperatures (*T*) of 350°C were applied; 400°C and 450°C, elongation coefficient (*i*) 1.667 and 1.687, and peripheral disk speed ratio and yarn speed (*D/Y*) of 2.15; 2.20 and 2.25. The temperature of the second heater had a constant value of 180°C.

The breaking characteristics of the experimental material were determined on an automatic dynamometer in accordance with the standard EN ISO 2062:2009. The breaking speed is a constant 500 mm/min. Using typical software, the typical force-tensile curves for the tested textured yarn pattern are defined. Typical curves are represented in the form of a function of a ninth-degree polynomial, with the coefficients of the determination being about 0.999 (figure 1).

By the analysis of the flow of the elongation force function, are determined the elastic limit (F_1, ε_1), the creep limit (F_2, ε_2), the end of the creep zone (F_3, ε_3), the yield after the creep zone (F_4, ε_4) and the break (F_5, ε_5) of experimental material (figure 1). In the case of textile materials, we are mainly talking about zones in which some kind of deformation dominates. For textured multifilament yarns, the given limits depend on the properties of the starting multifilament, but also on the process parameters of yarn production.

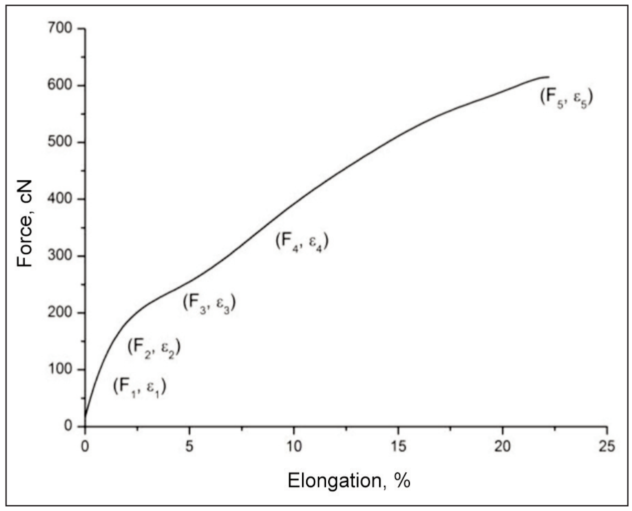

Fig. 1. Curve $F(\varepsilon)$ of multifilament polyester yarn

When stretching the yarn, the crimps, which were formed in the process of texturing, are initially straightened. Initially, a higher slope of the curve is noticeable i.e., a faster increase in force in relation to the stretching of the textured yarn to the point (F_1, ε_1). This point simultaneously represents the end of the elastic zone. Immediately after the elastic limit is the creep limit (F_2, ε_2). During further stretching, significant changes occur in the structure and all the way to the point (F_3, ε_3) there is a noticeable decrease in the slope of the force-elongation function. Then the slope increases again to the point (F_4, ε_4) and finally decreases until the interrupted textured yarn at the point (F_5, ε_5).

The elastic limit defines the recommended allowable load of textured yarns at which irreversible deformations of the material will not occur. The elastic limit of textured multifilament yarns was determined by analysing the flow function of tensile forces. By defining the local maximum of the first derivative of the function, where the second derivative of the function is equal to zero, the elastic limit is determined, as well as the parameters of forces and elongation at the elastic limit (F_1, ε_1).

The creep of textured multifilament yarns occurs by applying a load that causes stress in the yarn above the elastic limit. It is determined at the point of local minimum of the second derivative of the function i.e., at the corresponding zero of the third derivative of the function. At a given limit, the values of force and elongation at the creep limits are determined (F_2, ε_2). The creep limit of textured yarns is the upper acceptable load limit, to which the yarn can be subjected in subsequent technological processes, while the properties of the yarn are still acceptable for the production of textile products.

The creep zone begins at the creep limit and lasts until the textured yarn stops stretching faster and begins to provide significant resistance to the tensile force again. The end of the creep zone is determined at the point of a minimum of the first derivative of the function i.e., at the point where the second derivative of the function is equal to zero (F_3, ε_3).

