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Mathematical Modelling of the Parameters of Braided Textile Tapes

Matematično modeliranje parametrov za izdelavo prepletenih tekstilnih trakov

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Abstract
Braided textile materials are widely used in many industries and agriculture. Braided tapes are used for domestic purposes, in the food industry, in construction, in medicine, in aircraft manufacturing, in electrical engineering, etc. Every braided product must correspond to a unique group of parameters and properties, depending on the initial manufacturing parameters. The production of braided tapes is still insufficiently explored. In the process of designing and manufacturing products with specified parameters, it is necessary to substantiate the formation of braided products. The manufacture of products with specific parameters and properties, and the creation of rational technological modes for that production represent urgent scientific issues to be addressed. One way to solve this problem is to conduct factorial experiments. This article thus presents the results of a factorial experiment, during which the following input parameters were determined based on preliminary studies: type of raw material, the linear density of raw materials and speed of removal of the product from the formation zone. The following were chosen as output parameters: breaking load, breaking elongation, the linear density of tapes, product width and the number of strands per 10 mm. The limits of factor variation were determined for four types of raw materials. Based on the results of the processing of the obtained experimental data, linear mathematical models were developed. The results of the verification of mathematical models indicated that they adequately describe the process of braiding tapes within the intervals determined by the conditions of the experiment. We thus established a connection between the factors of the braiding process and the properties of braided tapes.
Keywords: braided tapes, braiding process, mathematical modelling

Izvleček
Prepleteni tekstilni materiali se pogosto uporabljajo v različnih industrijah in kmetijstvu. V gospodinjstvu, živilski industriji, gradbeništvu, medicini, letalski industriji, elektrotehniki itd. uporabljajo prepletene trakove. Vsak prepleteni izdelek ima edinstvene lastnosti, ki so odvisne od začetnih proizvodnih parametrov. Sama izdelava prepletenih trakov je še vedno premalo raziskana. Pri načrtovanju in izdelavi prepletenih trakov s specifičnimi parametri je treba definirati način oblikovanja njihove strukture. Izdelava trakov in ustvarjanje gospodarnih tehnoloških postopkov povzročata znanstvene probleme, ki jih je treba premagati. Eden od načinov reševanja teh problemov je faktorski poskus. V članku so predstavljeni rezultati faktorskega poskusa, pri katerem so bili na podlagi predhodnih študij določeni vhodni (su-

rovinska sestava, dolžinska masa niti in hitrost odvajanja oblikovanega traku) in izhodni parametri (izbrane lastnosti končnega izdelka (traku): pretržna obremenitev, pretržni raztezek in dolžinska masa trakov, širina izdelka in število niti na 10 mm). Za štiri vrste izbranih surovin so bile določene meje variiranja faktorjev. Na podlagi rezultatov obdelave eksperimentalnih podatkov so bili razviti linearni matematični modeli. Rezultati preverjanja matematičnih modelov so pokazali, da ti ustrezno opisujejo proces izdelave prepletenih trakov v intervalih, določenih z eksperimentalnimi pogoji. Ugotovljena je bila povezava med dejavniki postopka prepletanja in lastnostmi prepletenih trakov.
Ključne besede: prepleteni trakovi, postopek prepletanja, matematično modeliranje

1 Introduction

The world is witness to the constant development and improvement of the design of braiding machines and their components. Modern technologies, including information technology, are being introduced in production practices. At the same time, there is a wide range of problems and certain issues which hinder further development that remain insufficiently explored. In addition, the number of scientific works relating to the processing of textile materials is small compared with other technologies.

In recent works, it has been determined that braided structures can be tailored for a particular application by choosing the right set of parameters in order to obtain the desired level of properties based on predictive modelling [1].

Problems relating to the mechanical aspects of the braiding process have been investigated for many years and are discussed below. There is a description and analysis of the forces acting in and around the braiding zone, yarn direction, yarn tension, take-off and braiding velocities, all of which affect the quality of braids. Also discussed are connections between the prediction of braiding angles and picks per length, depending on the take-off [2]. Works dedicated to development of 3D braiding technology can be singled out, as well as research regarding the development of 3D braiding technology in terms of fabric, braiding technology and equipment. [3, 4].

Interesting is the development and use of software. Computer programs have been developed that are capable of designing geometric models, including braiding products. These programs include WiseTex, TexMind Software and SolidWorks [5–7].

At the same time, the manufacturers of woven textile materials require modelling between the input parameters of the technological process and the physical and mechanical properties of the finished products.

Let us briefly consider the formation of a braided product. The thread forming the braided product moves simultaneously in two planes. The first movement is provided by the towing device, while the second is caused by the continuous movement of the spindle along its trajectory [2].

On preparatory equipment, raw materials (threads) are spun onto bobbins that are tucked into spindles. On the upper web of the machine, there is a system of horn gears with several notches into which the spindles are installed. The thread is unspun from the bobbin by a towing device and passes into the product formation zone – the place of braiding – where the threads of all systems form the product.

The trajectory of the spindle in the horizontal plane is called the move and is a set of connected alternating semicircles. Single-stroke and two-stroke are the most widely used machines.

In addition to the threads of the braiding system, braided tapes can include threads of the base system [8]. The warp threads occupy positions in the product along its axis inside the braid. The position of the braiding threads (Figure 1(a)) is characterized by the angle of inclination of the thread relative to the axis of the product (α), the number of strands per 10 mm and the characteristics of the weave repeat (L) [9]. The number of strands can be determined by the horizontal or vertical axis of a product. The number of strands along the horizontal axis is used very rarely; it is deemed sufficient to determine the number of strands along the vertical axis, on the track that is parallel to the axis of the product.

Conventionally, a weave repeat is the smallest number of threads forming a complete weave pattern [10]. By analogy with a braided structure, the weave repeat of a braided product is the smallest number of threads, in which the order of intersection of the threads of the braiding system is repeated [9].

Typically, the starting point, when determining the repeat (L) of the braided tape, is the point A_{n-1} (Figure 1(b)), which corresponds to the extreme

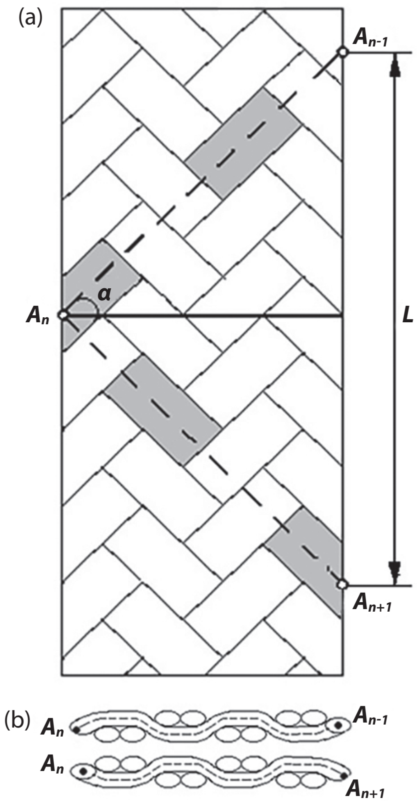

Figure 1: Schematic illustration of the structure of a braided product (a) and along its forming thread (b): angle to the axis of the product (α), distance of the pattern repeat (L), extreme points of the beginning (A_{n-1}) and end of repeat (A_{n-1}), and change of direction (A_n)

position that the thread axis can occupy. At the extreme points (A_{n-1}, A_n and A_{n+1}), the thread bends along the entire braid, changing the direction of movement to the opposite. Figure 1(b) presents a diagram of a section of a braided tape along the axis of the thread that forms it. In most cases, the threads in a braided product do cross not at a right angle, so cross-sectional images of the threads have the shape of an ellipse. For the convenience of depicting the section of the thread in the braid, we divide the repeat into two parts. All of the threads that form a braided tape cross twice in one repeat with other threads [11].

2 Methods

To study the mechanism of complex processes in the braiding of textile materials, it is necessary to establish the link between the factors of the process and the properties of the product, and present that link in a compact and convenient form with a quantitative estimation (in the form of a mathematical model). Traditionally, research methods in the textile industry are associated with experimentation. The methods of optimal experiment planning facilitate the use of mathematical apparatus, not only in the phase of processing the measurement results, but also for preparing and conducting research [12]. Four factorial experiments were carried out on a class 17 flat braiding machine (TP-17-3, produced by Tex-Inter Co. LTD). We chose four types of raw materials for the experiments: cotton thread (25 tex), polyester thread (34 tex), polyamide thread (29 tex) and fiberglass thread (68 tex). These types of raw materials are the most common used today in the production of braided tapes. Nevertheless, it should be noted that raw materials modified using modern methods can also be used to produce woven products [13, 14].