Upon completion of the creep, the multifilament textured PES yarn again provides greater tensile resistance and the slope of the tensile force curve increases. This increase in force lasts until the moment when significant changes in the structure of monofilaments occur again due to stretching. The yield point after creep is determined at the point of local maximum of the first derivative of the elongation force function i.e., the zero of the second derivative of the function at a given point. This point on the graph (F_4, ε_4) can represent the maximum stress that the textured multifilament yarn will withstand in the processes of exploitation, to deform, but still not break.

Further stretching causes significant changes in the structure of the textured multifilament yarn, destruction of individual monofilaments and finally breaking of the multifilament yarn, which is marked by a dot (F_5, ε_5) on the graph (figure 1).

RESULTS AND DISCUSSION

In order to get the impression of changes in the values of force and elongation at the elastic limit, creep limit, end of creep zone, yield and break limits, graphs were chosen to show the given changes at the same ratio of peripheral disk speed and yarn speed (2.15) and the same stretching in the process of texturing (1.665).

Force and elongation were registered at the elastic limit of textured PES multifilament yarns. Based on the obtained results, figure 2 shows graphs that indicate the influence of temperature and texturing speed of multifilament yarns on their properties at the elastic limit.

The results show that textured multifilament yarns produced at a primary heater temperature of 350°C have force values at the elastic limit generally higher than yarns produced at a primary heater temperature of 450°C. Also, the trend of increasing force at the elastic limit with increasing texturing speed up to 1000 m/min is observed in yarns produced using a primary heater temperature of 350°C, and then a decrease in force was registered, unlike yarns produced using a texturing temperature of 450°C, where force growth trend up to a texturing speed of 1100 m/min. Elongation values at the elastic limit are generally higher for yarns produced by applying a higher texturing temperature.

The creep limit defines the upper allowed load limit of textured polyester yarns in the following technological processes of its processing.

The values of force and elongation were registered at the creep limit of textured polyester multifilament yarns. Based on the obtained results, Graphs are given in figure 3 showing the influence of the speed and temperature of texturing on the values of force and elongation.

The results show that in the case of textured multifilament yarns produced at a primary heater temperature of 350°C, the values of the force at the creep limit are higher than the yarns produced at a texturing temperature of 450°C. In addition, the trend of increasing force at the creep limit with increasing texturing speed up to 1000 m/min is observed in yarns produced using a primary heater temperature of 350°C, and then a decrease in force was registered, in contrast to yarns produced using a texturing temperature of 450°C, where is a trend of increasing force up to a texturing speed of 1100 m/min.

The values of force and elongation at the creep limit and elastic limit show analogous changes at appropriate texturing speeds and temperatures.

The end of the creep zone of the textured multifilament PES yarn ends at the moment when the tensile force begins to increase again faster than the elongation.

Figure 4 shows graphs indicating the influence of the primary heater temperature and texturing speed of