To study the process of braiding tapes using an experimental planning method based on preliminary studies, the following input parameters were determined: breaking load (N); breaking elongation (%); linear density (g/m); width (mm); and the number of strands per 10 mm (s/cm).

We chose the following factors to study braided tapes: type of raw material; equipment class; linear density of raw materials (tex); and product withdrawal speed from the formation zone (m/h).

All experimental tests were carried out according to current methods and standards [15–17].

3 Results

The limits of variation of the factors given in *Table 1* were determined for four types of raw materials and two classes of equipment.

Other parameters of the weaving process (such as the height of the braiding point, yarn tension and bobbin winding tension) during the experiment were within technological parameters.

The experimental plan and the obtained input parameters are shown in *Table 2*, where X_1 represents the linear density of the raw material (tex), X_2 represents product withdrawal speed from the formation zone (m/h), Y_1 represents breaking load (N), Y_2 represents breaking elongation (%), Y_3 represents linear density (g/m), Y_4 represents the number of strands per 10 mm (s/cm) and Y_5 represents product width (mm).

Table 1: Factors and their levels of variation in the braiding process

Type of raw material	Factors	Variation levels	
		-1	+1
Cotton thread	X_1 – linear density of raw material (tex)	25	100
	X_2 –product withdrawal speed from the formation zone (m/h)	57	142
Polyamide thread	X_1 – linear density of raw material (tex)	29	116
	X_2 –product withdrawal speed from the formation zone (m/h)	57	142
Fiberglass thread	X_1 – linear density of raw material (tex)	68	272
	X_2 –product withdrawal speed from the formation zone (m/h)	57	142
Polyester thread	X_1 – linear density of raw material (tex)	34	136
	X_2 – product withdrawal speed from the formation zone (m/h)	57	142

Table 2: Experimental plan and obtained input parameters in the braiding process

Type of raw material	Experiment number	Factor scores				Input parameters				
		Coded		Natural						
		X_1	X_2	X_1	X_2	Y_1	Y_2	Y_3	Y_4	Y_5
Cotton thread	1	1	1	100	142	238.3	19.2	1.84	2.80	7.6
	2	–1	1	25	142	43.15	9.8	0.40	3.70	4
	3	1	–1	100	57	218.3	23.6	2.02	6.58	8.9
	4	–1	–1	25	57	49.23	10.6	0.42	6.3	3.8
Polyamide thread	1	1	1	116	142	974.78	26.8	2.01	2.4	7.3
	2	–1	1	29	142	235.75	23.6	0.49	2.1	3.6
	3	1	–1	116	57	923.79	42.2	2.17	5.1	8.2
	4	–1	–1	29	57	242.64	18.8	0.50	6.2	4
Fiberglass thread	1	1	1	272	142	967.92	14.8	4.72	3	8.5
	2	–1	1	68	142	411.49	8.2	1.14	4.3	3.4
	3	1	–1	272	57	929.67	14	5.02	6.2	9.2
	4	–1	–1	68	57	421.3	10.2	1.25	5.8	4.8
Polyester thread	1	1	1	136	142	759.6	46.2	2.82	2.7	15.5
	2	–1	1	34	142	195.74	41.0	0.74	4	8.2
	3	1	–1	136	57	725.3	57.3	2.95	7.18	16.9
	4	–1	–1	34	57	193.39	37.4	0.72	7.36	8.7

The calculation of the coefficients of regression equations made it possible to obtain linear equations in encoded values. The resulting equations are given in *Table 3*, where X_1 represents the linear density of the raw material and X_2 represents the product withdrawal speed from the formation zone.
The model adequacy hypothesis was tested using Fisher's F-test. The results of the calculation of F-test values for the obtained linear models are shown in Table 4.