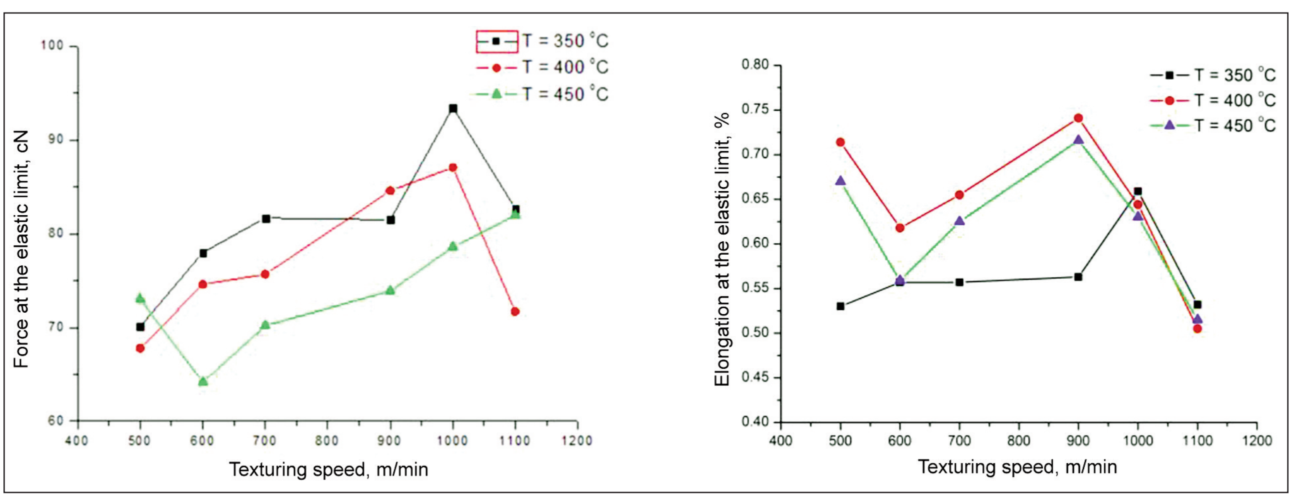

Fig. 2. The influence of texturing speed and temperature of primary heaters on force value and elongation at elastic limit (D/Y = 2.15, i = 1.665)

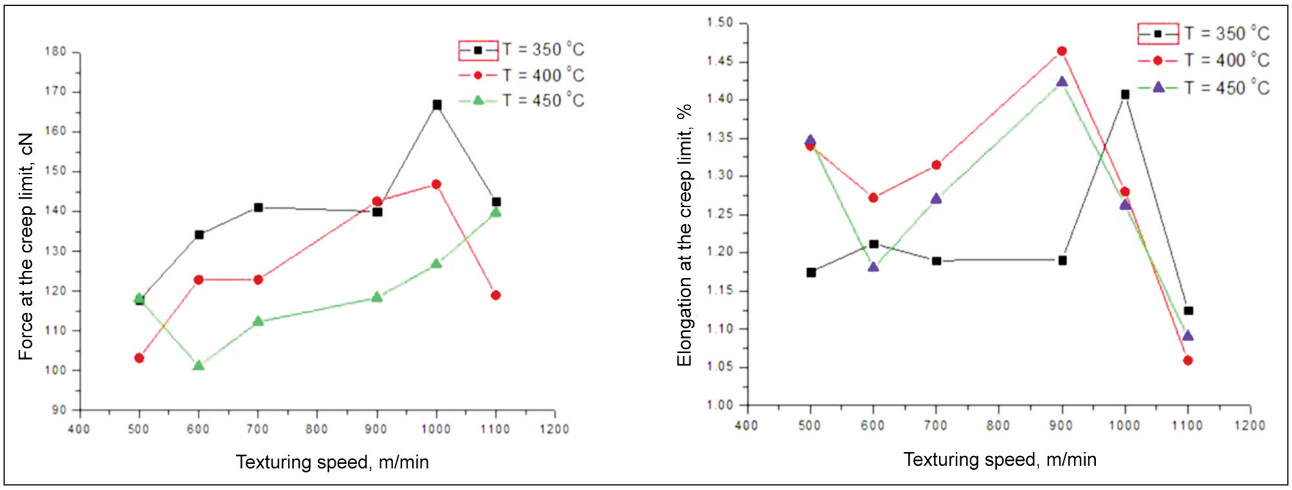

Fig. 3. The influence of texturing speed and temperature of primary heater on force value and elongation at creep limit (*D/Y* = 2.15, *i* = 1.665)

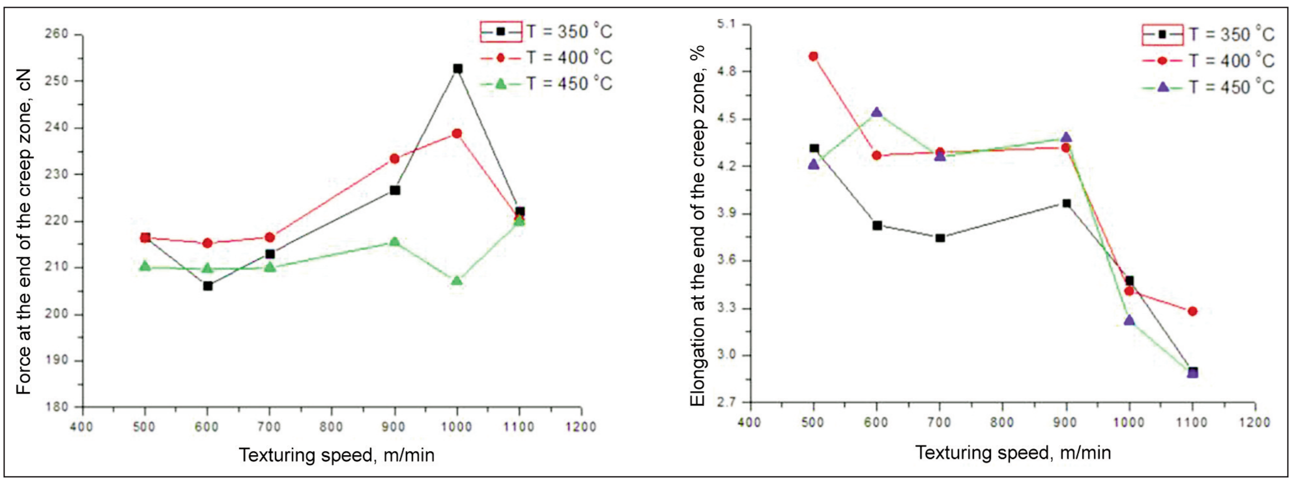

Fig. 4. The influence of texturing speed and temperature of the primary heater on the force value and elongation at the end of the creep zone (*D/Y* = 2.15, *i* = 1.665)

the polyester multifilament yarn on the properties at the end of the creep zone.

Analysis of the force value at the end of the creep zone at texturing temperatures of 350°C and 450°C shows that the force values are higher at a lower temperature, while the textured PES multifilament yarn elongates more at the end of the creep zone if produced at a higher primary heater temperature. Also, based on the obtained results, a significant decrease in elongation at the end of the creep zone can be stated in yarns produced at speeds higher than 900 m/min. The changes in the values of the forces in the creep zone are precisely the consequence of the uneven heat reception of the multifilament yarn, observed from the yarn surface towards the core. In his research, Eskin [15] showed that the difference in temperature of surface and core of yarn increases with increasing heater temperature, texture speed and decreases with yarn count, while the difference in temperature of yarn surface and core decreases with increasing heater length, which in this case is not a reason since these are HT heaters 1.050 m long.

Figure 5 shows graphs showing the influence of the temperature of the primary heater and the texturing speed of the polyester multifilament yarn on its properties at the yield point after creep.

The results show that textured yarns produced at a texturing speed of up to 900 m/min, at a primary heater temperature of 450°C have higher values of the force at the yield point compared to yarns produced at a primary heater temperature of 350°C. Elongations of textured yarns at the yield point have approximate values. Also, a trend of decreasing the value of force and elongation of the yarn at the yield point with increasing texturing speed was observed. There is a significant decrease in elongation at the yield point in yarns produced with texturing speeds above 900 m/min.

Figure 6 shows graphs showing the influence of primary heater temperature and texturing speed of polyester multifilament yarn on its breaking properties. Based on the obtained results, it can be noticed that the textured yarns produced at the temperature of the primary heater of 450°C have higher values of breaking force in relation to the yarns produced at the temperature of the primary heater 350°C. Textured multifilament PES yarns produced at a primary heater temperature of 400°C have higher breaking strength