The calculated F-test values for the models range from 1.07 to 4.41, and do not exceed the table value of the F-test for a confidence interval of 0.95 and the number of degrees of freedom 1 and 16 equal to 4.49. Taking this into account, the hypothesis that the obtained models adequately describe the process of tape braiding was confirmed.
The significance of the coefficients of regression equations was verified by constructing a confidence interval. *Table 5* shows the results of the calculation of the confidence interval for each of the obtained models.

Table 3: Mathematical models of braided tape parameters obtained from the results of the experiment

	Type of raw material	Mathematic models
Breaking load (N)	Cotton thread	$Y_1 = 137.25 + 91.06X_1 + 3.48X_2$
	Polyamide thread	$Y_1 = 594.24 + 355.05X_1 + 11.03X_2$
	Fiberglass thread	$Y_1 = 682.60 + 266.20X_1 + 7.11X_2$
	Polyester thread	$Y_1 = 468.51 + 273.94X_1 + 9.16X_2$
Breaking elongation (%)	Cotton thread	$Y_2 = 15.80 + 5.6X_1 - 1.3X_2$
	Polyamide thread	$Y_2 = 27.85 + 6.65X_1 - 2.65X_2$
	Fiberglass thread	$Y_2 = 11.65 + 2.45X_1 - 0.45X_2$
	Polyester thread	$Y_2 = 45.48 + 6.28X_1 - 1.88X_2$
Linear density (g/m)	Cotton thread	$Y_3 = 1.17 + 0.76X_1 - 0.05X_2$
	Polyamide thread	$Y_3 = 1.29 + 0.80X_1 - 0.04X_2$
	Fiberglass thread	$Y_3 = 3.03 + 1.84X_1 - 0.103X_2$
	Polyester thread	$Y_3 = 1.808 + 1.078X_1 - 0.028X_2$
Number of strands per 10 mm (s/cm)	Cotton thread	$Y_4 = 4.844 - 0.156X_1 - 1.594X_2$
	Polyamide thread	$Y_4 = 3.95 - 0.2X_1 - 1.7X_2$
	Fiberglass thread	$Y_4 = 4.83 - 0.225X_1 - 1.175X_2$
	Polyester thread	$Y_4 = 5.31 - 0.37X_1 - 1.96X_2$
Product width (mm)	Cotton thread	$Y_5 = 6.075 + 2.175X_1 - 0.275X_2$
	Polyamide thread	$Y_5 = 5.775 + 1.975X_1 - 0.325X_2$
	Fiberglass thread	$Y_5 = 6.475 + 2.375X_1 - 0.525X_2$
	Polyester thread	$Y_5 = 12.325 + 3.875X_1 - 0.475X_2$

Table 4: Testing of the model adequacy hypothesis for braided tapes using the F- test

Parameter	Type of raw material	Variance of the adequacy of the mathematical model	Variance of the measurement of the parameter	Calculated F-test value
Breaking load	Cotton thread	170.04	38.95	4.37
	Polyamide thread	837.52	425.97	1.97
	Fiberglass thread	577.44	164.48	3.51
	Polyester thread	255.20	230.91	1.11
Breaking elongation	Cotton thread	3.24	1.80	1.80
	Polyamide thread	102.01	23.93	4.26
	Fiberglass thread	1.21	0.52	2.32
	Polyester thread	54.02	12.36	4.37
Linear density	Cotton thread	0.01	0.00	2.94
	Polyamide thread	0.01	0.00	1.17
	Fiberglass thread	0.01	0.00	3.52
	Polyester thread	0.01	0.00	2.74
Number of strands per 10 mm	Cotton thread	0.35	0.08	4.22
	Polyamide thread	0.49	0.11	4.31
	Fiberglass thread	0.72	0.17	4.35
	Polyester thread	0.31	0.09	3.35
Product width	Cotton thread	0.56	0.18	3.17
	Polyamide thread	0.06	0.06	1.11
	Fiberglass thread	0.12	0.09	1.42
	Polyester thread	0.20	0.12	1.64

Table 5: Confidence interval values for testing the significance of regression coefficients