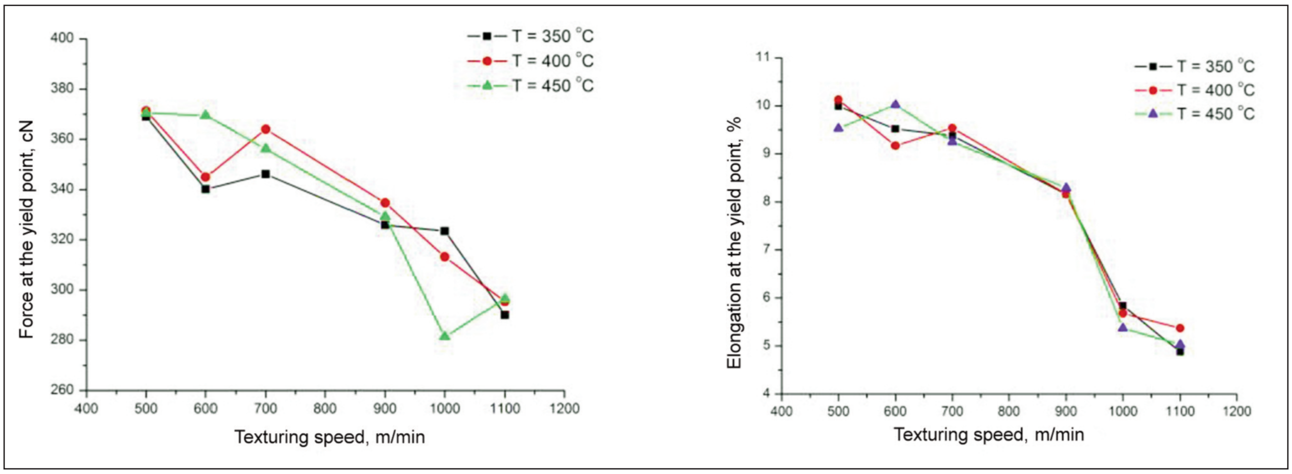

Fig. 5. The influence of texturing speed and temperature of the primary heater on the force value and elongation at the yield point (*D/Y* = 2.15, *i* = 1.665)

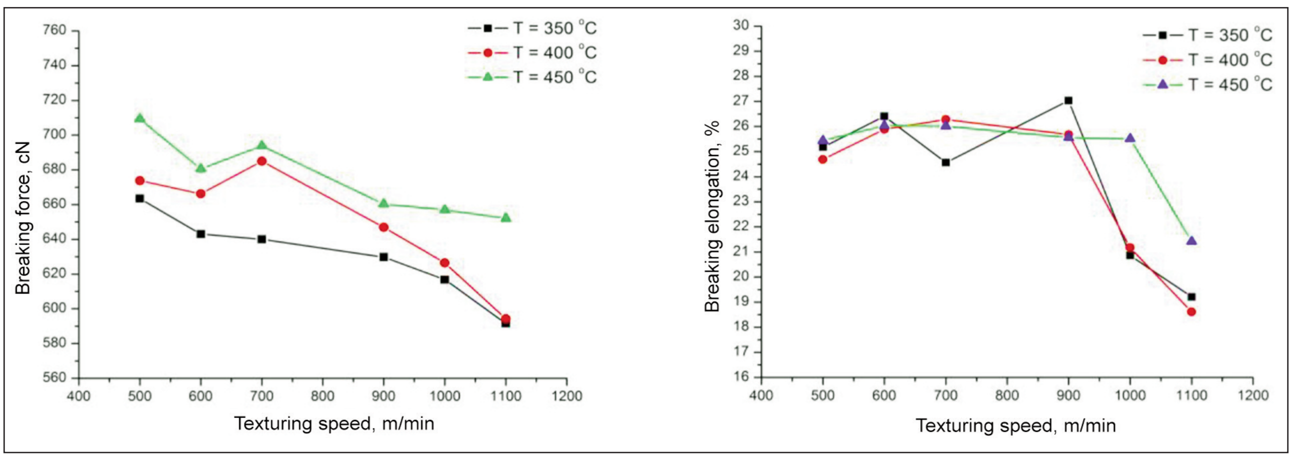

Fig. 6. The influence of texturing speed and primary heater temperature on breaking force and breaking elongation (*D/Y* = 2.15, *i* = 1.665)

values compared to yarns produced at a primary heater temperature of 350°C, and less than yarns produced at a primary heater temperature of 450°C. Also, a decrease in the breaking force of the yarn is observed with an increase in the texturing speed. Yarns produced at a texturing speed of 1100 m/min, at a primary heater temperature of 400°C, have approximate values of breaking force as yarns produced at a texturing temperature of 350°C, at the same other production process parameters. The breaking elongations of textured yarns have approximate values, with slightly higher values for yarns produced by a texturing temperature of 450°C at speeds of 1000 m/min and 1100 m/min. Also, there is a trend of decreasing the value of breaking force and breaking elongation with increasing texture speed above 900 m/min.