Parameter	Type of raw material	Confidence interval value	
Breaking load	Cotton thread	3.323	5.857
	Polyamide thread	10.990	24.350
	Fiberglass thread	6.83	68.581
	Polyester thread	8.092	19.526
Breaking elongation	Cotton thread	0.714	1.107
	Polyamide thread	2.605	0.871
	Fiberglass thread	0.385	0.863
	Polyester thread	1.872	1.414
Linear density	Cotton thread	0.025	0.064
	Polyamide thread	0.037	0.031
	Fiberglass thread	0.027	0.221
	Polyester thread	0.024	0.046
Number of strands per 10 mm	Cotton thread	0.152	0.148
	Polyamide thread	0.180	0.108
	Fiberglass thread	0.217	0.166
	Polyester thread	0.163	0.180
Product width	Cotton thread	0.224	0.292
	Polyamide thread	0.126	0.170
	Fiberglass thread	0.156	0.174
	Polyester thread	0.187	0.194

A comparison of the absolute values of the coefficients of regression equations with the corresponding values of confidence intervals allows us to conclude that all the coefficients of regression equations are significant. The value and sign of the coefficient in the linear model, presented in encoded values, determine the influence of a particular factor on the parameter value.

4 Discussion

The value of the breaking load is most influenced by the linear density of the raw material. An an increase in linear density, within the interval determined by the conditions of the experiment and at a product withdrawal speed from the formation zone of 100 m/h, results in increase in the value of the indicator by 127–394%.

Figure 2 illustrates the breaking load response function of braided tapes made on a class 17 machine and the dependence of the breaking load on the linear density of the raw material at a fixed value of the product withdrawal speed from the formation zone (the factor varies within the intervals determined by the experiment).

An increase in the product withdrawal speed from the formation zone, within the intervals established by the conditions of the experiment, resulted in an increase in the breaking load by 5–20% (at a fixed value of the linear density of the raw material). It should be noted that tapes made of polyamide threads have the highest breaking load value, while tapes made of cotton threads have the lowest value.

The greatest influence on the value of the breaking elongation is exerted by the linear density factor of the raw material. An increase in that factor, within the values established by the conditions of the experiment, results in an increase in elongation by 32–178%. Figure 3 shows the planes of the response functions of the breaking elongation, as well as the dependency of the breaking elongation of braided tapes made from fiberglass thread and polyester thread at a product withdrawal speed of 100 m/h on the linear density of the raw material.

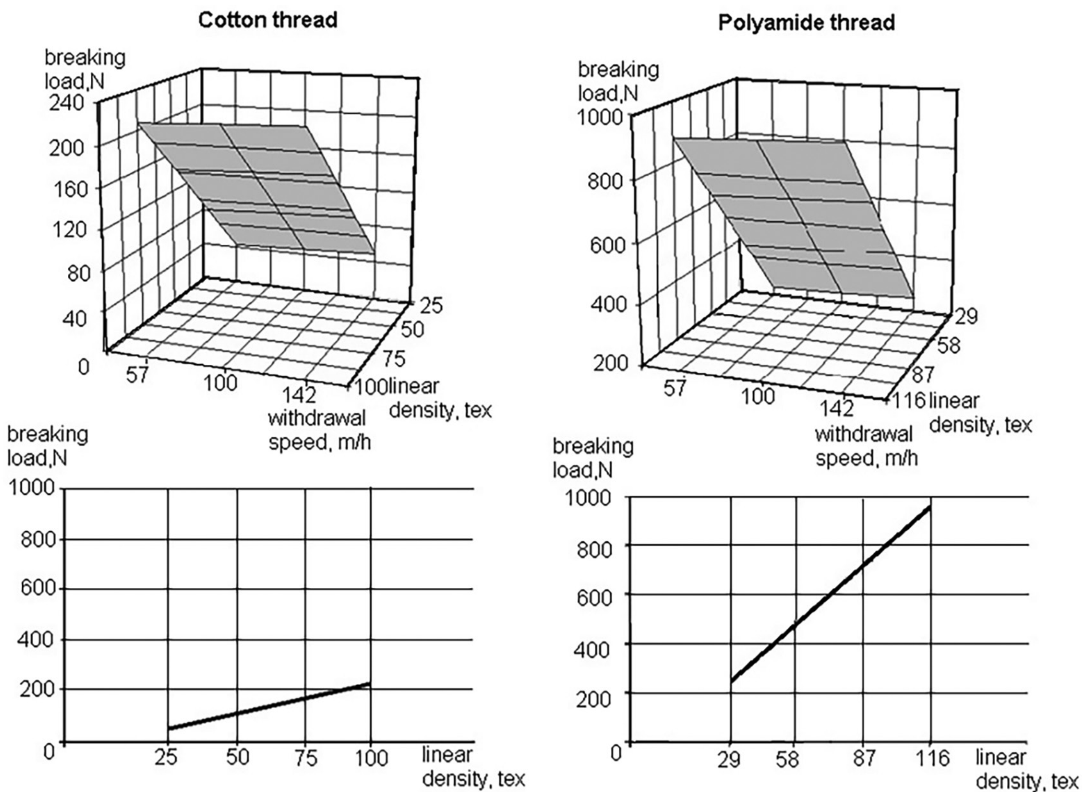

Figure 2: Planes of the response functions of the breaking load of tapes

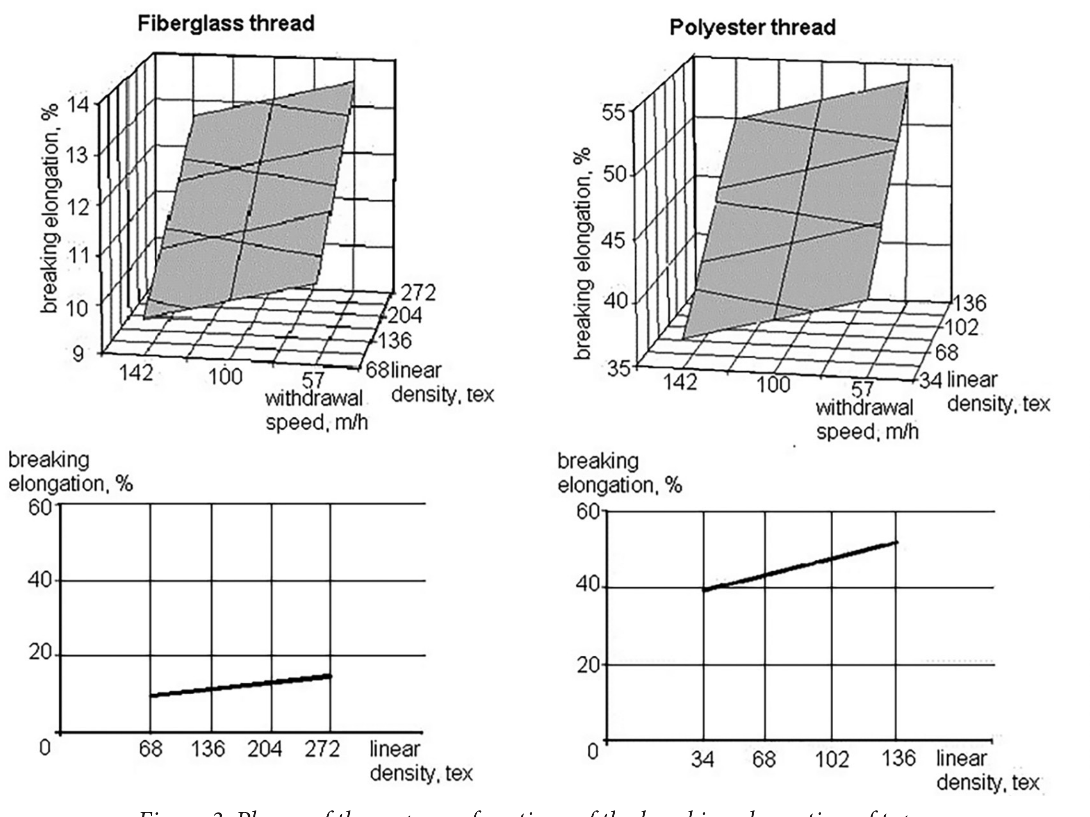

Figure 3: Planes of the response functions of the breaking elongation of tapes

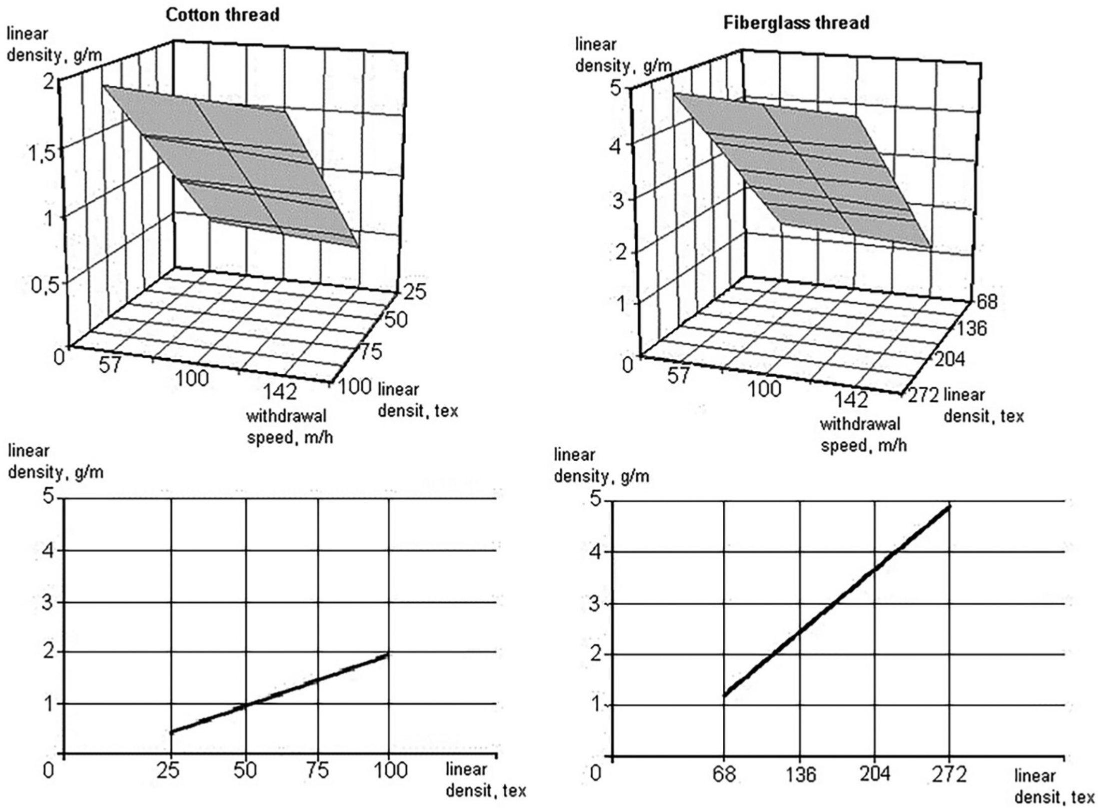

Figure 4: Planes of the response functions of the linear density of the tapes

An increase in breaking elongation by 7–19% is observed with a fixed value of the linear density of the raw material within the variation interval and a decrease in the product withdrawal speed from the formation zone.

The linear density of the product increases with an increase in the value of the linear density of the raw material factor by 295–390%. Figure 4 shows the planes of the response functions of the product linear density and the dependence of the linear density on the linear density of the raw material at a product withdrawal speed of 100 m/h. The graph is constructed according to linear equations characterizing the properties of tapes made from different types of raw materials.

The value of the linear density of the product decreases by 3–12% with an increase in the product withdrawal speed from the formation zone.

The greatest influence on the parameter of the number of strands per 10 mm of the product was exerted by the product withdrawal speed from the formation zone, an increase in which led to a decrease in the aforementioned parameter by 39–60%.A decrease in the number of strands per unit of length of the tape by up to 15% is observed up with an increase in the linear density of the raw material at a product withdrawal speed from the formation zone of 100 m/h.

The width of the tapes (Figure 5), *ceteris paribus*, increases by 87–123% with an increase in the linear density of the raw material and by 15% with a decrease in the product withdrawal speed from the formation zone. This indicator depends to a large extent on the linear density of the raw material.