The higher temperature of the primary heater and longer exposure to temperature contribute to stress relaxation within the molecular chains of filament yarns, which affects the elasticity of the yarn. Simultaneous action of friction discs causes disorientation of macromolecular chains in the sense of twisting and bending in the process of false twisting, and higher temperature and longer retention of yarn in the heater contribute to greater disorientation of macromolecules in the process of false twisting and slightly lower value of force at the elastic and creep limit. Relaxation of internal stresses in the yarn due to a higher temperature and longer temperature exposure is expressed in the values of yarn parameters at the yield point after the creep zone. Namely, during stretching, in the process of breaking on the dynamometer, the macromolecules are oriented in the direction of the yarn axis. It is expected that multifilament textured yarns produced by applying a higher texturing temperature have a better orientation of the macromolecular chains at the yield point, due to the lower internal stress of the yarns thus formed. This may be the reason mainly for slightly higher values of forces at the yield point and higher values of breaking forces of textured multifilament PES yarns, produced by applying higher texturing temperatures. In order to preserve the mechanical characteristics of multifilament textured PES yarns, it is very important to define the allowable yarn loads in the following technological processes. Especially since all monofilaments of multifilament yarn could not absorb the same amount of heat, due to their position in the yarn, so their properties will differ enough that we

Table 1

PARAMETERS OF FUNCTION *a*, *b* FOR DETERMINING THE VALUE OF FORCE IN POINTS 1 TO 5					
Function	**$F = a \times \varepsilon^b$ (cN)**				
Parameters	**a**	**St.error**	**b**	**St.error**	**r^2**
v = 500 m/min; T = 350°C	94.99763	2.42722	0.60357	0.00889	0.99662
v = 500 m/min; T = 400°C	81.65465	2.32775	0.6616	0.00987	0.99652
v = 500 m/min; T = 450°C	88.03712	2.12453	0.64778	0.00832	0.99735
v = 600 m/min; T = 350°C	101.49837	3.02126	0.56914	0.01032	0.99444
v = 600 m/min; T = 400°C	94.26997	2.29022	0.60384	0.00835	0.99698
v = 600 m/min; T = 450°C	80.33149	1.77259	0.66029	0.00749	0.99811
v = 700 m/min; T = 350°C	99.92983	3.32977	0.57814	0.01173	0.99319
v = 700 m/min; T = 400°C	85.48915	2.00175	0.64161	0.00802	0.99768
v = 700 m/min; T = 450°C	88.13831	1.81877	0.63819	0.00707	0.99815
v = 900 m/min; T = 350°C	115.62203	3.14297	0.51605	0.00951	0.99358
v = 900 m/min; T = 400°C	109.67339	2.75136	0.54877	0.00882	0.99524
v = 900 m/min; T = 450°C	96.22174	2.64515	0.59987	0.00956	0.99558
v = 1000 m/min; T = 350°C	127.07795	2.19324	0.52338	0.00657	0.99676
v = 1000 m/min; T = 400°C	120.38161	2.14329	0.54593	0.00666	0.99702
v = 1000 m/min; T = 450°C	107.32115	3.00239	0.58121	0.01018	0.99416
v = 1100 m/min; T = 350°C	124.46485	1.87702	0.53296	0.00586	0.99755
v = 1100 m/min; T = 400°C	119.72414	1.50149	0.55417	0.00483	0.99849
v = 1100 m/min; T = 450°C	121.07555	2.22649	0.54629	0.00689	0.99687

cannot talk about the homogeneity of multifilament textured PES yarn. This inhomogeneity of the structure will in any case lead to variation in the quality of the multifilament yarn, to which special attention must be paid when predicting the properties of these yarns. A responsible approach to the analysis of the properties of textured multifilament yarns can achieve energy savings in the texturing process and contribute to the optimization of the production of yarns produced on machines with HT heaters.