5 Conclusion

Based on the data of full factorial experiments, linear models were developed that adequately describe the braiding process within the intervals determined by the conditions of the experiment. A connection was established between braiding factors and the properties of a braided product. Analysing the resulting linear models, we can determine the following. The value of the breaking load of the tapes is most influenced by the linear density of the raw material. An increase in linear density, within the interval determined by the conditions of the experiment and at a fixed product withdrawal

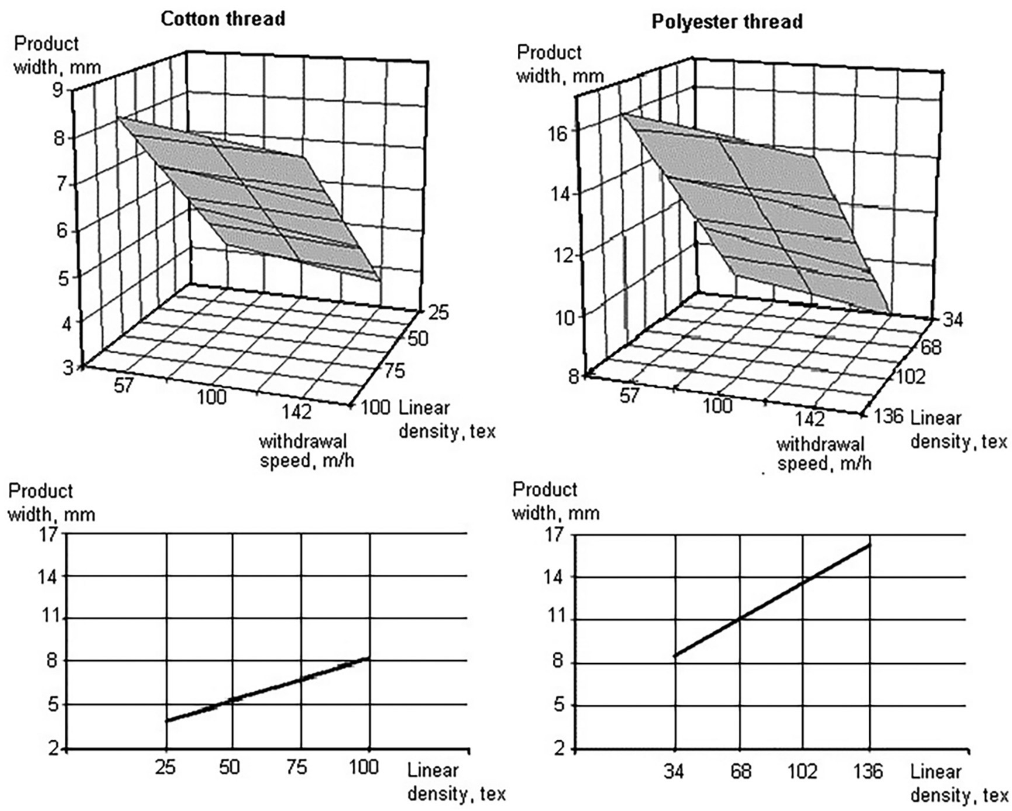

Figure 5: Planes of the response functions of the width of the tapes

speed from the formation zone within the interval, results in an increase in the value of the indicator by 127–394%. An increase in the product withdrawal speed from the formation zone results in an increase in the breaking load by 5–20%. The greatest influence on the value of the breaking elongation of the tapes is exerted by the linear density factor of the raw material, an increase in the value of which increases the elongation by 32–178%. An increase in breaking elongation of up to 19% is observed at a fixed value of the linear density of the raw material and a decrease in the product withdrawal speed.

The linear density of the tapes increases with an increase in the value of the linear density of the raw material by 295–390%. An increase in the product withdrawal speed from the formation zone results in a decrease in the value of the linear density of the product by up to 12%.

The greatest influence on the number of strands per 10 mm of tape was exerted by the factor of the product withdrawal speed from the formation zone, an increase of which led to a decrease in the parameter by 39−60%. A decrease in the number of strands per unit of length by 5–15% is observed with an increase in the linear density of raw materials.

The width of the tapes, *ceteris paribus*, increases with an increase in the linear density of the raw material by 87–123% and a decrease in the product withdrawal speed from the formation zone by 4–15%. The data obtained as a result of the studies carried out make it possible to optimally select the parameters of braiding and raw materials for the manufacture of products with the necessary properties at the design stage, which contributes significantly to improving the efficiency of the process of braiding textile materials.

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