In industry, a conclusion is often made about the quality of yarn, in terms of mechanical characteristics, only on the basis of its breaking characteristics. That is not a good solution. Knowing the values of forces and elongation at the limits of elasticity and creep of textured multifilament PES yarns gives a true picture of the values of forces that the yarn can be loaded in the technological processes of processing into textile materials. In that way, the properties of the yarn will be preserved and thus the good quality of the finished product will be ensured in accordance with the design of the textile material and the requirements of the standard.

Taking into account all the above, the optimal parameters of the texturing process must be chosen as a compromise solution having in mind the texturing temperature, texturing speed, stretching of multifilament yarn in the manufacturing process, the ratio of peripheral disk speed and yarn speed, POY PES multifilament quality, machine condition and crimp characteristics of the textured yarn. The obtained results showed that the partially oriented polyester yarn used in this paper can be textured at significantly higher texturing speeds compared to the standard texturing speeds (up to 700 m/min) used for processing the yarns of tested yarn count.

Figures 7, *a–f* show the relationship of parameters at the limits of elasticity, creep, end of creep zone, yield and break. Therefore, only images showing the correlation of the analysed parameters in textured multifilament yarns produced at a temperature of 400°C are presented. The values of force (cN) and corresponding elongations (%) at given points are described by equations:

$$F = a \cdot \varepsilon^b \text{ (cN)} \quad (1)$$

Table 1 gives the parameters of function *a*, *b* for determining the value of force in points 1 to 5 (figure 1), at texturing temperatures of 350°C, 400°C and 450°C and speeds of 500 m/min, 600 m/min, 700 m/min, 900 m/min, 1000 m/min and 1100 m/min i.e., for all 108 samples made in industrial conditions. The obtained results (at different texturing speeds and temperatures) include all samples where the values of *D/Y* are 2.15, 2.20 and 2.25, as well as stretching 1.665 and 1.685, since this range of changes did not have a significant effect on the deformation properties of the textured multifilament yarns analysed in this study.

The results are presented for textured multifilament polyester yarns produced using the appropriate primary heater temperature and texturing speed with a defined ratio of peripheral disc speed and yarn and elongation speed in the production process. The results can be applied to predict the properties of textured PES multifilament yarns at appropriate production process parameters. In addition, the obtained results can be used to predict the properties of

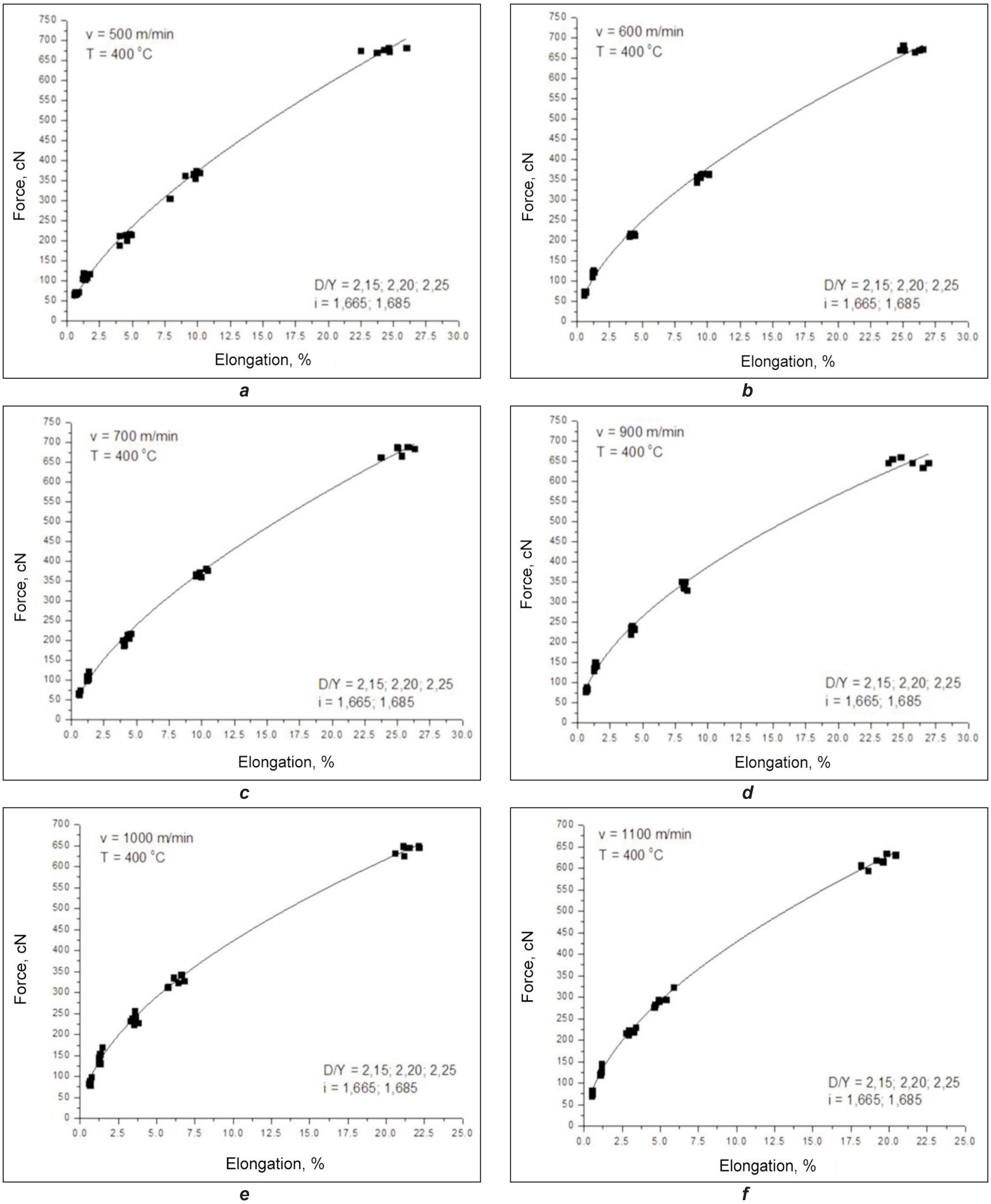

Fig. 7. Relationship of parameters at the limits of elasticity, creep, end of creep zone, yield and break: *a* – relationship of parameters (v = 500 m/min, T = 400°C); *b* – relationship of parameters (v = 600 m/min, T = 400°C); *c* – relationship of parameters (v = 700 m/min, T = 400°C); *d* – relationship of parameters (v = 900 m/min, T = 400°C); *e* – relationship of parameters (v = 1000 m/min, T = 400°C); *f* – relationship of parameters (v = 1100 m/min, T = 400°C)

textured multifilament PES yarns in subsequent production processes into textile products.

CONCLUSION

Knowledge of the deformation characteristics of textured multifilament PES yarn is very important from the aspect of predicting its behaviour in the processes of production into textile materials and products, as well as predicting the behaviour of textile products during exploitation.

The key points of deformation of textured multifilament PES yarn in the stretching process are defined and a method for determining the elastic limit, creep limit, end of creep zone and yield point after creep is proposed.

In addition, the results showed that the texturing temperature has an analogous influence on the values of the forces at the elastic and creep limits. It was found that lower texturing temperatures have a more favourable effect on the values of force at the elastic limit and force at the creep limit, while higher temperature values generally have a more favourable effect on elongation at the elastic limit and creep limit.

The influence of temperature on the value of the force at the yield point and on the breaking force of the yarn is opposite in relation to the changes in the value of the force at the elastic limit and at the creep limit. Namely, higher texturing temperatures generally give slightly higher values of the force at the yield point and higher values of the breaking force.

In order to contribute to the development of a method for predicting the behaviour of textured multifilament PES yarn in the next phases of processing, an equation is proposed that correctly connects the key points (force-elongation at the elastic limit, at the creep limit, at the end of the creep zone, at the yield point and yarn break) in the process of stretching the yarn, until it breaks.

The purpose of textured multifilament PES yarn and the tensile force of yarn in technological processes of production into textile materials must be observed simultaneously and the technological parameters of yarn texturing adjusted accordingly. In this way, energy savings in the texturing process can be achieved and contribute to the optimization of the production of textured multifilament PES yarn on machines with high-temperature heaters.

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